Verification and Validation Testing of the Parachute Decelerator System Prior to the First Supersonic Flight Dynamics Test for the Low Density Supersonic Decelerator Program

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The Parachute Decelerator System (PDS) is comprised of all components associated with the supersonic parachute and its associated deployment. During the Supersonic Flight Dynamics Test (SFDT), for the Low Density Supersonic Decelerators Program, the PDS was required to deploy the supersonic parachute in a defined fashion. The PDS hardware includes three major subsystems that must function together. The first subsystem is the Parachute Deployment Device (PDD), which acts as a modified pilot deployment system. It is comprised of a pyrotechnic mortar, a Kevlar ballute, a lanyard actuated pyrotechnic inflation aid, and rigging with its associated thermal protection material (TPS). The second subsystem is the supersonic parachute deployment hardware. This includes all of the parachute specific rigging that includes the parachute stowage can and the rigging including TPS and bridle stiffeners for bridle management during deployment. The third subsystem is the Supersonic Parachute itself, which includes the main parachute and deployment bags. This paper summarizes the verification and validation of the deployment process, from the initialization of the PDS system through parachute bag strip that was done prior to the first SFDT.

Nomenclature

CFD = Computational Fluid Dynamics
CDR = Critical Design Review
Do = Nominal Parachute Diameter
DGB = Disk-Gap-Band
IMU = Inertial Measurement Unit
JPL = Jet Propulsion Laboratory
LDSD = Low Density Supersonic Decelerator
NAWCWD = Naval Air Warfare Center Weapons Division
NFAC = National Full-Scale Aerodynamics Complex
SFDT = Supersonic Flight Dynamics Test ("- number" suffix indicates which SFDT test)
SNORT = Supersonic Naval Ordnance Research Tracks
SSRS = Supersonic Ringsail
SSDS = Supersonic Disksail
PDD = Parachute Deployment Device
PDS = Parachute Decelerator System
PDV = Parachute Design Verification

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PMRF = Pacific Missile Range Facility
RTB = Rigging Testbed
TPS = Thermal Protection System
TV = Test Vehicle
V&V = Verification and Validation or Verify and Validate
V&Ved = Verified and Validated

I. Introduction

THE Low Density Supersonic Decelerator (LDSD) project has undertaken the task of developing a large Supersonic Parachute to provide improved capabilities for future Mars landed missions. NASA has identified the need for a new parachute system to support an increase in payload mass, target higher altitude landing sites, and improve landing accuracy. As Mars-bound spacecraft continue to get larger and the possibility of future manned missions arises, the state of the art in low-density supersonic parachutes must also advance. To date, all seven of the successful Mars landings have employed disk-gap-band (DGB) parachutes, which were based on a design that was developed in the 1960's and 1970's for the Viking Mars mission. While the success of the MSL parachute expands the DGB flight proven size envelope, it still falls short of the necessary drag performance that future missions are expected to require. To increase the parachute diameter requires a new parachute qualification and, to that end, the LDSD project is continuing the process of developing and flight-testing these supersonic parachutes. The first supersonic test of the proposed next generation supersonic parachute for Mars was successfully tested on June 28th, 2014 in the Supersonic Flight Dynamics Test #1(SFDT-1).[1]

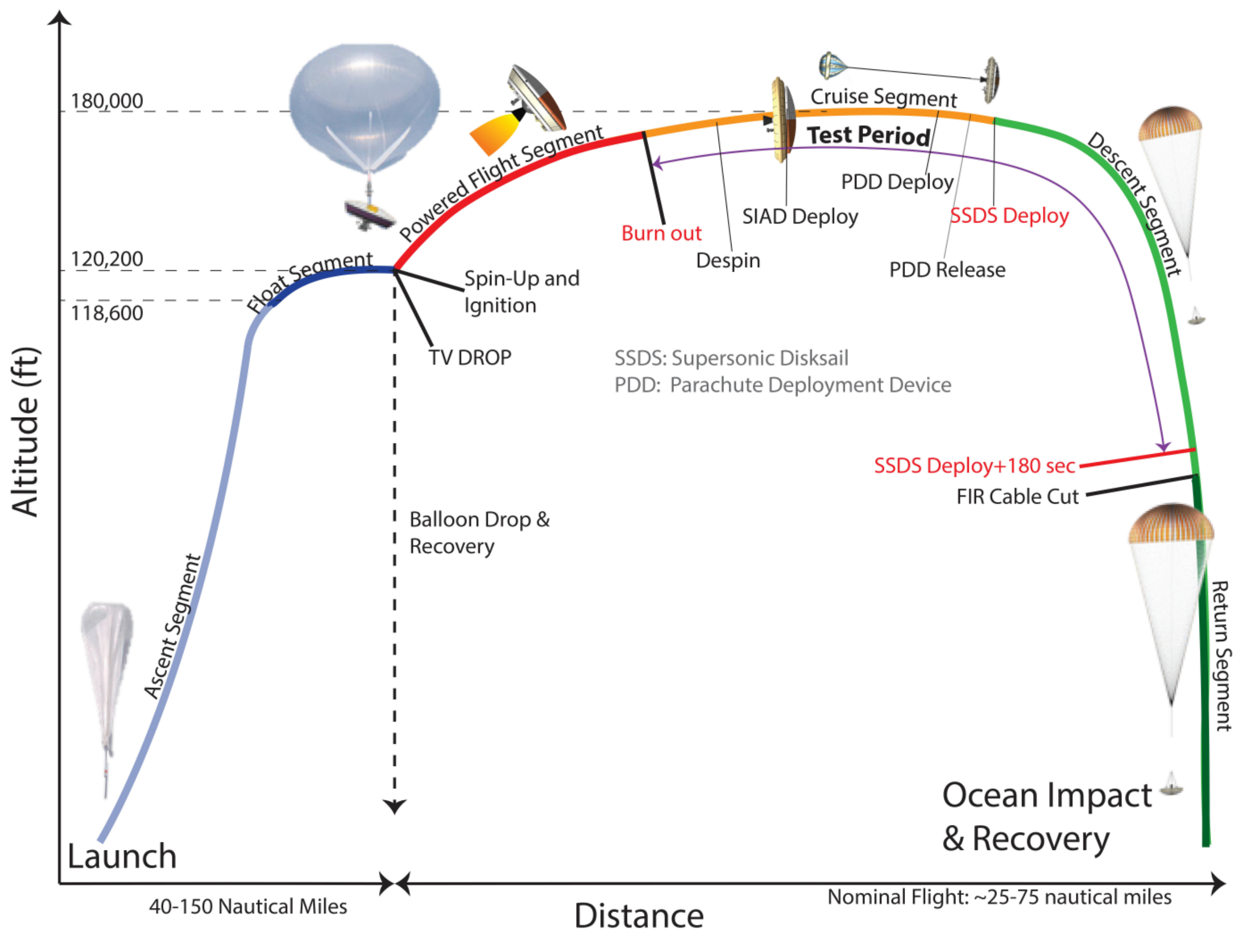

Figure 1: Overview of the LDSD Supersonic Flight Test Architecture

Figure 1 shows an overview of the SFDT. In this test, a large helium balloon is used to hoist a 4.7 m diameter blunt body test vehicle (TV) to an altitude of over 36 km. The test vehicle is released from the balloon, spun-up for stability, and a Star-48 solid rocket motor ignites. The motor accelerates the test vehicle to speeds over Mach 4 at an altitude of 50 km. Upon burn-out the vehicle is de-spun and the primary test phase begins. Shortly thereafter, the first of the technologies, a Supersonic Inflatable Aerodynamic Decelerator (SIAD) is deployed.[2] Later in the fight, the Parachute Deployment Device (PDD) is mortar fired, inflated, and subsequently used as a pilot device to extract and deploy the large supersonic parachute from the test vehicle.[3] The parachute decelerates the vehicle to subsonic conditions and the vehicle descends to the ocean for recovery.

SFDT-1 was conducted with a balloon launch from the Pacific Missile Range Facility (PMRF) on Kauai, Hawaii. The test successfully demonstrated all aspects of the integration and test, balloon launch, balloon operation, test vehicle operation, test vehicle flight, and recovery. The parachute was successfully deployed within the desired operational envelope and succeeded in becoming fully inflated, however in the midst of parachute inflation, at least three large tears were observed in the disk portion of the Supersonic Disksail (SSDS). This paper provides documentation of the Verification and Validation (V&V) program of the Parachute Decelerator System (PDS). The intent of the paper is to provide a comprehensive look at the V&V program as a whole and not provide detailed information about any specific V&V activity, but rather provides references where those specifics can be found. JPL and Pioneer Aerospace jointly provided the V&V program's oversight. Support for this program included many aerospace partners to perform the various required V&V activities. This paper presents these activities not in a chronological order in which they happened, but rather in the order each V&V process played in the PDS deployment phase.

II. Parachute Decelerator System

In order to understand the V&V process, one must first be provided an overview of the PDS hardware and an overview of deployment for the PDS. The PDS is comprised of the following hardware:

1) Parachute Deployment Device
   a) Mortar
   b) Ballute
   c) Inflation Aid
   d) Rigging and Thermal Protection

2) Supersonic Parachute Rigging Hardware
   a) Bridle Stiffeners
   b) Deployment Bags (Inner and Outer)
   c) Thermal Protection Hardware

3) Supersonic Parachute
   a) Canopy
   b) Suspension Lines
   c) Braided Riser Bridle

Prior to deployment, the PDS is stowed on the aft deck of Test Vehicle (TV). Figure 2 shows an overview of the PDS hardware and their configuration in the PDD deployed state, as well as in the final state with the parachute deployed.

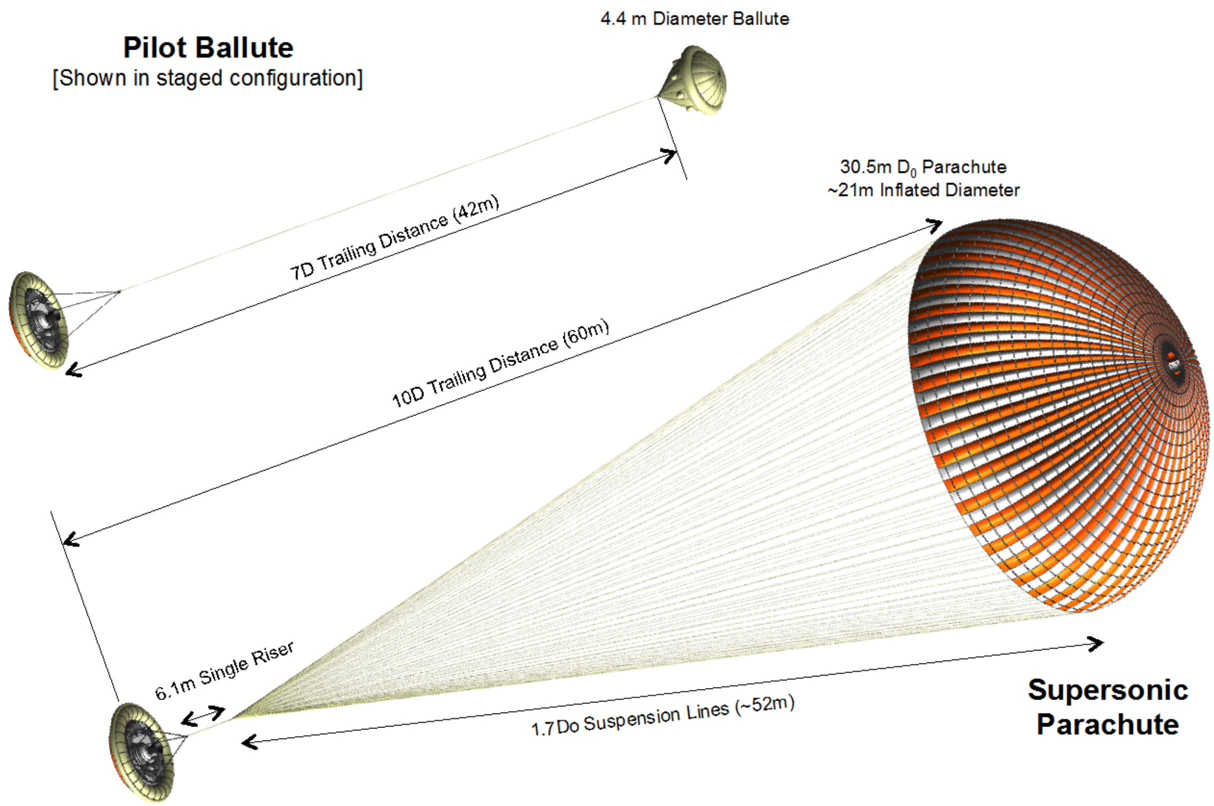

Figure 2: Parachute Decelerator System

The Ballute and SSDS are stowed in parachute cans that face toward the back of the TV. All deployments extract the next phase away from the vehicle. Figure 3 shows a storyboard of the following deployment phases:

Phase 1) A velocity trigger determined by the TV fires the PDD mortar, as well as line cutters, that prior to cut act as launch locks for the PDD bridles stowed on the aft deck and stowage box. Upon mortar fire, the packed portion of the PDD is ejected from the mortar tube. As the pack travels away from the TV, the PDD bridles start to stand up and the riser deploys out of the back of the mortar fired pack.

Phase 2) The mortar-fired pack continues to travel away from the TV. Once line stretch is achieved, the ballute begins to emerge from the parachute bag. The ballute continues to be extracted from the bag as the bag continues to strip off using its own inertia. Once the burble fence of the ballute extracts, two lanyards pull activation cords on the inflation aid and activate it. The inflation aid is located at the riser/ballute interface and when activated pyrotechnically expels aqueous methanol into the ballute's inner cavity, which flash vaporizes as it expands and contacts the ballute's broadcloth.

Phase 3) The combination of air ingestion from the inlets as well as the expansion of the aqueous methanol provided by the inflation aid results in the rapid ballute inflation. The ballute's aerodynamic drag is reacted by the triple point attachments on the aft deck of the TV. These attachments remain for a predetermined time post mortar firing.

Phase 4) Upon pyrotechnically firing of the aft deck PDD attachment release mechanisms, the ballute is momentarily unreacted by the TV. After traveling a short distance the slack is taken up in the SSDS pack lazy leg. At this point the ballute begins to react against the SSDS pack. During the load transfer from the triple bridle to the lazy leg, line cutters (donut cutters) are activated passively which releases the SSDS pack restraints, allowing it to be extracted from the parachute can. The ballute extracts the parachute from the can. At this point no riser or suspension lines are allowed to exit the back of the SSDS pack, but rather the SSDS triple bridle is deployed through its aft deck thermal protection system (TPS) and stands up. The bridle legs include bridle stiffeners, which aid in keeping the bridle deployment orderly as well as mitigate backsliding of the bridles into the hot Star-48 rocket motor nozzle.

Phase 5) Once the SSDS triple bridle is successfully stood up, a large break-tie at the SSDS pack mouth closure is broken and the activation of passive line cutters opens the pack mouth. Riser and suspension lines are then allowed to be extracted out of the aft of the SSDS pack.
Phase 6) The parachute is packed in an inner/outer bag configuration. The inner bag contains the SSDS canopy and a small portion of the suspension lines. The outer bag contains inner bag restraints as well as the remaining of the suspension lines and the packed riser portion. At a predetermined deployment distance, line bights release the inner and outer bag. This allows the outer bag to be stripped from the inner bag and fly away with the ballute. The inner bag at this point is in free-flight with the momentum provided to this point in deployment.
Phase 7) The free-flight inner bag continues to travel away from the TV, deploying the parachute in a process similar to a free-flight mortar fired deployment. The free-flight pack's inertia deploys the SSDS canopy to bag strip. As bag strip occurs the deployed canopy portion is exposed to the supersonic environment and begins the inflation process as air is ingested.
Phase 8) Once bagstrip occurs, the canopy is allowed to continue inflating in the supersonic environment.
Phase 9) Once inflation has occurred, the vehicle continues to decelerate from the deployed Mach to subsonic terminal velocity.

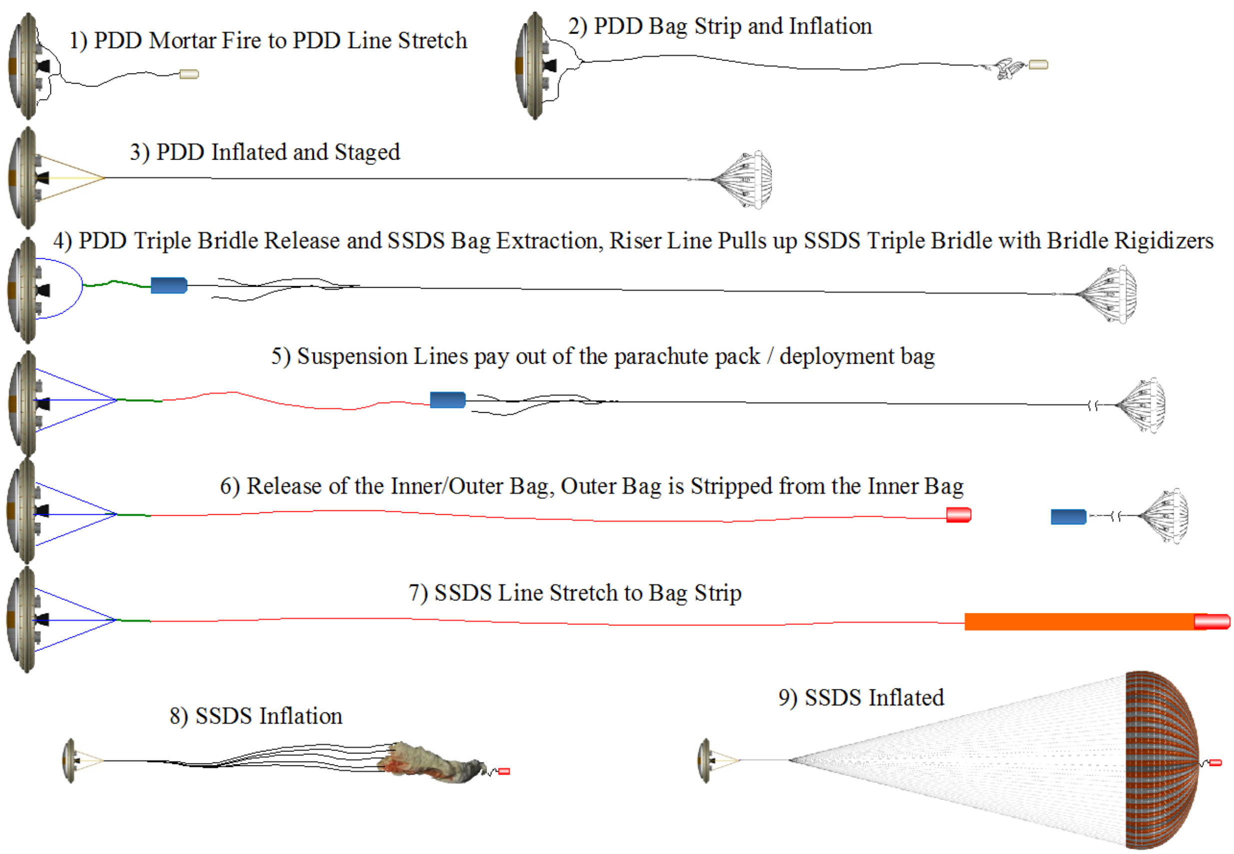

Figure 3: Parachute Decelerator System Deployment Phases

The PDS was designed such individual hardware groups of the system could be V&Ved independently without worrying about detailed changes in other areas of the design. This separation is the same as the hardware groupings as defined above. The interaction between the hardware groups is depicted in Figure 4. The interaction between the various hardware groups is shown with the green connecting lines. These interactions were defined early by requirements that allowed each group to develop and V&V its hardware independently. The PDD system's primary interaction with the supersonic parachute deployment hardware was to provide a pull force via the ballute. Due to the supersonic aerodynamics and test vehicle (TV) dynamics, the ballute essentially could be thought of a constant force, regardless of the delta velocity or relative position to the TV. The ballute's low inertia also aided in this approximation, and drove the V&V facilities of the supersonic parachute deployment hardware to also act with low inertia as well. The primary interactions between the supersonic parachute deployment hardware and the supersonic parachute again could be decoupled. The deployment hardware was not dependent on details of the parachute design, but rather the deployment bags that said parachute would be packed in. There was a dependency on the mass of the parachute on the deployment hardware, however again, this was controlled early on via a requirement and held nearly constant during the development cycle.

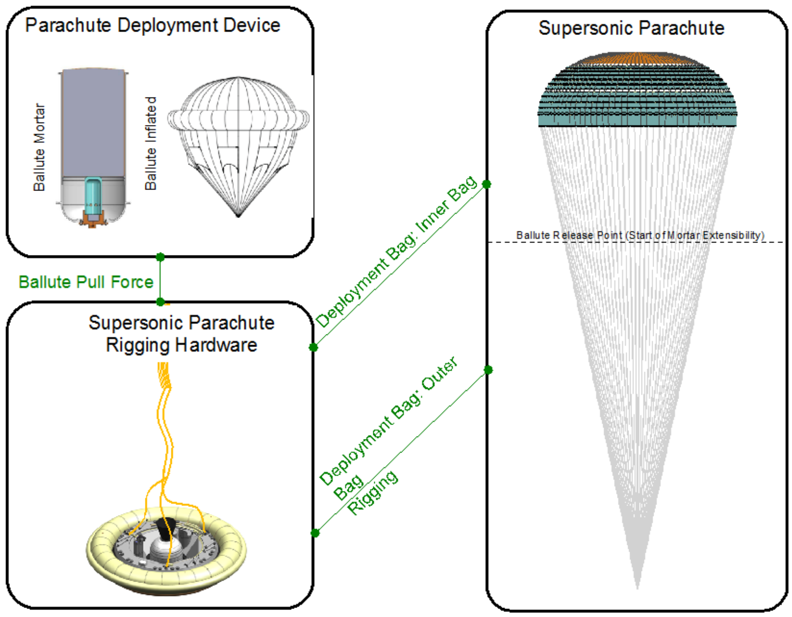

Figure 4: PDS Interactions

III. Success Tree

A success tree was used to formulate and check for completeness of the PDS V&V program. A success tree was used to provide the V&V engineers with a comprehensive look at the flow, dependencies and importance of each event in the PDS deployment. A success tree was used, rather than a fault tree, to provide a clear picture of the events that were important for a successful system. This tree was flowed from the high level branch, or tree trunk of "Parachute Deploys, Inflates and Performs as Expected" and from there flowed down to each individual component or leaf that was required for a successful system. Figure 5 shows a pictorial example of the success tree used by the LDSD parachute team. This was the tree as it was at the time of the PDS critical design review (CDR). Modifications and updates have been done as the project has advanced and new knowledge is uncovered on dependencies and relationships of various leaves. The example is provided to illustrate the basics of the foundation of the tree, and is not intended to provide a complete success tree for the PDS, as many changes have occurred since the CDR. For example many changes post SFDT-1 have occurred in the areas of "Parachute Inflation Successful" due to the new knowledge gained from that test.

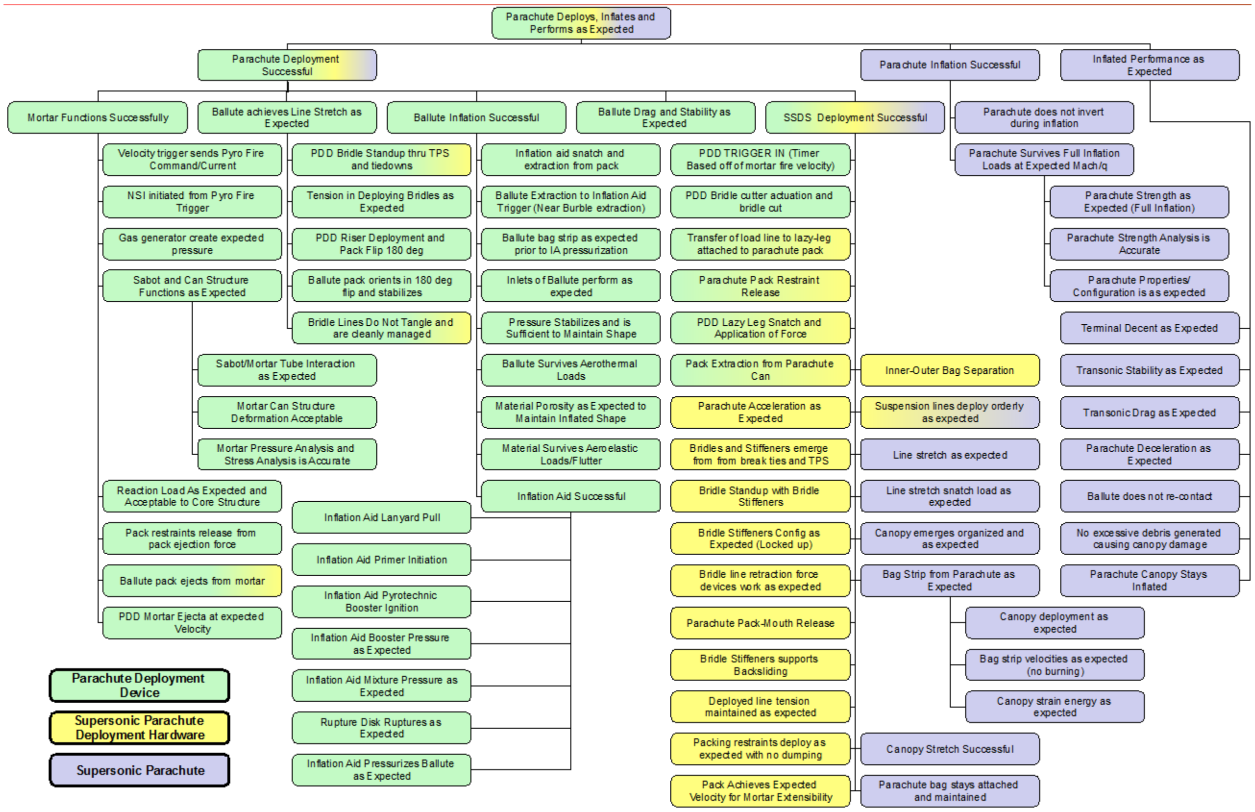

Figure 5: PDS Success Tree (Example Only)

The tree has been color coded to highlight the dependencies of each leaf on the three hardware groups. This was done to demonstrate the criticality and interactions of hardware groups. As shown, a large amount of the leaves are of the PDD and deployment hardware, and not the primary test article, the supersonic parachute. The LDSD parachute team used this insight to ensure each hardware group got the resources required to properly V&V its components.

Once each leaf was identified, they were individually analyzed to determine how the leaf was going to be properly V&Ved. The following items were identified for each leaf:

1) Description: A clear description of what the leaf entailed.
2) Pertinent Requirement: Any PDS requirements that were levied on the leaf.
3) Development Activities: A list of all the required activities that would be required to develop/analyze/test the intent of the leaf.
4) Hardware: For leaves that required hardware for the development, a list was generated. This included all hardware that was to be used during the development, from prototypes, to engineering development units and then finally to qualification or proto-flight hardware.
5) Facilities: This was a list of all hardware test facilities required for all of the development. In some cases the prototype development would be done on a benchtop level, then qualification would require environmental test laboratories and facilities.
6) Qualification: The set of tests, analysis, inspection or demonstration that would be performed to qualify that the leaf was complete.

The above elements were filled out for each of the leaves and a picture of the entire V&V program was then presented. At this point LDSD parachute engineers started the task of the development of facilities, laboratories, development hardware and all other resources required to complete the defined V&V program. In some cases, the V&V could only be performed in a SFDT environment; this was the case for many of the supersonic inflation and performance leaves for both the ballute and the supersonic parachute.

A development flow was then defined. This flow demonstrated the dependency of items within a hardware group as well as how they interacted externally. A diagram of this can be shown in Figure 6.

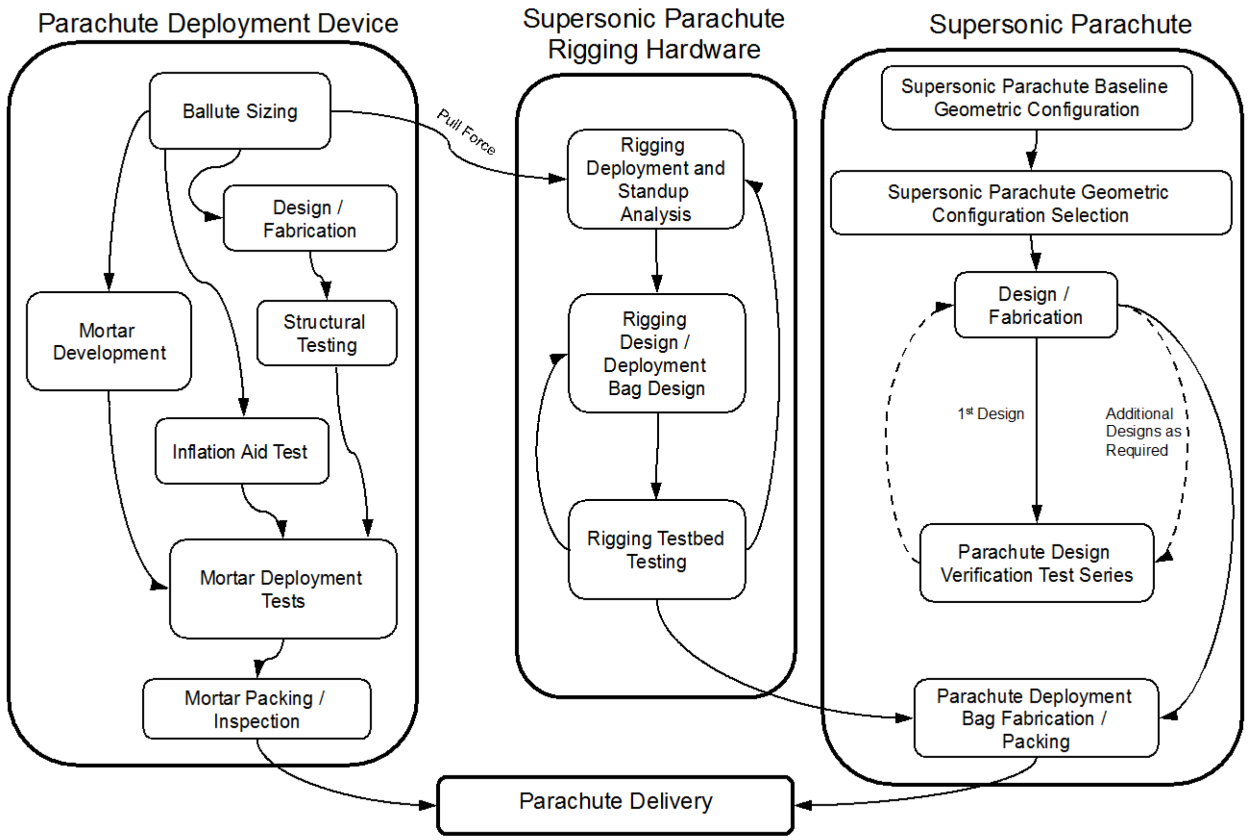

Figure 6: PDS Development Flow

The development flow again demonstrates the independence of each of the three hardware groups. The final product of the deployment hardware is delivered to the supersonic parachute hardware group, and then that group is combined with the PDD hardware in the final PDS delivery which was then given to the LDSD integration and test team to be installed, with the support of the parachute team, on the TV.

IV. Parachute Deployment Device Verification and Validation

The parachute deployment device is comprised mainly of a mortar, a ballute, an inflation aid for the ballute, and all the rigging and thermal protection required. Using past supersonic ballute test data and computational fluid dynamics (CFD) analysis, the required ballute size was developed. References 3, 4 and 5 discuss the analysis of the aerodynamics, aerothermal and inlet design that was conducted to aid in the ballute's design. Once this design was established, the rest of the hardware in the PDD could start to be defined. Definition of ballute material that met the strength, thermal, and porosity requirements also defined the mass and configuration that the ballute would be. This fed into the design of the inflation aid, mortar and the detailed design and fabrication of the ballute.

The ballute's inflation aid utilized aqueous methanol to rapidly inflate the ballute upon bag strip. Once the ballute sizing was completed, the required amount of aqueous methanol that the inflation aid would need to dispense was defined. A trade was done to determine the best way to dispense the fluid. Due to the high accelerations seen during mortar firing, it was determined that the fluid would need to be housed in a rigid structure to ensure that it did not prematurely begin to dispense. This also allowed for positive seals to be applied, ensuring that that there was minimal leaking prior to use. It was also determined that the easiest way to distribute the aqueous methanol was to utilize a pyrotechnic device. A trade was completed on the triggering of the pyrotechnic and it was determined that a timer off of mortar fire would not be accurate enough as there was some variability in the time of bag strip, which complicated the desire to initiate the inflation aid as close to bag strip as possible. This resulted in an inflation aid that was actuated via a lanyard at the time of burble fence extraction from the deployment bag. V&V of the inflation aid at this point decoupled from the ballute other than the structural interface and definition of the lanyard that would actuate the pyrotechnic. The inflation aid went through a series of dispensing tests prior to a demonstration in a vacuum chamber, which simulated the atmospheric environment in which the device would be activated. One of these vacuum tests also included a prototype ballute in which the inflation rate and final pressure could be characterized. V&V of the inflation aid was primarily conducted to ensure 1) that the inflation aid would reliably dispense the required amount of aqueous methanol upon a lanyard pull, 2) that the inflation aid would receive adequate lanyard pull force at the correct time required during ballute bag strip, 3) that the inflation aid would provide a structural load path and connection between the PDD's riser and the ballute, and 4) that the inflation aid would not start to dispense any aqueous methanol prior to lanyard pull, especially during mortar firing. Details of the inflation aid's design, development, and V&V can be found in reference 6.

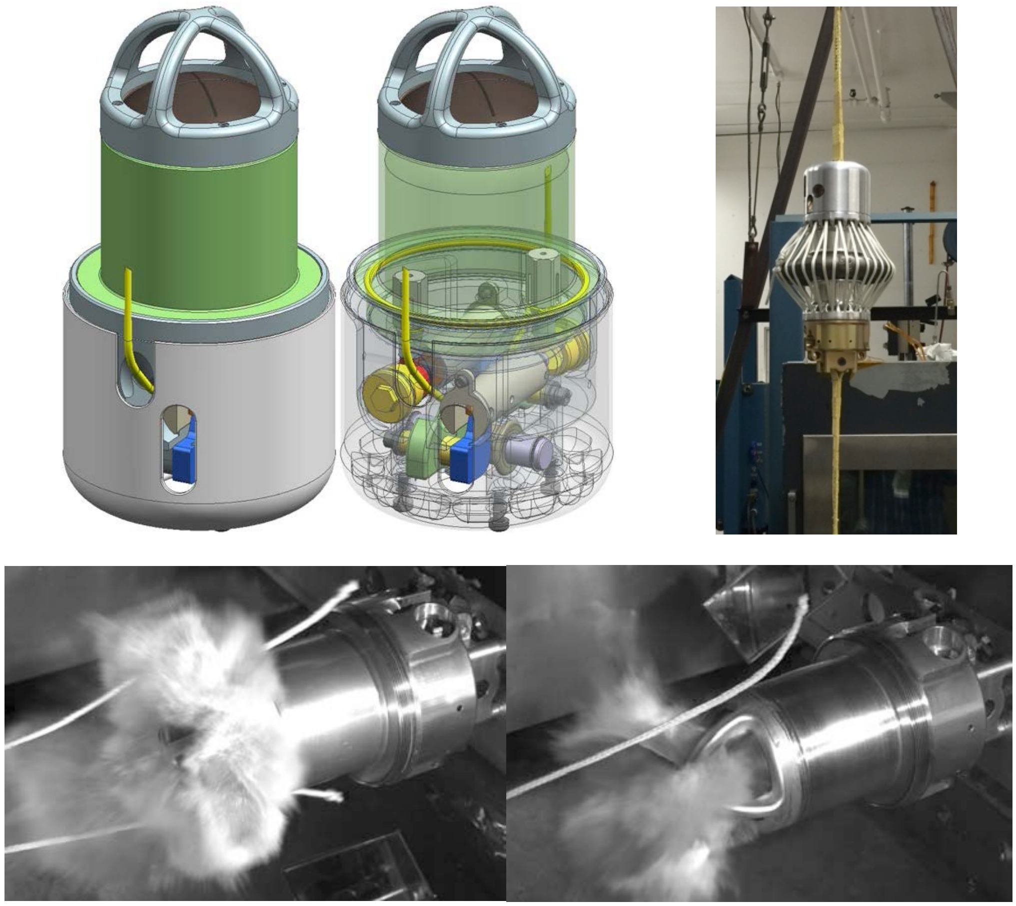

Figure 7: Top Left: IA Assembly; Top Right: IA Under Structural Testing; Bottom: IA Dispensing Tests

Using the mass of the ballute, inflation aid, and deployment bag packed rigging, along with a required muzzle velocity, the mortar development began. An aspect ratio was defined for the ballute's deployment bag, which in return defined the mortar's diameter. The design of the mortar leveraged off the past design of parachute mortars. Sizing of the gas generator and ullage was done via analysis and was tested in prototype mortars where dunnage packs were used in place of the actual packed ballute assembly. Standard structural analysis and hydrostatic testing was performed on the mortar tubes and gas generator to ensure structural adequacy and margin. Limited thermal testing was done due to the relatively thermal insensitive nature of pyrotechnics and fairly benign thermal environment of the PDD on the TV. Qualification of the mortar consisted of thermal hot fire tests as well as two ambient live fire tests in which a representative flight ballute pack was used as the ejecta. Limited additional information of the mortar's V&V can be found in references 3 and 7.

The design of the ballute itself was primarily done via analysis utilizing LS-DYNA. Here the inflated shape and stresses in the Kevlar fabric were calculated. Kevlar 29 was selected for the material of the entire ballute. Silicone was used to decrease the porosity of the material to near 0 cfm. Lot acceptance testing was done to validate the broadcloth's strength. Seam and joint testing was conducted on all joints. Nylon and vectran prototype ballutes were built using the defined patterns to validate the inflated shape and to investigate inlet design options. The ballute was flown with truck tow tests as well as flown in NASA Ames' National Full-Scale Aerodynamics Complex (NFAC).

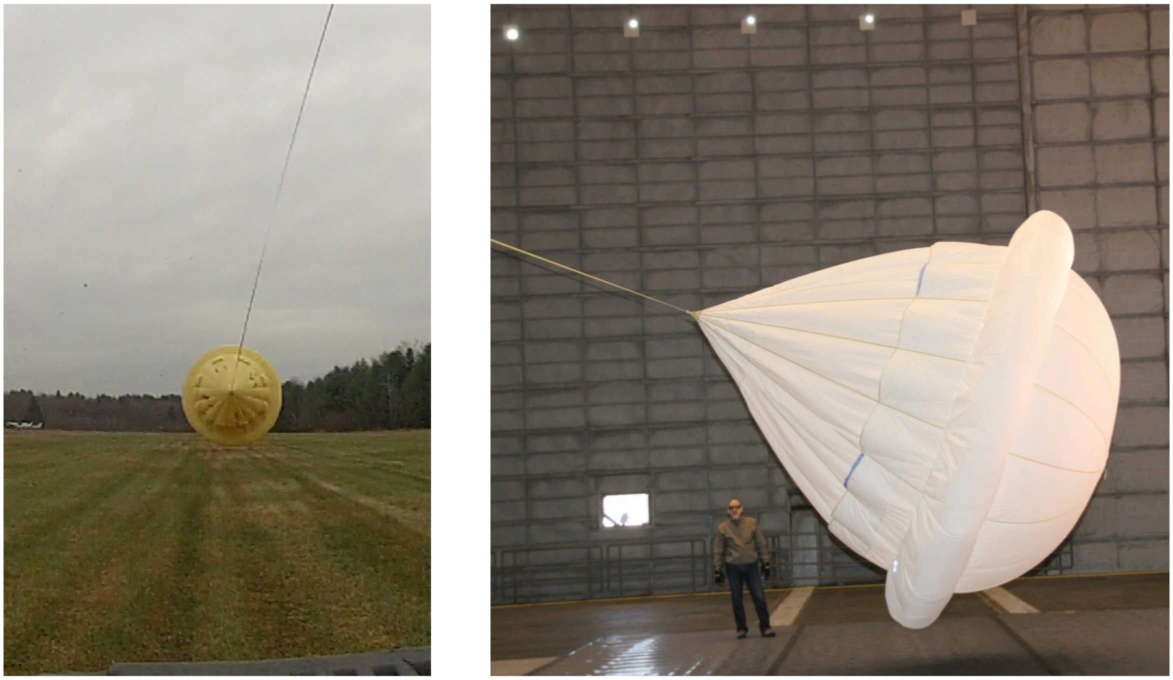

Figure 8: Ballute Testing; Left: Truck Tow Testing; Right: NFAC Testing

In both of these free flight venues, the performance of the inlets during inflation as well as the inflated shape was studied. The difference between high-density subsonic flights and low-density supersonic flights was acknowledged during this investigative phase. In general, the subsonic testing was used to look at the inflated shape under load, check fabrication patterns, gather subsonic drag performance (although the ballute did not have subsonic flight requirements for the SFDT) and investigate the inlet shape and design. The inlets were one of the primary concerns during the development. In the event that the inflation aid did not function, it was desired to have as much inlet area as possible to minimize flutter of the broadcloth prior to inflation. The concern was that the supersonic flutter could damage and tear apart the fabric prior to the ballute taking an inflated and rigid shape. Additional details of the ballute's design, analysis and V&V can be found in reference 3, 4 and 5. V&V of the supersonic performance of the ballute was completed via analysis, studies of past supersonic flight tests and relevant wind tunnel tests. Supersonic flight demonstration could only be demonstrated in the SFDT architecture. In SFDT-1, the ballute was successfully tested supersonically and the results of the performance of the ballute can also be found in the previously mentioned references 3, 4 and 5.

Air mortar tests were conducted to investigate the ballute's bag extraction performance. These tests were initially done with a mock inflation aid. Packing of the ballute, inflation aid and associated rigging became one of the more challenging developments with the PDD system. Packing a metallic inflation aid between the riser and the ballute posed many challenges. The ballute and riser packing volumes both required voids to be present, in which the inflation aid could live and survive during mortar firing. Many variations of the packing were performed until a final packing configuration was selected. This configuration was V&Ved initially in an air mortar test, and then finally V&Ved in a live pyrotechnic firing of the entire PDD subsystem. In this final high fidelity test, the muzzle velocity, rigging strip-out, inflation aid snatch, ballute pack extraction, inflation aid lanyard pull (which activated the inflation aid) and bag strip were all successfully demonstrated. For additional information about the PDD deployment V&V refer to reference 3 and 7.

Figure 9: Left: Air Mortar Testing; Right: Live Mortar Firing

Rigging of the PDD system was V&Ved utilizing the Rigging Testbed (RTB, which will be described in more detail in the following section). Demonstration of the release of the rigging and deployment from the aft deck and stowage box was conducted utilizing the RTB's mock test vehicle and bungee cord extraction force to simulate the tension force assumed to be present during deployment. Limited additional information on this testing can be found in references 3 and 9.

Inspections of the final installation and delivery served as the final V&V for the PDD subsystem once it was installed on the TV in PMRF. Due to shipping constraints on the ordnance and aqueous methanol, the PDD system had to have its final assembly on-site at PMRF. Five subassemblies had to be assembled during this process. These were comprised of 1) gas generator, 2) inflation aid, 3) packed ballute assembly with a mock inflation aid to preserve the inflation aid volume during transport, 4) mortar tube and finally 5) associated rigging and TPS. Closeout V&V was conducted at each stage of assembly during the PDD integration via inpection. Personnel that were present and involved with prior developmental tests and demonstrations of the PDD assembly performed these inspections. In all cases two-party verification was performed at each closeout step. Additional information on the final install V&V can be found in reference 3.

Figure 10: PDD Engineer Installing the PDD on the SFDT Vehicle

V. Supersonic Parachute Rigging Hardware Verification and Validation

The complexity of the rigging required for the various PDS deployments was identified in the early stages of the LDSD project. With this acknowledgement, a facility to V&V the rigging was also identified as a critical aspect of the ground testing V&V for the PDS. The rigging testbed (RTB) was the result of this insight. The RTB consisted of a mock test vehicle aft deck as well as a force device that could simulate the ballute's aerodynamic force. Due to the deceleration frame of the TV during PDV deployment equaling approximately 1g, the RTB was oriented vertically with the aft of the mock TV pointed upward. Along with the mock TV, a pneumatic force device was developed to simulate the ballute's reaction force. This resulted in a test facility that provided a representative environment for PDS rigging development. The RTB aided in the development and V&V of the following stages of PDS deployment:

1) PDD rigging deployment and standup
2) Parachute pack restraint structural capability
3) Parachute pack restraint release and lazy leg load path transfer to the PDD
4) Parachute pack extraction from the stowage can
5) Bridle deployment and standup with bridle stiffeners and associated TPS
6) Full parachute extraction from the parachute deployment bag, including demonstration of inner/outer bag separation at representative bag strip velocities

The RTB served as a backbone for much of the PDS ground V&V testing. The facility was nearly continuously in use during the PDS development and conducted over 100 tests covering the aforementioned stages. There were two primary locations that this facility operated at. The first was in a highbay. This location allowed development and V&V of everything except the full extraction of the entire parachute system. The second location was an outdoor area in which a 300-ft mobile truck crane was utilized, which allowed for a full demonstration, from PDD bridle cut to parachute bag strip. Detailed information on the RTB can be found in references 9 and 10.

Figure 11: Left: RTB in the Highbay; Right: RTB utilizing 300-ft Crane During Parachute Extraction

In addition ground testing, analysis was also used to perform some V&V of the supersonic parachute rigging hardware. MatLab scripts were written receive the results the flight system's dynamic Monte-Carlo simulations and perform PDS specific rigging analyses. These results fed into the parameters at which the RTB ground tests were conducted. These analyses were focused primarily on the parachute extraction and deployment, as this included the portion of the PDS deployment most influenced by results of the flight system's dynamic simulation. From the results of this analysis, requirements were levied on the supersonic parachute rigging hardware as well as the parameters that would be utilized in the RTB for component V&V. At the end of the development cycle of the rigging hardware, a series of tests were conducted to demonstrate the capability of the hardware at the bounds of expected dynamics. Details on the deployment analysis can be found in reference 7 and 8.

Final V&V of the parachute rigging hardware was again done via inspections during rigging installation on the test vehicle. This installation was conducted prior to shipment to PMRF. As was described in the PDD installation, the same personnel that installed the hardware for the development and V&V tests on the RTB mock TV also installed the rigging on the TV. Two-party verification was again done prior to any final closeout of the rigging hardware.

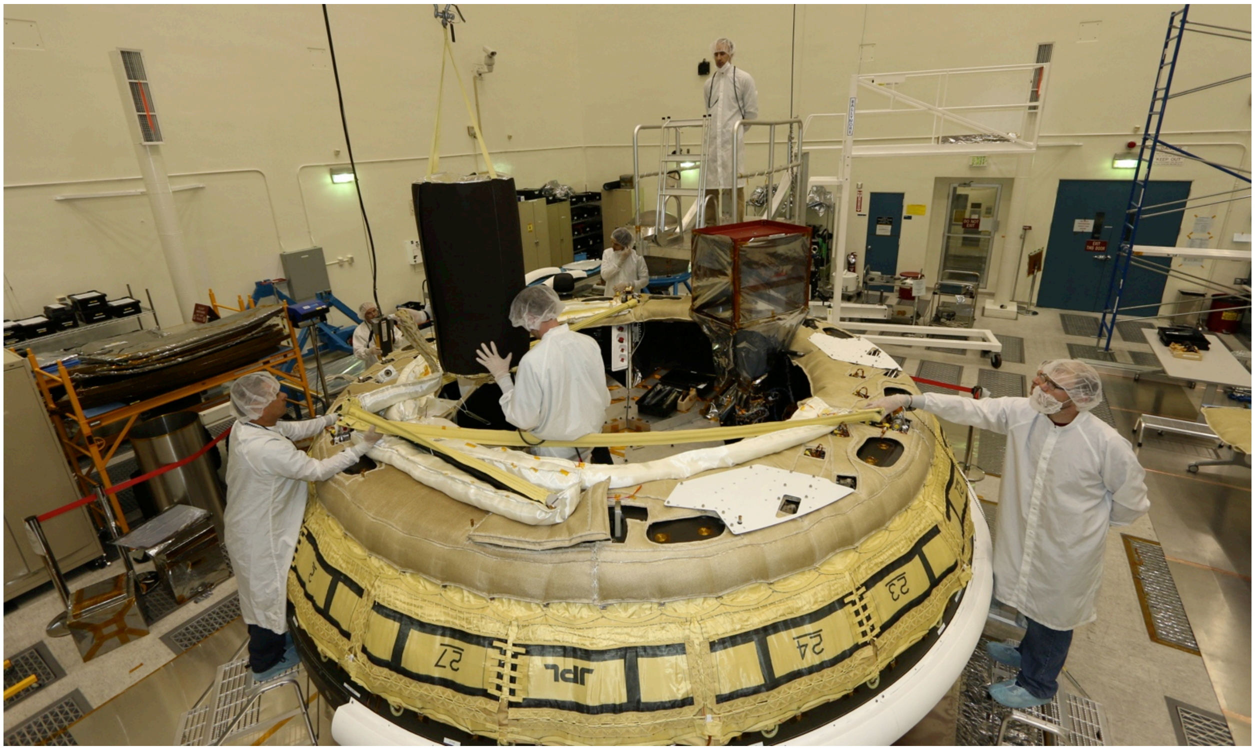

Figure 12: SFDT-1 Parachute Rigging Installation

VI. Supersonic Parachute Verification and Validation

Supersonic parachute V&V prior to the SFDT-1 was limited to high density subsonic testing. Parachute configuration and comparative stability performance was conducted with scaled parachute at NASA Ames' NFAC facility. Here multiple configurations were investigated and compared. At the end of this investigation, the Disksail configuration was chosen. For information on the testing conducted and the down-selection process refer to references 11 and 12.

Once a configuration and geometric porosity was defined, analysis was conducted to size the parachute's materials. Seam and joint testing was done on all non-heritage configurations. Design and testing iterations were conducted until positive margins were seen. At this point, two parachutes were built, one for the parachute design verification and one for the TV for SFDT-1.

Figure 13: Left: NFAC Testing of a Scaled Disksail; Right: PDV Testing of a Full Scale Disksail

The parachute design verification (PDV) test is a rocket sled powered parachute strength testing architecture. The test utilizes the Supersonic Naval Ordnance Research Tracks (SNORT) at the Naval Air Warfare Center Weapon Division (NAWCWD) in China Lake, CA. The test architecture was designed, developed and implemented by a joint effort between JPL and NAWCWD. Detailed information on the facility can be found in references 13 and 14. The PDV architecture is designed to apply structural aerodynamic loading to a fully inflated parachute, similar to that seen in a wind tunnel. PDV was developed due to the fact that the LDSD parachute had outgrown all currently operating wind tunnels. Structural verification of a fully inflated canopy historically has been the means of qualification in place of performing a supersonic low-density test, which typically were viewed as too expensive for the added benefit over a subsonic structural qualification. In addition, it has been assumed that a supersonic parachute will see its peak loading at full inflation. This is due to the rapid inflation of supersonic parachute, which does not allow significant deceleration of the payload prior to full inflation. Therefore, unlike typical high-density subsonic parachute inflations, which typically see their peak loading just prior to full inflation, supersonic parachute see their peak loading at peak inflation. This assumption has been made for all Mars bound parachutes since Viking. The LDSD acknowledged this assumption and this was the justification of building the PDV architecture, rather than performing airdrop tests for qualification. It was planned to perform a PDV test on the Disksail prior to SFDT-1, however there were only funds available for one attempt and unfortunately the one test attempt conducted resulted in a no-test due to high winds resulting a miss-latch of the bullet into the latch sled. Therefore, there was no demonstration of structural capability of the Disksail prior to going into SFDT-1. During the forensics activities post SDFT-1 a PDV tests (designated as PDV1-1b) was completed on one of the PDV Disksail parachutes. The results from this test as well as those from SFDT-1 were used in aiding in the design modifications for potential ringsail parachute designs for the SFDT-2.

V&V of low-density performance of the supersonic parachute can only be demonstrated in a SFDT. The three main events of interest are 1) supersonic inflation including area oscillations, 2) supersonic aero performance and 3) transonic and subsonic performance. The Disksail parachute was successfully tested in the SFDT-1. During the test, the parachute was deployed at the targeted Mach and dynamic pressure. Although the supersonic Disksail parachute experienced an anomaly during the inflation process, the PDS was tested successfully in the environment it was designed to operate within. The nature of the failure seen originated in the disk portion of the canopy. High-speed and high-resolution imagery of the anomaly was captured and has been used to aid in the forensics of the failure cause. In addition to the imagery, an inertial measurement unit (IMU) recorded test vehicle dynamics and loadcells captured the bridle termination forces. In reviewing the imagery and load data a number of hypothesizes have been generated in an attempt to explain the cause of the anomaly. Reference 15 provides detailed information about the Disksail performance in SFDT-1.

VII. Conclusions

The LDSD project has undertaken the task of developing the next generation of larger supersonic parachutes for Mars applications. In this development, the parachute must go through tests that demonstrate the maturity of the system; and to that end, a V&V program was generated. This paper provides a comprehensive look at the process that was performed to generate the V&V program as well a summary of the tasks that were done. Details were provided on of how the PDS V&V was broken down into hardware subsystems so that these subsystems could develop their hardware without significant interactions with the other subsystems. References to multiple other papers was provided to allow the reader to research deeper into the details of each of the subsystem's V&V as well as the facilities that were utilized, and in some cases developed in support of the PDS V&V efforts.

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NOTE: HIGHLIGHTED REFERENCES NEED TO BE UPDATED PRIOR TO SUBMITTING

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