

The Mission Loads Environment and Structural Design of the Mars Science Laboratory Spacecraft

**University of California
Irvine
Feb 17, 2012**

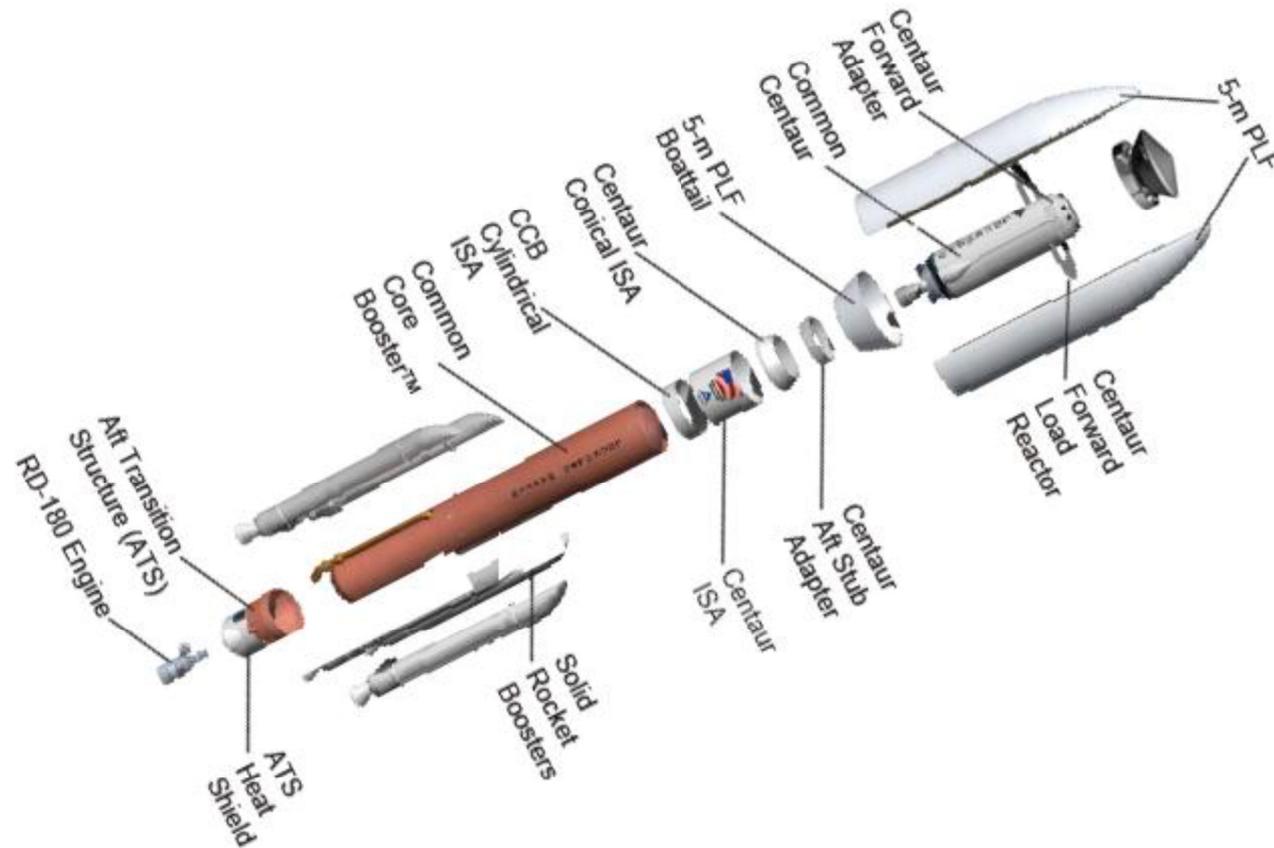
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California Institute of Technology



MSL: Loads Environment and Structural Design

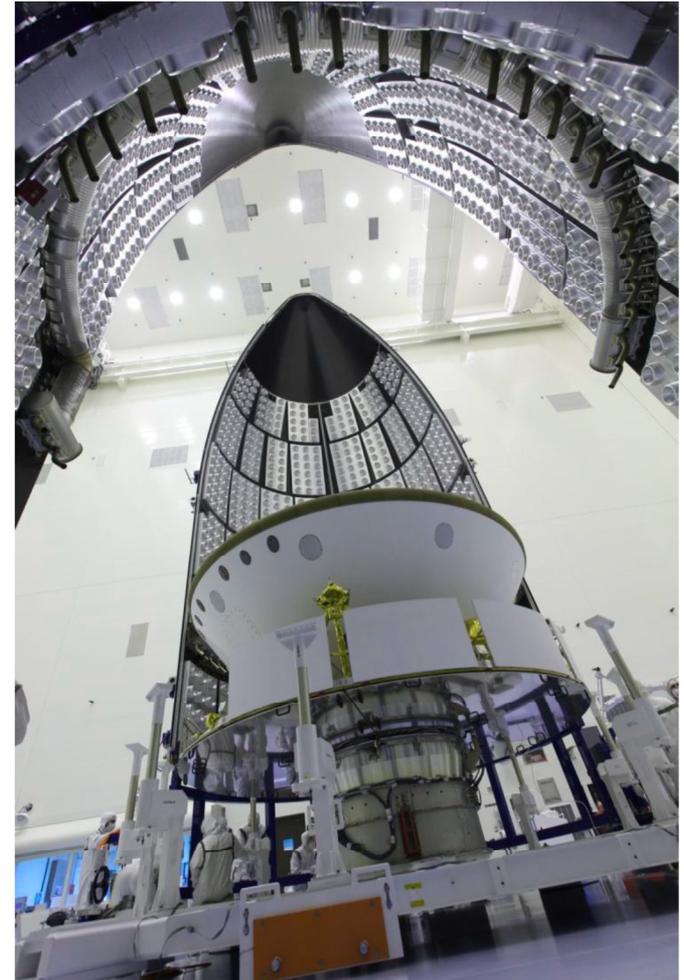
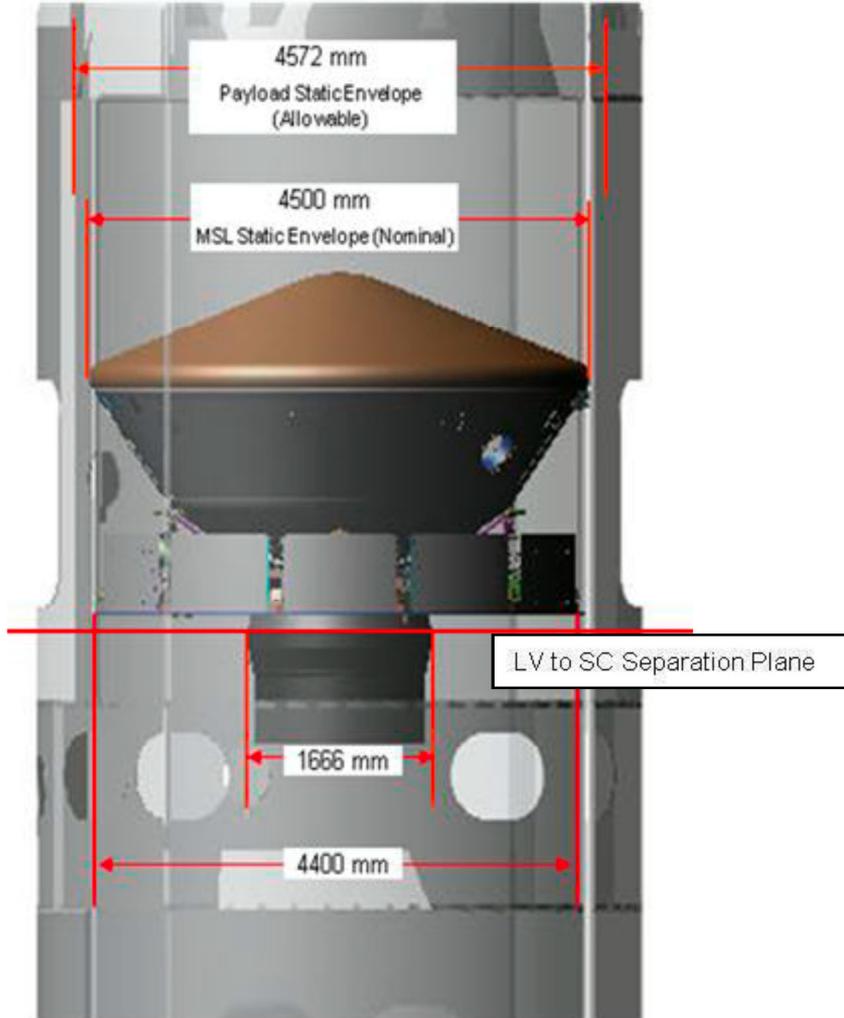


Atlas V 541 (5 m fairing, 4 SRB, 1 Centaur engine) Mission Launch Vehicle November 26, 2011



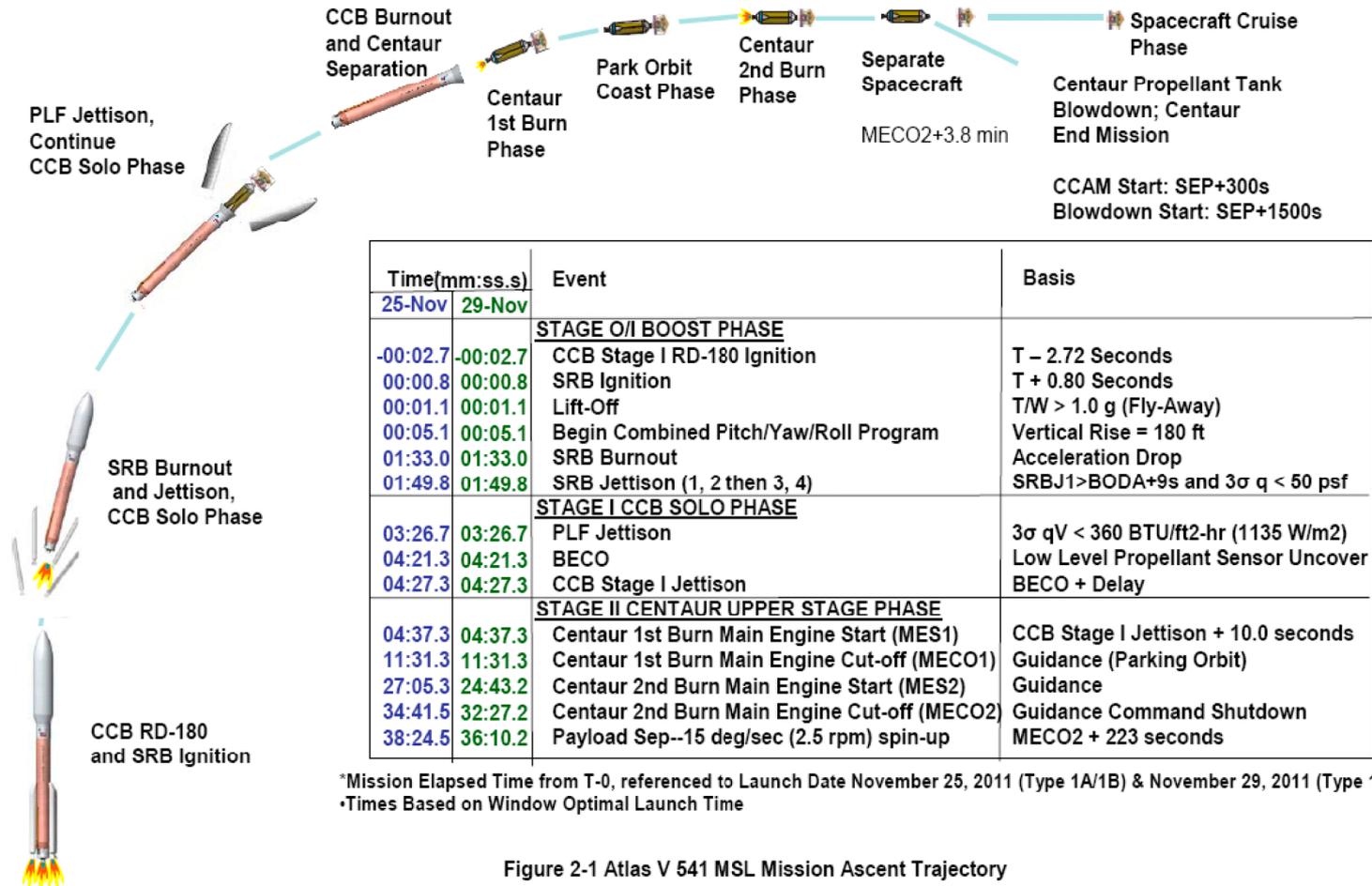


MSL S/C on Atlas V w/D-1666 Payload Adapter





Atlas V (541) Mission Launch Ascent Profile November 26, 2011



*Mission Elapsed Time from T-0, referenced to Launch Date November 25, 2011 (Type 1A/1B) & November 29, 2011 (Type 1C)
•Times Based on Window Optimal Launch Time

Figure 2-1 Atlas V 541 MSL Mission Ascent Trajectory



Launch Cruise Entry Events

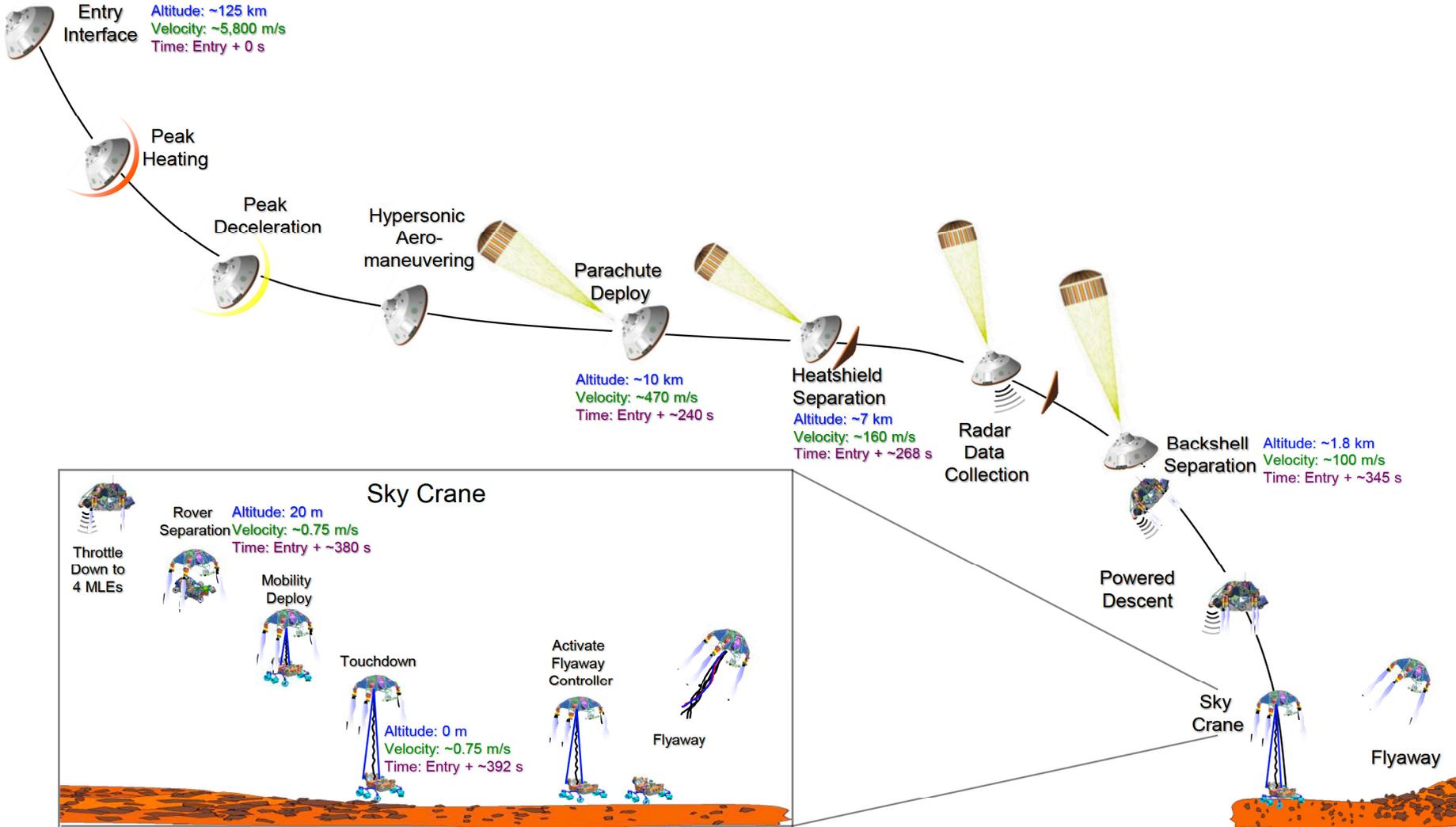


- Launch → Time = Launch + 0 Mass = 4033 kg
Loads: 1.0 g's X-Dir; 1.1 g's Y-Dir; 2.6 g's Z-Dir (Max lateral: Mach-1/Max-Q)
- CCB Burn → Time = Launch +3 min 30 Sec
Loads: 0.3 g's X-Dir; 0.2 g's Y-Dir; 6.1g's Z-Dir (Max vert)
- Cruise → Time = Launch +187 to 215 Days (TCM 1, 2, 3)
 - Approach → Time = Entry -45 days
TCM 4 at E - 8 days
- Start of EDL Sequence → Time = Entry -5 days
TCM 5, 6 at E-2 days to E-9 hours
- Cruise Stage Separation → Time = Entry -9 minutes
TCM 5, 6 at E-2 days to E-9 hours
- Entry → Time = Entry + 0 Mass = 3316 kg
Altitude = 125 km (Mars r = 3522 km), velocity = 5,800 m/sec
 - Peak Heating → Time = Entry +85 seconds
Altitude = 26 km, velocity = 4,600 m/sec
 - Peak Deceleration → Time = Entry +96 seconds
Altitude = 19 km, velocity = 3,700 m/sec
Loads: 0.65 g's X-Dir; 15 g's Z-Dir
(At E+231 sec, Alt=12km, velocity=525 m/sec)
- Parachute Deployment → Time = Entry +245 seconds
Altitude = 10 km, velocity = 470 m/sec
65,000 lbs Cord load ~ 9.7 g's with 37 radian/sec²
- Heatshield Separation → Time = Entry +274 seconds
Altitude = 7 km, velocity = 160 m/sec





Entry - Descent - Landing Events

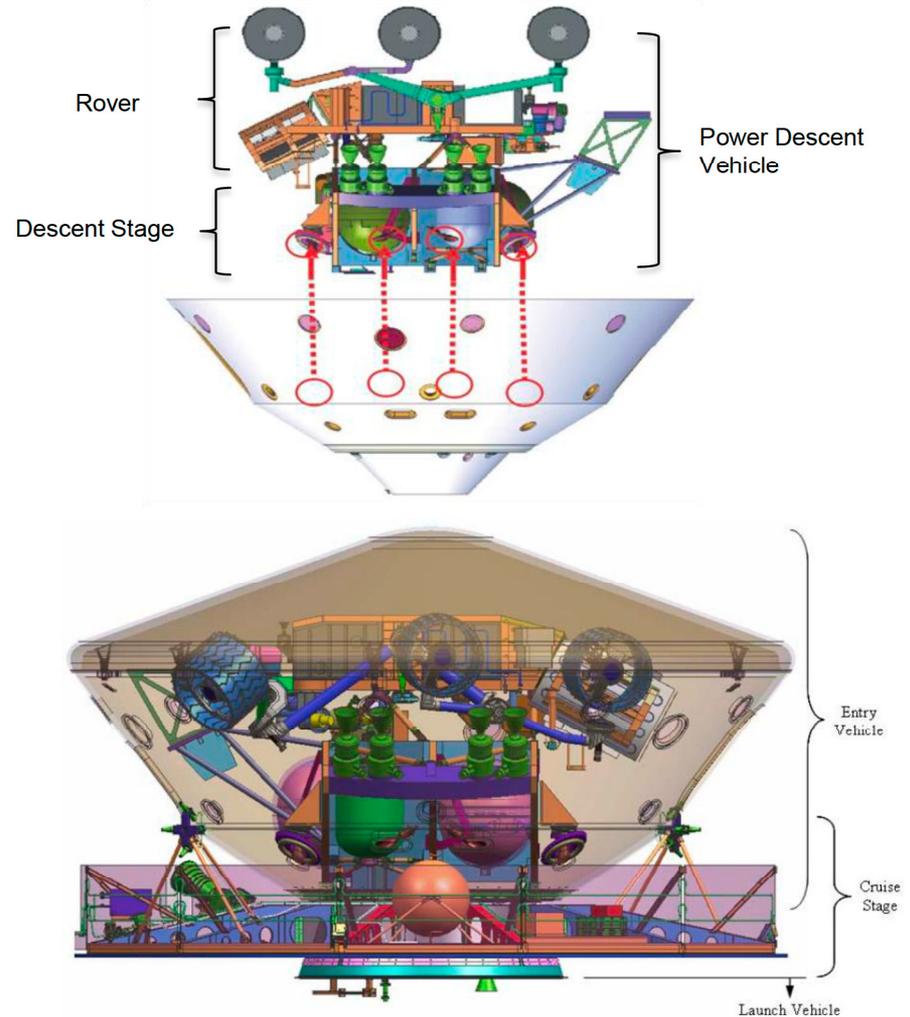


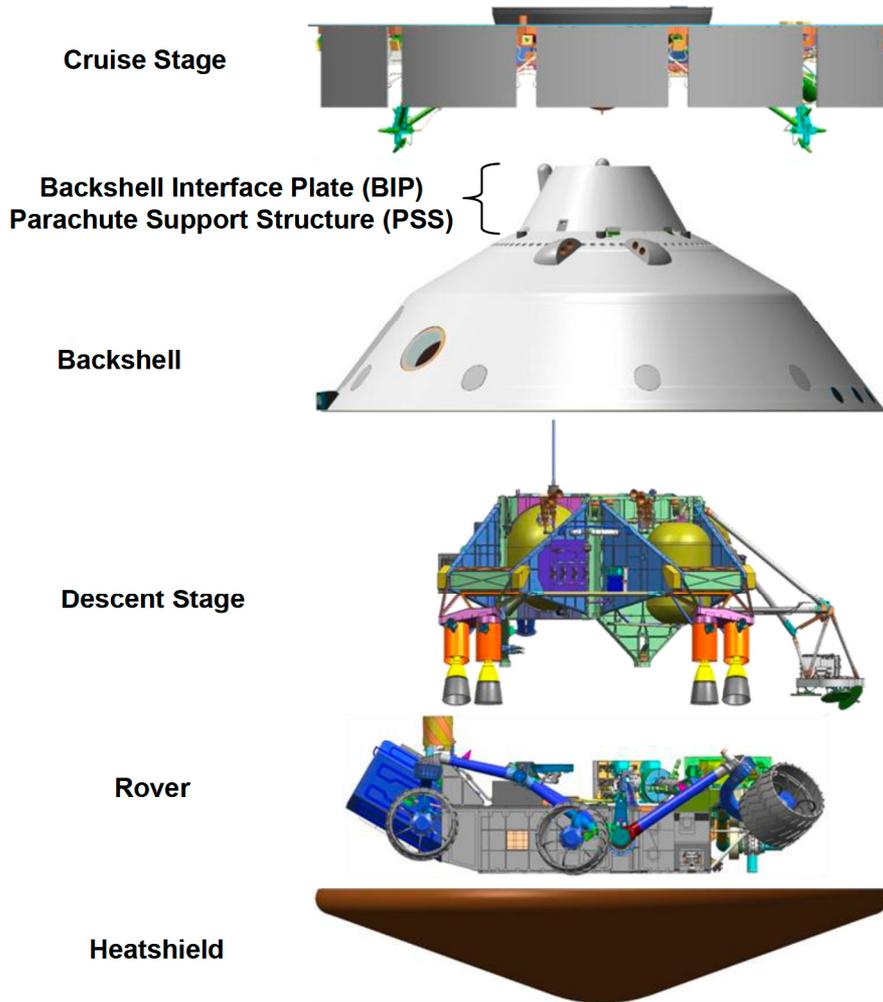


MSL: Loads Environment and Structural Design



- MSL spacecraft flight system Assemblies
 - Cruise Stage
 - Entry Vehicle
 - Aeroshell
 - Powered Descent Vehicle
 - Descent Stage
 - Rover





MSL Spacecraft Primary Interfaces

PAF/LVA I/F

- Marmon Clamp (dia = 66")

Cruise Stage/BIP I/F (bolt circle dia = 54")

- 6 - 5/8" bolts

BIP/Descent Stage I/F (bolt circle dia = 58")

- 6 - 5/8" bolts

Descent Stage/Rover I/F (bolt circle dia = 47")

- 3 - 5/8" bolts

Heat Shield/Backshell (bolt circle dia = 157")

- 9 - 3/8" bolts

Note: Permanent I/F's are Cruise stage to LVA, Aeroshell to BIP, Parachute Can to BIP

Weight = 4015 kg (= 8852 lbs)

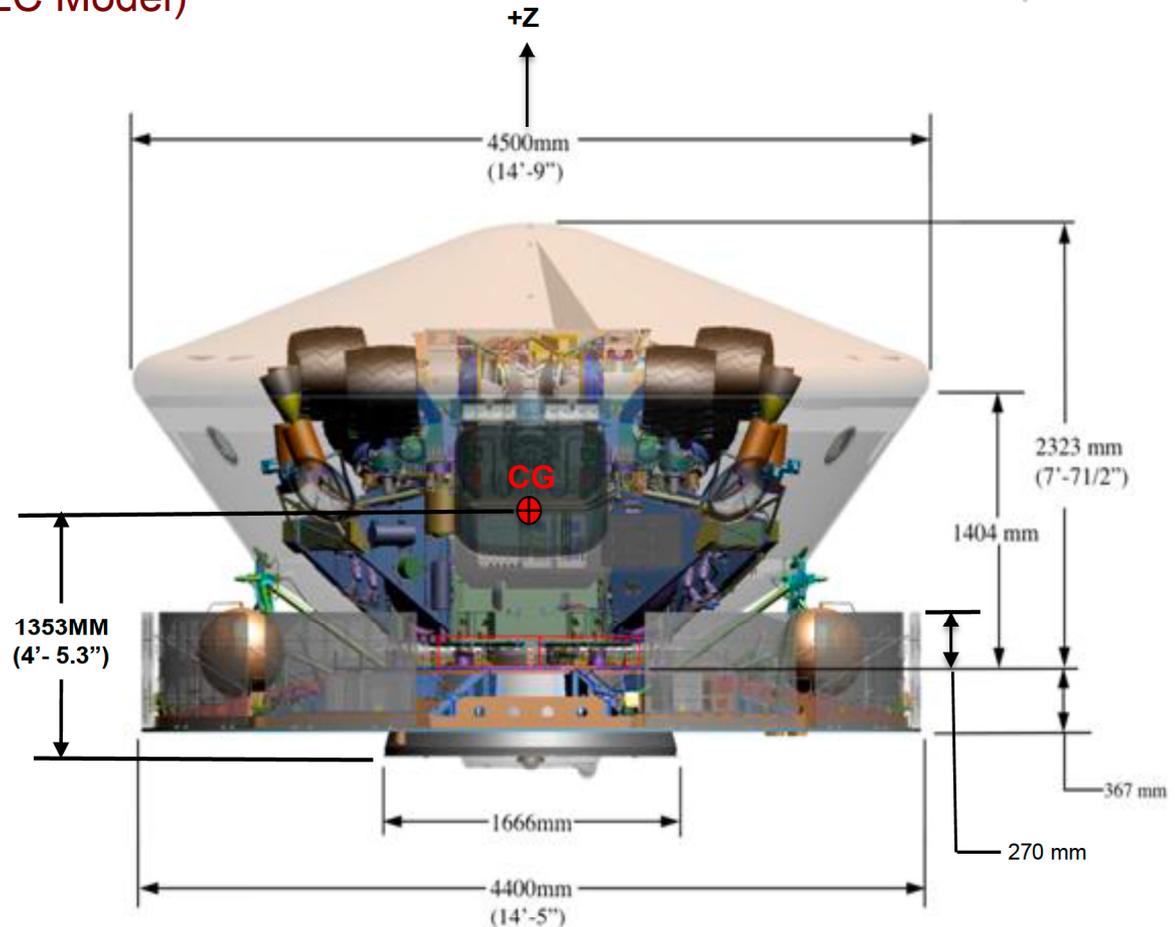


MSL: Loads Environment and Structural Design



MSL Spacecraft Masses (VLC Model)

- **Rover** **943.8 kg**
 - Rover Chassis 723.4 kg
 - Rover Mobility 220.4 kg
- **Landing Mass** **943.8 kg**
- **Descent Stage** **1121.5 kg**
 - Descent stage 581.7 kg
 - 3 Full Fuel Tank 459.8 kg
 - 8 MLE's 80.0 kg
- **Powered DV mass** **2065.3 kg**
- **Aeroshell/BIP** **1390.0 kg**
 - Heatshield 475.4 kg
 - Backshell W/ BIP 418.7 kg
 - Parachute W/ Lid 168.0 kg
 - Entry Balance Mass 175.6 kg
 - Cruise Balance Mass 153.3 kg (Jettisoned from Aeroshell)
- **Entry mass** **3301.9 kg**
- **Cruise Stage** **560.0 kg**
 - Cruise Stage 455.7 kg
 - Secondary Structure Incl Above
 - 2 Full Full Tank 104.3 kg
- **Total Launch Mass** **4015 kg (= 8852 lbs)**
- **$Z_{cg} = 1353 \text{ mm} = 53.28''$ (Measured to bottom of Cruise Stage)**





Launch Loads Methods

Objectives: estimate loads and accelerations for strength margins assessment

- **Physical MAC Method – no Finite Element Model required**

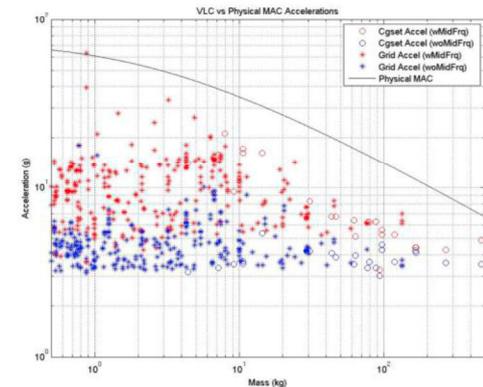
- Conservative “bound” of acceleration as a function of mass
- Applicability
 - Cantilevered masses 1 – 500 kg
 - Frequencies 0 to 80 Hz
- Curve is verified/adjusted by subsequent loads analyses

- **Modal MAC Method – requires Finite Element Model**

- Extension of physical MAC concept to modes of the structure
 - Each mode represents spring-mass system cantilevered from S/C Interface with some “effective mass”
 - Modal MAC is developed to “bound” modal response as a function of effective mass
 - Element loads are the RSS of the modal bounds
- Applicability – lumped mass and distributed mass systems
- Curve is verified/adjusted by CLA

- **Launch Vehicle Coupled Loads Analyses**

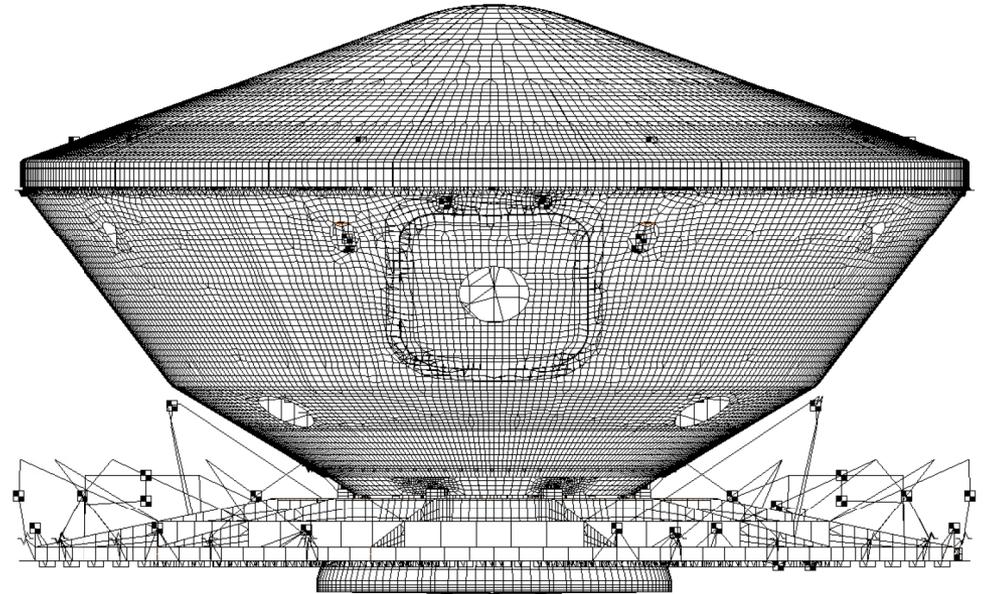
- Send stiffness and mass matrix modal models to Launch Vehicle provider for launch loads analyses





Finite Element Model Statistics (VLC Model)

- **Total Mass** **4015 kg**
- **Model Size**
 - TOTAL NUMBER OF GRID POINTS** = 76574
 - TOTAL NUMBER OF ELEMENTS** = 91908
 - NUMBER OF CBAR ELEMENTS = 7307
 - NUMBER OF CBEAM ELEMENTS = 3479
 - NUMBER OF CBEND ELEMENTS = 619
 - NUMBER OF CBUSH ELEMENTS = 279
 - NUMBER OF CELAS2 ELEMENTS = 3314
 - NUMBER OF CHEXA ELEMENTS = 3218
 - NUMBER OF CONM2 ELEMENTS = 466
 - NUMBER OF CPENTA ELEMENTS = 828
 - NUMBER OF CQUAD4 ELEMENTS = 65798
 - NUMBER OF CROD ELEMENTS = 60
 - NUMBER OF CSHEAR ELEMENTS = 695
 - NUMBER OF CTRIA3 ELEMENTS = 4123
 - NUMBER OF GENEL ELEMENTS = 6
 - NUMBER OF PLOTEL ELEMENTS = 91
 - NUMBER OF RBE2 ELEMENTS = 1361
 - NUMBER OF RBE3 ELEMENTS = 264

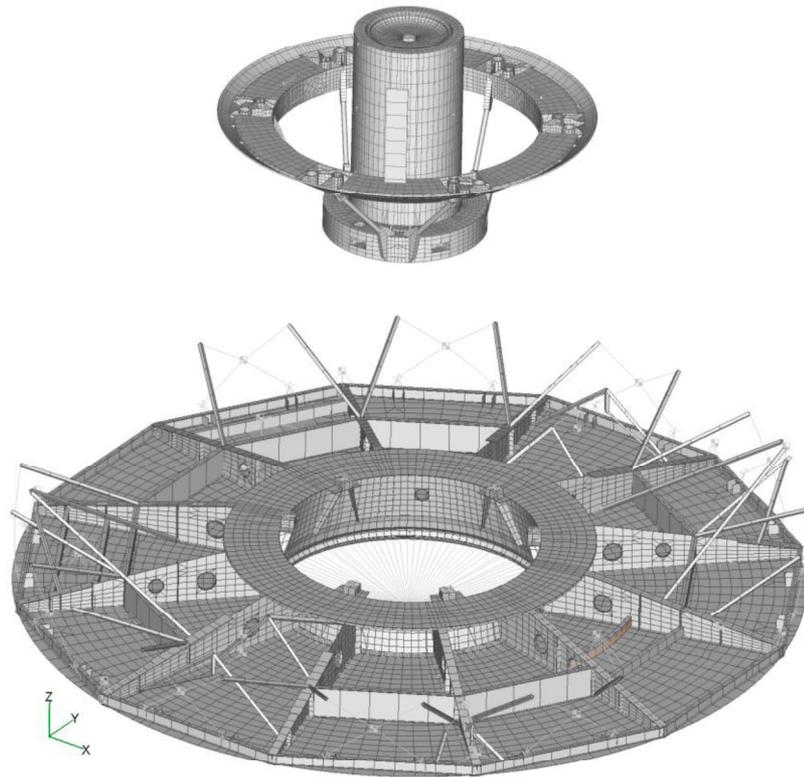


- **Modal Results**

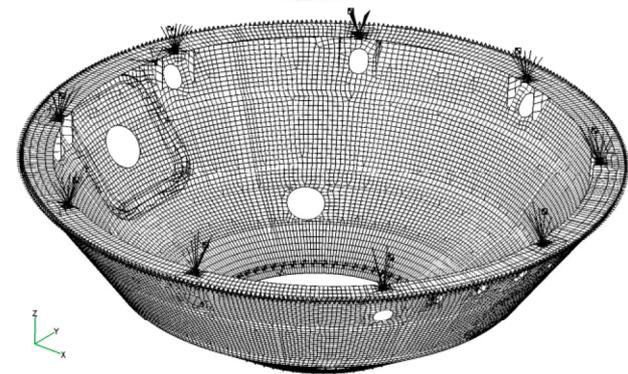
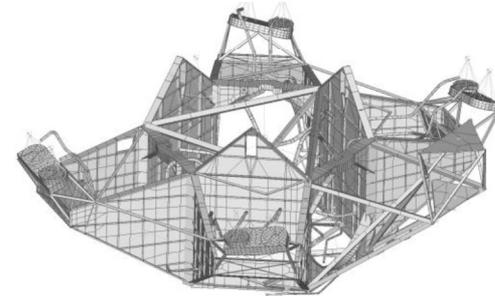
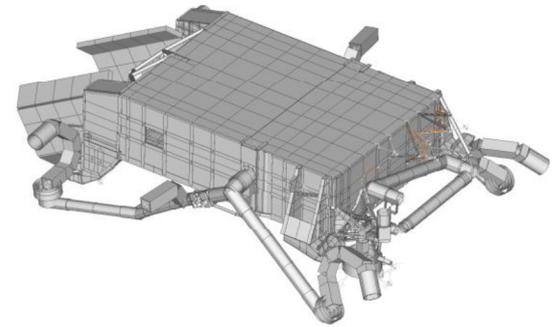
- Frequencies: Lateral X = 9.7 Hz; Lateral Y = 10.9 Hz; Axial Z = 24.3 Hz
- Total % Effective Mass Cumulated to 80 Hz:

X-Trans	Y-Trans	Z-Trans	X-Rot	Y-Rot	Z-Rot
91%	91%	94%	99%	99%	99%

Finite Element Model (VLC model)



Cruise Stage, BIP, and PSS

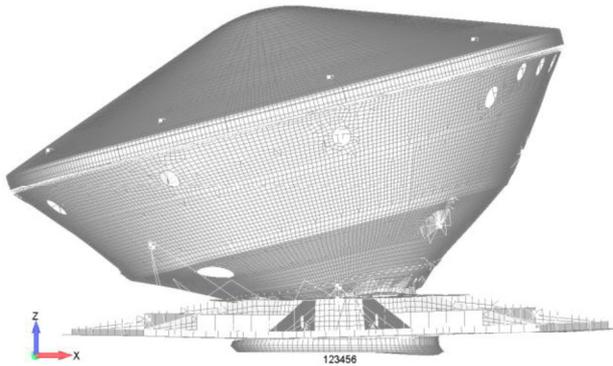


Backshell, Descent Stage, and Rover

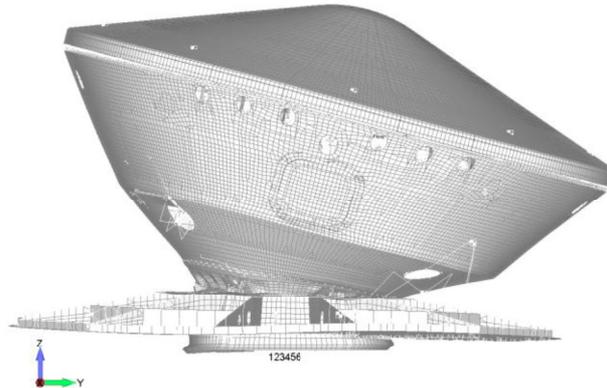
Primary Spacecraft Mode Shapes

- Spacecraft Lateral Modes
 - $f_{\text{lat}} = 9.67 \text{ Hz}$ X-dir (goal 8 Hz)
 - $f_{\text{lat}} = 10.87 \text{ Hz}$ Y-dir (goal 8 Hz)
- Spacecraft Vertical Modes
 - $f_{\text{vert}} = 24.27 \text{ Hz}$ Z-Dir (goal 15 Hz)

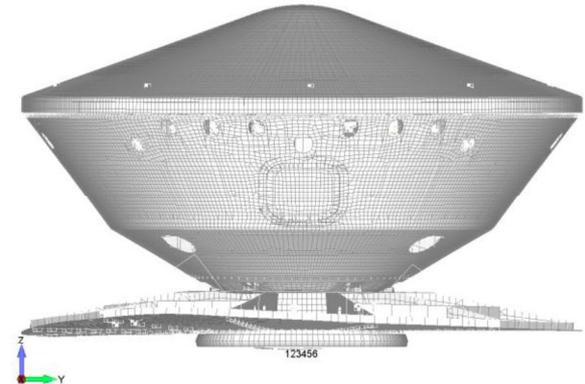
$f_1 = 9.69 \text{ Hz}$



$f_2 = 10.87 \text{ Hz}$



$f_{20} = 24.27 \text{ Hz}$





Entry, Parachute Inflation, Powered Descent Loads Analyses

Entry Loads

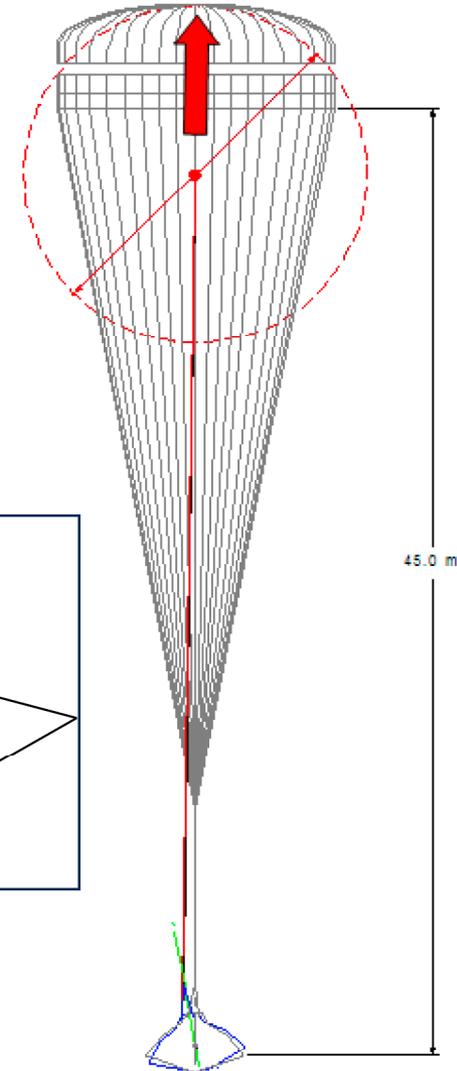
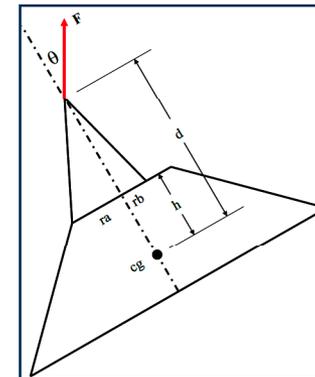
- Derived from 05-22 POST simulations (via Langley Research Center)
- 10,000 cases with 1.16 Loads Uncertainty: 15 g's axial with .65 g's lateral X-direction

Parachute Inflation Loads

- Derived from classical Pflanz semi-empirical method
- 4 Degree of Freedom entry body: translation along velocity and 3 rotational DOF
- 15,000 cases with 1.50 uncertainty on bridle angle and 1.1 LUF on peak inflation load
- Load Cases where angle θ is combined with bridle slacking
 - 65,000 lbs at $\theta = 0$ degree (3 bridles)
 - 65,000 lbs at $\theta = 7.5$ degrees (2 & 3 bridles)
 - 35,000 lbs at $\theta = 12$ degrees (2 & 3 bridles)
 - 20,000 lbs at $\theta = 22.5$ degrees (1 & 2 bridles)

Powered Descent Loads

- Acceleration loading based on static thrust (mass/thrust)
- Load Case: 1.4 g's vertical with .15 g's lateral and 11.1 rad/sec²

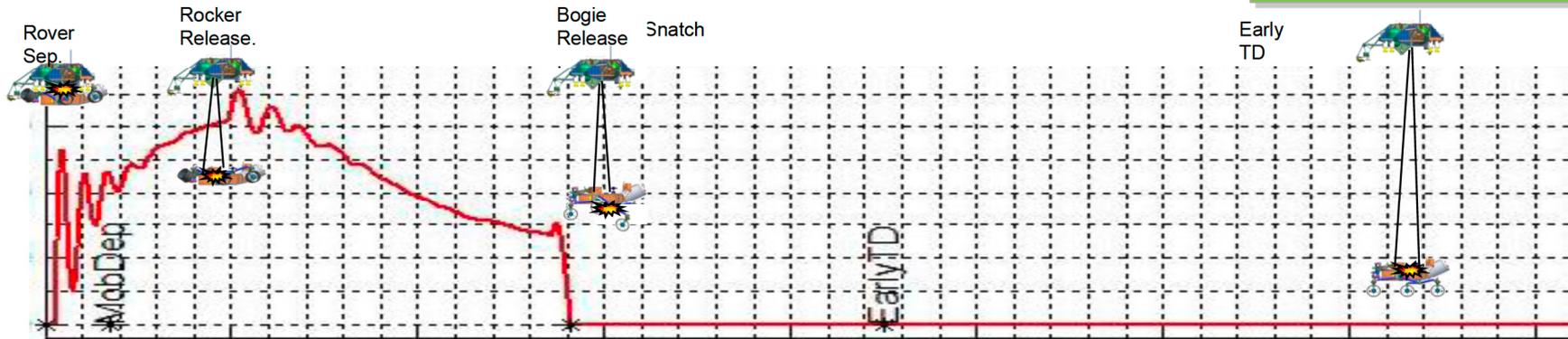




Mobility Deploy and Touchdown Landing Loads Analyses

ADAMS Mobility Deploy Sims

ADAMS Touchdown Sims



- **Objectives: estimate loads and accelerations for strength margins assessment**
 - Compute the loads in the mobility elements and joints
 - Compute the loads at deployed appendages
 - Compute the accelerations on the rigid body Rover chassis
 - Evaluate ground clearance
- **In-house Three Stage Development**
 - Preliminary Design: Loads Bowl and Rock Strike
 - Final Design: Monte Carlo Approach
 - Verification Loads: End-to-End Simulations

Mobility Deploy, Touchdown, and Traverse Loads Analyses

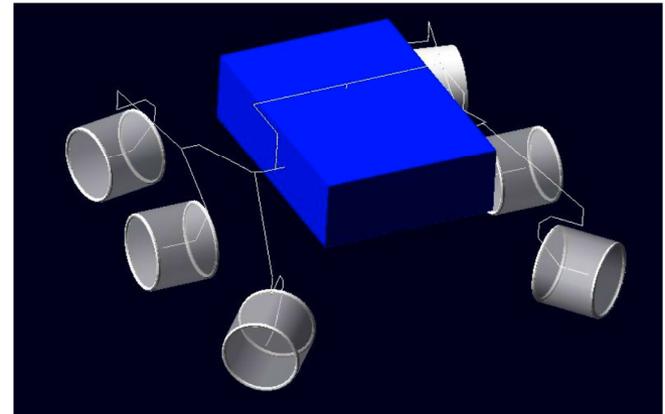
- **Analyses – ADAMS Transient Analyses**

- Modeling Statistics (Loads Bow/Traverse Model)

- 164 Moving Parts (not including ground)
- 120 Beam Forces
- 9 Revolute Joints
- 6 Spherical Joints
- 3 Translational Joints
- 20 Fixed Joints
- 2 Inplane Primitive_Joints
- 3 Motions
- 781 Degrees of Freedom

- Model Assumptions and Idealizations

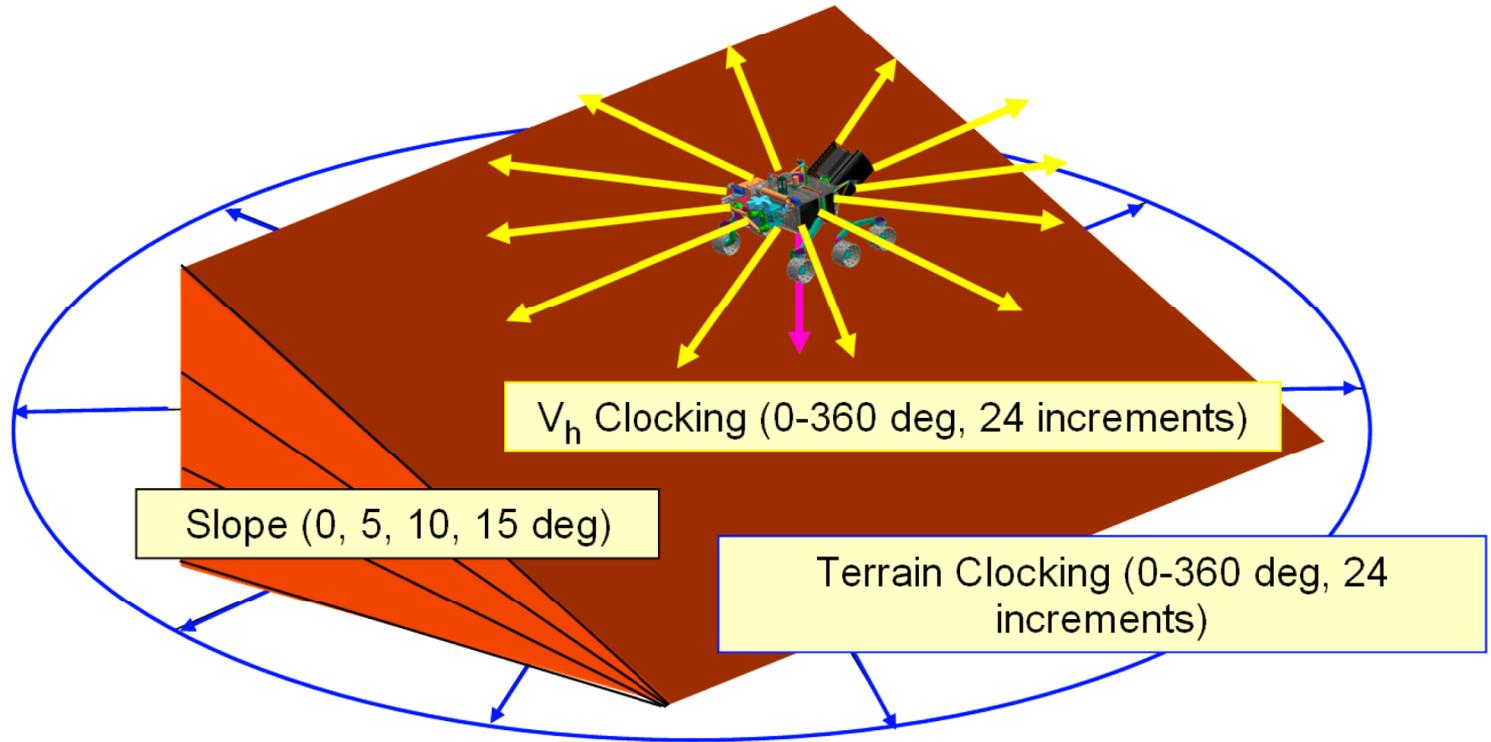
- Descent Stage
 - Modeled as rigid body
 - MLE forces applied as external 'follower' loads
- Rover
 - Chassis modeled as rigid body
 - Mobility system modeled with flexible elements and end-of-range hardstops
 - Joints incorporate nonlinear behavior due to dead zones and hardstop stiffness
 - Simplified wheel model with 6x6 stiffness matrix at hub
- Bridle Umbilical Device (BUD)
 - Bridles modeled as tension only elements whose length varies per solution of BUD state equations
 - Umbilical force modeled by a bounding "sawtooth" profile of test data



Touchdown Loads Development (cont.)

“Loads Bowl” of Touchdown Load Cases

- A “Super Bowl” of 1,752 load cases have been developed to cover all the possible combinations of slope angles ($0^\circ, 5^\circ, 10^\circ, 15^\circ$), slope orientations (0° - 360° , 24 increments), and the clocking of horizontal landing velocity (0.5 m/sec, 0° - 360° , 24 increments).



Mobility Traverse Loads Analyses

Objectives

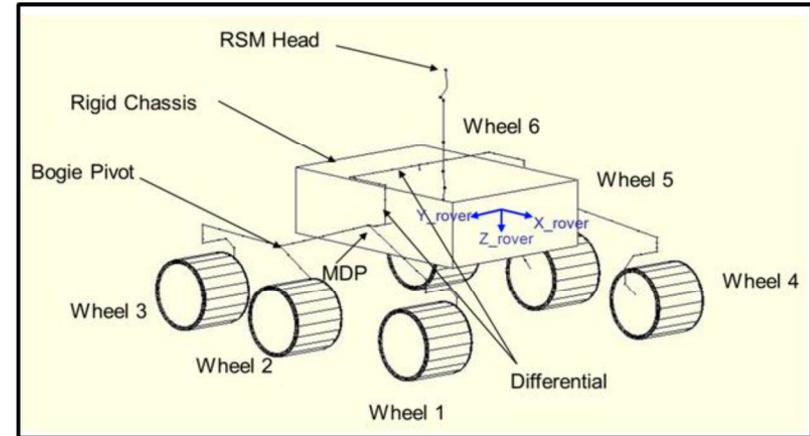
- Compute maximum wheel impact loads and suspension system station cut loads for design
- Compute loads at deployed appendages
- Compute chassis accelerations

Loads Analysis Methodology

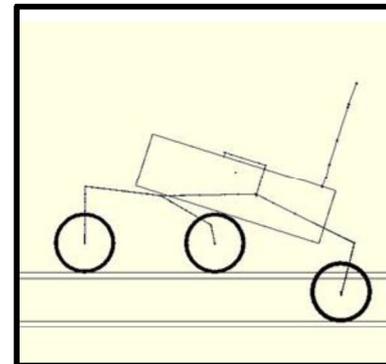
- Use ADAMS simulation software transient analysis to generate time domain loads
- Includes all reasonable egress and surface mobility cases
- Assume maximum wheel drop of 40 cm in 3/8 Mars gravity field
- Assume $\mu_{fr} = 1.0$ between wheel and infinitely stiff ground

General Configuration

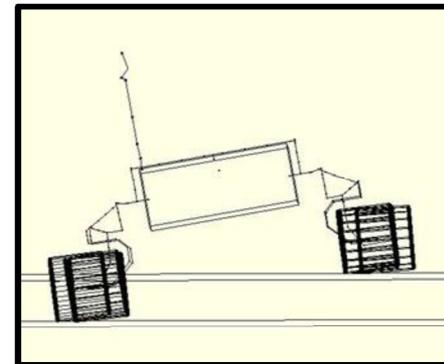
- Deployed mobility system with latched rocker arms
- Deployed RSM
- Total Rover system mass = 960kg
- Seven traverse cases: Cases 2 & 7 were critical



Traverse Rover Configuration



Load Case 2



Load Case 7



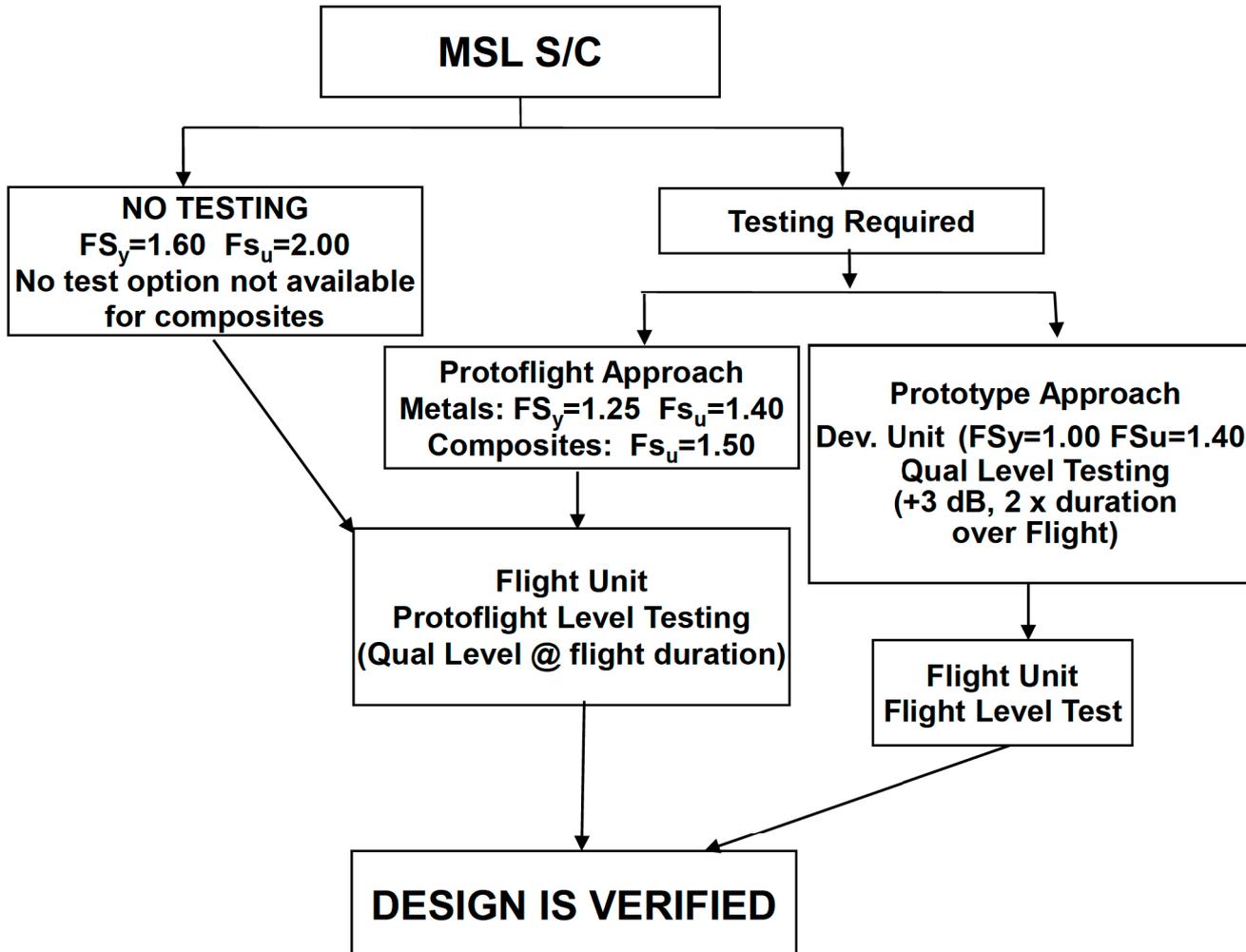
Loads Environment Summary

- **Launch: Minimum Design Load is Verification Load Cycle Results w/o mid-frequency augmentation (LUF = 1.25 to account for Rover model correlation challenges) → values shown below derived from Station cut loads with mid-freq aug**
 - S/C acceleration: 1.2 g's lateral with 2.3 g's vertical (max lateral case, Mach 1)
.14 g's lateral with 6.1 g's vertical (max vertical case, 17HzBD)
 - Rover Acceleration: 1.5 g's lateral with 2.6 g's vertical (max lateral case, Mach 1)
.84 g's lateral with 6.6 g's vertical (max vertical case, 17HzBD)
 - Maximum component level acceleration: 16.8 g's for 30.7 kg APXS (on Turret of Rover SaSPaH)
- **Entry (LUF=1.16), Parachute Inflation(LUF=1.10), Powered Descent (max thrust)**
 - Entry: .65 g's lateral with 15 g's vertical
 - Parachute Inflation: 1.2 g's lateral with 9.2 g's vertical and 41 rad/sec² (65,000 lbs cord load)
 - Powered Descent: .15 g's lateral with 1.4 g's vertical and 11.1 rad/sec²
- **Mobility Deploy, Touchdown Landing (LUF=1.2): acceleration for chassis cg**
 - Mobility Deploy (Verification Cycle): a (suspended mass)= 1.59 g's with $\alpha = 38.2$ rad/sec²
 - Touchdown (Verification Cycle): a (suspended mass)= 1.27 g's with $\alpha = 35.5$ rad/sec²
- **Mobility Traverse (LUF = 1.0): acceleration for chassis cg**
 - 40 cm wheel drop cases: a (suspended mass)=1.74 g's with $\alpha = 25.1$ rad/sec²

Note: LUF shown is for the Verification Loads Cycle. It is common to use LUF as high as 1.5 for preliminary design loads when the structure is immature.



Structural Verification Plan - Test



Cruise Stage

- Aluminum Structure
- Flight unit (1)

Descent Stage

- Aluminum structure
- DTM, Flight unit (1)

Aeroshell

- M55J face sheet H/C sandwich panels
- Flight unit (1) – Backshell
- DTM, Flight unit (1) – Heat Shield

Rover

- Aluminum chassis
- Titanium Mobility, RSM mast, RTG struts
- Honeycomb Heat Exchanger and Belly Pan
- DTM, Flight unit (1)



Structural Verification Plan – FOS and Loads

- All Structure must demonstrate Positive Margins of Safety against Yield and Failure

$$\text{M.S.} = \frac{\text{Allowable Load or Stress}}{\text{Limit Load or Stress} \times \text{F.S.}} - 1 \geq 0$$

Factor of Safety:

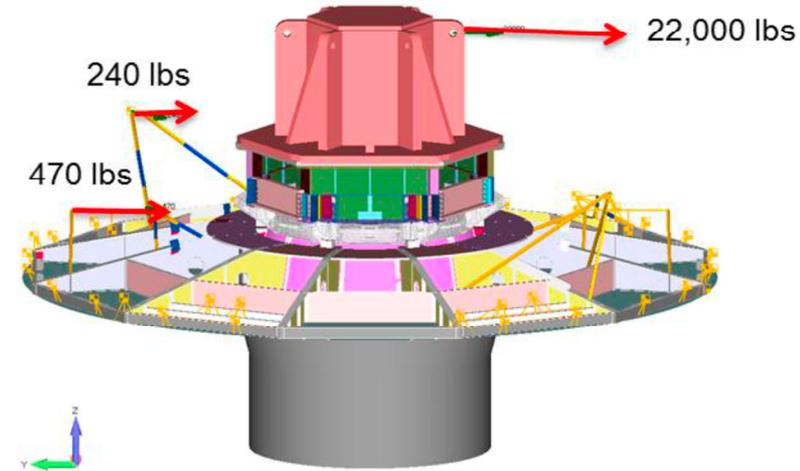
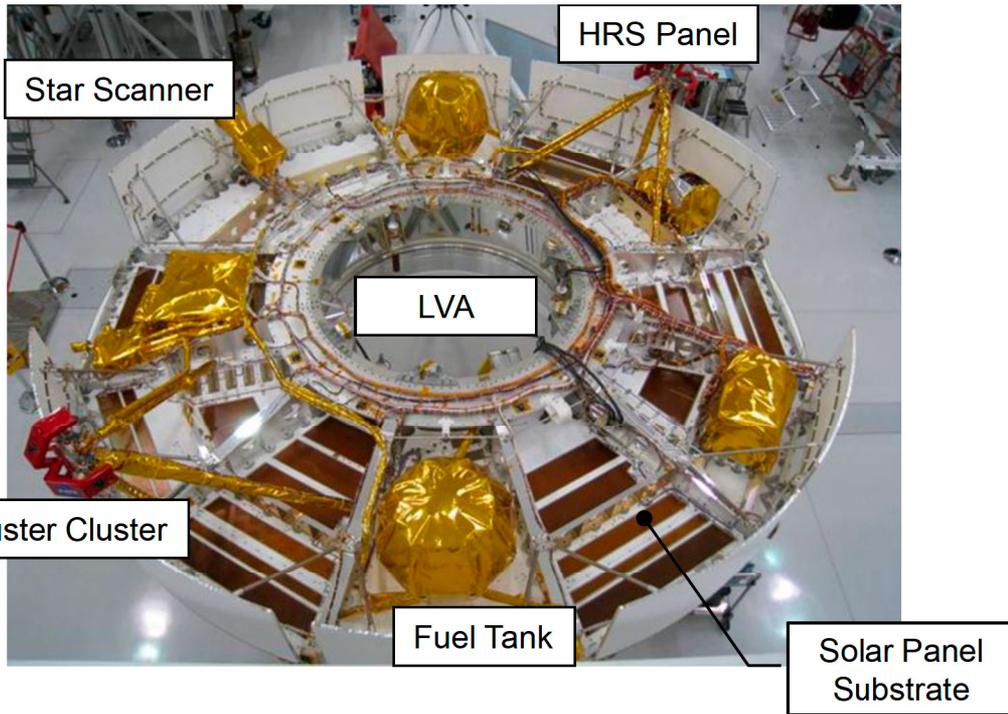
	Qual by Test FLT	Qual by Test FLT	Not Tested
	Metallic	Composite	
F.S. _{ult}	1.40	1.50	2.00
F.S. _{yield}	1.25		1.60

Additional Fitting Factor = 1.15 where applicable

- Limit Loads must envelope worst case environment
 - Quasi-static accelerations
 - Low (<40 Hz) and Mid-frequency (40-80 Hz) launch vehicle transients
 - Structurally significant vibro-acoustic excitations
 - Entry, descent, landing and maneuvering loads



Cruise Stage Configuration and Tests



Cruise Stage weight = 560 kg total

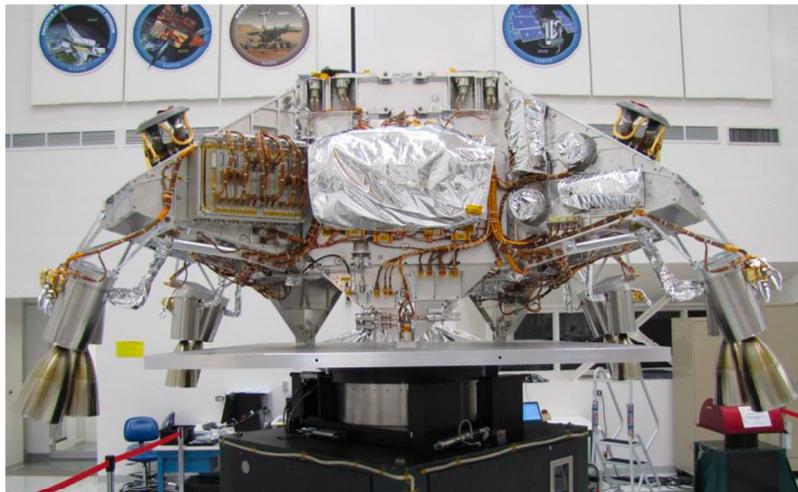
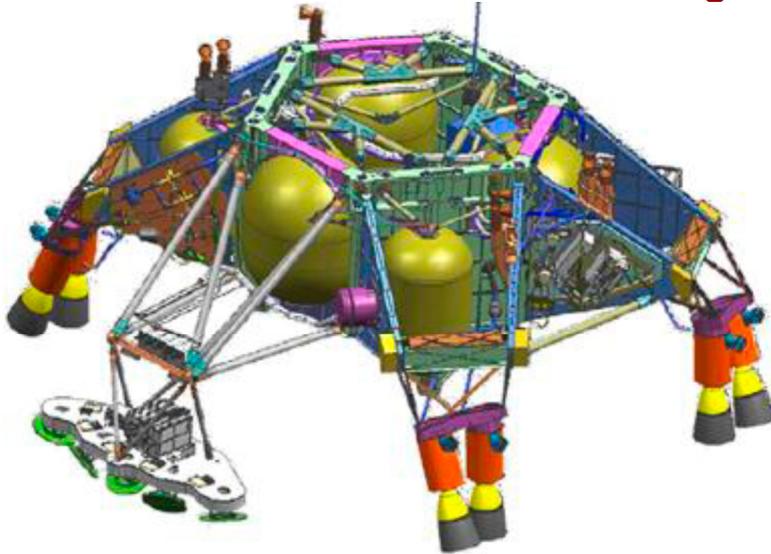


4.5 m Aeroshell



- **Static Test Levels**
 - Heat Shield Entry Deceleration (15 g's): 131,700 lbs total pressure (compression in Back Shell)

Descent Stage Configuration

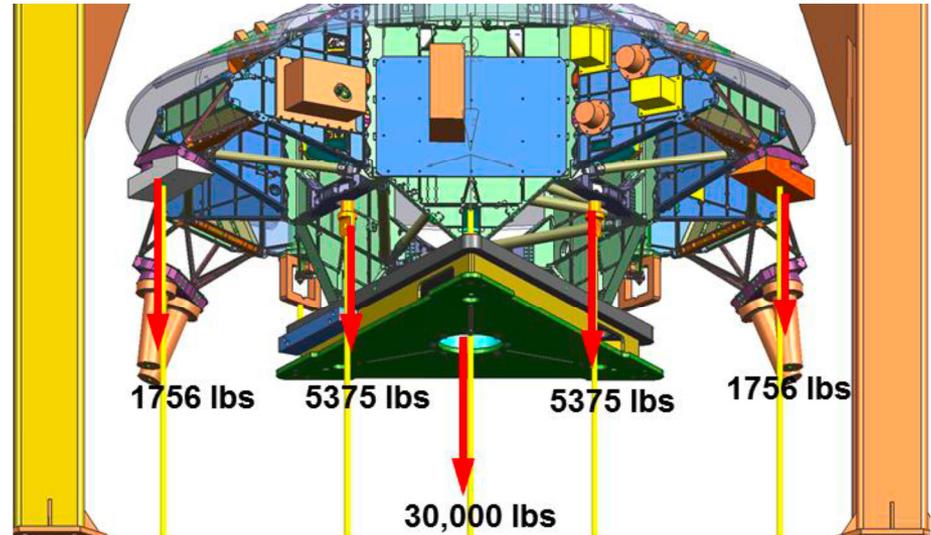


- **Primary Structure**
 - Aluminum panels, beams, and tube trusses.
- **Propulsion & Thermal Support Structure for:**
 - 3 fuel tanks (23"x29")
 - 2 pressurant tanks (16"x29")
 - 8 Mars Lander Engines (MLE)
 - 8 entry RCS thrusters
 - Pressurant & Fuel Control Assemblies (PCA & FCA)
 - Two and Six Pyro Valve Plates (2PV, 6PV)
 - Fuel lines, helium lines, pyro valves, filters, etc
 - HRS lines to X-Band plate and Avionics Plate
- **CDH & Power Support Structure for:**
 - Descent Power Assembly (DPA)
 - Descent Power and Analog Module (DPAM)
 - Descent Motor Control Assembly (DMCA)
 - Pyro Thermal batteries (PYTB) (2)
 - Power Thermal batteries (PWTB) (2)
 - Base Load Resistor Assembly (BLRA)
- **GNC Support Structure for:**
 - Descent Inertial Measurement Unit (DIMU)
 - Terminal Descent Sensor (TDS)
- **Telecom Support Structure for:**
 - 1 UHF Di-Pole Relay Antenna & coax routing
 - X-Band HRS Plates (with TWTA, SDST, Diplexer, etc)
 - 1 DTE Low Gain Antenna and dual waveguide routing
- **Pyro-Mechanical Devices**
 - Mega Cutters (4)
 - 5/8" Separation Nuts (15)
- **Major Interfaces**
 - Rover/DS: 'kinematic' 3 point bi-pod interface
 - DS/BIP cup/cones (6)
 - DS/Cruise Stage interfaces (6)
 - DS/BS rails/rollers (3)
 - Bridle and Umbilical Device (BUD)
 - RCS Window Seal hw (4)

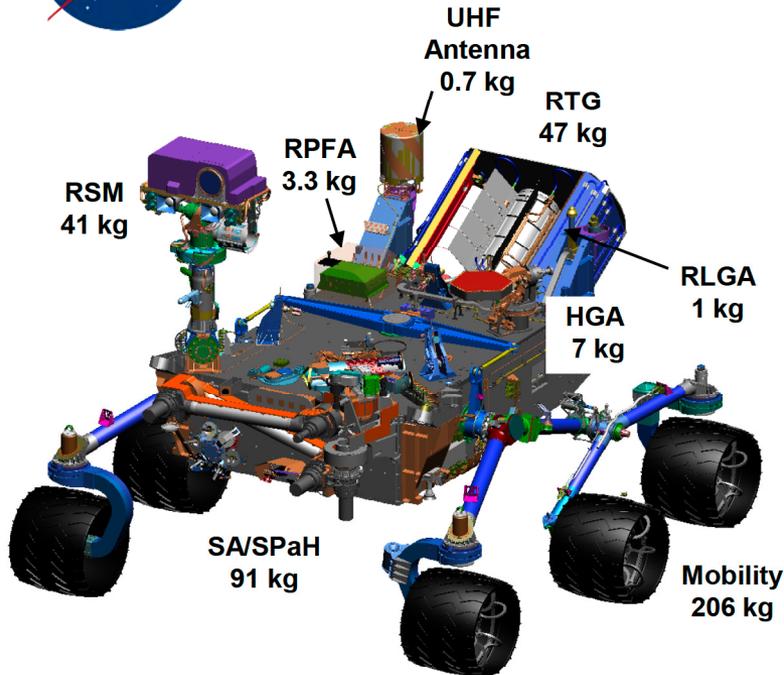
Descent Stage Structural Configuration and Test

- **Structural configuration and concept**

- Hexagonal structural core with alternating shear panels and open frames to accommodate propulsion tanks
 - Shear panel terminate with pseudo bipods to interface with Rover top deck (three point attachment)
 - Corners of Hex Core interface to the BIP/Aeroshell with six separation bolts for Entry case
 - Pairs of separation bolts located on the top of each shear panel attach through the BIP to the Cruise Stage for the launch interface with total of six bolts



Rover Equipment



- **Primary Structure**
 - Aluminum panels, aluminum honeycomb panels, titanium RTG adapter
- **Thermal Support Structure for:**
 - RTG Heat Exchangers
 - HRS Tubing
 - Thermal Enclosures for warm components
- **Avionics & Power Support Structure for:**
 - Rover Pyro FET Assembly (RPFA)
- **GNC Support Structure for:**
 - 4 Hazard avoidance cameras
- **Telecom Support Structure for:**
 - 1 UHF quad helix antenna and coax routing
 - 1 X-Band RLGA Low Gain Antenna and waveguide routing
 - 1 High Gain Antenna (HGA)
- **Major Interfaces**
 - Remote Sensing Mast (RSM)
 - Sample Acquisition/Sample Processing and Handling (SA/SPaH) System
 - Rover/DS Separation interface: 'kinematic' 3 point bi-pod interface, cup/cones (3)
 - BUD exit guides and soft goods
 - RTG
 - Mobility system – differential
 - Mobility system – corner mobility supports



MSL: Loads Environment and Structural Design



Chemistry and Camera (ChemCam)
*Chemical composition
 High-res imaging*

Mast Cameras (Mastcam): *Color imaging and video, Medium and high resolution*

Rover Environmental Monitoring Station (REMS)
Meteorology and UV

ON THE TURRET:
Mars Hand Lens Imager (MAHLI)
Color microscopic imaging

Alpha Particle X-Ray Spectrometer (APXS)
Chemical composition

Power Source

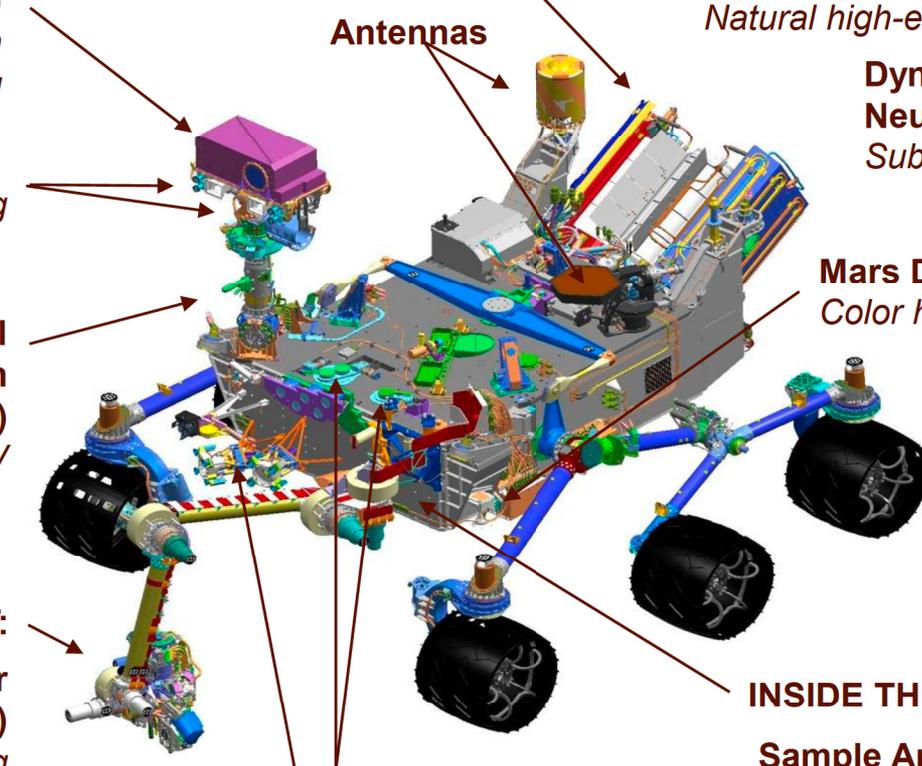
Antennas

NOT VISIBLE:

Radiation Assessment Detector (RAD)
Natural high-energy radiation

Dynamic Albedo of Neutrons (DAN)
Subsurface hydrogen

Mars Descent Imager (MARDI)
Color high-definition descent movie



Sample Inlets

Spare Drill Bits

Sampling System: *Arm, powdering drill, brush, scoop, and sieves*

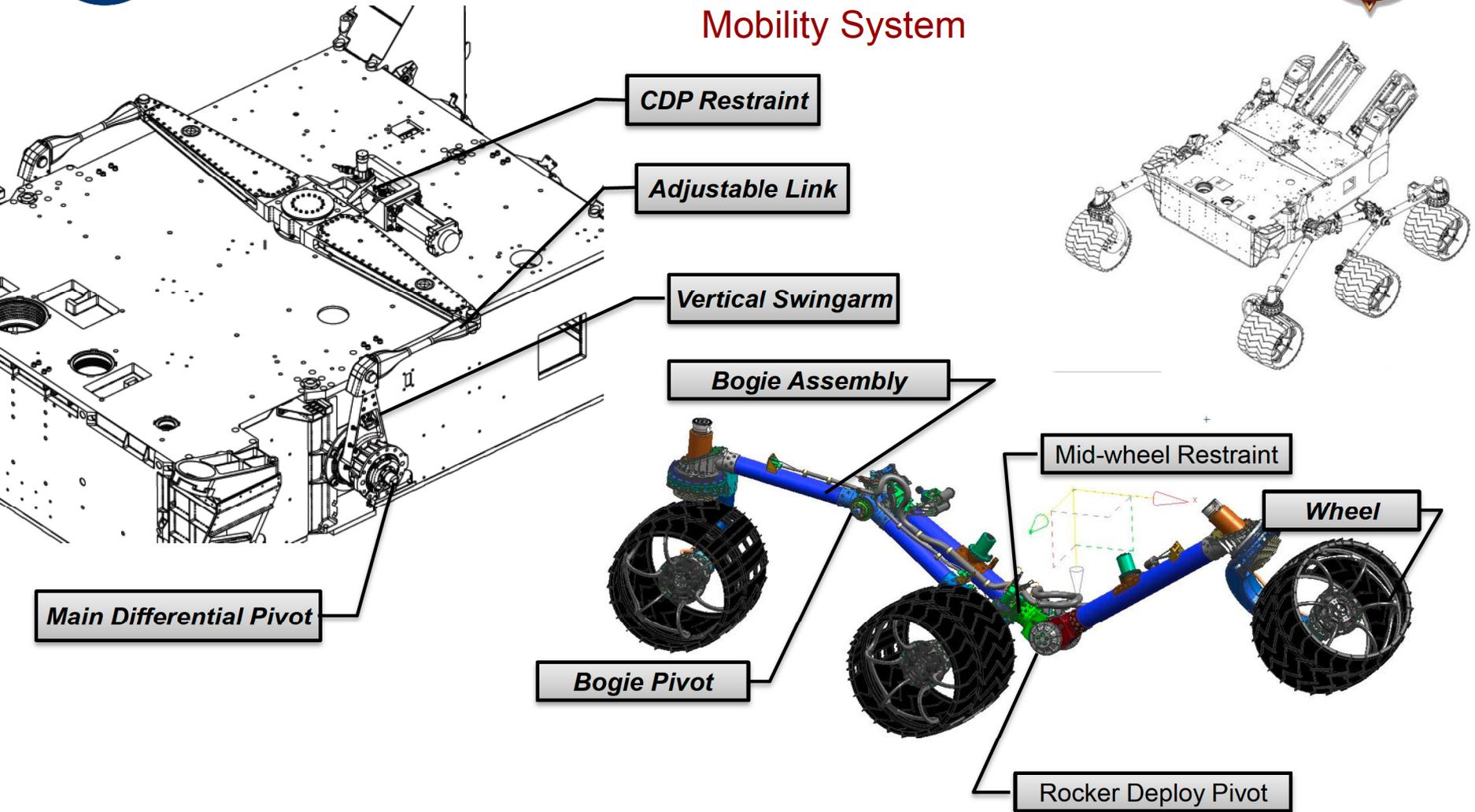
INSIDE THE ROVER BODY:

Sample Analysis at Mars (SAM)
Composition and isotopes of rock, soil, and air samples; organics

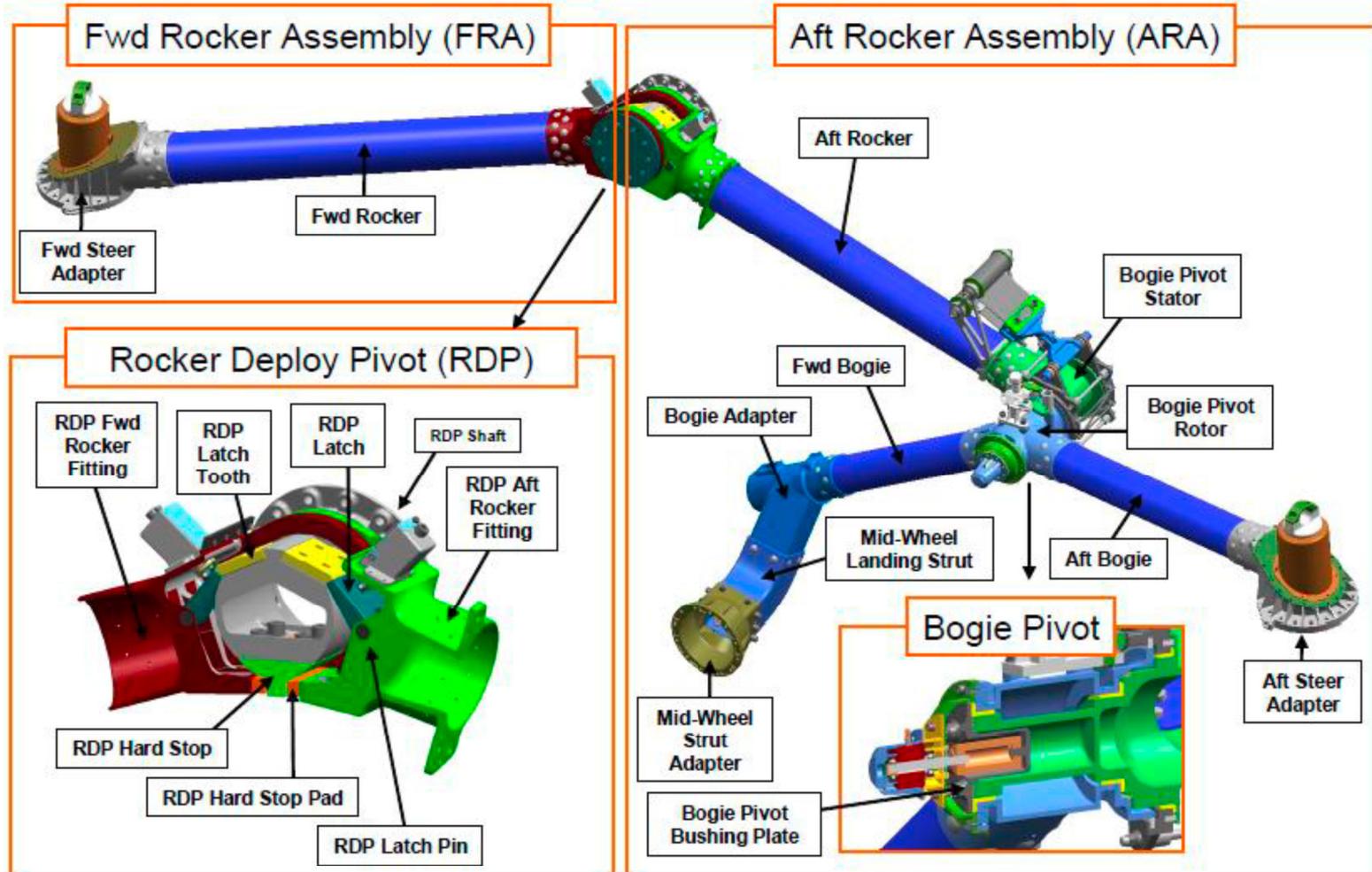
Chemistry and Mineralogy (CheMin): *Mineralogy of rock and soil samples*



Mobility System



Rover Mobility System Hardware Elements





Rover Traversing





Stress Analysis Approach Overview for Mobility Hardware

- **Loads Application Strategy**
 - First Pass (most conservative): apply case consistent load components in all possible sign combinations
 - Second Pass: identify the critical load component which is dominate in contributing to the critical stress state, identify the time in which the load component is maximum, extract all the other load components at this time step
- **Strength Analysis**
 - First Pass: perform linear static analyses
 - Second Pass: perform material nonlinear analyses and compute margins of safety based on strain
 - Third Pass: refine the model fidelity if necessary and perform linear/nonlinear analyses using contact elements
- **Test Verification**
 - Elements of the mobility system have been test verified to FLL with Test Factor > 1.0 (goal 1.2)
 - The Rover Differential Pivot was tested to verify capacity beyond 1.4 x FLL

Note: final strength margins were updated to Monte Carlo Load Cycles (Aug 2010 Touchdown, Nov 2010 Mobility Deploy)



Wheel Development Program

- **Prototype program**
 - Verify design to 1.4 x Flight Limit Loads by testing to relevant load case
 - No detrimental yielding at 1.0 x FLL
- **Radial Stiffness**
 - Wheels are first defense against minimizing touchdown and traverse loads → nominal stiffness 2174 lbs/in used in final ADAMS model (design goal was 2500 lbs/in)
- **Strength Analyses**
 - $FS_{yield} = 1.00$ $FS_{ult} = 1.40$
 - The low stiffness of the wheel assembly (aluminum tire and titanium flexures) undergoes considerable deflection → perform material and geometric nonlinear analyses
 - Margins were computed in the flexures against strain to rupture capacity (rupture strain is .08 in/in, yield strain is .011 in/in)
- **Verification**
 - June 2007 Development Unit Test, July 2008 Flight Design Test
 - Titanium flexures test verified in static testing
 - Wheel cleats and surfaces thoroughly tested for odometry, wheel impact, functionality – localized denting & rupture, ovalization permitted



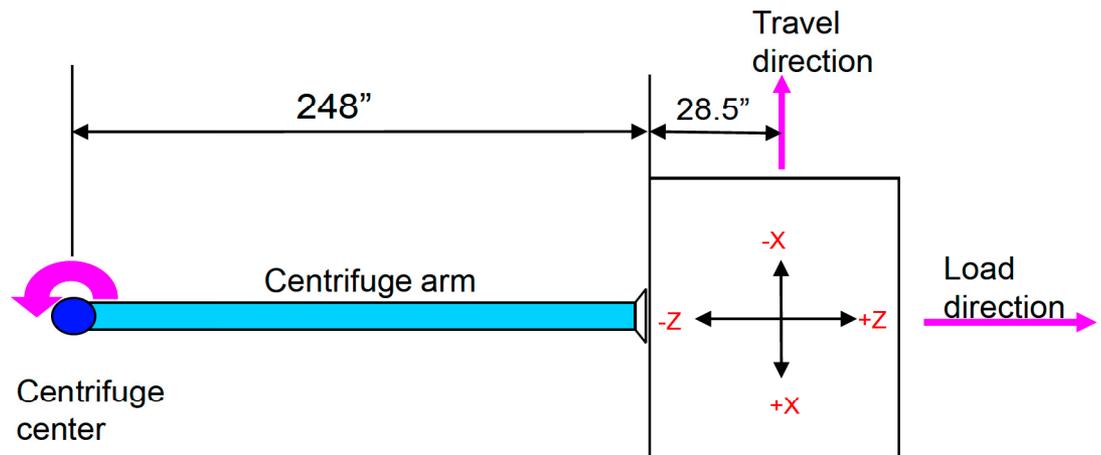
Development Unit Test



MSL: Loads Environment and Structural Design



- **Sine Pulse Test Objective:** To verify the MSL Rover structure primary interface for launch lateral loads (~4 g's lateral)

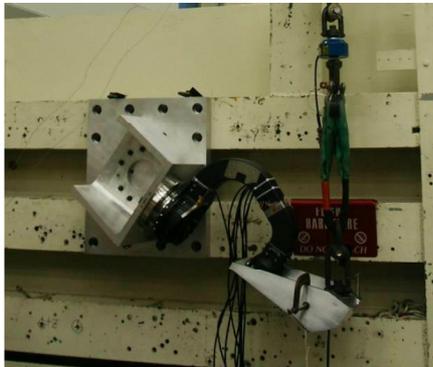


- **Centrifuge Test Objective:** Demonstrate the structural integrity of the MSL DTM rover chassis and mobility restraint for the 15 g's Mars entry case



Suspension System Tests

Objective: Verify maximum element loads at Forward Rocker, Aft Rocker, Aft Bogie, and Fwd Bogie



Fwd CLSA Test



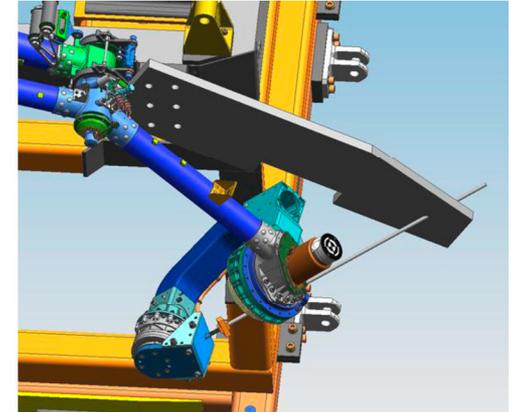
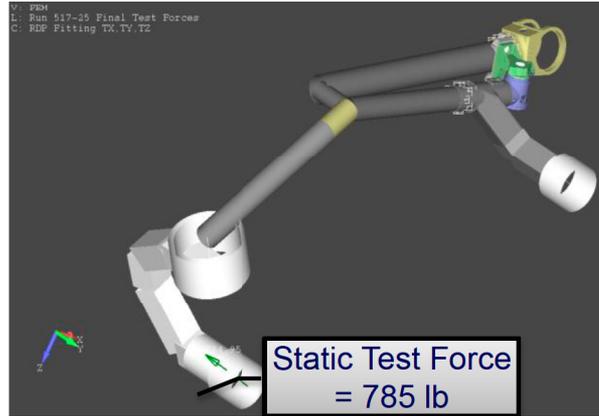
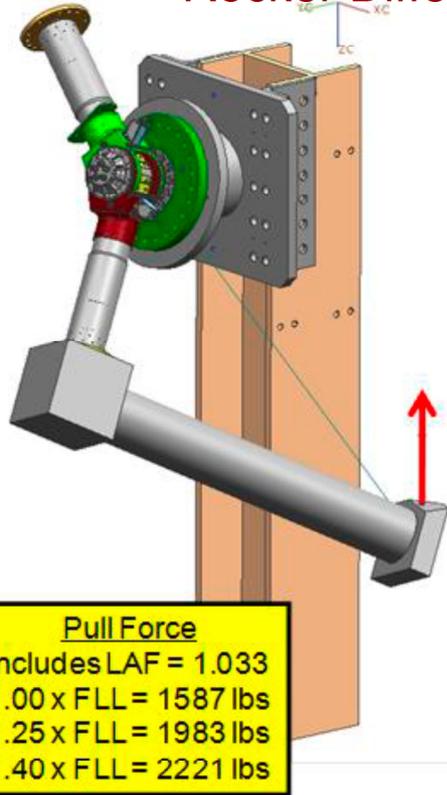
Aft CLSA Test

Corner Landing Strut Tests

Objective: Verify maximum element loads at Fwd and Aft Corner Landing Strut Assemblies (CLSA)



Rocker Differential Pivot (RDP) and Mid-wheel Restraint Tests



Mid-wheel Restraint Test

Objective: Verify structural integrity of the Mid-wheel Restraint (MWR) and the RDP fitting flange to the critical Mobility Deploy Loads and the RDP fitting

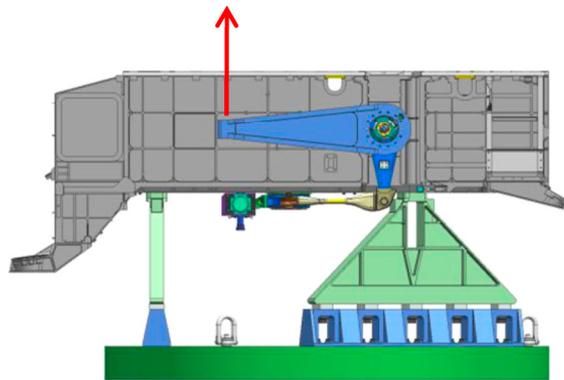
Rocker Diff Pivot

Objective: Verify structural integrity of the Fwd & Aft Rocker Fittings and the main shaft as well as testing to capacity to verify ultimate capacity

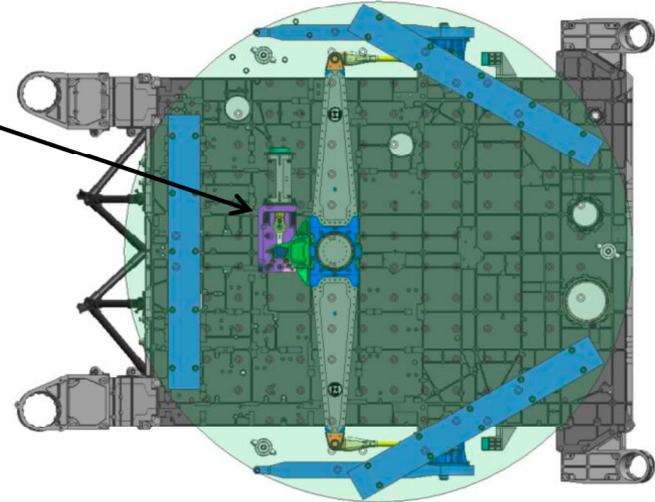
Horizontal Swing Arm & CDP Restraint Tests

Horizontal Swing Arm, CDP Restraint, Main Diff Pivot Tests

Objective: Verify structural integrity of the redesigned HSA, redesigned CDP restraint hardware and associated interfaces with the HSA and chassis top deck

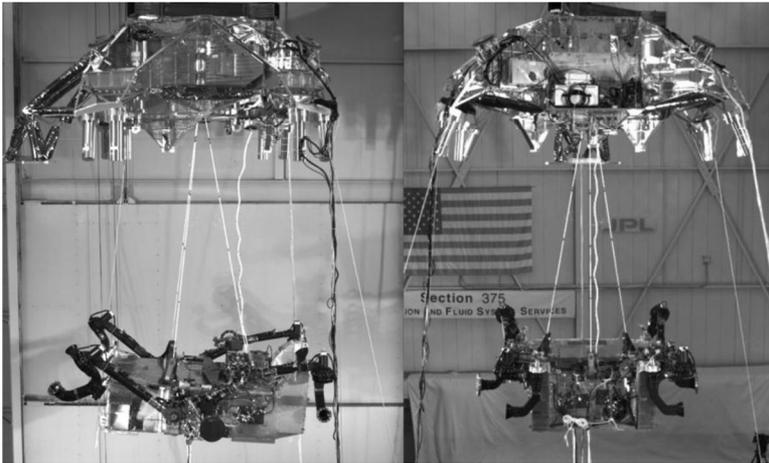


CDP
Restraint Pin
ENGAGED





ADAMS Model Validation - Rover Touchdown and Deployment Tests



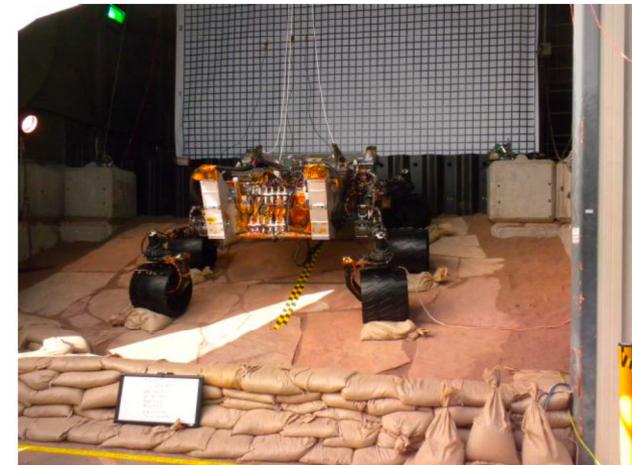
Mobility Deploy Validation – Skycrane Full Motion Drop Test (Jan 2011)

Test: PDV supported by SAF facility crane, pyro release of Rover, BUD deploy with simultaneous Mobility Deploy
Objectives: Validate loads models using loads and rover kinematic data



Touchdown Loads Validation (Feb 2011)

Test: DTM Rover and nylon bridles lowered from over-head winch, TD on sloped surface tiled with flagstones, rocks, and ditches
Objectives: Validate loads, look for TD modeling escapes





November 26, 2011!

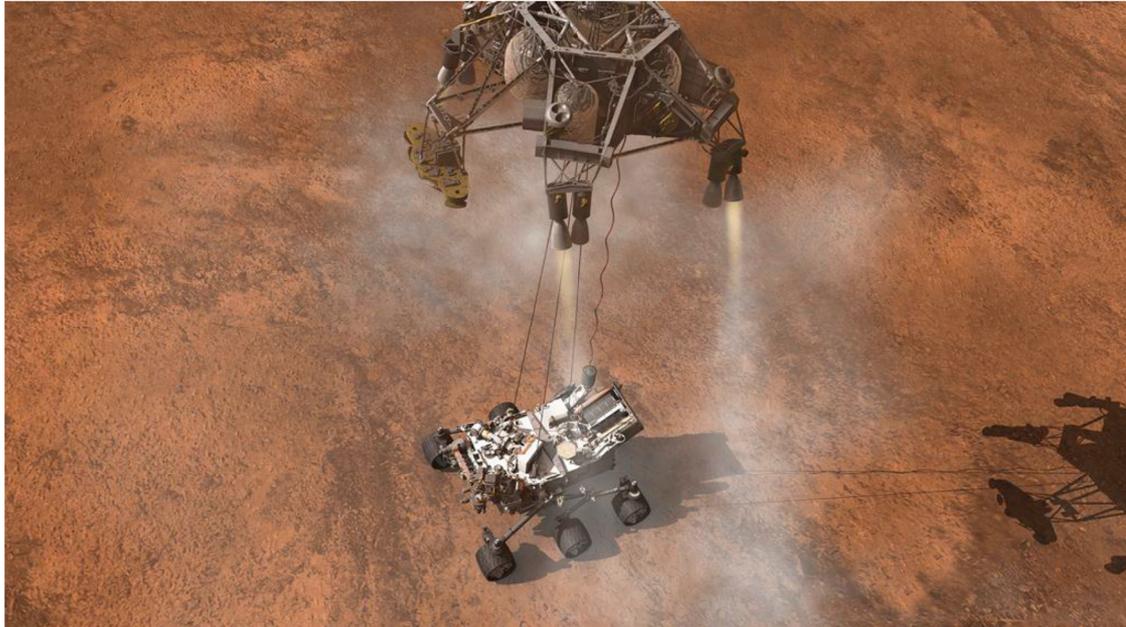
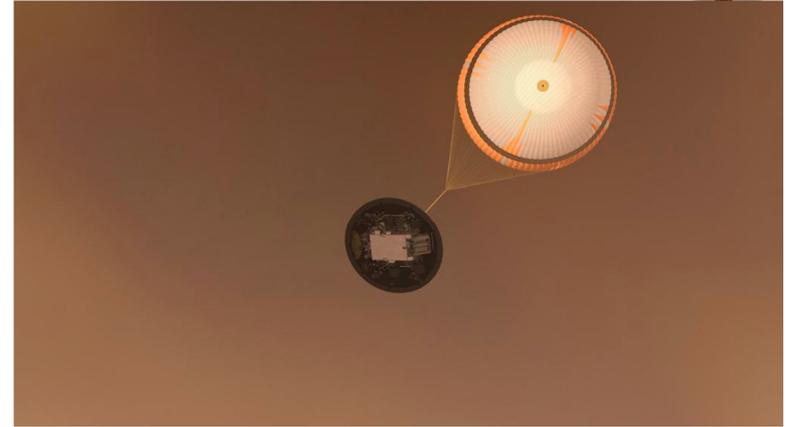
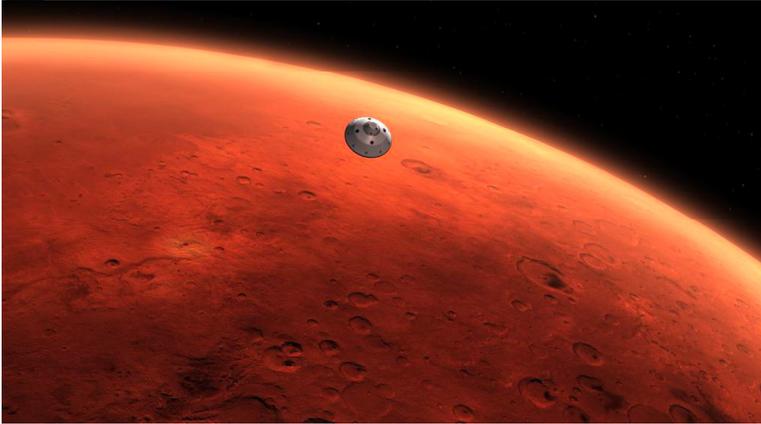


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August 5, 2012



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and Beyond!

