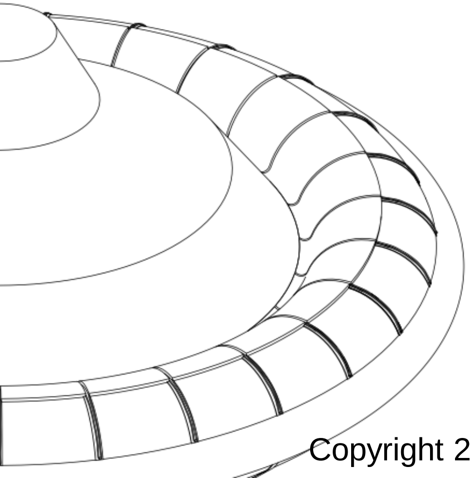
Jet Propulsion Laboratory
California Institute of Technology

LDSD
Low Density Supersonic Decelerators

Low Density Supersonic Decelerator

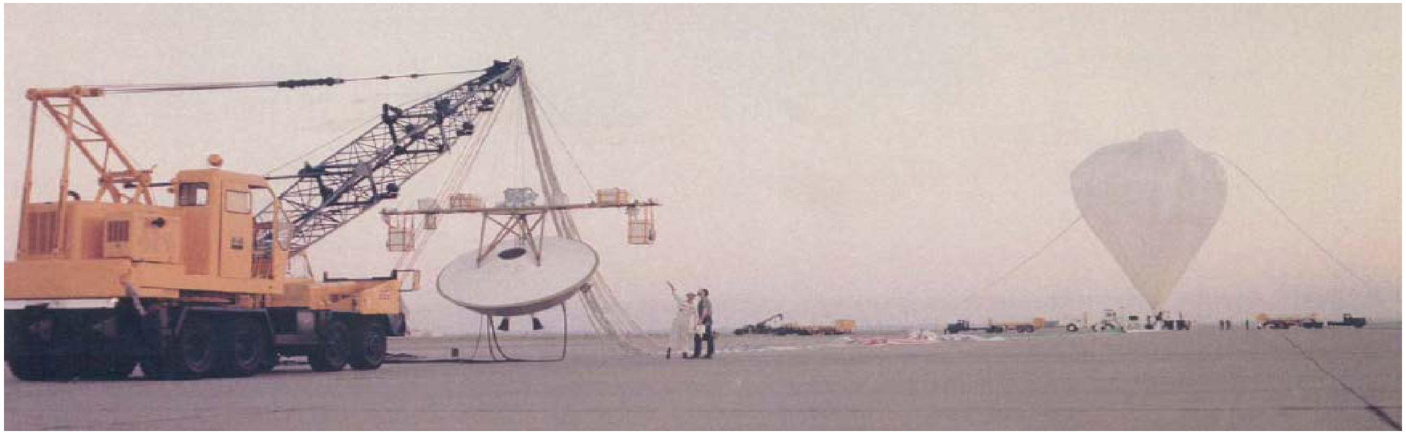
Overview to the NAC Technology, Innovation, and Engineering Committee



Ian Clark (JPL/Caltech) - Principal Investigator

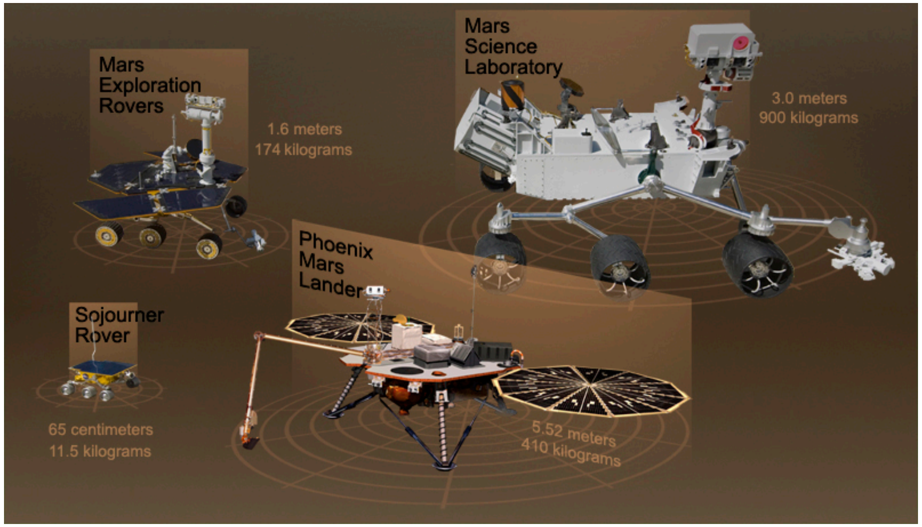
Mars EDL Technology

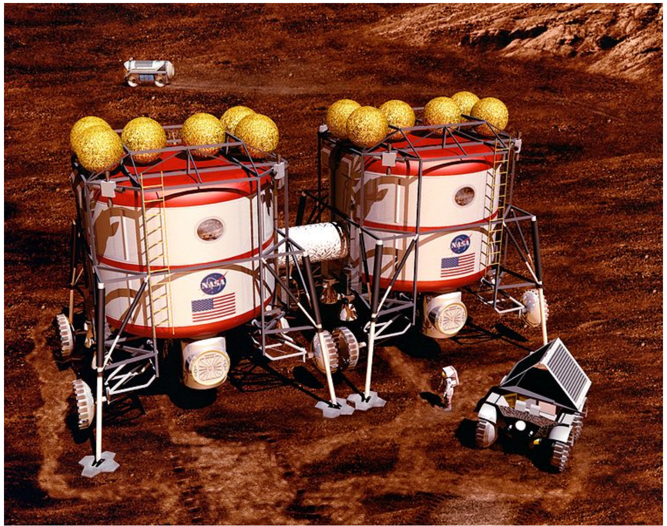
- In the early 1970’s, the Viking project developed the technology to land a spacecraft on Mars
    - **E**ntry heatshield shape, thermal protection, L/D, three-axis control
    - **D**escent disk gap band supersonic parachute
    - **L**anding throttled engines, landing legs, and terminal guidance
- Since then we have made some advances on that technology
    - **E**ntry tiled-PICA thermal protection, guided hypersonic flight
    - **L**anding airbags, pulsed thrusters, and skycrane system
- *But no progress on descent*, other than a little extrapolation
    - **D**escent still uses the Viking parachute design and 1972 qualification data



Square-Cube Law Problem

- As Mars landers grow, ballistic coeff. (β) goes up (square-cube law problem) — currently at 1600 kg landed mass for MSL (Rover + Dry Descent Stage)
- Launch vehicle fairing size not going up, lift / drag not going up





Artist's Concept

- Need to deploy a parachute at Mach ~2, but …
- *As β keeps going up, eventually we hit the ground at Mach > 2*
- Need to begin the scale-up to crewed Mars landers ~50,000 kg (!)
- What can we do before these things hit the ground?

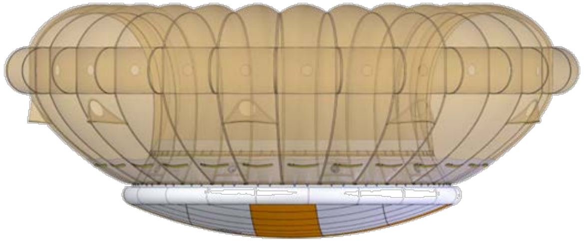
LDSD Decelerators and Test Venues

LDSD's technologies will serve as the foundation of supersonic decelerators for the next several decades

SIAD-R

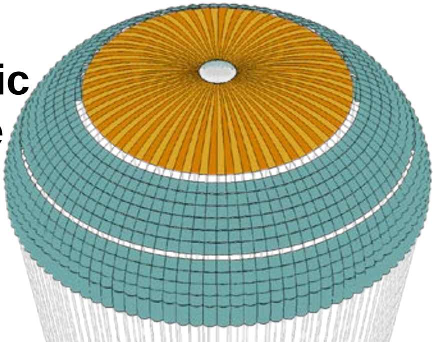
- 6 m, Mach 3.75 inflatable decelerator
- Negligible aeroelastic deformation
- 50% increase in drag area over MSL

SIAD-E



- 8 m, Mach 3.75 inflatable decelerator
- Ram-air inflated, flexible structure
- 2.25x drag area of MSL

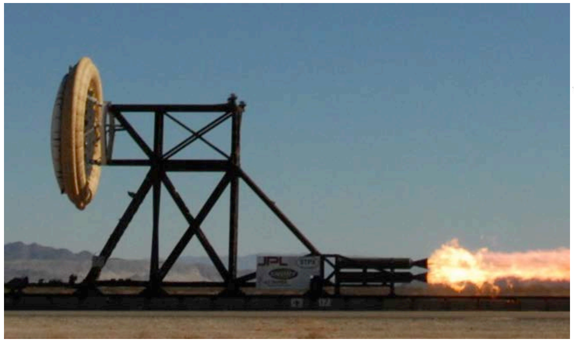
Advanced Supersonic Parachute



- 30.5 m, Mach 2.5 parachute
- Extensible to reefing and clusters
- 2.5x drag area of MSL parachute

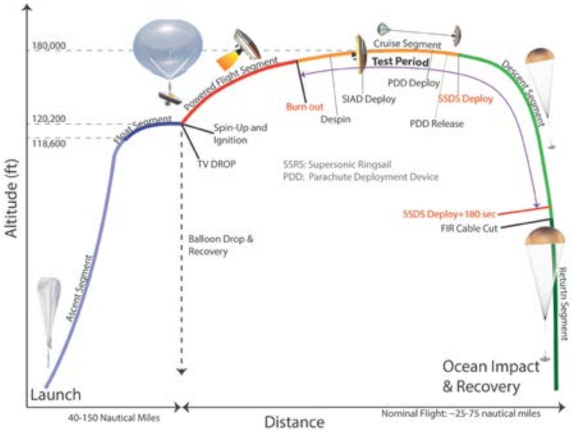
LDSD is developing the infrastructure necessary to enable the qualification and future development of supersonic decelerator technologies

SDV



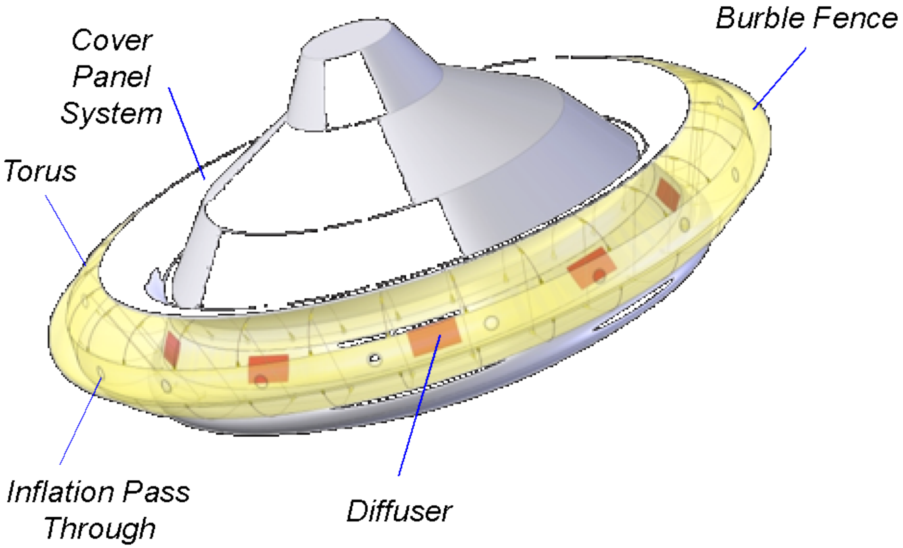
PDV

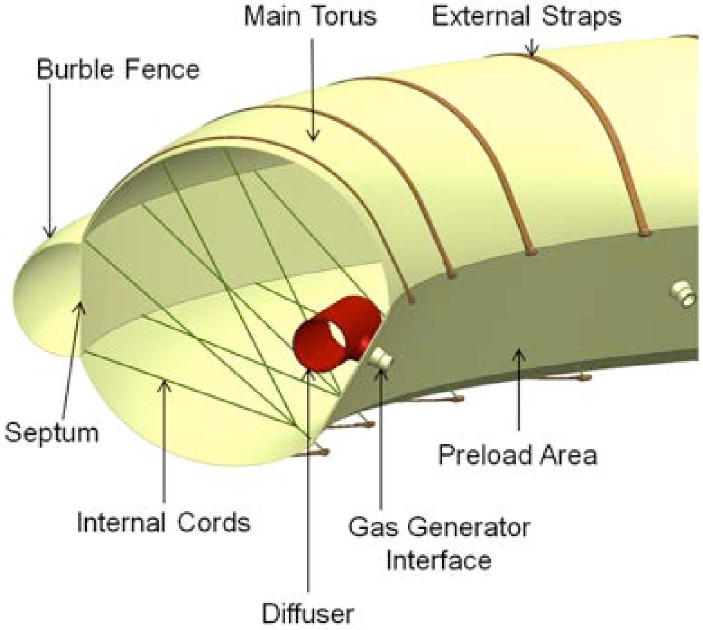
SFDT



6m Attached Torus Overview

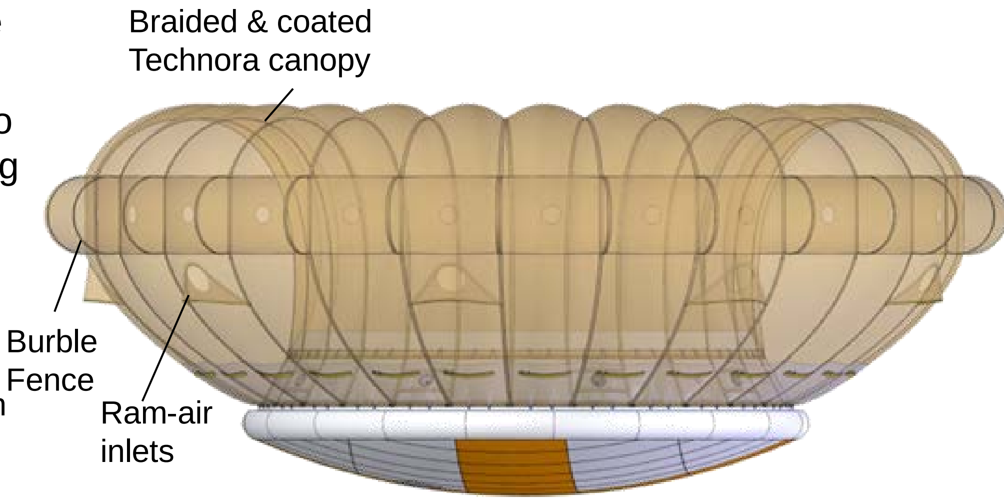
- Single pressurized torus with a burble fence for stability
- Simple, low-mass design to provide a ~50 - 70% increase in drag over an MSL aeroshell
- Internal pressure (<4.5 psi) will produce a rigid shape absent of aeroelastic deformations
  - Simplifies qualification for future users by allowing for traditional qualification techniques
- Allows for rapid inflation in <1 sec, minimizing vehicle disturbances
- Designed for deployment and operation at up to Mach 4

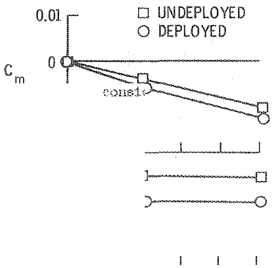


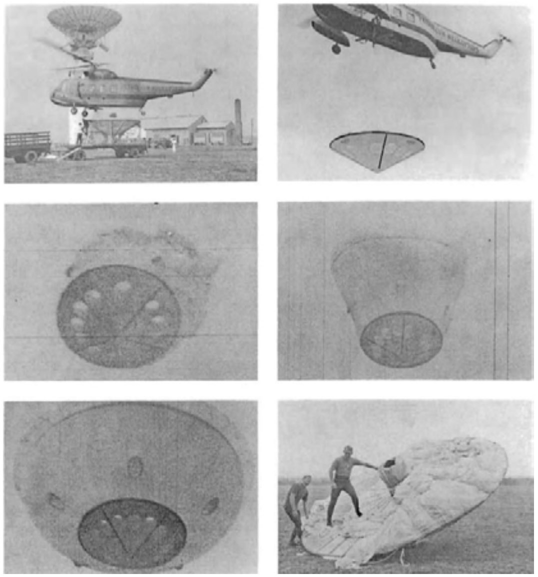


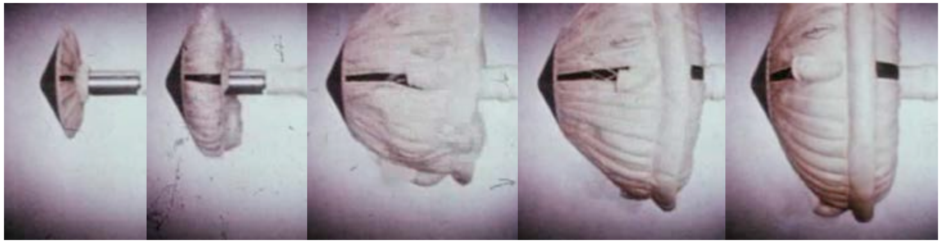
8m Attached Isotensoid Overview

- Represents first forays into understanding nature of highly flexible attached decelerator systems
- Shape derived from simple analytical approach to provide favorable stress distribution in a high drag shape
- Structurally favorable design allows for minimal inflation pressure
  - Low-stresses => reduced canopy mass
  - Design allows for ram-air inflation (reduced inflation system mass)
- Subject of considerable subscale testing prior to Mars Viking program
  - Recently tested at sub/transonic conditions by NASA
- Will be largest non-parachute decelerator ever tested at supersonic conditions
- Coupled with parachute, will begin to explore regime of large forebodies and large parachutes
- Designed for deployment and operation at up to Mach 4 (planned test to Mach 3.8)



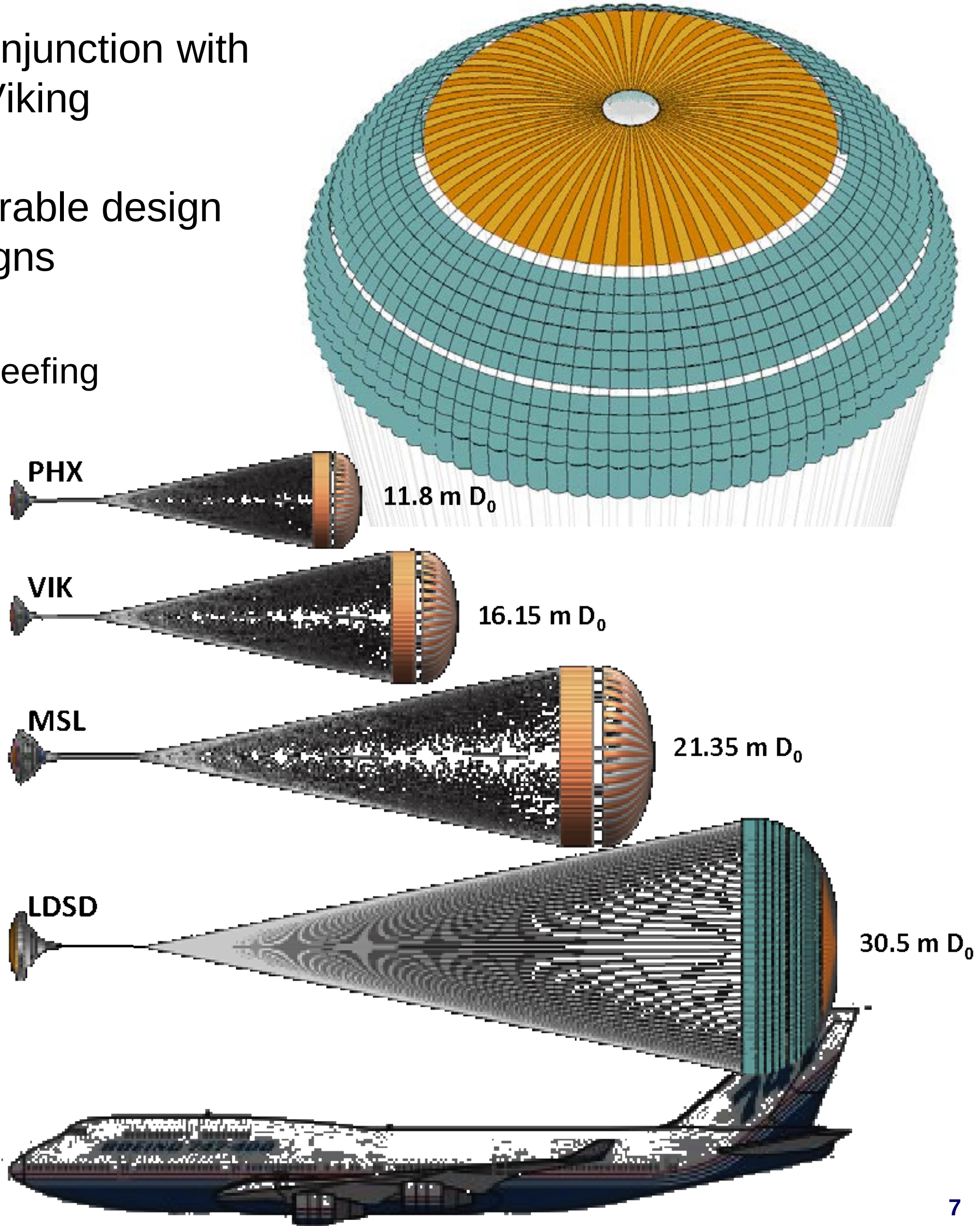






30.5 m Supersonic Parachute Overview

- Ringsail configuration originally tested in conjunction with the Disk-Gap-Band for supersonic use on Viking missions
- LDSD Disksail configuration combines favorable design elements from both Ringsail and DGB designs
- Disksail design features:
  - Provide ability to mitigate inflation loads via reefing
  - Improve drag per unit mass of parachute
  - Allow from improved opening reliability
  - Amenable to use in supersonic clusters
- Required C_DA of 540 m^2



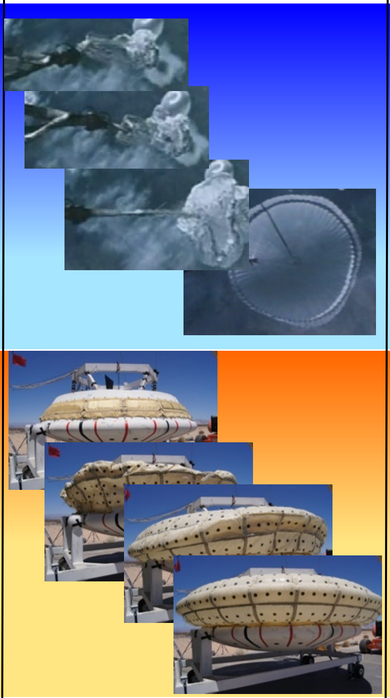
Aerodecelerator Qualification Summary

Phase 1: Initial Deployment

Driving Physics:
Applied deployment forces much greater than aero forces.

Relevant Test Parameters
Hardware designs and deployment forces.
Scale

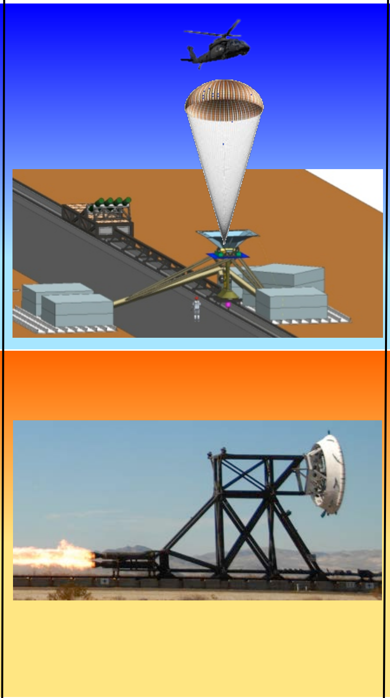
Phase 2: Inflation Dynamics



Driving Physics:
Transition from fabric inertial forces dominating to aero forces dominating.

Relevant Test Parameters
Mach Number
Wake Structure
Scale

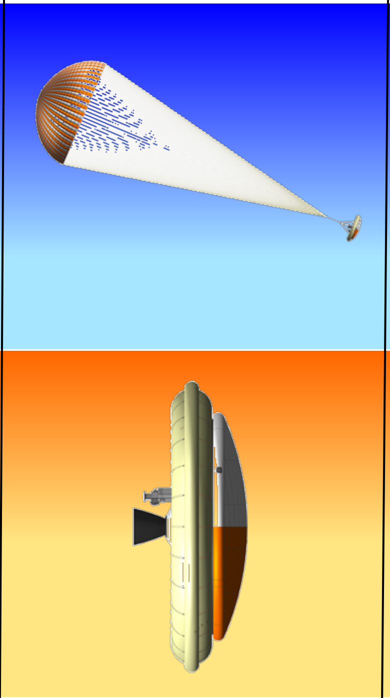
Phase 3: Peak Strength



Driving Physics:
Stress and Strain state of the aero-decelerator.

Relevant Test Parameters
Dynamic pressure
[Temperature]
Scale

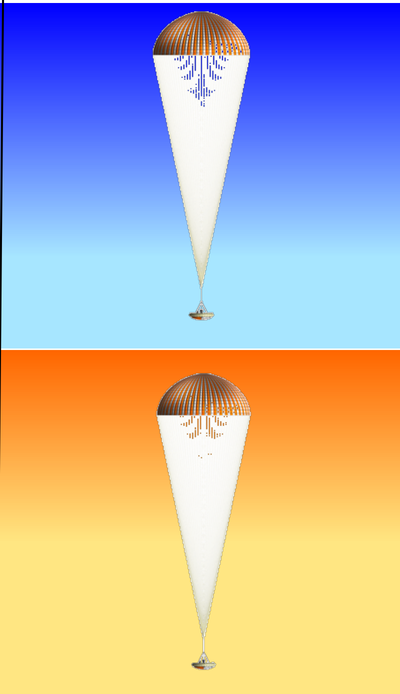
Phase 4: Supersonic Performance



Driving Physics:
Aerodynamics
Aerothermodynamics

Relevant Test Parameters
Mach number
Atm. density

Phase 5: Subsonic Performance



Driving Physics:
Aerodynamics

Relevant Test Parameters
Mach number
Atm. density

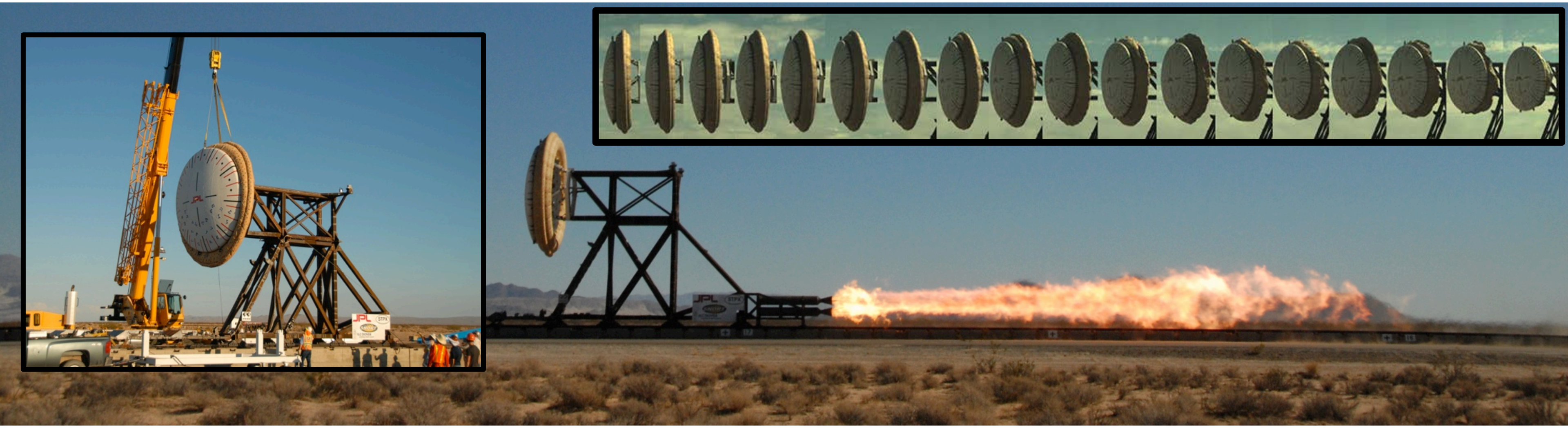
Test Approach

Phases 1–2	Phase 3	Phases 4–5
High-altitude flight testing (SFDT)	Full-scale struct. test (SDV/PDV)	High-altitude flight testing (SFDT)

SDV Test Architecture

SIAD Design Verification (SDV) Testing

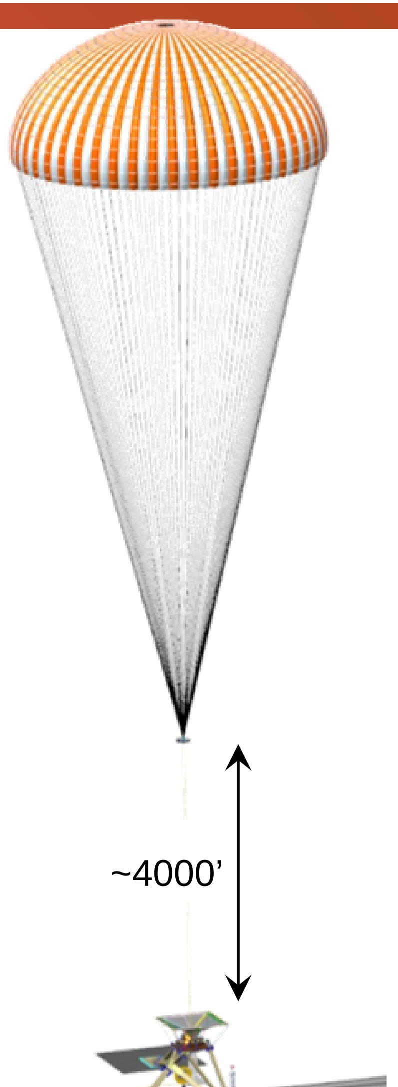
- Uses the Supersonic Naval Ordnance Research Track at the Naval Air Weapons Station, China Lake, California
- Rocket sled brings SIAD-R and SIAD-E to flight loads plus 25%
- Deploy and operate SIAD at full-load condition
- Extensive instrumentation on the sled including high speed cameras, load cells, accels, GPS
  - Derive aerodynamic loads, inflation profile, aeroelastic deflection, and inflated shape at subsonic conditions
- Conduct three runs for each campaign, two campaigns per SIAD
- Tests would be repeated by adopting project as part of their qualification program
- All tests completed successfully for SIAD-R configuration



PDV Test Architecture

Parachute Design Verification (PDV) Testing

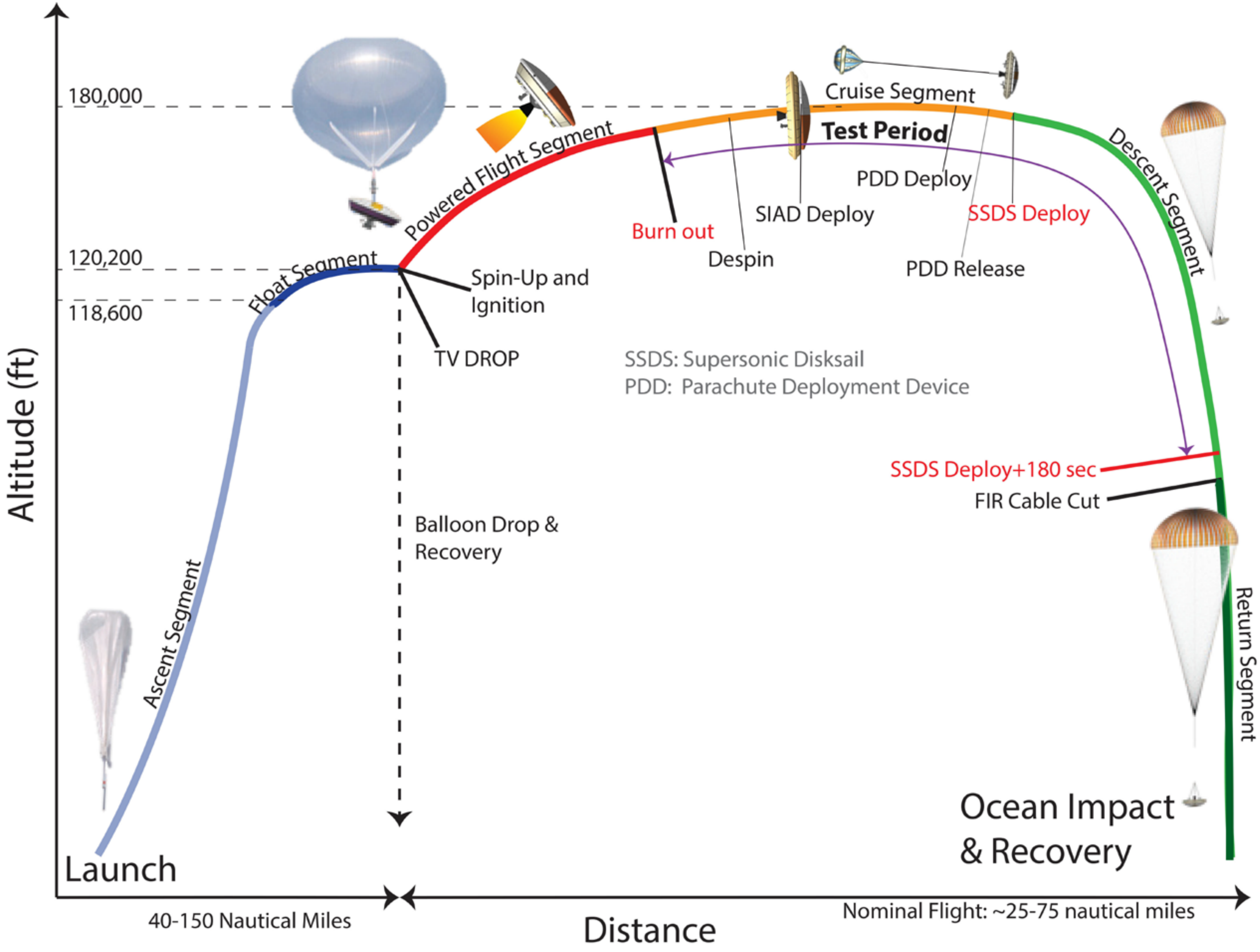
- Traditional loads qualification testing performed at NFAC 80x120 wind tunnel
  - Size of LDSD parachute prohibits full-scale testing at NFAC => new capability needed
- Uses SNORT rocket sled track
- Drop parachute from helicopter, use rocket sled to pull parachute *down* through a pulley
- Bring parachute to flight loads plus 25% (100,000 lbs) by pulling it at ~40 m/s
- Strength test only — not deployment
  - Separate rigging test bed for deployment
- Conduct 2 runs for each campaign; two campaigns.
- Tests would be repeated by an adopting project as part of their structural qualification program
- Architecture, once established, provides an economical test capability for large parachute load testing



Have to Fly Them

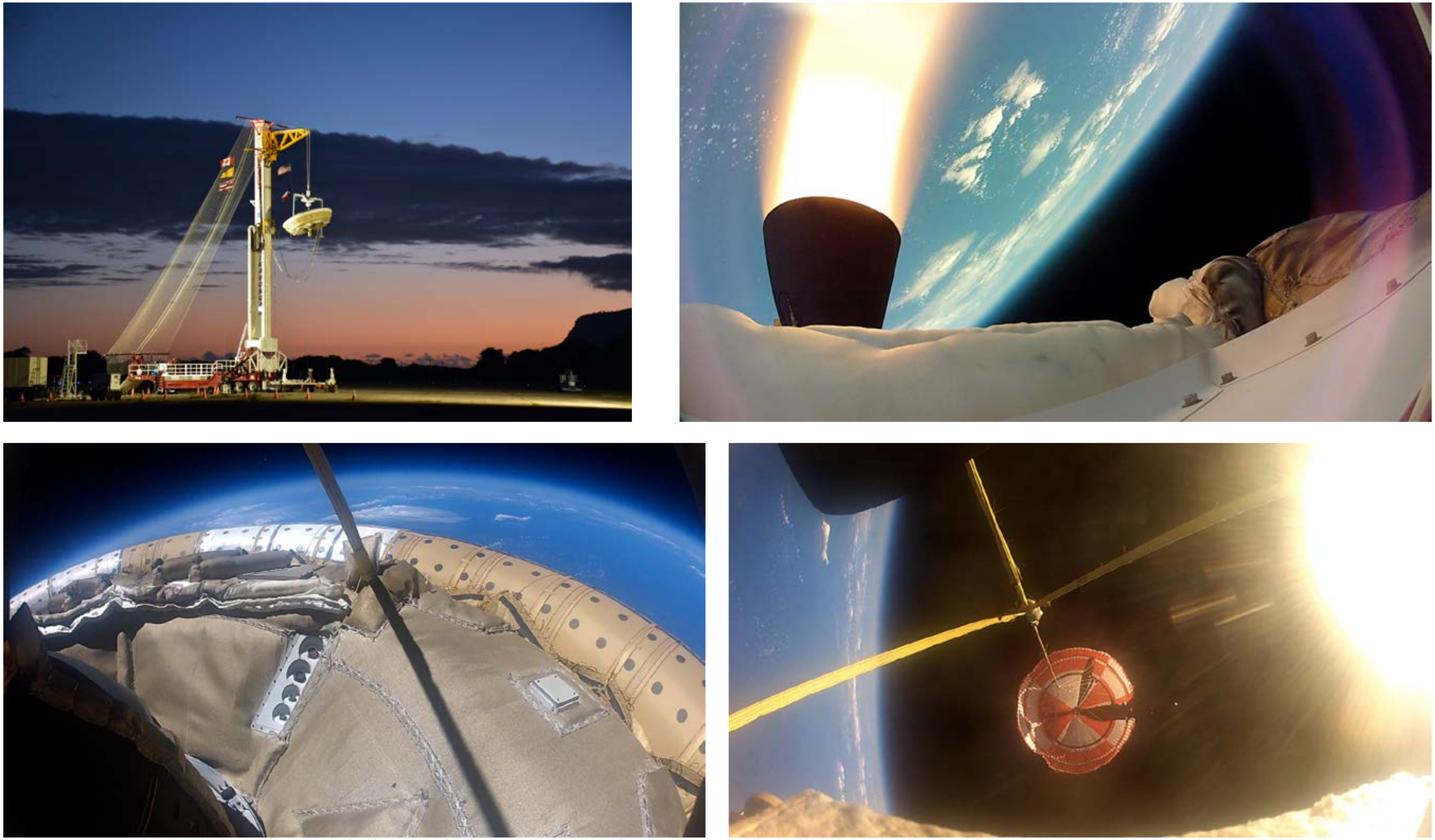
- The qualification of soft-goods deployables requires testing of the devices at *full-scale* in a *relevant environment*
  - The motion of the soft-goods at very small scales is critical to the overall behavior of the system, making simulation impractical

Supersonic Flight Test Architecture



SSDS: Supersonic Disksail
PDD: Parachute Deployment Device

SFDT1 — June 28, 2014



SFDT1 Minimum Success Criteria

1. Launch with a Star-48 on a balloon from PMRF to float altitude
2. Conduct a powered flight, demonstrating the ability to target test Mach and dynamic pressure requirements
3. Collect real-time telemetry from the test vehicle sufficient to assess the powered flight objective and to demonstrate the operation of all RF links
4. Recover the balloon envelope from the ocean for disposal

- SFDT1 Goals:
  - Deploy and collect data on SIAD-R operation and dynamics
  - Deploy and collect data on SSDS operation and dynamics
  - Fly camera mast assembly and other SIAD and SSDS sensors
  - Recover the test vehicle or flight image recorder from the ocean

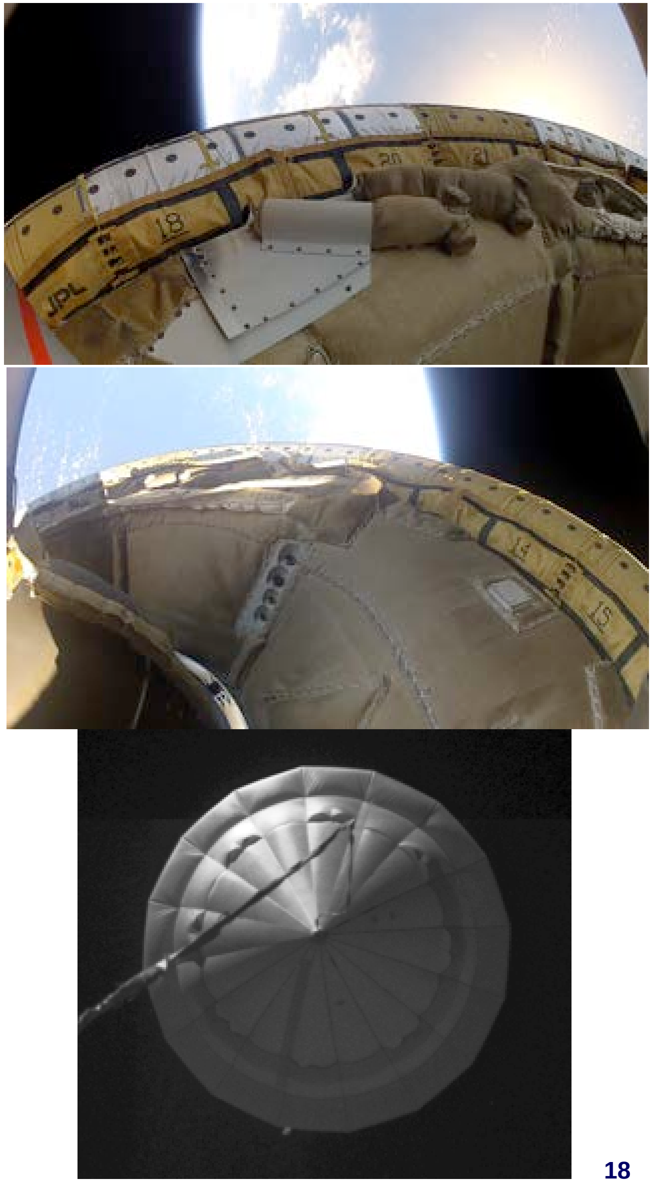
SFDT1 Results

- Met *all* success criteria for this first shakeout flight
  - *Launched, targeted Mach and density, returned all telemetry, recovered balloon*
  - All required Balloon launch system and Test Vehicle systems worked perfectly
    - WFF/CSBF balloon capability, reliability, and experience critical to SFDT success
- Met all four bonus goals for the first flight
  - *Deployed SIAD-R and SSDS, operated all cameras and sensors, recovered TV*
  - The observation of the SSDS operation and dynamics was very brief, but tremendously instructive
- Beyond the goals
  - All test vehicle systems required for next year’s flights worked perfectly as well
    - All cameras, all required technology and trajectory sensors, all telemetry
  - SIAD-R functioned perfectly — all indications are that it is now at TRL-6, a year ahead of schedule, subject to the completion of the data analysis
  - All articles were recovered, including an unplanned recovery of the pilot ballute
  - The data collected and phenomena observed during the parachute deployment, inflation, and failure represents a major advance in our understanding of supersonic parachutes

SFDT-1 Technical Success and Firsts

LDSD’s SFDT-1 shake-out flight achieved several technical accomplishments and notable firsts:

- Largest blunt body aeroshell ever flown supersonically
- SIAD-R was a phenomenal success
  - Largest Inflatable Aerodynamic Decelerator (IAD) *ever* deployed and tested at supersonic conditions
  - Minimum vehicle disturbances: SIAD inflated to a rigid geometry in <1/3 sec using off-the-shelf automotive gas generators
  - Extremely rigid geometry: Maximum measured aeroelastic deflection of <4 mm during operation, <12 mm during parachute deploy at an internal pressure of <3 psi
  - No observed aerothermal damage or degradation
- Largest ballute (PDD) ever successfully flown at supersonic conditions
- First ever supersonic pilot deployment
- Largest supersonic parachute ever deployed
- Unprecedented quantity and quality of data collected
  - Several order of magnitude increase in the amount of data available on supersonic aerodynamic decelerators
  - Most detailed set of data ever collected on any of the three decelerators flown

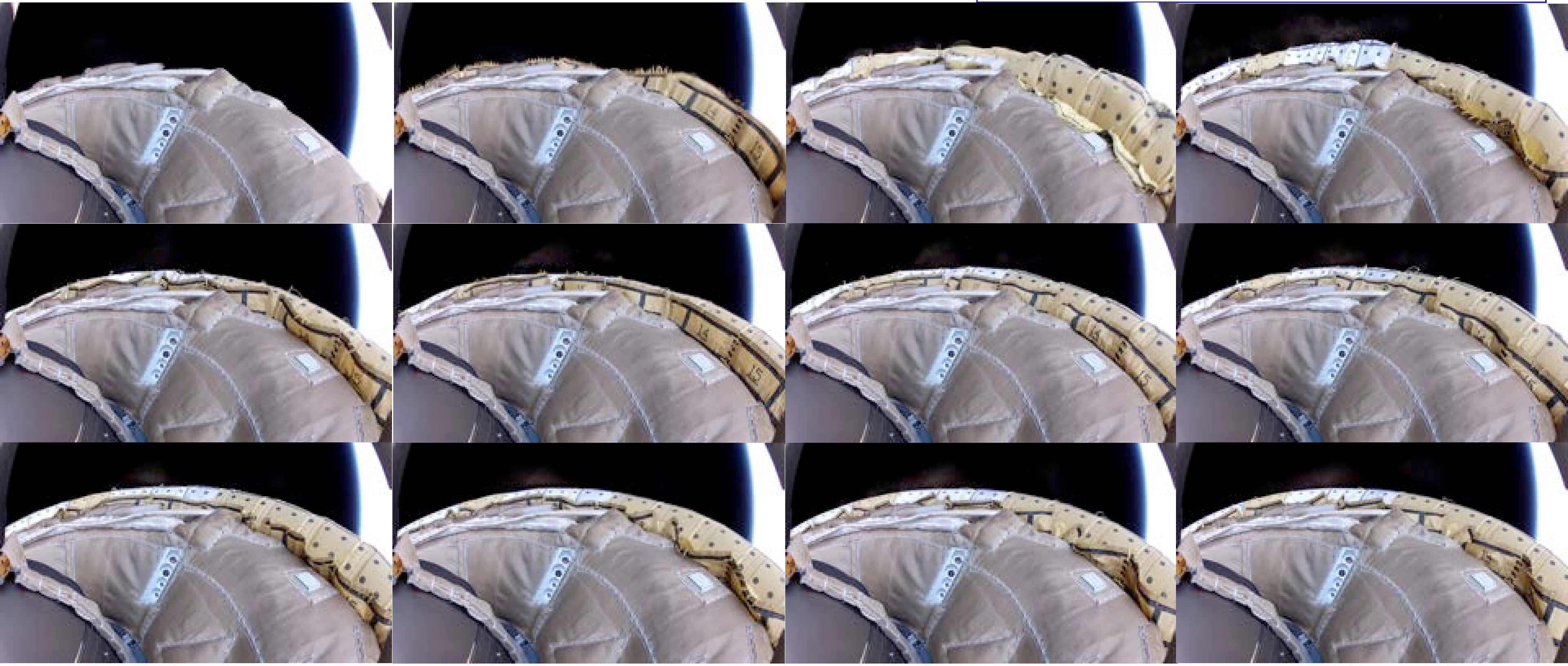


SIAD-R Deployment

- SIAD-R inflation occurred rapidly and orderly
  - Time from initial emergence to rigid appearance between 0.3 – 0.4 seconds
- Vehicle disturbances during inflation appear negligible/non-existent

SIAD-R Deployment Conditions

Parameter	Value	Units
Mach	4.10	
Altitude	58.08	km
Dyn. Pressure	324.80	Pa
Time from Drop	82.63	sec

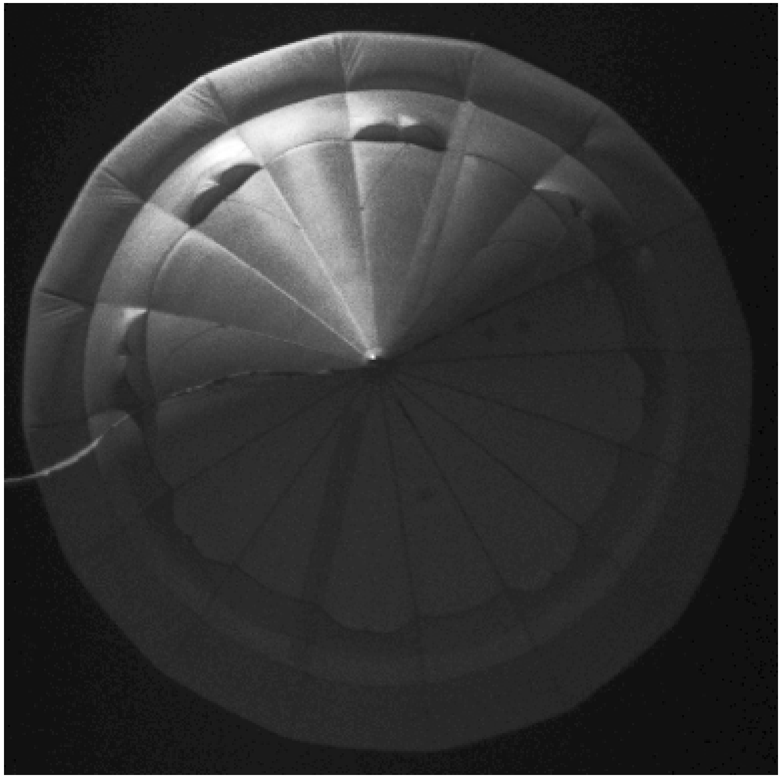


Ballute Deployment and Operation

- Overall performance of the ballute was phenomenal
  - Originally considered one of the riskiest elements of the entire flight
- Clean separation of jettisoned elements, mortar sabot retained
- Inflation time < 0.5 seconds
- Early estimates are that inflation aid provided most of the required inflation pressure
  - Subsequent increases in dynamic pressure coupled with full ballute shape indicates inlets performing as needed
- At 4.4 m, largest ballute ever successfully flown supersonically

Ballute Mortar Fire Conditions

Parameter	Value	Units
Mach	2.73	
Altitude	49.98	km
Dyn. Pressure	419.50	Pa
Time from Drop	161.51	sec



Parachute Deploy and Line Stretch

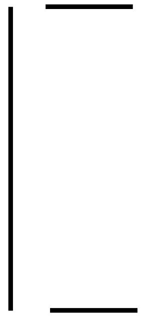
- Early results indicate all key parameters associated with parachute deployment were within estimates
  - e.g. line stretch velocities, durations
- Parachute inflation took ~0.7 seconds

Parachute Line Stretch Conditions

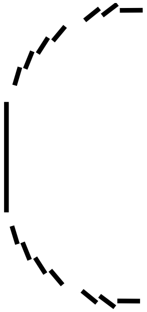
Parameter	Value	Units
Mach	2.54	
Altitude	47.04	km
Dyn. Pressure	528.61	Pa
Time from Drop	168.60	sec

Disk Loading Hypothesis

Constructed Geometries

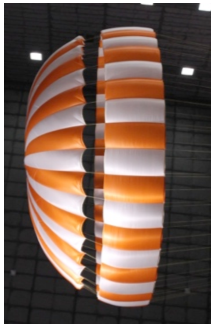


DGB

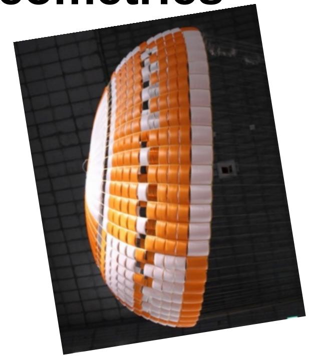


Disksail

Inflated Geometries

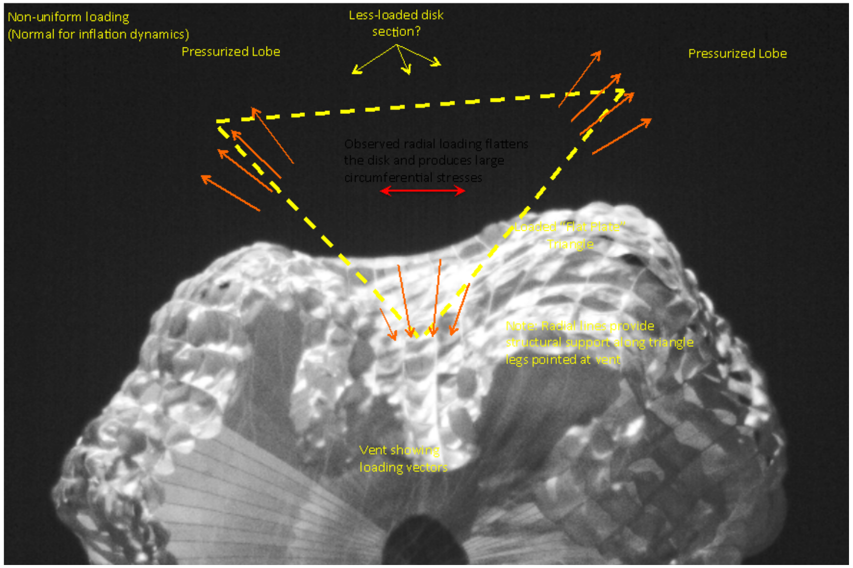


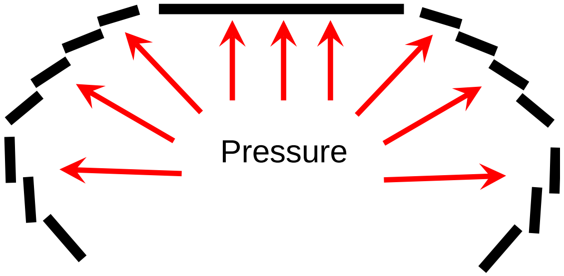
DGB



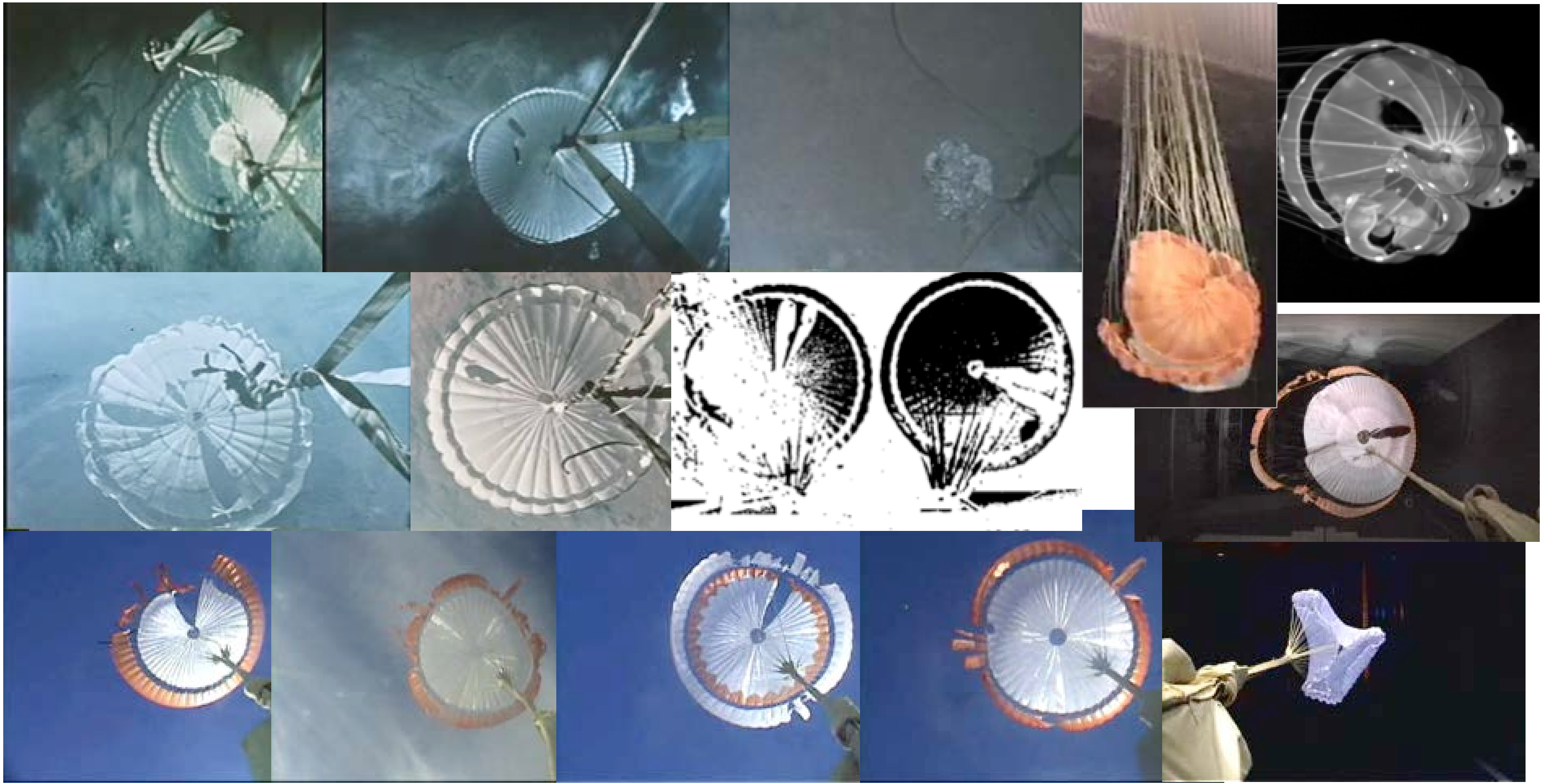
Disksail

Transient Inflated Geometry





Challenges of Mars Parachute Testing



Although prior NASA Mars missions have experienced failures of their parachutes during testing, every single one of them resolved the issues and successfully landed on Mars

Value of SFDT-1 Dataset

- Supersonic parachute inflation is a complex, non-linear dynamical event that demands high quality data to understand the phenomena
- Imagery and dataset collected by SFDT-1 is by far the best *ever* collected on a supersonic parachute inflation
  - >10x camera resolution (inch/pixel vs. ~foot/pixel); 15 and 135 frames per second
  - Resolution and frame rates have enabled additional insights to be made from grainy, 50-year old film of parachute inflations
- Early data analysis suggests that the Disksail configuration has unacceptable supersonic inflation dynamics
  - Transient inflation dynamics appear more important than previously envisioned, at least for this canopy configuration
    - Canopy rebounds, asymmetrical inflations, and local stress concentrations are common characteristics of supersonic inflation
    - Successful inflation requires robust parachute that can transit the intermediate inflating configurations successfully
    - Disksail configuration may not be robust to controlling stresses in the intermediate inflated shapes
- 40 year old paradigms about inflation, onset of parachute loading, and stress environments are being revisited in light of SFDT-1 data
  - Analysis still underway to determine if intermediate inflation stresses should be a concern for currently planned flight programs for NASA (e.g. InSight, Mars 2020)
  - *The LDSD test infrastructure represents a critical NASA resource for understanding parachute dynamics and quantifying the risk for current and future planetary missions*

Closing Words

- For 40 years the knowledge base of supersonic parachutes has been the Viking Balloon Launched Decelerator Test Program
  - LDSD will have a similar heritage with its technologies and data set

- Matured technologies will allow for full utilization of the current stable of launch vehicles and enable the next decades of Mars missions