Rocket Sled Propelled Testing of a Supersonic Inflatable Aerodynamic Decelerator

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Inflatable Aerodynamic Decelerators (IADs) have traditionally been tested in wind tunnels. As the limitations of these test facilities are reached, other avenues must be pursued. The IAD being tested is a Supersonic IAD (SIAD), which attaches just aft of the heatshield around the perimeter of an entry body. This 'attached torus' SIAD is meant to improve the accuracy of landing for robotic class missions to Mars and allow for potentially increased payloads. The SIAD Design Verification (SDV) test aims to qualify the SIAD by applying a targeted aerodynamic load to the vehicle. While many test architectures were researched, a rocket sled track was ultimately chosen to be the most cost effective way to achieve the desired dynamic pressures. The Supersonic Naval Ordnance Research Track (SNORT) at the Naval Air Warfare Center Weapons Division (NAWCWD) China Lake is a four mile test track, traditionally used for warhead and ejection seat testing. Prior to SDV, inflatable drag bodies have been tested on this particular track. Teams at Jet Propulsion Laboratory (JPL) and NAWCWD collaborate together to design and fabricate one of the largest sleds ever built. The SDV sled is comprised of three individual sleds: a Pusher Sled which holds the solid booster rockets, an Item Sled which supports the test vehicle, and a Camera Sled that is pushed in front for in-situ footage and measurements. The JPL-designed Test Vehicle has a full-scale heatshield shape and contains all instrumentation and inflation systems necessary to inflate and test a SIAD. The first campaign that is run at SNORT tested all hardware and instrumentation before the SIAD was ready to be tested. For each of the three tests in this campaign, the number of rockets and top speed was increased and the data analyzed to ensure the hardware is safe at the necessary accelerations and aerodynamic loads.

I. Introduction

OVER the last half decade, many analyses and studies have found that Supersonic Inflatable Aerodynamic Decelerators (SIADs) are a promising technology for enabling growth in payload delivery performance (mass, altitude and accuracy) to atmosphere covered bodies such as Mars. The IAD's shape is maintained by a closed, pressurized body. Its primary function is to provide a large increase in drag area in a post peakheating, post peak-deceleration environment, prior to parachute deployment.

The Low Density Supersonic Decelerators project aims to develop two types of SIADs and one ringsail parachute.

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Following a philosophy similar to past parachute testing, there are five areas of testing that need to conducted for the SIAD. These areas are initial deployment and inflation, inflation dynamics, strength and integrity, supersonic performance, and subsonic performance. Out of the five main pillars of qualification, the SIAD Design Verification Test (SDV) addresses three. The primary objective achieved by SDV is the deployment strength and integrity of the fabric. The other two are addressed with certain caveats due to slower velocities and higher air densities at sea level.

The SDV test brings the stowed SIAD to appropriate dynamic pressure conditions in a free-stream and then deploys the SIAD. It tests the SIAD at the qualification load to determine its survivability.

II. Test Facility Research

A. Wind Tunnel

The majority of aerodynamic testing in the past has been conducted in wind tunnels. The test article is fixed to a stationary position and air is passed over it. The primary limitations to wind tunnels are the max velocity of the air, the size of the tunnel before significant blockage occurs, and the max load that the facility ground can react. The National Full-Scale Aerodynamics Complex (NFAC) tunnels at Ames Research Center came closest to meeting the requirements for the SIADs the project was aiming to test. The two largest tunnels have cross sectional areas of 40 ft x 80 ft and 80 ft x 120 ft. Generally, the smaller the cross section, the higher the wind speeds that can be reached. The 40 ft x 80 ft tunnel could house the 6 m attached torus SIAD, but at 6 m it approaches the maximum size the tunnel can support before blockage occurs.

Had a wind tunnel been chosen for the test architecture, a support structure would have been designed to hold a test vehicle into the airflow. Wind tunnels have a definitive advantage over other test architectures in that lots of data can be taken over long test durations. Unlike a drop test, the article is stationary, allowing for improved photography and measurements in a controlled airflow.

B. Helicopter Drop Testing

Drop testing is the act of bringing a test vehicle up to altitude, dropping it from an aircraft, and deploying the SIAD at a specific speed. This technique is often used to test parachutes. For most parachutes, the test corresponds directly to real usage, since most parachutes are deployed from aircraft in the earth atmosphere. When testing the SIADs, very large speeds must be achieved to match the dynamic pressure that would be seen in a Mars entry. Any drop test that would be used needs a high altitude and a heavy enough vehicle to reach a terminal velocity that equates to this desired dynamic pressure. Once the SIAD is deployed, drag area is naturally increased, slowing the vehicle down and reducing the dynamic pressure. This affect makes it difficult to maintain what is known as an "infinite mass" scenario, where there is very little reduction in speed at decelerator deployment – an effect that is observed during Mars entry.

Figure 1 shows some of the simulation results for drop testing from a Sikorsky helicopter. In the simulation runs, altitude and mass are maximized and a full-scale test vehicle is used.

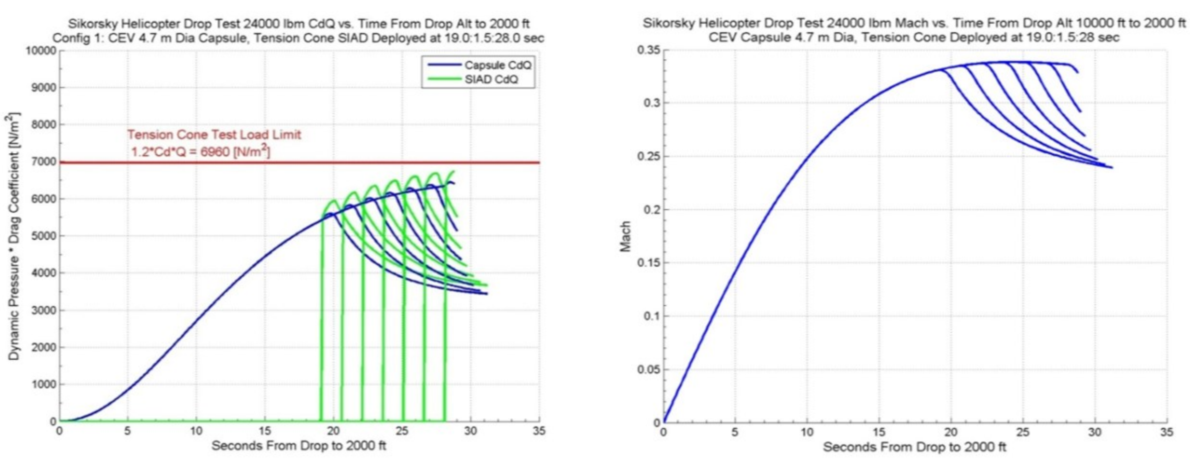

Figure 1. Helicopter drop simulation results

These runs were looking just at 6.5 m tension cone SIADs. The simulations used an Orion Crew Exploration Vehicle (CEV) capsule drag coefficient, and showed that the test conditions could not be achieved, due to the large drag prior to SIAD deployment ($C_D \sim 0.85$).

A test vehicle configuration with a low drag coefficient would be necessary to increase the velocity and dynamic pressure at deploy time, allowing for a dynamic pressure to be applied to the SIAD soft goods and achieve test conditions. A drastically different shape would have to be designed to achieve such low drag coefficients, which is largely undesirable.

C. C17 Drop Testing

C17 airplanes are large cargo-carrying planes that are used for many drop tests. Compared to helicopters, the C17 can reach higher altitudes and carry much heavier vehicles. The full-scale vehicle needed for SDV testing fits inside the cargo area of the plane.

The major disadvantage of drop testing from a plane compared to a helicopter is the nature in which the vehicle must be extracted from the aircraft. Unlike a helicopter, where the vehicle is simply dropped from the bottom of the hovering aircraft, on an airplane the vehicle must be pulled out of the back of the plane on an extraction cart. A parachute would pull the cart out of the plane, and then multiple other parachutes would be used to separate the vehicle from the cart and align the vehicle upright. Those chutes would have to be discarded to allow the vehicle to reach a high enough velocity for testing. The risk involved in this method of testing was considered high, and has resulted in tumbling vehicles in past Orion testing.

D. Super High Velocity Airflow System (SHIVAS)

The SHIVAS is located at the Naval Air Warfare Center Weapons Division (NAWCWD) at China Lake, California. It utilizes 9 jet engines to create the effect of an outdoor wind tunnel. The flow is considered dirty, both in composition and flow consistency. The inflated 6 m SIAD has a cross sectional area of just over 14,000 in^2. The SHIVAS produces a flow of 250 knots to an area of 12,500 in^2. The area increases as the object is placed further away, but the flow velocity decreases significantly.

Figure 2. SHIVAS @ China Lake

E. Rocket Sleds

Rocket sleds are rocket-propelled sleds that glide along steel tracks. They are used for a wide variety of applications, ranging from weapons testing to ejection seat testing. They have been used for drag bodies in the past, including parachutes and ballutes, but never used to push a ballute in front of a sled, which would be required for testing a SIAD.

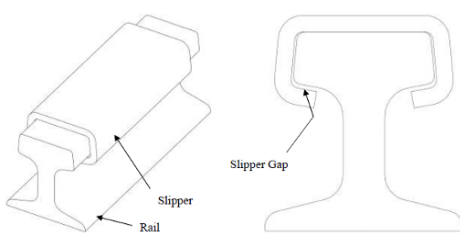

Figure 3. Slipper on rail utilized at rocket sled tracks

Holloman Air Force Base, located in New Mexico, possesses the country's longest rocket sled track. The track is 50,788 ft long and 7 ft wide rail-to-rail. They have conducted parachute and ballute testing in the past on the order of 23 ft diameter chutes at up to Mach 1.5. The sleds, as seen in Figure 4, are large puller sleds with a parachute or ballute attached at the top. The facilities include a host of instrumentation and videography that is available to customers.

Figure 4. Rocket Sled Track @ Holloman Air Force Base

The Supersonic Naval Ordinance Research Track (SNORT) is located at NAWCWD China Lake. It has been in operation since 1953 and conducts regular track testing including: ejection seat tests, warhead tests, arena tests, radar testing, improvised explosive device emplacements, drop testing, and static rocket motor firings. The track is 21,600 ft long, 5 ft rail-to-rail, and most sleds run along the track south to north.

Figure 5. SNORT testing capabilities

There is a water brake capability that creates a water trough between the rails that will slow down a sled from supersonic speeds. A track-side velocity measurement system can track speeds of sleds to over Mach 3. There is a main bunker, located near the breach at the south end. There is also shelter for personnel down-range for selected tests.

Figure 6. SNORT main track

SNORT has conducted parachute and drag body testing in the past including aerodynamic drag-brake systems pushed in front of a tall sled. Incorporating ballutes onto a sled of this magnitude was a new undertaking for them.

The base is located three hours north of the Jet Propulsion Laboratory. The team at SNORT is small, versatile, and experienced. SNORT is ultimately chosen as the venue for SDV testing.

III. Sled Components and Overview

The sled has several components to hold the Test Vehicle high enough off the ground to avoid ground interaction during testing, propel the Test Vehicle forward, and take all necessary data at velocity.

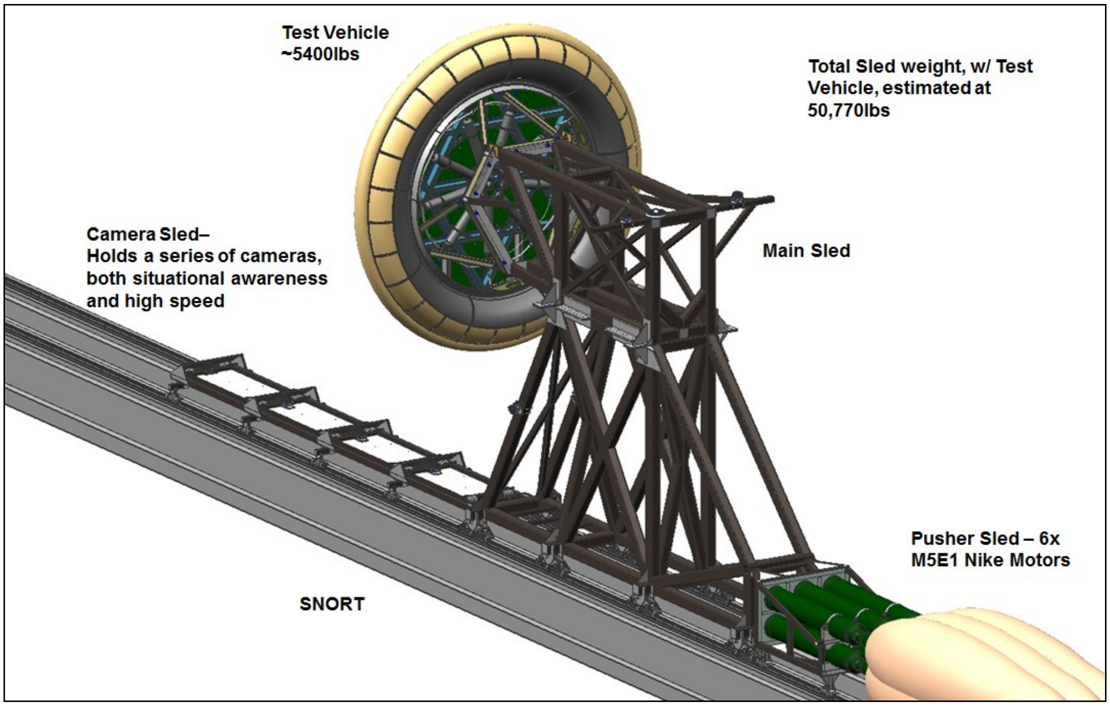

Figure 7. Test architecture overview

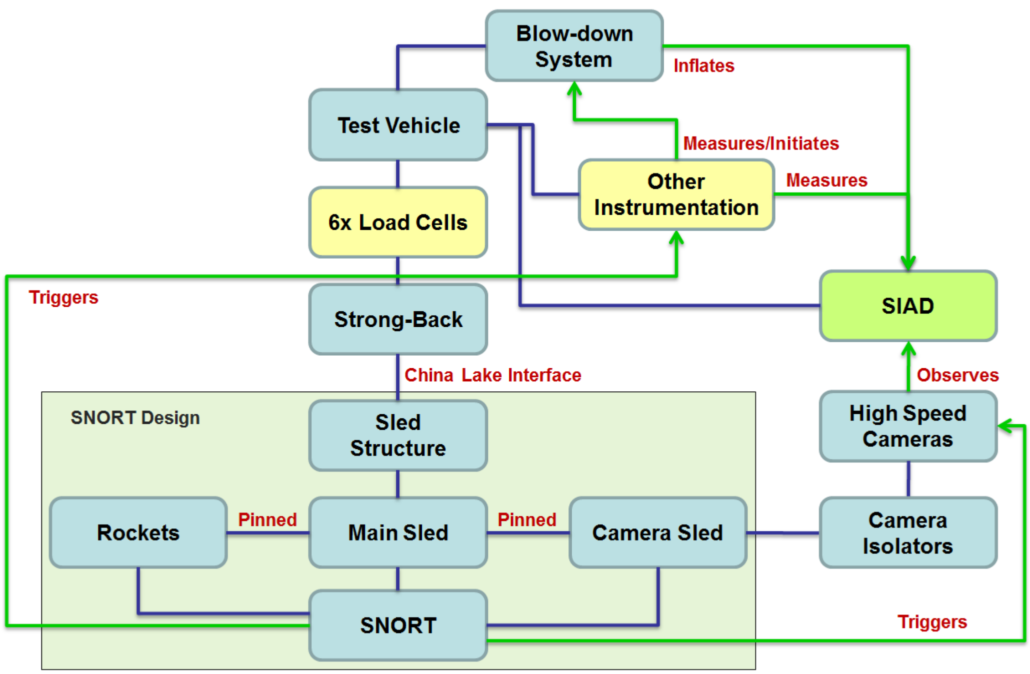

Figure 8. SDV system diagram

A. Pusher Sled

The Pusher Sled is attached at the rear of the entire sled assembly. It houses the rockets that propel the sled forward down the track. The Pusher Sled used on SDV is a steel structure, which can contain anywhere from 1-6 rockets, depending on the desired trajectory. These rockets can be either triggered initially at the start of test, or some can be used as sustainer rockets down track to test at different velocities for longer periods of time.

B. Item Sled

The Item Sled is a tall, steel structure that contains the interface for the Test Vehicle. It is comprised of 2 pieces, one upper and one lower. It sits between the Pusher Sled and Camera Sled.

C. Camera Sled

Video imagery of the test article is taken from a camera sled that is pushed in front of the Item Sled. In order to achieve clear video, it was necessary to isolate the cameras from the harsh vibrations imposed by the track. The primary goal when designing the isolation system was to reduce high frequency vibrations such that blurring of frames would be prevented. Lower frequency vibrations could be permitted so long as their period was long as compared to the camera frame rate (30 Hz for situational awareness cameras).

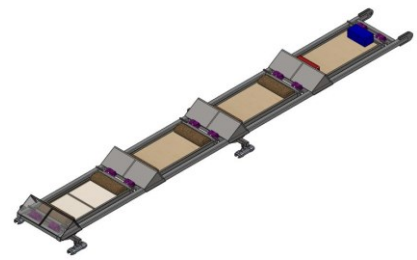

Figure 9. SDV camera sled with isolator pods installed

The Camera Sled is split into four isolated pods to which cameras and electronics can be mounted. The base of each frame is constructed out of structural steel tubing, with plywood decks providing a convenient mounting interface for cameras and electronics. Each pod is connected to the sled with four wire rope isolators, two on each end. In order to prevent wind buffeting, sheet metal wind breaks were installed to the sled ahead of each pod.

Figure 10. Typical wire rope isolator

In considering the different types of isolators each pod was modeled, to first order, as a spring-mass system with a goal of achieving the lowest possible natural frequency.

Wire rope isolators were selected because they offered the best combination of low spring rate and high loading capability, while additionally providing a modest amount of damping.

For this analysis, it was assumed that the sled would impart a given acceleration to the isolator regardless of the isolator mass. Based on this, comparisons could be made between isolator size and platform mass.

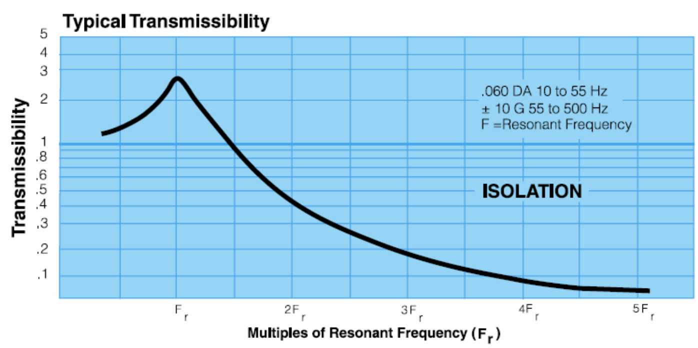

Figure 11. Typical transmissibility of wire rope isolators

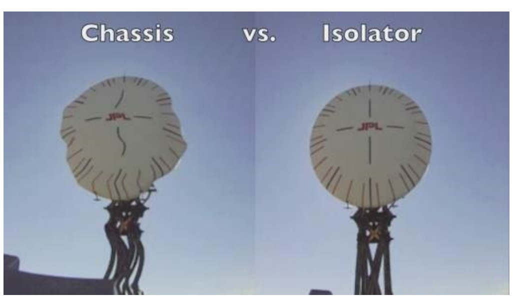

Figure 12. Comparison of video from chassis mounted cameras and isolator mounted camera.

The lowest natural frequency is achieved by the system with the highest allowable travel. Unfortunately, the larger wire rope isolators become increasingly expensive, and require a substantial amount of mass to actually achieve the desired natural frequency. A compromise in size was achieved.

Without cameras or electronics installed, each isolator pod weighs only 200 lbs, so depending on the amount of equipment installed they should be ballasted up to the maximum weight in order to achieve maximum performance.

Figure 12 shows the dramatic improvement in image quality that was achieved with the isolators as compared to cameras mounted directly to the chassis of the camera sled.

D. Test Vehicle

The Test Vehicle can be broken up into 6 key assemblies. The heatshield is comprised of 3 lb/ft^3 foam. The foam is machined from 13 individual parts, which match the heatshield profile on one side and interface to the Test Vehicle on the other. They make up the entire thickness that would normal be seen from the heatshield separation plane to the front outer mold line. The foam compression strength is enough to take the expected dynamic pressure along the track. As opposed to a hollow design, which would have required a honeycomb lattice for stiffness, the foam provided a cheap, relatively light way to maintain the OML shape at velocity. Two layers of fiberglass surround the foam, but are not needed for strength, only durability.

The aluminum honeycomb panels provide a stiff transition from the foam to the steel structure. While the foam has enough compression strength, it has very little bending stiffness. The honeycomb panels provide the bending stiffness necessary to support the foam. Threaded inserts are bonded into the panels to allow them to be fastened to the steel structure.

The primary structure is a 6-point star pattern utilizing 3 in x 8 in steel. The star structure has the conical aft section, made of sheet steel, welded directly to it, along with multiple load plates and brackets for attaching the rear hexapod structure and electronics.

Three ground support mounting points, used for trailer attachment and crane-lift operations, exist on steel sliders that engage into steel tubing found on the star structure. When engaged, pins are used to hold in place and take the full weight of the Test Vehicle. The sliding action allows the team to disengage the parts after attaching the vehicle to the sled. When removed, the OML matches the design reference vehicle much more closely for better testing conditions. It was found upon assembly that the pins were difficult to reach while the Test Vehicle is attached to the sled, and ultimately the sliders were left on during testing.

The inflation system is comprised of nine helium tanks and pneumatic ball valves. The system serves to duplicate the functionality of the gas generators that would be found on a flight vehicle. They fasten directly to the primary structure with steel straps onto welded-on cradles. The exit pipes fit through the side section and terminate sub-flush to the conical sheet metal backshell.

The hexapod structure has six struts, each with rod-ends at both ends and a one degree-of-freedom load cell at one end. The struts attach to clevises on the strongback and clevises on the primary structure. Knowing the angles of the struts and using the six load cells, one can calculate the six degree-of-freedom loads and moments of the Test Vehicle as seen by the strongback. Changing out struts for different lengths gives the ability to change the angle of attack of the Test Vehicle attached to the sleds.

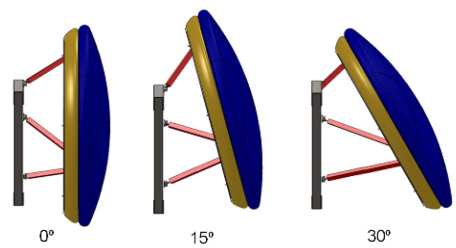

Figure 13. Hexapod allows for different angles of attack

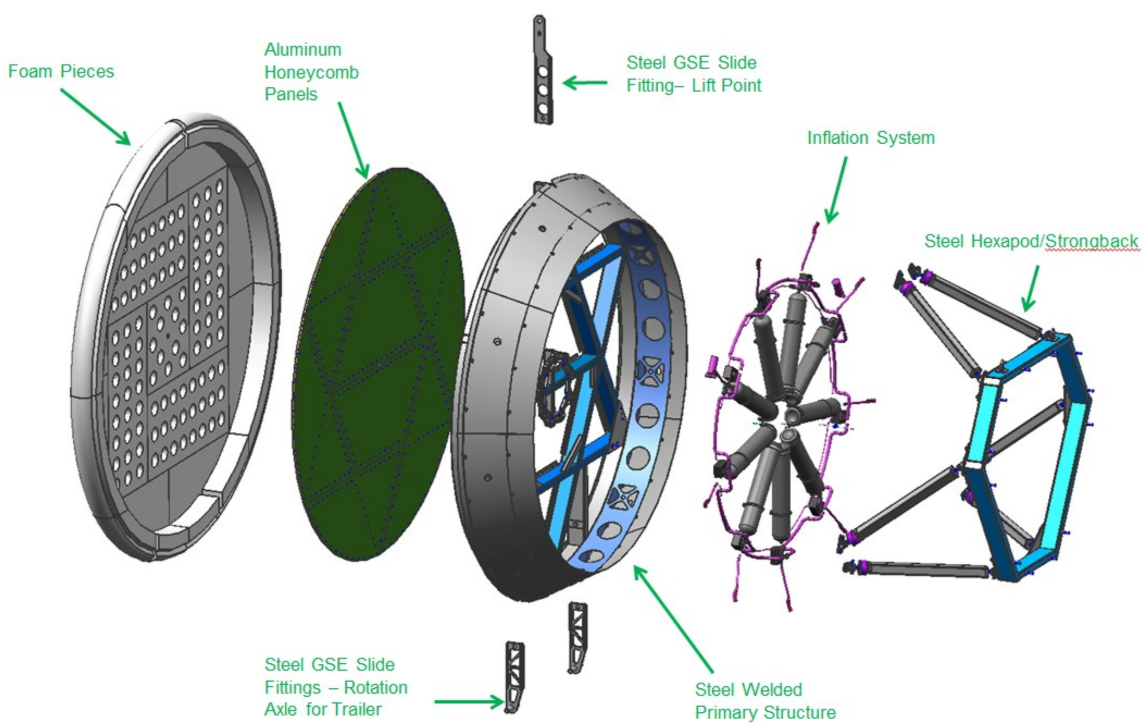

Figure 14. Test Vehicle Components

The Trailer is used for Test Vehicle build-up, assembly, transportation, and crane operations. It is made from the same tubular steel as the primary structure. It utilizes two pneumatic castors and two static wheel assemblies. Four jack stands are welded at the corners and a tow bar attached to the front. The two vehicle attachments points in the rear allow for vehicle rotation about the trailer, while the third in the front overhangs the trailer and is used for a crane lift point. This feature can be used to flip the vehicle either nose down or nose up when the hexapod is removed. The trailer is good for speeds of up to 10 mph, at which point the front castors begin to bounce and spin sporadically. This is thought to be due to the stiffness of the assembly. For moving from one point to another at China Lake, it works well.

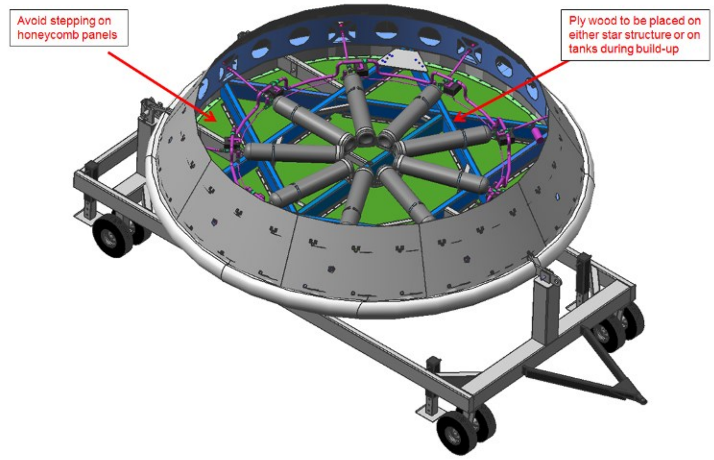

Figure 15. Test Vehicle on Trailer

E. Trajectory

The first campaign is considered to be a shake-out test of the structure and all instrumentation prior to attaching a SIAD. Several trajectories were looked at in order to increase the amount of propulsion used between tests. The faster tests included a sustainer rocket, which is meant to hold a particular velocity of interest. Depending on the targeted velocity for the sustainer, the slope of velocity will be different during that time due to the drag felt by the Test Vehicle. Several of these predicted trajectories can be seen in Figure 16.

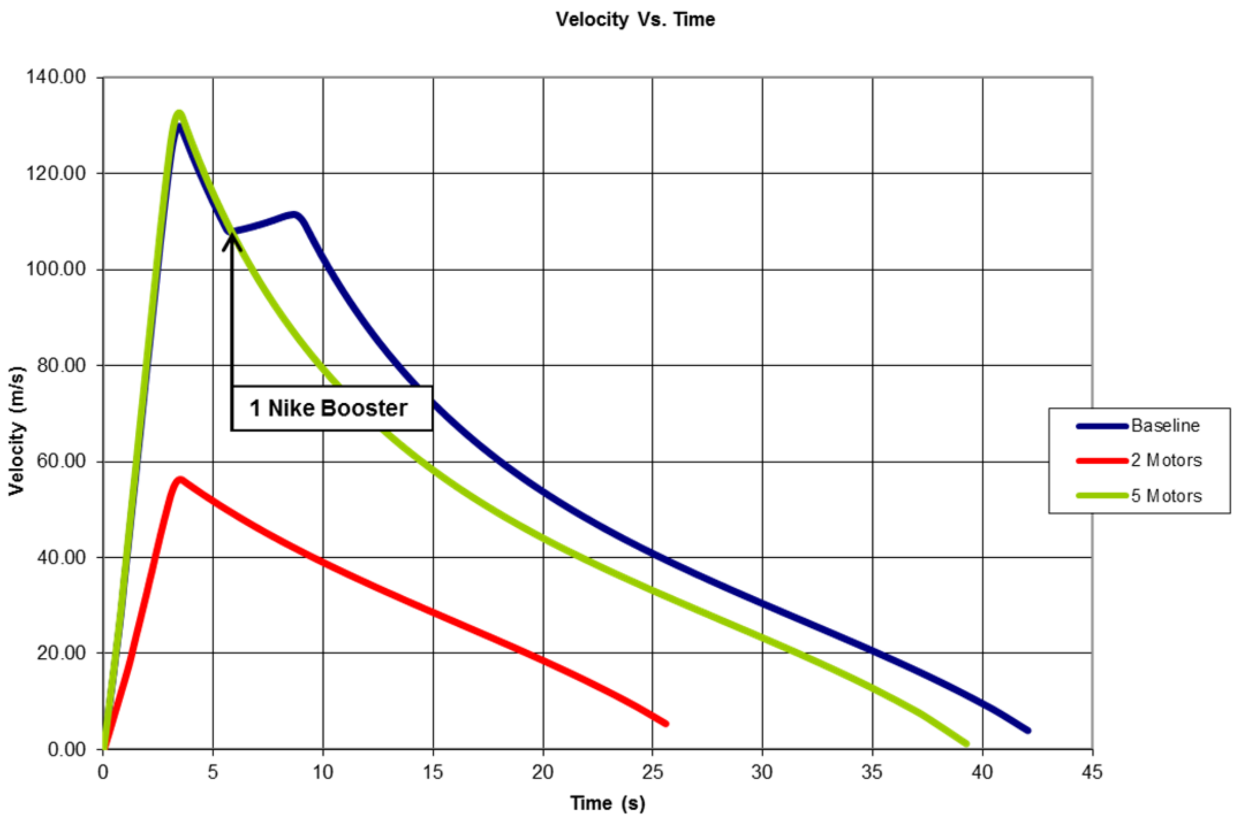

Figure 16. Predicted trajectories

In a nominal test, the sled is accelerated past the targeted test velocity. Since there are a discreet number of rockets to choose from, it is an easier task to hit a velocity beyond the desired velocity. During deceleration, a track-based trigger ignites the final sustainer rocket. This sequence is outlined in Figure 17.

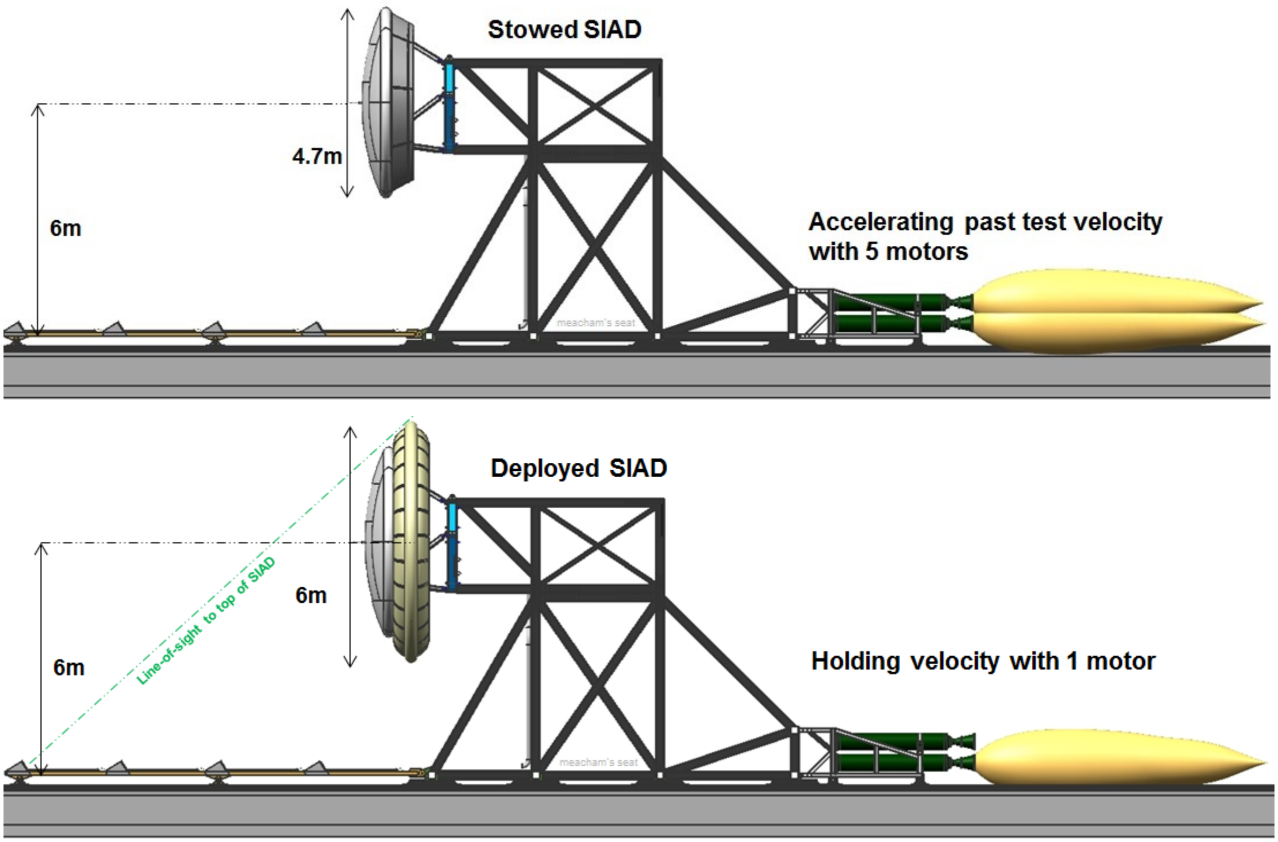

Figure 17. SDV acceleration and deceleration

IV. Campaign

A. Assembly

The fabrication and assembly of the Test Vehicle and sleds was performed at NAWCWD China Lake. The fabrication process took roughly six months to complete. The trailer, which is normally used to tow the Test Vehicle around base, was doubled up as an assembly stand for much of the final fabrication and painting.

Figure 18. Test Vehicle Buildup

B. Results

Much of the reasons for ramping up the velocity slowly during the first campaign was the fear of vortex shedding on the Test Vehicle. There was little existing data at these Reynolds numbers prior to this test, and it was thought that if there was indeed vortex shedding, it would occur very near the first frequency mode of the structure. The data was analyzed between tests carefully, looking at loads and acceleration data. The hexapod structure with load cells can be compared to acceleration data in the vehicle to extract aerodynamic loads. Some of these results are shown below.

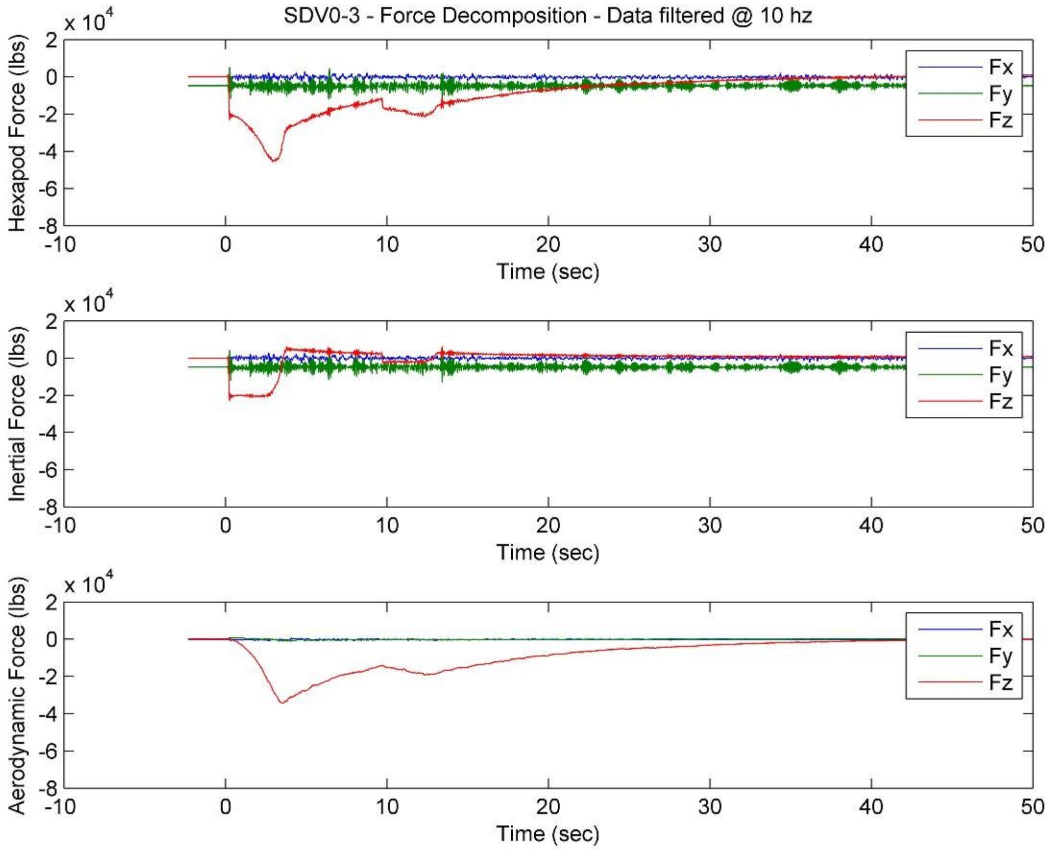

Figure 19. Aerodynamic loads extracted from load cell and accelerometer data.

While the first mode of the structure was seen in the data, vortex shedding was never noticed during any of the tests. The structure is thought be excited only by inputs from the track and propulsion. The accelerations were all within the structure's capabilities.

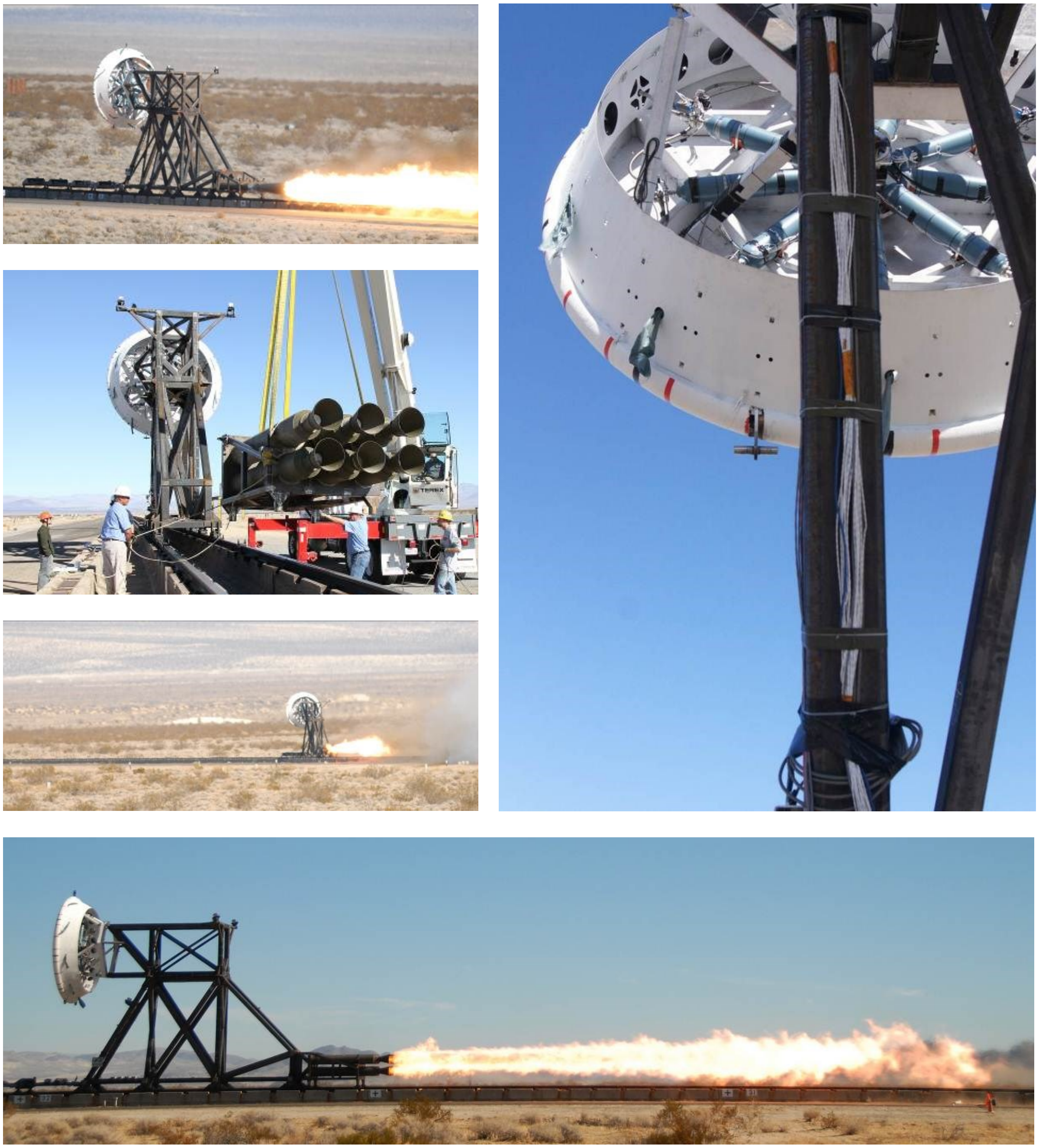

Figure 20: Photos From The SDV0 Campaign

The targeted dynamic pressures were reached to within 1%. The atmospheric density on test day was one of the largest contributors to the variation of the achieved dynamic pressure.

C. Test Issues

The Test Vehicle took longer than expected to attach to the sleds. The holes were originally match-drilled while the interfaces were located with hooks and a tapered locating feature. It is believed that debris under the hook caused the Test Vehicle to ride higher than anticipated. Drift pins and hammers were used to force the vehicle to sit lower and the holes to align.

Lifting the Test Vehicle off the trailer took a full crane crew. Only one strap out of the three was tensioned during the initial part of the lift. It was not until the vehicle reaches the vertical orientation that the other two straps pick up load. The geometry of the vehicle was such that resulting angle was sensitive to these strap lengths. If the straps were not exactly the correct length, and the vehicle was at the wrong angle, it would have to be placed back on the trailer and shackles added to the straps to change lengths accordingly.

Because of all the harnessing and instrumentation that had to be rechecked and secured before each test on test day, it was difficult to determine the exact time of day the test would fire. Sometimes even bad duct tape was the cause of a thirty minute delay in testing. This unpredictable nature affected some of the photographs and videos taken, as the sun was in a different position in the fields of view than was planned.

The data acquisition system used to collect data yielded values that would drift over time. The effect would add a 1-2% offset in the data over the course of about thirty minutes. To minimize this effect, all data was zeroed in post processing just prior to testing. The load cells were measured directly with a digital multi-meter after installation of the Test Vehicle to the Item Sled. In post-processing, the load cell values were forced to these measured values as the true loads just prior to testing.

Prior to testing, the team was unsure of whether the sleds could be towed back to the start of the track. The plan was to disassemble the sleds and drive the pieces back on a flatbed truck between tests. Fortunately, after greasing the full length of the rails, the SNORT team was able to successfully tow the sleds back to position with a front end loader and cable.

Photography and videography were generally difficult in a rocket sled environment. The vibrations and accelerations caused some of the helmet cams to switch off right at ignition. The consumer-grade cameras that were attached directly to the sled would sometimes turn off or generate blurry images. The cameras that were located high up on the sled required programming before each test, which was time consuming with a man-lift operation. Most of the challenges were solved during the first campaign, and the footage was very sharp from most of the cameras.

The first campaign took place in the winter, when there are high winds and rainfall at the base. Tarps were used to protect the vehicle, field joints, and instrumentation on the camera sled. These tarps did not live up to the winds very well. Even the thicker canvas tarps began to rip open after long periods of winds. Coupling that with the fact that the SNORT team was not able to replace the tarps when high gusts are present, much of the onboard instrumentation was exposed to the elements. There was no severe damage to any of the components, but a few intermittent shorts were seen in some of the instruments. These shorts could have been due to the weather.

V. Conclusion

As the boundaries continue to be pushed on Mars missions, traditional test facilities might not be able to keep up with the demand. New facilities and capabilities must be explored to circumvent the constraints inherent to historic test methodologies and spread the work-load across multiple facilities. The SIAD Design Verification test showed that with collaboration between different centers and innovation in design, a rocket sled track could successfully surpass the capabilities of a wind tunnel for this application. The SDV campaign proved a very cost effective way to achieve high dynamic pressures on large drag objects.

Successful demonstrations like SDV have provided a new avenue for testing large decelerators. Today, structure is currently being added to the SNORT track to load-test large ringsail parachutes even while the SDV Test structure is scheduled for re-utilization by another decelerator program.

This test campaign demonstrated the power of cooperation and collaboration within a diverse, cross-functional team. All players knew the end goal of clean-sheet design to meet test objectives, without the built-in limitations of conventional testing strategies.

Acknowledgments

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