Development and Testing of a New Family of Supersonic Decelerators

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The state of the art in Entry, Descent, and Landing systems for Mars applications is largely based on technologies developed in the late 1960's and early 1970's for the Viking Lander program. Although the 2011 Mars Science Laboratory has made advances in EDL technology, these are predominantly in the areas of entry (new thermal protection systems and guided hypersonic flight) and landing (the sky crane architecture). Increases in entry mass, landed mass, and landed altitude beyond MSL capabilities will require advances predominantly in the field of supersonic decelerators. With this in mind, a multi-year program has been initiated to advance three new types of supersonic decelerators that would enable future large-robotic and human-precursor class missions to Mars.

Increases in entry mass of ∼30% above MSL are possible with the present stable of medium-class launch vehicles. However, only marginal increases in aeroshell size may be possible, thus leading to large increases in ballistic coefficients. To take advantage of the increase in entry mass that is possible, two key improvements are needed. First, supersonic decelerators must be developed that can be utilized at Mach numbers and dynamic pressures greater than those allowable with the Viking-heritage Disk-Gap-Band parachute. Second, a new family of parachutes must be developed that will bring the increased masses to suitable terminal descent staging conditions. An objective of the Low Density Supersonic Decelerator (LDSD) program is to bring to TRL-6 a 6-meter diameter attached torus inflatable aerodynamic decelerator (IAD) and a 33.5-meter diameter supersonic Ringsail parachute. The combination of these two technologies would enable future missions to maximize the launch vehicle capability of an Atlas V rocket, deliver in excess of 1200 kg to an elevation of +1 km MOLA altitude, as compared to MSL's capability of 900 kg to −1 km MOLA altitude, and provide considerable improvements in the landed accuracy of the system.

With an eye towards human-precursor missions, and the even larger entry masses that they will require, the LDSD program will also advance to TRL-5 a second, larger IAD of 8 meters in diameter. Maturation of such an IAD, in combination with the large Ringsail parachute, could enable future missions to maximize the capacity of a Delta IV-H or similar launch vehicle.

I. Introduction

The state of the art in Entry, Descent, and Landing (EDL) technologies for Mars applications is heavily based on a core set of technologies developed for the Mars Viking missions of the 1970's. Although the recent Mars Science Laboratory (MSL) mission incorporated several new technologies, these were only in the areas of entry (first use of PICA TPS and active entry guidance at Mars) and landing (sky crane landing system). Increases in entry mass above that of MSL's ∼3300 kg are possible with the current stable of medium and heavy class launch vehicles. However realizing increases in landed mass, altitude, and/or accuracy will require further improvements in EDL technologies. A number of historical and recent studies have identified inflatable aerodynamic decelerators (IADs) as a promising technology for realizing those benefits.[1,2,3] With this in mind, NASA's Office of the Chief Technologist and the Space Technology Mission

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Directorate initiated the Low Density Supersonic Decelerator (LDSD) Project, aimed at maturing the next generation of supersonic decelerators. The project's objective is to develop full-scale supersonic decelerators for application in low-density atmospheres such as at Mars, and to demonstrate their operation in relevant environments at Earth. LDSD is developing three decelerator technologies:

1. A 6-meter diameter Supersonic Inflatable Aerodynamic Decelerator targeted for Atlas V 551 large robotic class missions (SIAD-R)
2. An 8-meter diameter SIAD targeted for Delta IV-H or human pre-cursor class missions (SIAD-E)
3. A 33.5-meter nominal diameter Supersonic Ringsail Parachute (SSRS)

These decelerators are being developed using the expected flight materials, configurations, and interfaces, and will be tested at full scale in relevant dynamic pressure and Mach environments. The dynamic pressure environments will be simulated with near sea-level Earth pressures and appropriately scaled velocities. The Mach environments will be simulated in Earth's stratosphere at Mars-like density, with the decelerators deployed at Mach from an aeroshell, 4.7 meters in diameter, as they would be at Mars. The supersonic tests will each combine a SIAD with the SSRS. Successful tests would bring the SIAD-R and SSRS to Technology Readiness Level (TRL)-6, and the SIAD-E to TRL-5.

This paper is intended to provide an overview of the LDSD technologies and test program. Greater details on individual technologies and test programs may be found in papers presented during the 2013 AIAA Aerodynamic Decelerator Systems Conference.

II. Technology Overview

The LDSD project is developing three new aerodynamic decelerators that are targeted for use in future Mars missions. Two of these devices are SIADs and the third is a new SSRS. Each of the two SIADs is named for the class of mission for which it is envisioned to be used for, either robotic class missions (SIAD-R) or exploration class missions (SIAD-E). As a combined SIAD/parachute system, these technologies could allow for increases in landed mass, landed altitude, and landed accuracy beyond what is presently possible with the heritage set of decelerator technologies.

A SIAD is a class of aerodynamic decelerator that is intended to alter the aerodynamic characteristics of an entry vehicle by augmenting drag or lift and/or improving the stability of the entry vehicle. Since they are inflated structures, SIADs provide benefits in mass and packaging and allow for increases in the aerodynamic surfaces of an entry vehicle beyond those provided by a rigid aeroshell constrained to fit within a launch vehicle fairing. As a supersonic decelerator, they are deployed well after the peak heating and deceleration phase, but at Mach numbers above those for which parachutes can be used. In that manner, they provide a bridge from hypersonic entry to a Mach and dynamic pressure regime in which a parachute may be used.

A. SIAD-R

The robotic-class SIAD consists of an inflated torus with a total diameter of 6 meters. The design of SIAD-R is intended to provide an inflated structure that can be pressurized sufficiently to exhibit little or no change in shape when operating in a supersonic flowfield. This feature greatly simplifies the analysis and testing that would be necessary prior to incorporation on a flight mission. For example, since SIAD-R behaves as a rigid structure, aerodynamic characterization can still be performed using traditional techniques that assume rigidity such as Computational Fluid Dynamics (CFD), subscale wind tunnel testing, and ballistic range testing.

Though primarily an inflated torus, the SIAD-R design has a number of features designed to improve performance and rigidity (see Figure 1). The burble fence on the periphery of SIAD-R provides a location of uniform flow separation that improves the stability of the vehicle, particularly at lower supersonic, transonic, and subsonic conditions. The primary torus also contains a series of internal cords that provide additional stiffness in the structure and help resist axial deflection and rotation of the torus under large aerodynamic loads.

The SIAD-R is constructed using silicone-coated Kevlar-29. The structure is fabricated using 27 gores sewn together to produce a nearly circular cross section. Inflation of the SIAD-R is achieved using an on-board inflation system of nine gas generators spaced uniformly apart at 40° intervals. To achieve its rigidity,

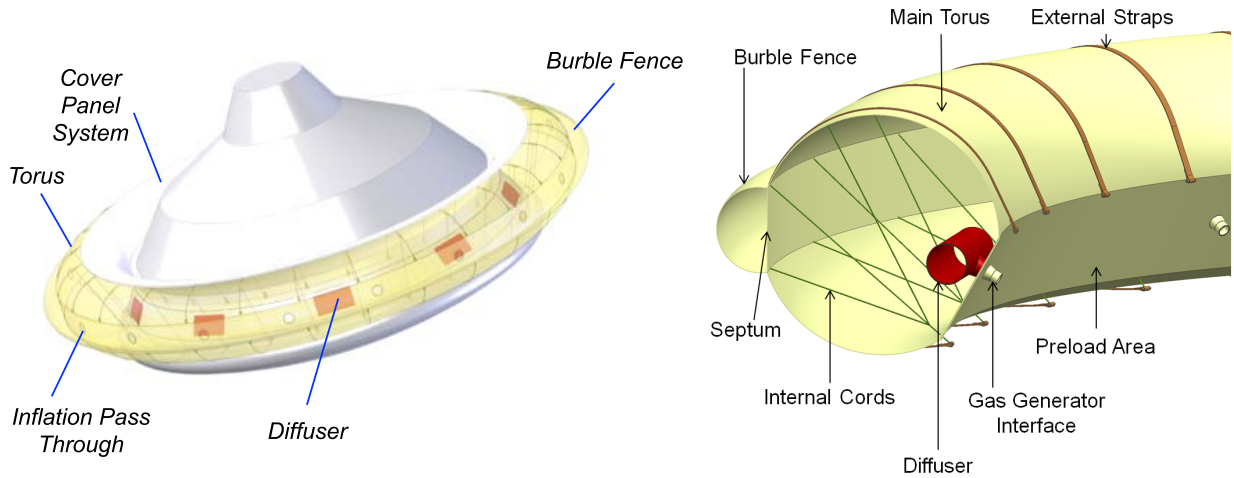

Figure 1. SIAD-R configuration and primary design features.

the SIAD-R is pressurized to an inflation pressure of 48 kPa. The inflation pressure is largely driven by the magnitude of the aerodynamic loads expected and the value of 48 kPa is based on a deployment at a dynamic pressure of 2200 Pa, which is considered to be a conservative bound of likely conditions for Mars use. SIAD deployments at lower dynamic pressures would equivalently be able to scale the inflation pressure. The relatively small size of the SIAD-R also allows for rapid inflation in about one second, thereby minimizing disturbances on the entry vehicle.

B. SIAD-E

Although small SIADs can be pressurized sufficiently to make them rigid, as they grow in size flexibility and aeroelastic deformation is inevitable. Furthermore, the inflation pressure requirements become prohibitively large and require massive inflation systems. Thus, understanding the aeroelastic behaviors of large SIADs becomes important to their viability. With this in mind, a SIAD-E configuration was selected that is known to exhibit a strong coupling between aerodynamics and shape. The geometry is historically referred to as an attached isotensoid. Studied extensively in the 1960s and 1970s, the isotensoid shape is derived initially using linear membrane theory to produce a shape that under ideal conditions exhibits constant meridional and circumferential stresses across the entire surface.[4] The result is a shape that has low stresses, allows for lightweight materials to be used, and has inflation pressure requirements low enough to allow for inflation via ram-air inlets, thereby reducing the mass and size of an inflation system.

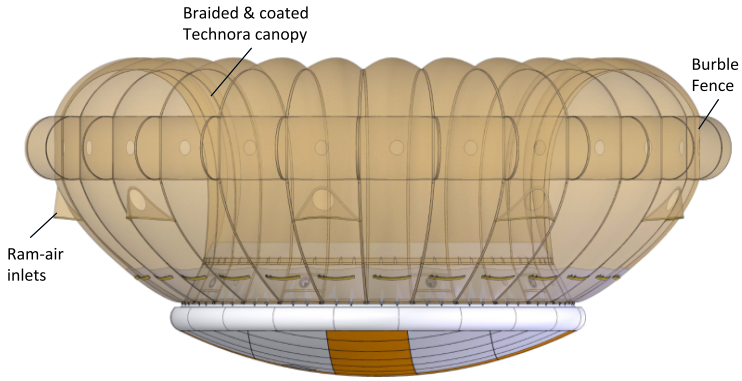

Figure 2. SIAD-E configuration and primary design features.

The SIAD-E geometry, shown in Figure 2, is nominally 8 meters in diameter and is constructed with 27 gores using braided Technora coated with silicone. The use of a braided material for the SIAD canopy

simplifies construction by allowing for individual gores constructed on the bias to be built from a single layup. This has the advantage of avoiding transverse stiffness discontinuities due to seams and which adversely affect shape as well as reducing seam count and simplifying fabrication.

C. SSRS

Supersonic parachutes have been used for over 50 years. However, with the exception of small munitions parachutes, development and testing largely stopped in the early 1970s with the completion of the Mars Viking Project. Since then, planetary spacecraft have mostly relied on the heritage Disk-Gap-Band (DGB) parachute flown by the Viking program. Though DGBs have been used successfully by all landed U.S. Mars missions, other parachute configurations have been shown to provide better drag and stability. In particular, the Ringsail configuration has been used extensively on spacecraft by a number of programs including the Mercury, Gemini, Apollo, and Orion capsules. Consisting of a series of concentric rings and sails, the Ringsail geometry provides a number of realized or potential improvements over the standard DGB. These include:

- **Increased drag:** Ringsails have traditionally exhibited higher drag coefficients than DGB canopies, although with lower total porosities. Although testing conducted on both DGB's and modified Ringsail geometries during the Planetary Exploration Parachute Program (PEPP) demonstrated similar drag characteristics between a DGB and Ringsail,[5] more recent high altitude testing of a Ringsail canopy showed drag coefficients roughly 30% larger than typically seen for a DGB.[6]
- **Reduced opening loads:** Ringsail parachutes distribute the geometric porosity (gaps) across the canopy. The distributed porosity is thought to reduce the opening loads by reducing the canopy pressure buildup which can occur during the inflation process.
- **Inflation reliability:** Another advantage of the sails is that during inflation they act as surfaces to catch the wind and help pull the canopy open.
- **Heritage with reefing:** As parachutes get larger, the desire to reduce the opening loads leads to reefing. Early tests of reefed DGB parachutes produced a variety of unfavorable behaviors. Ringsails on the other hand have been extensively used in reefed configurations.

The Supersonic Ringsail parachute (SSRS) being developed by LDSD has a nominal diameter of 33.5 meters and it is constructed from 96 gores and 22 panels per gore using low-permeability nylon. The nominal configuration, Figure 3, includes a small gap near the shoulder of the parachute to further improve the stability of the canopy, particularly in low-density or supersonic conditions. However, a variety of configuration modifications are being explored in an effort to better tune the drag vs. stability trade typical of parachutes. Once flown, the LDSD parachute will be the largest parachute ever flown supersonically and will provide 2.5 times the drag of the largest DGB flown to date (see Figure 4).

Figure 3. Baseline Ringsail Configuration.

III. Technology Application Analyses and Configuration Selection

Although there have been a number of mission studies conducted that focused on the performance improvements possible with SIADs, these have generally been very high level. That is, their focus was predominantly on drag area augmentation capabilities and mass impacts of incorporating a SIAD system. LDSD identified a number of deficiencies with the system study literature that led to a series of initially broad but increasingly more focused system studies on how SIADs could best be incorporated into future missions. The results of those studies will be published in a more comprehensive technical report at a later date. However, a summary of the results to date is provided herein.

The early focus of the LDSD system study effort was to help provide focus on the types and sizes of decelerators that the project would target. This was simplified by considering only two general classes of missions, each defined by the capabilities of the current launch vehicle fleet. Near term robotic missions are likely to be limited by budget constraints to fit within the capabilities of an Atlas V or similar launch

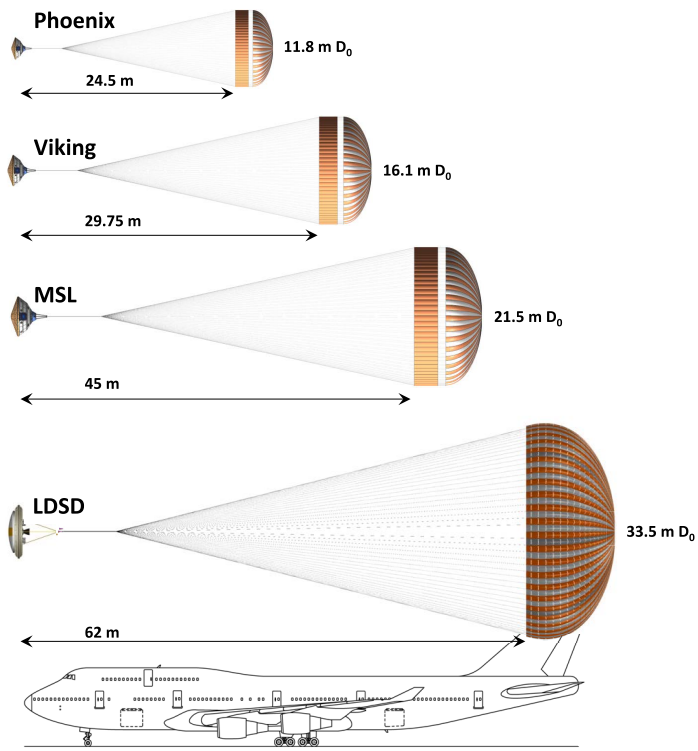

Figure 4. Scale comparison of the LDSD SSRS with prior Mars parachutes and a 747-400.

vehicle. This became the driver for a robotic class design reference mission. The next step in mission class considered was restricted to the capabilities of the Delta IV-H launch vehicle. This became the Exploration class design reference mission, where an example would be a large human pre-cursor mission to test power systems and in-situ resource utilization. Using payload mass vs. C_3 numbers for an Atlas V 551 and Delta IV-H launch vehicle and taking an average C_3 to Mars over the next decade of opportunities, a throw mass to Mars was calculated. A rough sizing of a cruise stage was conducted to arrive at two general entry masses for the two missions considered. Those values are summarized in Table 1. Extensibility to even greater mass mission classes was considered when selecting the Exploration class decelerators.

Table 1. Mass definitions for the two mission classes considered.

	Robotic Class	**Exploration Class**
Launch Vehicle	Atlas V 551	Delta IV-H
Throw Mass (kg)	5200	7625
Entry Mass (kg)	4250	5825

First analysis efforts were aimed at understanding the performance benefits of different types and sizes of aerodynamic decelerators. Two candidate SIAD configurations were selected to be representative of the different types of SIAD configurations, an attached isotensoid geometry and a tension cone decelerator (Figure 5). Both SIAD types have a sufficient amount of testing and literature available to assemble aerodynamic and mass models. Furthermore, the two configurations are sufficiently different in aerodynamic drag characteristics, inflation system requirements, and material acreage requirements that they provided sufficient coverage of the broader range of possible SIAD configurations. Each SIAD type was similarly paired with a parachute for achieving adequate propulsive terminal descent velocity conditions. Lastly, the SIAD was only evaluated for ballistic, zero degree angle of attack usage. For the assumed MSL-like guided entry sequence, this requires adjusting the heading alignment phase of flight to earlier in the trajectory.

Initial sizing exercises explored a broad range of SIAD and parachute sizes and deployment conditions.

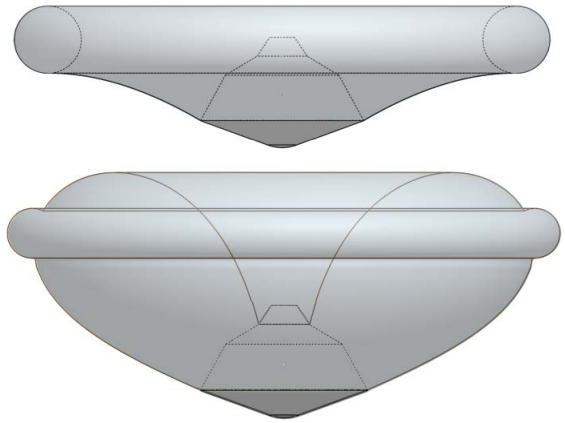

Figure 5. The two SIAD configurations initially evaluated: tension cone (top) and attached isotensoid (bottom).

SIAD diameters from 6 to 18 m were considered and parachute nominal diameters of up to 35 m were evaluated. For both mission classes, the entry vehicle was kept fixed as a 4.7 m diameter MSL-like aeroshell. The MSL as flown aeroshell was 4.5 m in diameter, but work with the launch vehicle providers has shown that future missions could grow the diameter out to as much as 4.7 m with minimal risk. This study assumed that a project would first utilize this additional performance capability before adopting a SIAD. The SIAD would then provide additional performance as needed. Key results from the sizing effort are as follows:

- The low subsonic drag characteristics of SIADs make a two-stage supersonic decelerator system (SIAD with supersonic parachute) extremely attractive. The drag coefficients of blunt bodies drop off considerably in transonic and subsonic Mach number regimes. Staging at supersonic conditions provides considerable improvements in landed altitude.
- Staging from a SIAD at Mach numbers below unity, either to a propulsive system or a parachute required very large SIADs of between 12 and 16 meters diameter.
- Maximizing landed mass generally favors using the smallest SIAD that is feasible. Larger SIADs can be used to improve landed altitude, but will also reduce the landed mass capability.
- Better landed accuracies were achieved with lower Mach SIAD deployment conditions. Deployment of the SIAD was assumed to occur with the vehicle in a near zero-degree angle of attack state and this event was coupled with when the MSL-like guidance algorithm would transition from range control to heading alignment phase of flight. Performing this transition earlier reduced the time for guided flight and began introducing additional errors in the vehicle position at parachute deploy. Thus, optimizing for landing accuracy led to SIAD deployments at Mach numbers around 3.
- For large IADs ($\sim$10+ m) deployed at high dynamic pressures ($\sim$1500+ Pa), attached isotensoids have a better mass per unit drag area than the tension cone configuration.
- For the Robotic Class mission, the combination of a 6 m tension cone and a 30 m parachute allowed for full utilization of the Atlas V 551 entry mass and provided a 2 km increase in altitude over the current capabilities of an MSL-like mission. Such a combination had a landed mass (mass brought to near zero velocity) of 2000 kg. The delivered mass depends on the landing system. For a sky crane system, the delivered mass would be 1200 kg.
- For the Exploration Class mission, the combination of an 8 m tension cone or a 10 m attached isotensoid and a 30 m parachute allowed for full utilization of the Delta IV-H entry mass and provided a 2 km increase in altitude over the current capabilities of an MSL-like mission. This combination provided a landed mass of $\sim$2750 kg, and a sky crane delivered mass of 1800 kg.

Final selection of the diameters of the two SIADs was made in large part based on the latter two results. For both mission classes, the objective was to be able to fully utilize the entry mass capabilities of the current

launch vehicle fleet while providing improvements in landed mass, landed altitude, and landed accuracy over an equivalent MSL based entry system. The 2 km increase in landed altitude was deemed adequate and enabled improvements in landed accuracy by moving from a velocity based decelerator trigger to a range based trigger.

Although system study results pointed to a 6 m tension cone and either an 8 m tension cone or 10 m isotensoid, a number of additional factors were considered before arriving at the present SIAD configurations. With regards to a 6 m tension cone, such a device, when interfaced with a 4.7 m diameter aeroshell, degenerates into an attached torus since there is little room for the tension shell portion. This was considered advantageous in many ways, most notably because it allowed for a more rigid structure with a simpler interface to the entry vehicle. Subsequent analyses indicated that the aerodynamic performance assumed for a 6 m tension cone was consistent with that of the 6 m attached torus.

The exploration class SIAD was initially selected as a 10 m attached isotensoid based on the system study results. The choice of the attached isotensoid over the tension cone was also driven in part by consideration of interface complexity, mainly that an inflation system piped to a large torus would be a significant undertaking. The primary driver, however, was that the attached isotensoid was considered to have more applicability to the large SIADs that would be required for missions beyond a Delta IV-H class launch vehicle. Specifically, the attached isotensoid is a structurally efficient shape that is heavily influenced by the aerodynamic flowfield around it. This level of interdependence between the structural and fluid dynamic components is something that will have to be addressed as larger SIADs are considered. Thus, an attached isotensoid would provide the first large scale investigations of this form of aerodynamic decelerator. Although initial sizing of the attached isotensoid pointed to a 10 m device, this would later be reduced to an 8 m diameter device based on a desire to maximize commonality of interfaces and test architectures with the 6 m device. A more detailed systems study confirmed that the performance metrics initially targeted were still possible with an 8 m device.

The size of the supersonic parachute was grown from the 30 m nominal diameter indicated by the systems study to a final size of 33.5 m nominal diameter. While working with the selected parachute contractor, Pioneer Aerospace, the driving requirement of a subsonic drag area was established that was commensurate with the assumptions used in the systems study. The drag area calculated for a 30 m ringsail had assumed a modest improvement in drag coefficient over a traditional DGB configuration. Pioneer noted that there was limited data available to support this, and thus requested that a larger parachute be considered to ensure that the drag area requirement was met. Furthermore, a 33.5 m ringsail design already existed from the earlier 2005 subsonic parachute technology task,[6] and could meet the mass requirement. Lastly, it was felt that from an extensibility stand point, the larger the canopy, the better. Reducing the size of a parachute compared to a previously tested configuration is thought to hold less risk than increasing it beyond a previously tested configuration.

IV. Test Architecture Development

The objectives of the LDSD project are to bring the SSRS and SIAD-R to TRL-6, and the SIAD-E to TRL-5. To achieve this, the technology development test program was modeled on the fight qualification approach that has been employed historically for deployable aerodynamic decelerators. This qualification approach is similar to that applied for the Viking Mars program and more recently by the Mars Science Laboratory mission.[7] The qualification approach decomposes the decelerator functions chronologically into five distinct phases:

1. Initial Deployment: addresses mechanical performance as the decelerator is released from its stowage compartment and the deployment forces applied to it far outweigh external aerodynamic forces.

2. Inflation Dynamics: addresses shape evolution of the decelerator as the external aerodynamic forces grow to far outweigh the initial deployment forces.

3. Peak Strength: addresses structural integrity of the decelerator under its flight load and temperature conditions.

4. Supersonic Performance: addresses aerodynamic performance of the decelerator under flight like Mach and wake conditions at Mach numbers greater than 1.

5. Subsonic Performance: addresses aerodynamic performance of the decelerator under flight like Mach and wake conditions at Mach numbers less than 1.

Illustrated in Figure 6, these five phases exist for both the LDSD parachute as well as each for the two SIAD devices being developed.

This qualification approach provides guidance on which phenomena need to be tested for each phase while the TRL level definitions provide guidance on the fidelity of the test articles as well as the fidelity of the test conditions needed to establish a specific TRL. For SIAD-R and the parachute, TRL-6 is defined as "system/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Engineering feasibility fully demonstrated in actual system application."

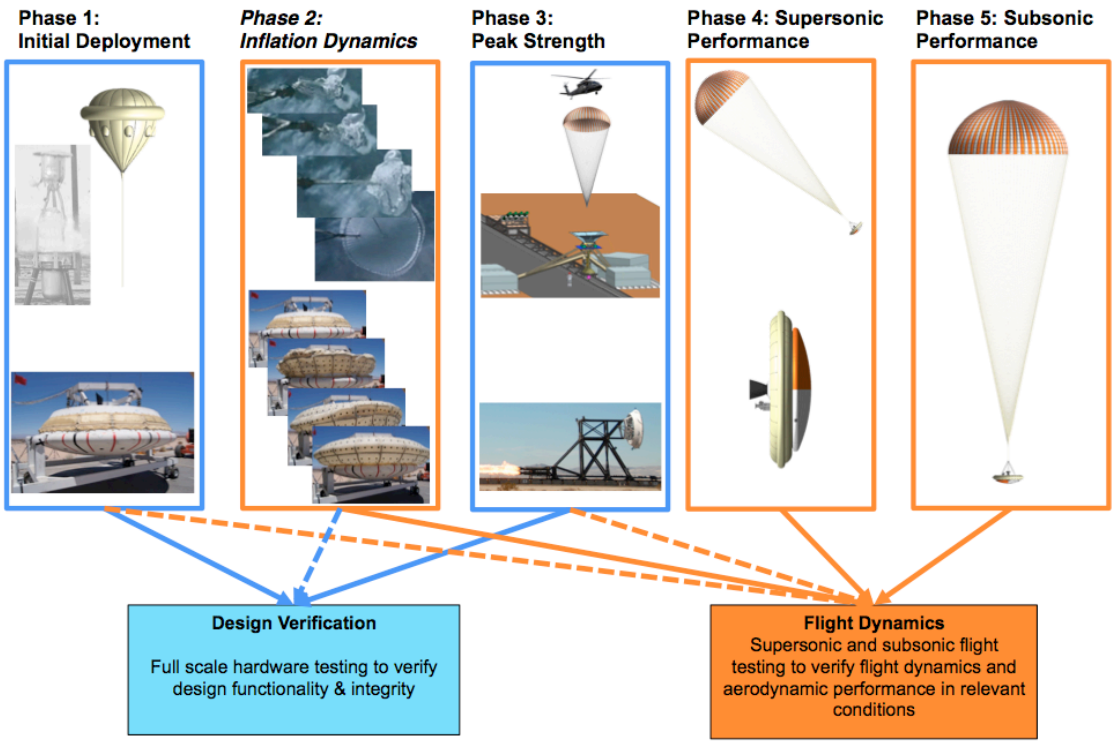

Figure 6. The five pillars of qualification for deployable aerodynamic decelerators.

The end-to-end environment of interest for the LDSD technologies is the aerodynamic and aerothermodynamic environment, which generally distills down to the vehicle geometry, Mach number, and the dynamic pressure of the tests. The Mach number is needed to obtain the proper aerodynamic performance of the decelerators since the aerodynamic flowfield has a strong Mach dependency. The dynamic pressure is required to demonstrate structural integrity of the candidate designs. Achieving TRL-6 on soft good decelerators calls for full scale testing because of the dependence of scale on the behavior of the decelerator. "Partially integrated with existing systems. Engineering feasibility fully demonstrated in actual system application" was interpreted as needing to integrate the candidate decelerators into a relevant blunt body aeroshell that provides relevant interfaces, as well as provides a relevant forebody and wake flow environment for the aerodynamic decelerators to operate in.

A test program was devised that adheres to the TRL-6 criteria on test article and environmental fidelity and takes advantage of the functional decoupling of the five phases of decelerator qualification. Two major branches of the test program were established. Branch 1 is the design verification branch, in which the primary objective is to demonstrate mechanical functionality and structural integrity of all of the elements of the system. Phases 1 and 3 are addressed by Branch 1 testing. Branch 2 is the flight dynamics branch in which the primary objective is to demonstrate the deployment and aerodynamic performance of the decelerators in a relevant environment.

It is expected that any adopting project would need to repeat the Branch 1 tests in order to elevate their implementation of the LDSD technologies up to TRL-8. Phases 2, 4, and 5 are addressed by Branch 2 testing. It is an important objective of LDSD that an adopting project does not need to repeat any Branch 2 tests in order to declare TRL-8 on the adopted technologies.

The following subsections break down the test approaches for the SSRS, SIAD-R, and SIAD-E. The SSRS and SIAD-R will be brought to TRL-6 through the LDSD test program and by virtue of the fact that their designs will be sufficiently well established to not require significant changes by the adopting project. The SIAD-E will only be brought to TRL-5 since it is anticipated that the results of the tests will spur the need to make notable changes to the configuration, thereby requiring additional testing of the new configuration as part of TRL-6 development after LDSD.

A. Supersonic Ringsail Qualification Pillars

1. Phase 1: Initial Deployment

The preferred method of deploying a parachute behind a blunt body robotic spacecraft in a supersonic flowfield has been and continues to be via mortar deployment. This is primarily due to the technique's test and flight heritage, its insensitivity to aerodynamics, its ability to be qualified without flight testing, and its overall simplicity. Due to configuration constraints in the design of the LDSD test vehicle, it is not possible to stow the parachute on the vehicle's centerline. Off-centerline initiation of a very large mortar would produce unacceptably large torques on the test vehicle and likely lead to vehicle tumble. A counter-mortar approach was investigated but was too heavy to accommodate on the test vehicle. As a result, LDSD intends to deploy the SSRS using a pilot ballute deployed with a much smaller mortar.

In order to substitute a pilot deployment in place of a mortar deployment LDSD has identified 4 similarity parameters that will be preserved by the design of the pilot ballute deployment. By separating the ballute from the parachute deployment bag prior to line stretch and by preserving the similarity parameters identified below it is postulated that the parachute will behave from that point onward as if it had been mortar deployed.

1. **Parachute packed configuration.** The aspect ratio, pack density, and deployment bag configuration of the SSRS deployment bag must all be similar to those that would be used in a mortar-deployed system.

2. **Lock number.** The ratio of aerodynamic forces acting on the canopy to the inertial forces of the canopy, from the start of the inflation process (line stretch) up to bag strip, must be in family with those present during a mortar deployment. This parameter is generally not seen outside of aeroelasticity, but is still relevant to parachute deployment dynamics. Given that this is a full-scale system being tested in a relevant Mach-q environment, the ballute deployment naturally preserves this ratio.

3. **Characteristic bag strip velocity.** The average bag strip velocity (the length of extended canopy divided by the time from line stretch to bag strip) must be in family with the ratio present during a mortar deployment. This preserves the propensity of the canopy to begin inflating during bag strip or not.

4. **Parachute strain energy at, and immediately following, bag strip.** It is recognized that a typical pilot deployment generally accelerates the parachute pack until it is fully deployed and that a mortar deployment will always see a decelerating pack until the parachute is fully deployed. It is important that the design of the test deployment system preserves the parachute's strain energy state at the end of bag strip to be similar to that which would be present had the parachute been mortar deployed. This ensures that the canopy is neither accelerated back towards the test vehicle via strain energy nor held taut in a manner not replicated by a mortar deployment.

2. Phase 2: Inflation Dynamics

The initial inflation process refers specifically to the evolution of the canopy's shape that happens in the time period starting with completion of line stretch until shortly after bag strip when the canopy's shape has evolved to the point at which the aerodynamic forces acting on the canopy greatly exceed the canopy's inertial forces and the canopy configuration and strain energy state render it no longer at risk of inflation related failure modes such as inversions.

The most important test parameters to be controlled are the free-stream Mach number and the wake structure behind the forebody. These two key parameters are the driving requirements that result in the need to perform high-altitude supersonic test flights. The SFDT campaign is designed to provide the proper Mach and wake flow needed for phase 2 inflation dynamics testing of the LDSD parachute.

3. Phase 3: Parachute Peak Strength

Peak strength testing is used to verify the structural integrity of the candidate parachute design. Parachute inflations at Mars result in near infinite mass boundary conditions due to the extremely high speed inflations seen under supersonic deployment conditions. This means that the peak parachute forces are applied to the fully open parachute. It is critical to replicate this boundary condition in order to accurately test the parachute's structural design. After extensive evaluation of traditional test approaches the LDSD team determined that neither aerial drop testing nor wind tunnel testing could adequately meet this requirement in a cost effective way. As a result LDSD is developing the Parachute Design Verification (PDV) test system, discussed later, in conjunction with the Naval Air Warfare Center China Lake.

4. Phases 4 & 5: Parachute Supersonic and Subsonic Performance

Phase 4 and 5 test objectives are to characterize the static and dynamic aerodynamic performance of the parachute under flight like Mach and wake flow conditions. It is important to reproduce both conditions simultaneously since there is a strong dependency of the aerodynamics of the parachute on Mach and wake structure. In order to determine the dynamic aerodynamics of the parachute it is also necessary to replicate the ratio of apparent mass of the canopy to the suspended mass of the payload. The SFDT flights are designed specifically to meet these objectives. The targeted parachute Mach number range will be between 2.0 and 2.5 at line stretch. As the test vehicle decelerates it will decelerate through all of the Mach numbers of interest. The SFDT flight system will collect data to be able to reconstruct the descent trajectory and extract the aerodynamic coefficients needed by an adopting flight project.

B. SIAD Qualification Pillars

1. Phase 1: Initial Deployment

SIAD initial deployment refers to the initial release of the SIAD's retention and release (R&R) system. Phase 1 starts when the R&R pyrotechnic release devices have fired and ends once the SIAD fabric has successfully been released from its stowed configuration. Both SIAD-R and SIAD-E use a gas generation system so the initial deployment force applied by the internal gasses far outweighs externally applied aerodynamics for a brief period of time. Phase 1 testing focuses on demonstrating functional performance of the R&R system as well as any internal gas diffusion needed to properly distribute the gas generator flow. For the R&R concepts developed for the two SIADS, testing does not require any flowfield to demonstrate functionality of the R&R system.

2. Phase 2: SIAD Inflation Dynamics

SIAD inflation dynamics has two primary elements, dynamic loads imparted to the SIAD structure and vehicle flight dynamics imparted by the evolving shape of the SIAD. Phase 2 testing must replicate the vehicle geometries, mass properties, and aerodynamic flow conditions sufficiently to allow the inflation time history of the deploying SIAD to evolve and couple with the entry body in a dynamically representative manner. Much like parachute inflation dynamics the packaging configuration, the Lock number and the characteristic inflation speed must all be in family with the Mars flight application in order to properly test the SIAD. Full scale testing is the most reliable way of simultaneously meeting these conditions. Phase 2 SIAD testing relies on the high altitude SFDT campaign to demonstrate successful inflation dynamics. The subsonic SIAD Design Verification (SDV) inflation tests are exceptionally useful in building confidence that the SIADs will deploy with minimal disturbance to the entry vehicle.

3. Phase 3: SIAD Peak Strength

Peak strength testing is used to verify the structural integrity of the candidate SIAD design. The SIADs are stressed by the combination of internal pressure as well as external aerodynamic loads. Peak strength

testing is used to recreate the combined stress state in the SIAD. Since peak strength performance is specific to a constructed design, it is necessary for these tests to use full scale flight like hardware in order to achieve TRL-6. Material strength degradation can either be accounted for in the test design or can be applied as a margin knock-down analytically. LDSD has chosen to do the latter in conjunction with a detailed material strength at temperature test program. The SDV test campaign is specifically designed to subject the SIAD to peak strength test loads 1.25 times the anticipated maximum flight limit load at Mars. Since the drag coefficient of the SIAD and test vehicle is lower at the SDV subsonic test speeds compared to supersonic conditions, the SDV dynamic pressure should be higher than the expected Mars dynamic pressure to generate appropriate loads. Thus, the SDV tests match the product of drag coefficient and dynamic pressure (C_D x q_∞) between supersonic and subsonic conditions.

4. Phases 4 & 5: SIAD Supersonic & Subsonic Performance

Phase 4 and 5 test objectives are to characterize the static and dynamic aerodynamic performance of the SIADs under flight like Mach conditions. Full scale flight testing of a structurally representative SIAD configuration provides what will be the primary source of data for aerodynamic database development. As such, an emphasis is placed on being able to extract high quality flight dynamics data needed to determine the system's static aerocoefficients (C_A, C_N, and C_m) and to the extent possible, the dynamic damping coefficients as well (e.g. $C_{m_{\dot{\alpha}}}$). SIAD aerothermoelastic behavior is a primary system characteristic that must be matched in order to produce the proper flight dynamics performance. This is achieved by flying full scale test articles made of flight materials at conditions that will expose them to appropriate heat rates.

V. Test Program

The core of the LDSD test program is comprised of the three components necessary to satisfy the five pillars. This includes the ground based SIAD Design Verification (SDV) and Parachute Design Verification (PDV) tests and the high altitude Supersonic Flight Dynamics Tests (SFDT). Each of these is discussed in detail below.

A. Parachute Design Verification Test

Structural verification testing is a common parachute test and has been repeated by each Mars mission since Viking. The typical approach is to apply an aerodynamic load on the parachute that is equivalent to the maximum load expected during supersonic inflation by means of a low-altitude subsonic drop test or via full-scale wind tunnel testing. Both options were evaluated initially for use by LDSD, but both were found to have limitations. A flight limit load of 445 kN (100,000 lbs) was established for the LDSD canopy based on early predictions of the loading environment expected for SFDT flights. Ways of achieving this load plus a 25% margin via a low-altitude drop test were evaluated and seen to require extremely large payload masses and aircraft in the family of a C-17 to achieve the drop test. Achieving the desired test conditions is also complicated by the lack of an infinite mass inflation and rapidly changing dynamic pressures during the drop. Scheduling of C-17 tests was noted to be more difficult and would limit the ability of the project to react to problems found during the development phase. Lastly, the costs associated with a C-17 type drop test campaign were prohibitive within the LDSD budget. Elimination of a wind tunnel test option came much easier. The largest wind tunnel in the world is the 80' x 120' test section of the National Full Scale Aerodynamics Complex (NFAC) located at Ames Research Center. However, the size of the LDSD canopy at 33.5 meters nominal diameter is far too large to allow for testing of a full open canopy. Testing of a reefed canopy was not considered to be representative enough of the stress state expected during peak inflation.

Having eliminated the traditional parachute load application approaches, LDSD began investigating a new test approach. Working in conjunction with the Naval Air Warfare Center China Lake, a rocket sled approach was developed. This test architecture (see Figure 7) utilizes a helicopter to bring the stowed parachute to an altitude of approximately 1500 m. The parachute is attached to a long rope that passes around a pulley and is tied at the other end to the rocket sled. The test begins with the release of the parachute from the helicopter. The weight of the rope pulls the parachute towards the ground and initiates inflation of the parachute. A winch, located near the pulley on the ground, takes up the rope slack. Once the parachute has achieved full inflation, the rockets are ignited and the sled moves down the track, pulling the parachute towards the ground at a velocity necessary to achieve the required load.

Figure 7. PDV Test Architecture (not shown to scale).

This test architecture was seen to have a number of advantages over the alternatives. The test architecture is not limited by the size of the parachute being tested, nor by the desired load. The load applied to the parachute is also more deterministic than a traditional drop test as it is limited to the thrust of the rocket sled. Similarly, significantly larger loads can be achieved through the use of a greater number of rockets or more powerful rockets. The PDV architecture also ensures that the load is applied to the parachute in a full open configuration, thus applying the appropriate stress state to the canopy and suspension lines. Testing at a fixed location near the ground permits far better instrumentation to observe the test, as compared to a drop test. The availability of the test apparatus to a flight project on a fixed schedule is very attractive. When a problem is found and the delivery schedule is fixed, it becomes imperative to be able to test as frequently as necessary to overcome the problem. Lastly, the overall cost of the PDV architecture was found to fit within the project budget.

B. SIAD Design Verification Test

As with parachute design verification test, the SIAD design verification test required the development of a new test architecture. Though a wind tunnel test program was initially preferred, there is not a wind tunnel large enough to test both the SIAD-R and SIAD-E devices at full scale and at appropriate dynamic pressures. The developed architecture, shown in Figure 8, utilizes a rocket sled to accelerate the test article to the required test conditions.

The SDV architecture is comprised of a large central sled with a full scale 4.7 m diameter test vehicle that provids interfaces identical to the SFDT test vehicle, a camera and instrumentation sled to image the SIAD, and a pusher sled containing the necessary rocket motors. In a nominal test, the main sled is accelerated to the desired velocity and dynamic pressure and the SIAD is deployed by means of an on board cold gas inflation system. The use of a sustainer rocket after full SIAD inflation allows for an extended period of testing at condition.

The first round of SDV tests on SIAD-R was successfully completed in November of 2012. This campaign consisted of three separate runs of a single SIAD-R test article at increasing dynamic pressures. An image from one of the runs is shown in Figure 9. The SDV architecture is currently being modified to accommodate testing of the larger SIAD-E article. The primary modification entails extending the support structure further away from the main sled so as to keep the support structure from interfering with the more swept back geometry of SIAD-E.

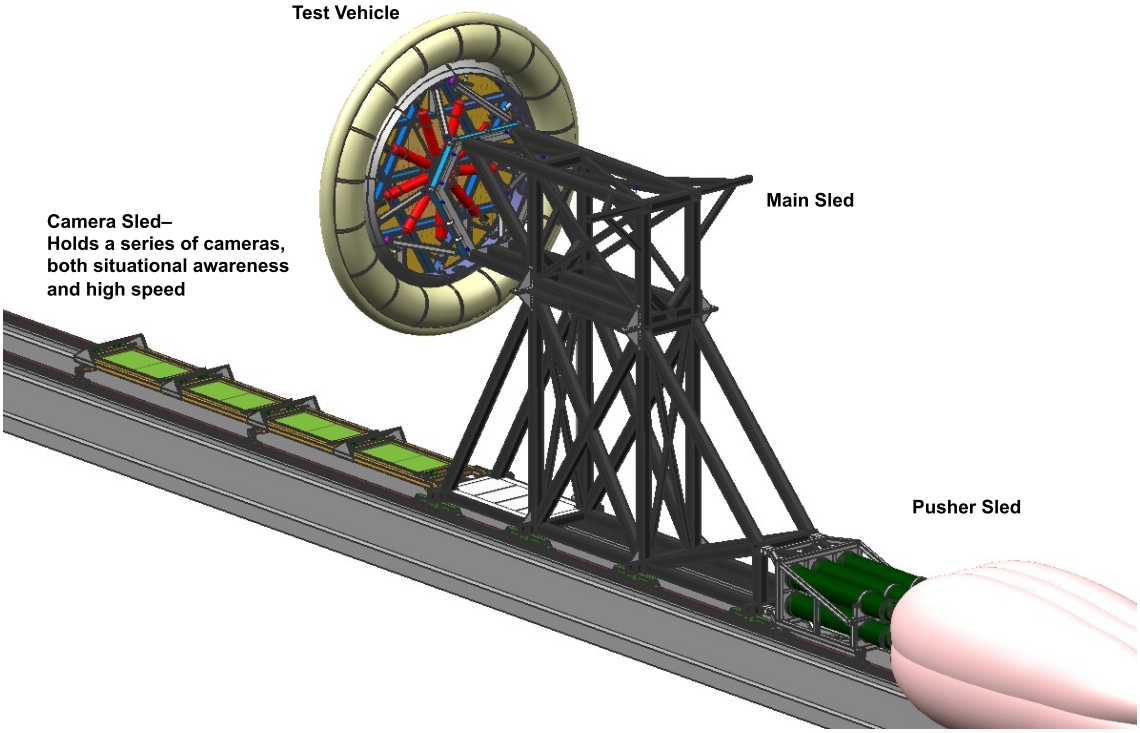

Figure 8. SDV Test Architecture (shown with deployed SIAD-R).

Figure 9. SDV run with fully inflated SIAD-R and sustainer rocket ignition.

C. Supersonic Flight Dynamics Test Campaign

The culmination of the LDSD project is a set of four high-altitude supersonic flight tests that are intended to test the full scale decelerators at Mars relevant conditions. The test approach is similar to that utilized by the Viking Mars Program for the qualification of the supersonic DGB parachute[8] and previously by the Planetary Exploration Parachute Program (PEPP).[5] Shown in Figure 10 is the SFDT trajectory overview. To achieve the needed test conditions, a full scale aeroshell is nominally lofted to an altitude of approximately 36 km by a large helium balloon. The aeroshell is planned to be released, spun up for stability, and the main motor is ignited to accelerate the test vehicle to an altitude of approximately 50 km at Mach 4. At this point the vehicle would be despun and the main test period begins with SIAD deployment.

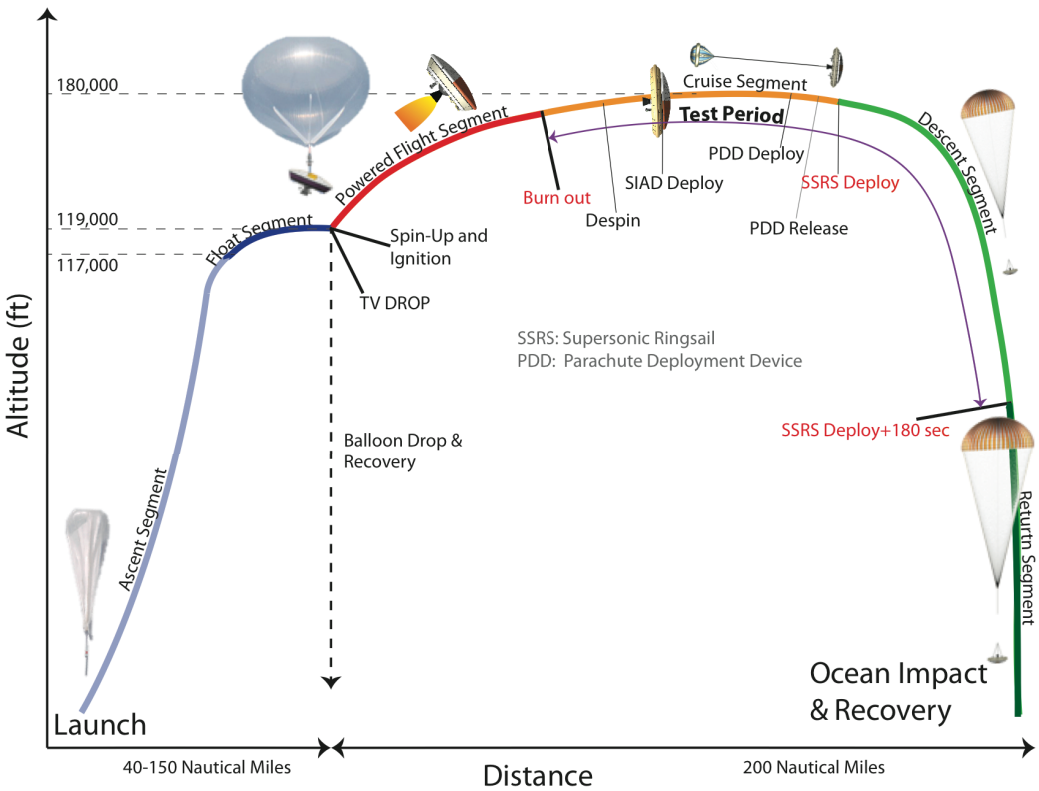

Figure 10. Supersonic Flight Dynamics Test trajectory overview.

The first SFDT flight is scheduled to occur in June of 2014 and is planned to incorporate the SIAD-R test article and the 33.5 m parachute. Three more flights are planned to occur beginning in June of 2015, with the first two of those also testing the SIAD-R configuration and the last flight testing the SIAD-E configuration. All four test flights will nominally include the 33.5 m supersonic parachute, where at least one flight will deploy the parachute initially to a reefed state.

1. *Test Condition Definition*

In selecting the targeted test conditions a number of factors were considered. The results of the systems studies conducted by LDSD provided guidance on the environments and conditions that the devices would be exposed to during Mars flight. However, some consideration was given in trying to assure mission flexibility by an adopting project. Thus, some margin in targeted conditions was established using the capabilities of the SFDT architecture. A comparison of the SFDT deployment conditions with those predicted through Mars systems studies is shown in Figure 11. The results shown correspond to individual test points predicted

through Monte Carlo analyses. Mars conditions are targeted to maximize altitude and accuracy at parachute deployment with the largest mass possible. SFDT test conditions are targeted for a nominal Mach number at SIAD inflation of 3.75 and a parachute deploy Mach number of 2.25.

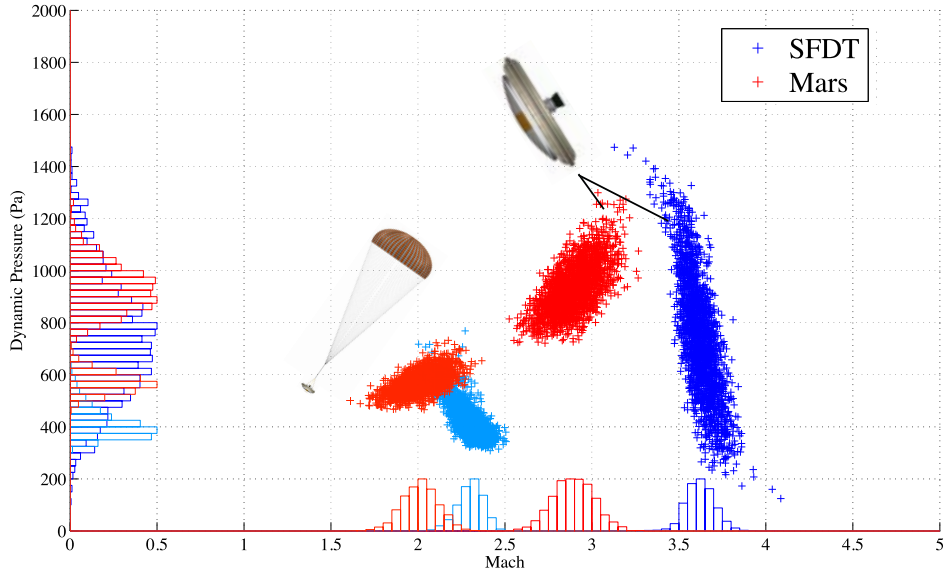

Figure 11. Comparison between SFDT Mach and dynamic pressure conditions at deployment versus those predicted through Mars systems studies for SIAD-R.

Of note is that while the Mach numbers at SIAD and parachute deployment at Mars are well bounded by the SFDT conditions, SFDT is likely to undertest the dynamic pressure on both. Because of the difference in atmospheric composition and temperature between Earth and Mars, it is not possible to provide margin on dynamic pressure conditions without greatly exceeding the Mach number test conditions. The implications of this to bringing the technologies to TRL-6 are minor since the dynamic pressure predominantly influences the aerodynamic loading on the test articles, which is tested and qualified through the ground based Design Verification tests. Another consequence of the atmosphere difference is that the aerothermodynamic environment at Earth is conservative when compared against expected Mars heat rates. Though less than 2 W/cm^2, the heat rates encountered by either SIAD at Earth are 2-3x those predicted for Mars applications.

D. Auxiliary Tests

To support both the technology development and the SFDT campaign, a number of additional tests are being conducted by the LDSD project. These include subscale wind tunnel tests, parachute deployment and rigging stand up tests, and sub-scale vacuum inflation tests. The subscale parachute wind tunnel test campaign is being conducted to provide insight into the trade of drag and stability that is possible with a Ringsail parachute and to provide data for the eventual downselection to a final configuration. These tests are exploring modifications to the canopy's geometric porosity and porosity distribution in the hopes of optimizing the drag for a given stability.

Due to a number of vehicle constraints, the parachute will be deployed via a pilot ballute device rather than a traditional mortar system. This, when coupled with the mass constraints of the test vehicle leads to a complicated balance of forces during the parachute deployment phase. Assurance that there is adequate tension in the parachute rigging and suspension lines during deployment and that the rigging deployment occurs in an orderly manner is the task of a rigging test bed being built by LDSD. This test bed models the extraction forces provided by the pilot ballute and allows for testing of the phasing and staging of the rigging system.

VI. Conclusion

The technologies being developed by the Low Density Supersonic Decelerator project, once successfully demonstrated, could enable dramatic improvements in our ability to access the surface of Mars in the dimensions of entry mass, landed mass, altitude, and precision. In addition, new methodologies for testing these devices at full scale in relevant environmental conditions are being developed and exercised by LDSD, which provide for high confidence in the reliability and performance of the technologies in Mars missions, as well as offering new opportunities for other technology developments for the descent phase at Mars, or for other high-Mach, low-atmospheric-density applications.

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References

[1]Musil, J. L., "Study of Expandable, Terminal Decelerators for Mars Atmospheric Entry: Volume I - Final Summary Report," Goodyear Aerospace Corporation Technical Report GER-12842, Goodyear Aerospace Corporation, Oct. 1966.

[2]Bohon, H. L. and Miserentino, R., "Attached Inflatable Decelerator Performance Evaluation and Mission-Application Study," AIAA Paper 1970-1163, Sept. 1970.

[3]Clark, I. G., Hutchings, A. L., Tanner, C. L., and Braun, R. D., "Supersonic Inflatable Aerodynamic Decelerators for Use on Future Robotic Missions to Mars," *Journal of Spacecraft and Rockets*, Vol. 46, No. 2, March 2009, pp. 340–352.

[4]Houtz, N. E., "Optimization of Inflatable Drag Devices by Isotensoid Design," AIAA Paper 1964-437, 1964.

[5]Murrow, H. N. and McFall Jr, J. C., "Some Test Results from the NASA Planetary Entry Parachute Program," *Journal of Spacecraft and Rockets*, Vol. 6, No. 5, June 1969, pp. 621–623.

[6]Mitcheltree, R. A., Bruno, R., Slimko, E., Baffes, C., Konefat, E., and Witkowski, A., "High Altitude Test Program for a Mars Subsonic Parachute," AIAA Paper 2005-1659, 2005.

[7]Adams, D. and Rivellini, T., "Mars Science Laboratory's Parachute Qualification Approach," AIAA Paper 2009-2913, 2009.

[8]Moog, R. D., Bendura, R. J., Timmons, J. D., and Lau, R. A., "Qualification Flight Tests of the Viking Decelerator System," AIAA Paper 1973-457, May 1973.