Mars Science Laboratory Loads Environment and Verification of the Descent Stage Propulsion Lines

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Stanford, California
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Jet Propulsion Laboratory, California Institute of Technology
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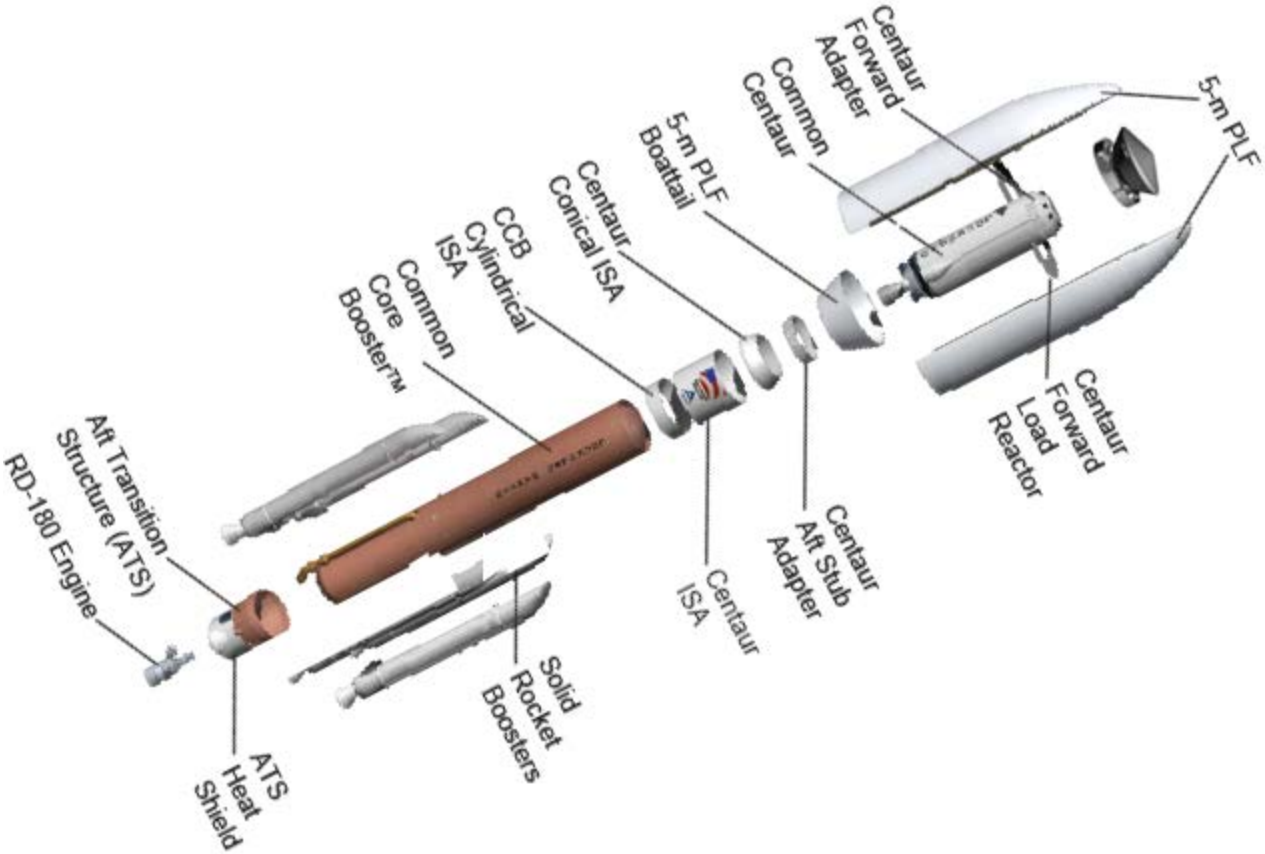
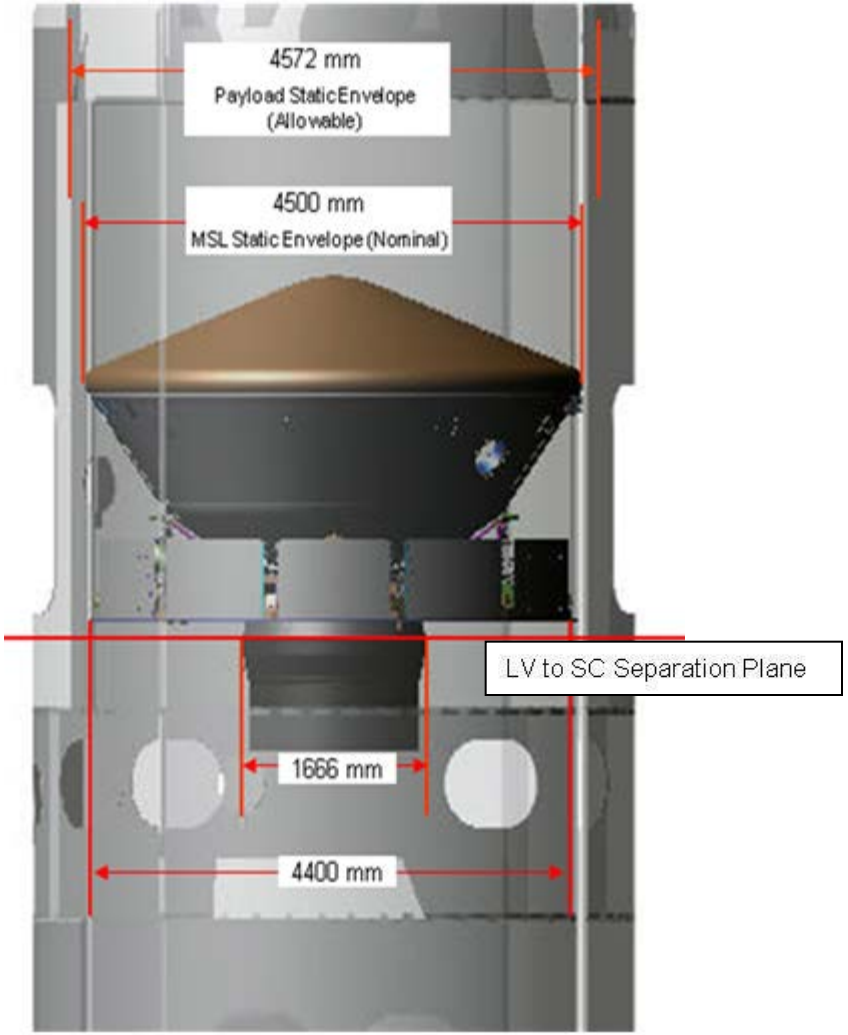
MSL: Loads Environment

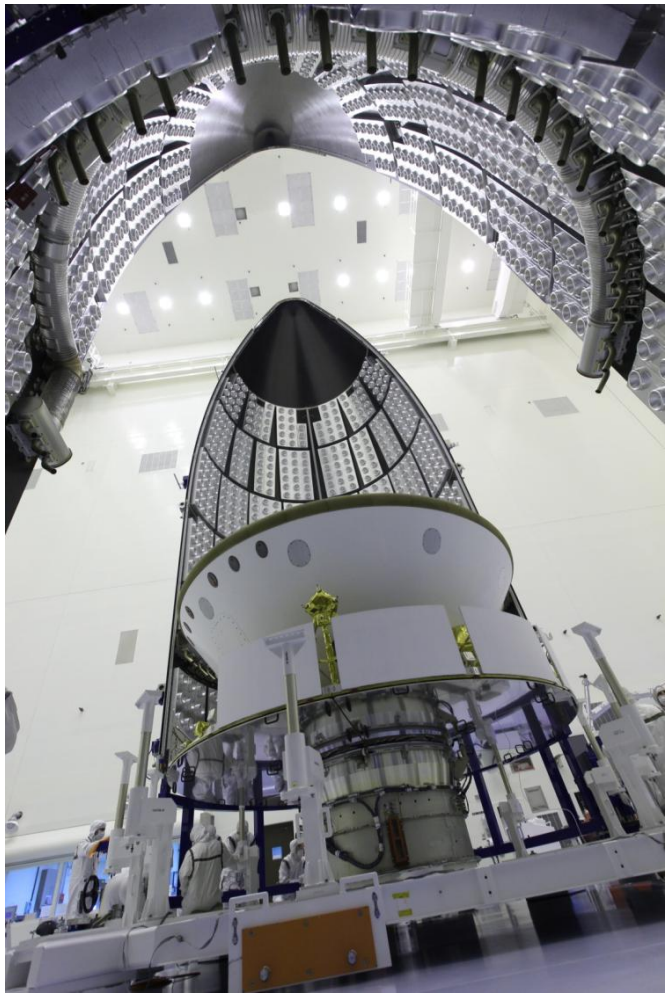
Atlas V 541 (5 m fairing, 4 SRB, 1 Centaur engine) Mission Launch Vehicle
November 26, 2011



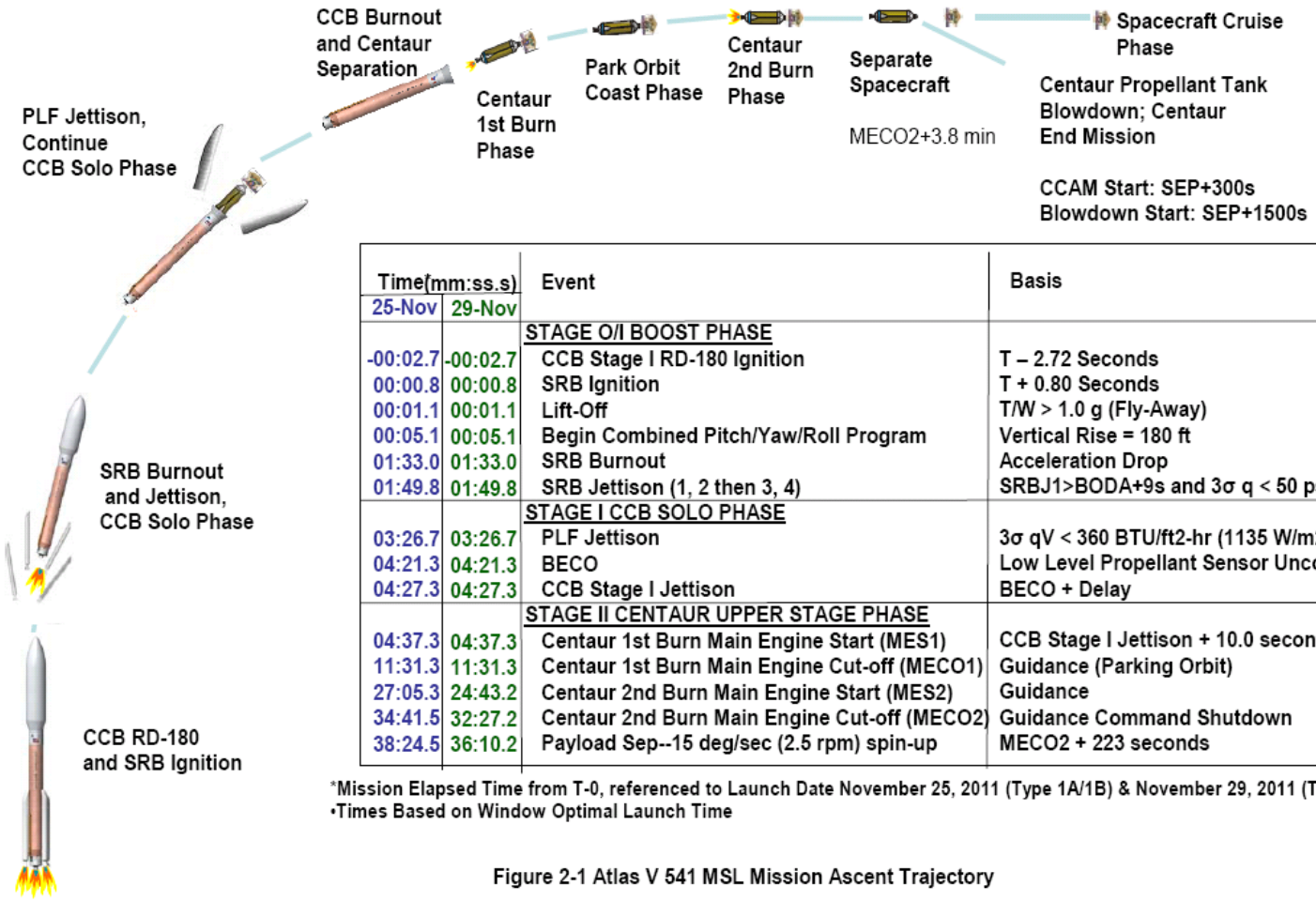
MSL: Loads Environment

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





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

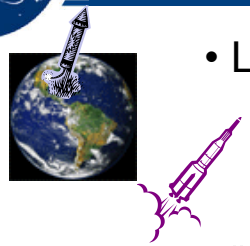


Time(mm:ss.s) 25-Nov	29-Nov	Event	Basis
		STAGE O/I BOOST PHASE	
-00:02.7	-00:02.7	CCB Stage I RD-180 Ignition	T – 2.72 Seconds
00:00.8	00:00.8	SRB Ignition	T + 0.80 Seconds
00:01.1	00:01.1	Lift-Off	T/W > 1.0 g (Fly-Away)
00:05.1	00:05.1	Begin Combined Pitch/Yaw/Roll Program	Vertical Rise = 180 ft
01:33.0	01:33.0	SRB Burnout	Acceleration Drop
01:49.8	01:49.8	SRB Jettison (1, 2 then 3, 4)	SRBJ1>BODA+9s and 3σ q < 50 psf
		STAGE I CCB SOLO PHASE	
03:26.7	03:26.7	PLF Jettison	3σ qV < 360 BTU/ft2-hr (1135 W/m2)
04:21.3	04:21.3	BECO	Low Level Propellant Sensor Uncover
04:27.3	04:27.3	CCB Stage I Jettison	BECO + Delay
		STAGE II CENTAUR UPPER STAGE PHASE	
04:37.3	04:37.3	Centaur 1st Burn Main Engine Start (MES1)	CCB Stage I Jettison + 10.0 seconds
11:31.3	11:31.3	Centaur 1st Burn Main Engine Cut-off (MECO1)	Guidance (Parking Orbit)
27:05.3	24:43.2	Centaur 2nd Burn Main Engine Start (MES2)	Guidance
34:41.5	32:27.2	Centaur 2nd Burn Main Engine Cut-off (MECO2)	Guidance Command Shutdown
38:24.5	36:10.2	Payload Sep--15 deg/sec (2.5 rpm) spin-up	MECO2 + 223 seconds

*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

MSL: Loads Environment

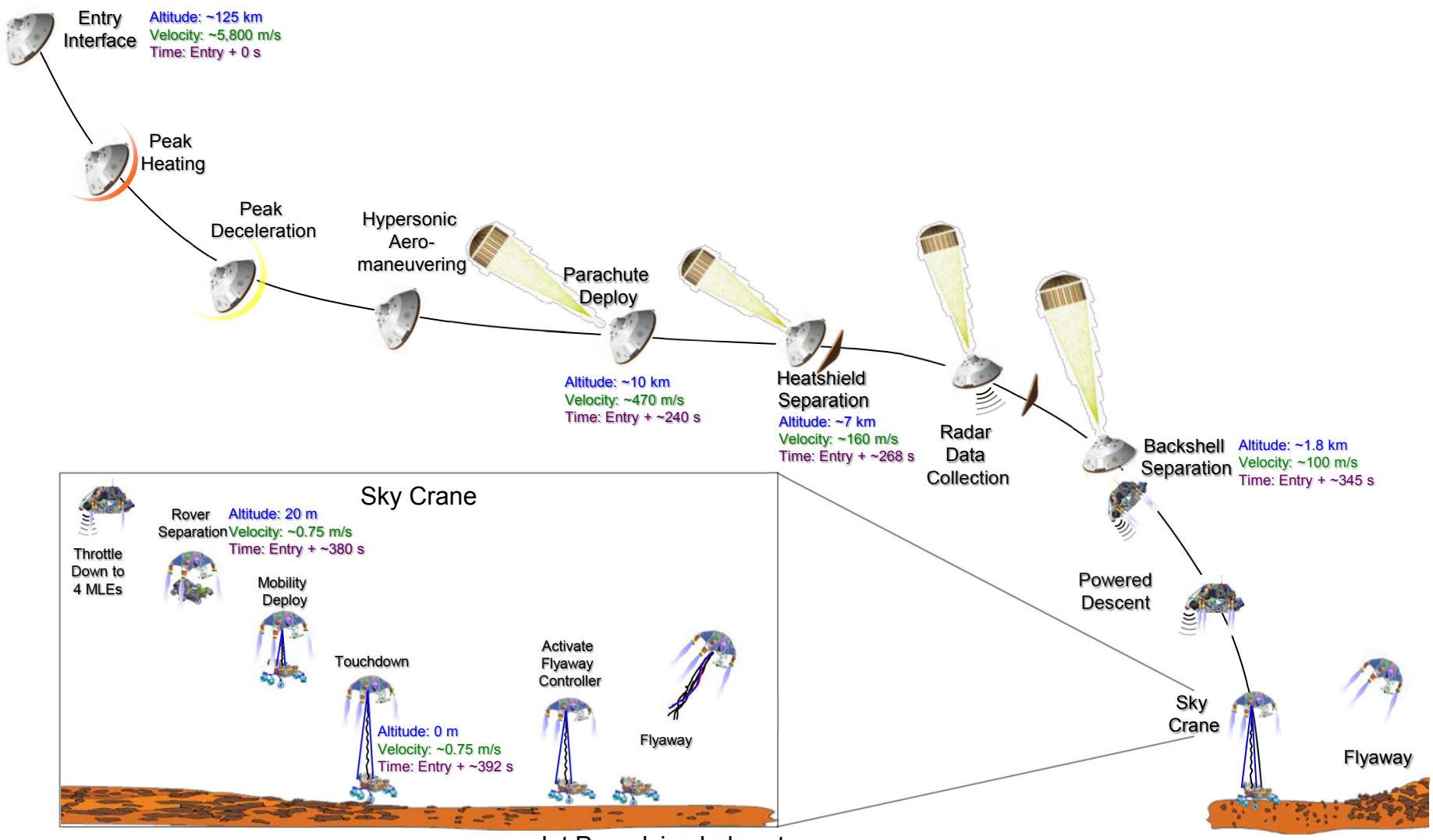


Launch
Cruise
Entry
Events

- 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 seconcs
  - Altitude = 10 km, velocity = 470 m/sec
  - 65,0000 lbs Cord load ~ 9.7 g's with 37 radian/sec^2
- Heatshield Separation → Time = Entry +274 seconds
  - Altitude = 7 km, velocity = 160 m/sec

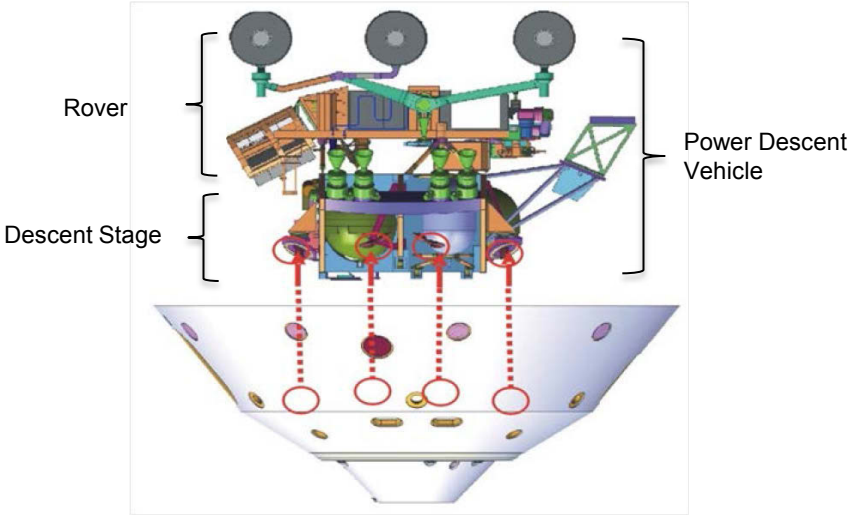
MSL: Loads Environment

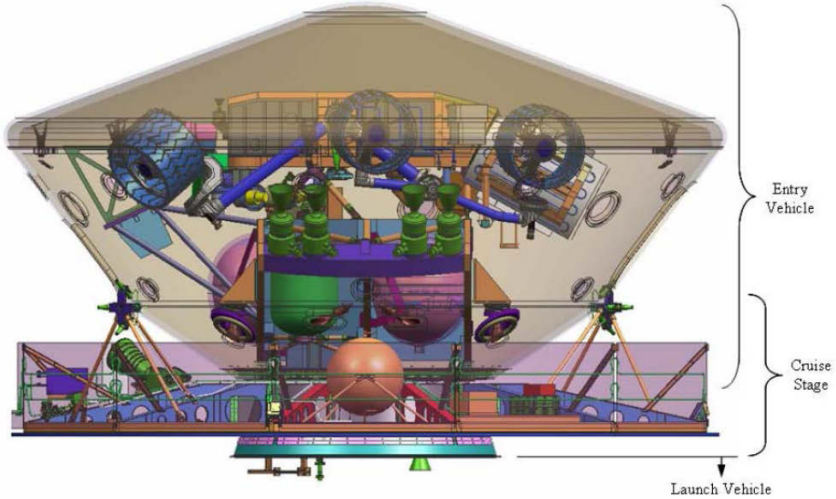
Entry - Descent - Landing Events



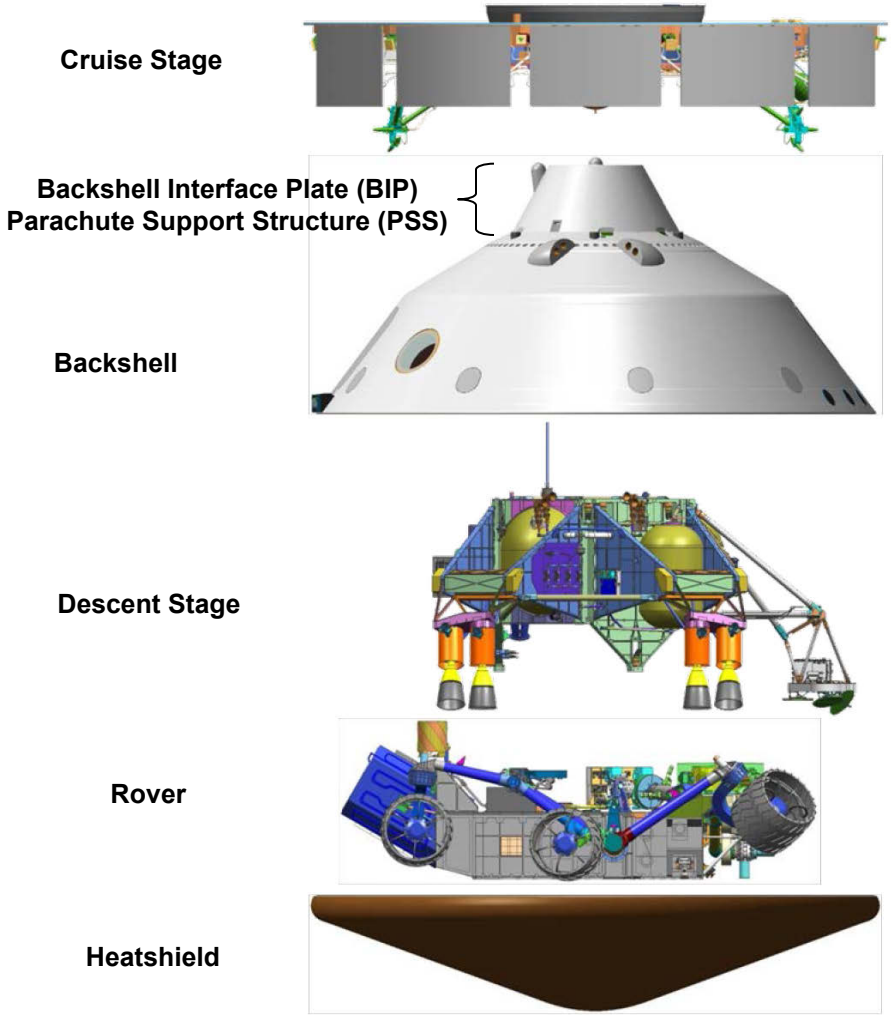
MSL: Loads Environment

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





MSL: Loads Environment



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

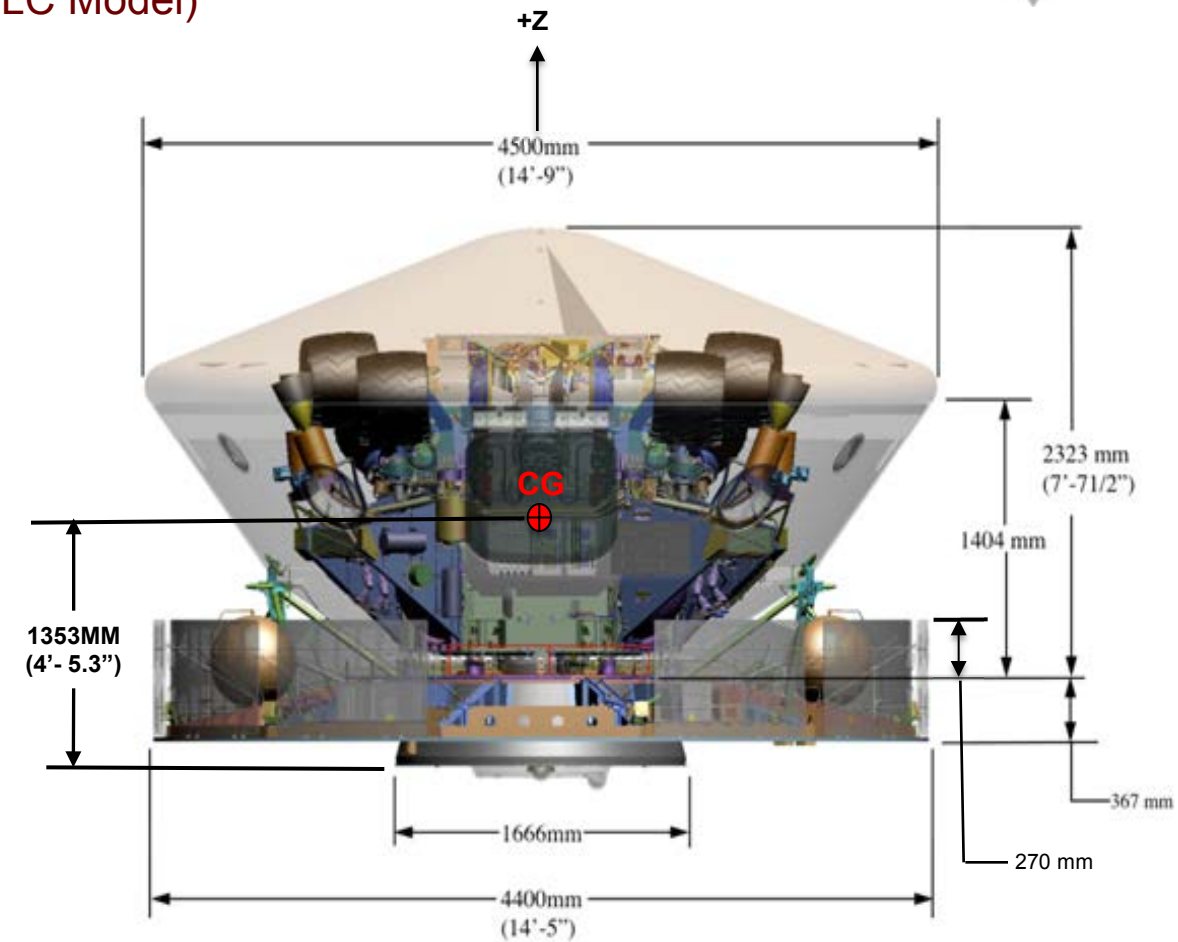
MSL Spacecraft Masses (VLC Model)

- **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***

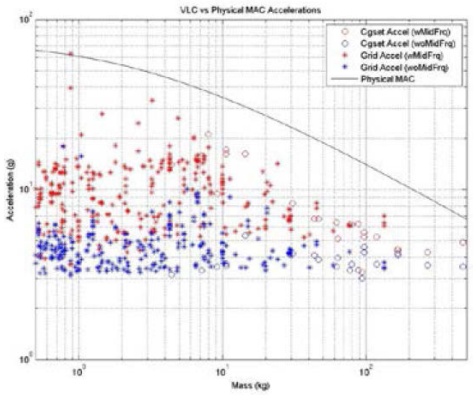
- **Cruise Stage** **560.0 kg**
  - Cruise Stage 455.7 kg
  - Secondary Structure Incl Above
  - 2 Full Full Tank 104.3 kg
- ***Total Launch Mass*** ***4015 kg (= 8852 lbs)***
- ***Z_{cg} = 1353 mm = 53.28" (Measured to bottom of Cruise Stage)***



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

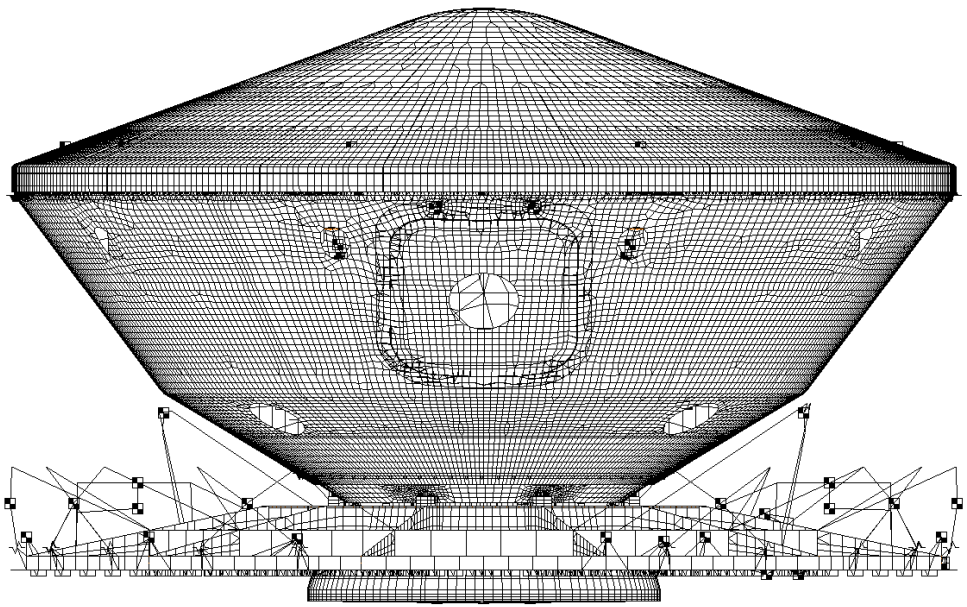


- **Modal MAC Method – requires Finite Element Model**
  - Extension of physical MAC concept to modes of the structure
    - Each mode represents spring-mass system cantilevered from S/C Interface with some "effective mass"
    - Modal MAC is developed to "bound" modal response as a function of effective 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

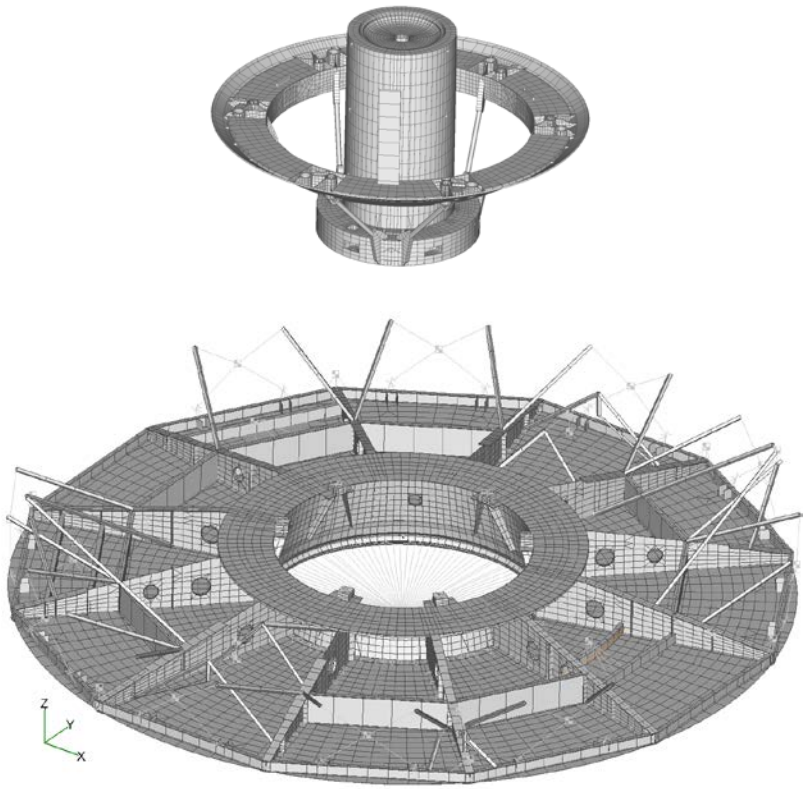


- **Modal Results**
  - Frequencies: Lateral X = 9.7 Hz; Lateral Y = 10.9 Hz; Axial Z = 24.3 Hz
  - Total % Effective Mass Cumulated to 80 Hz:

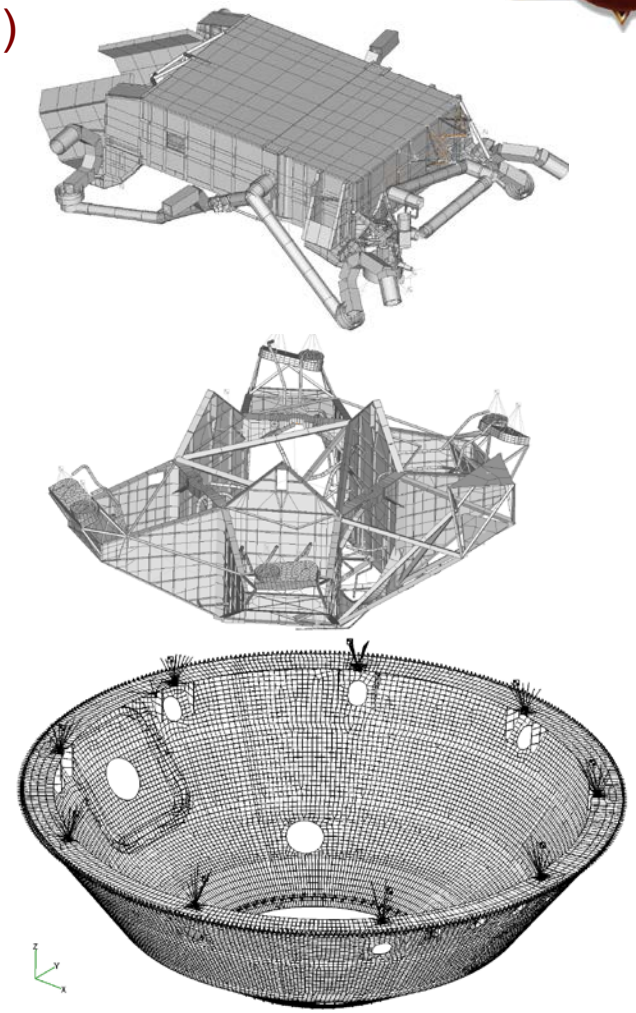
X-Trans	Y-Trans	Z-Trans	X-Rot	Y-Rot	Z-Rot
91%	91%	94%	99%	99%	99%

MSL: Loads Environment

Finite Element Model (VLC model)



Cruise Stage, BIP, and PSS

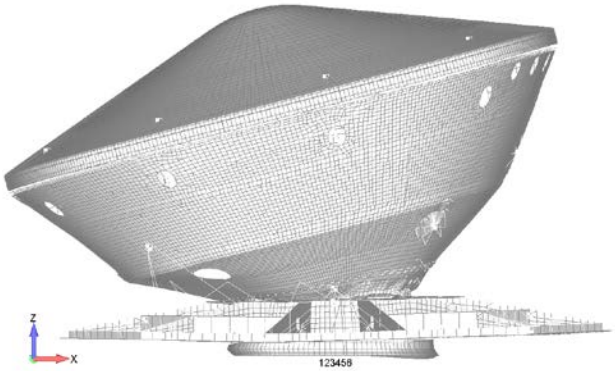


Backshell, Descent Stage, and Rover

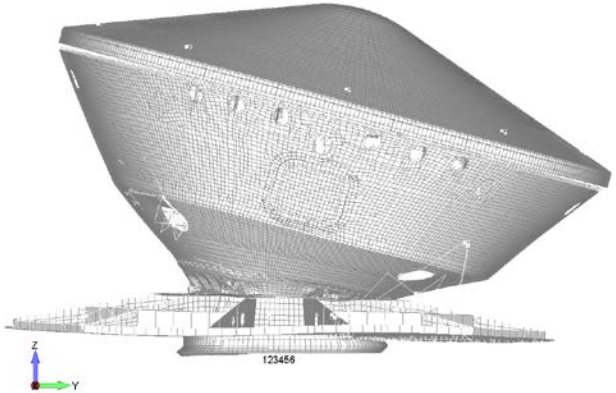
Primary Spacecraft Mode Shapes

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

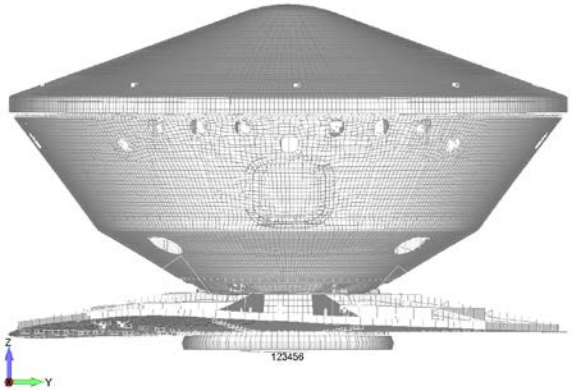
f_1 = 9.69 Hz



f_2 = 10.87 Hz

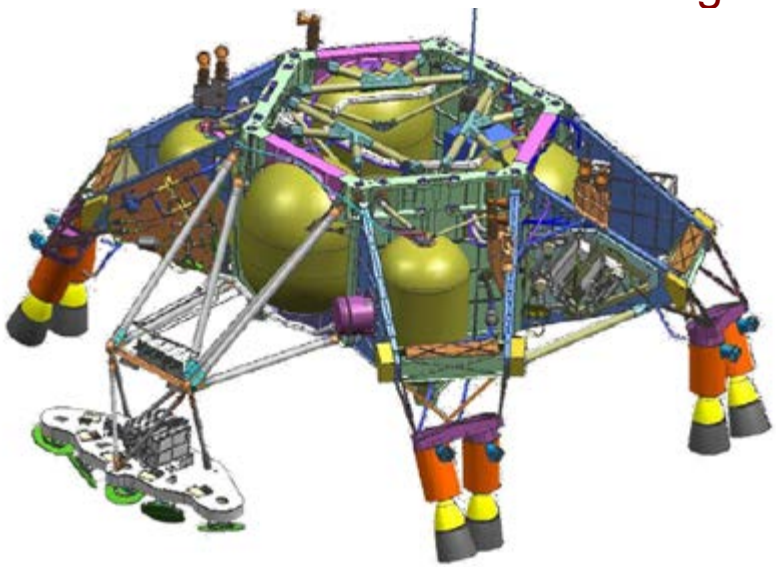


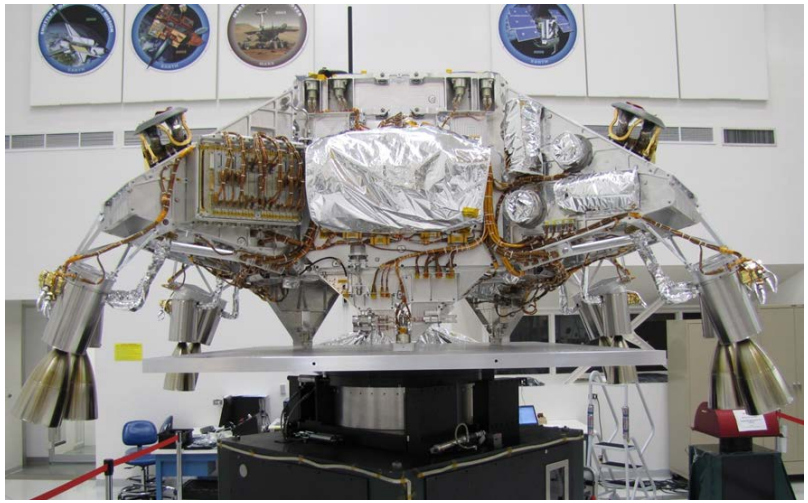
f_{20} = 24.27 Hz



MSL: Loads Environment

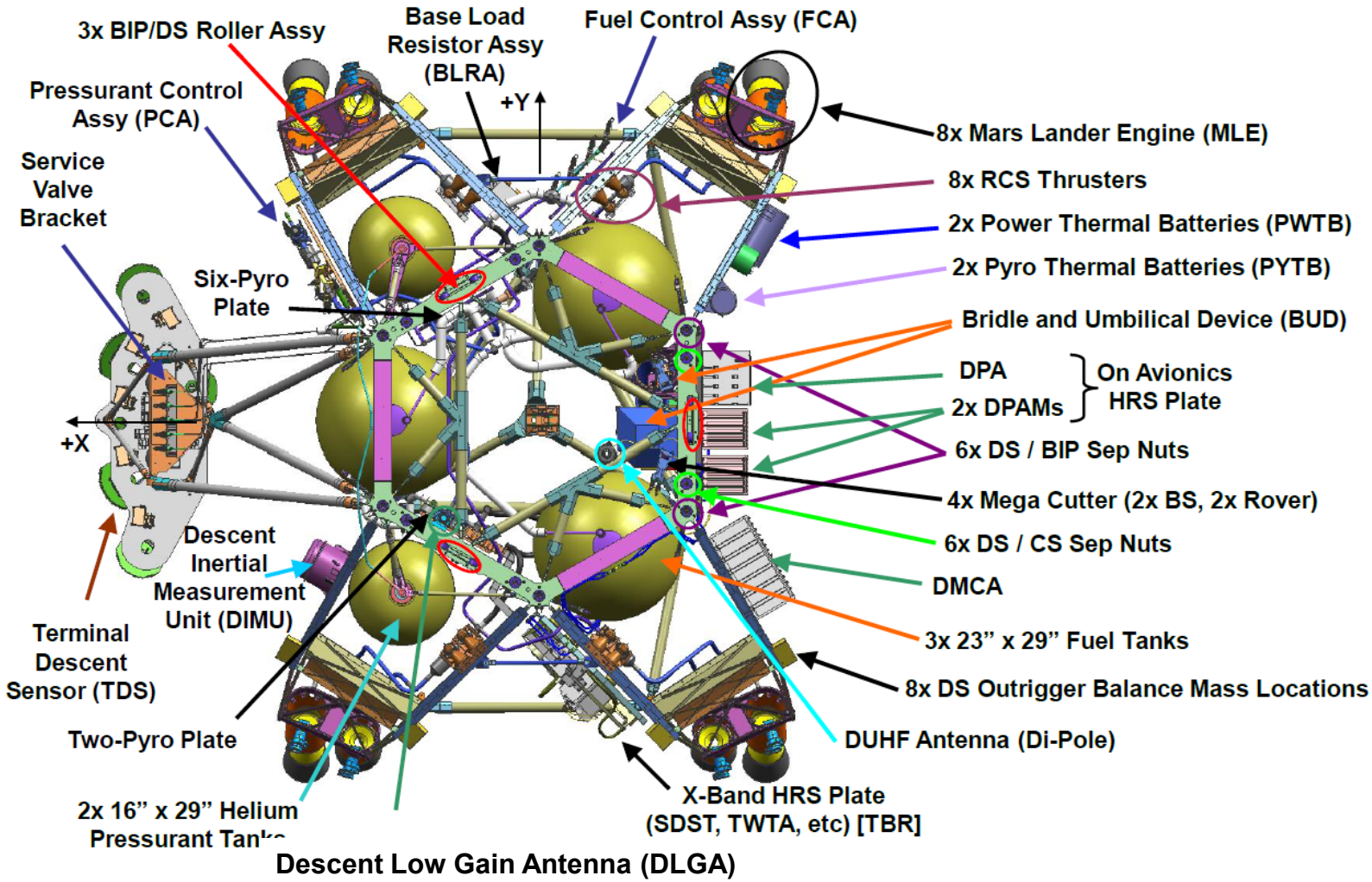
Descent Stage Configuration





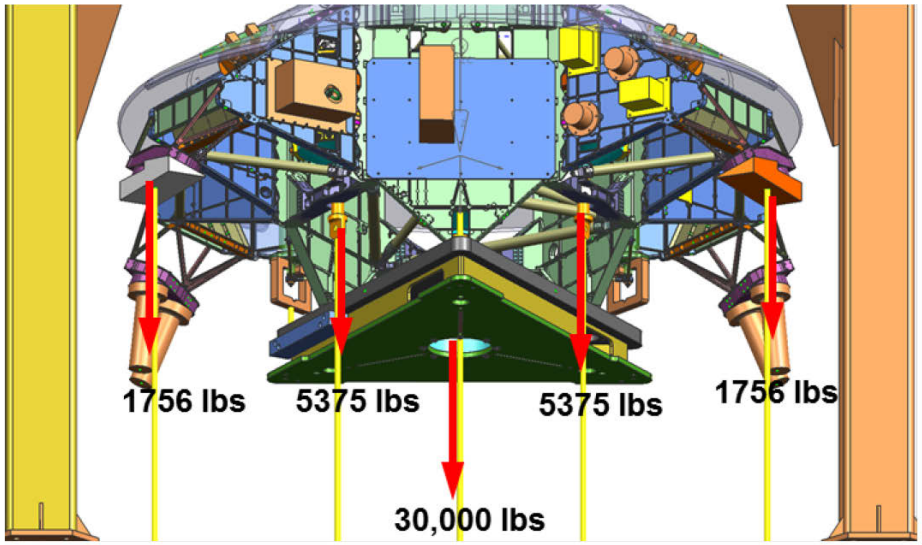
- **Primary Structure**
  - Aluminum panels, beams, and tube trusses.
- **Propulsion & Thermal Support Structure for:**
  - 3 fuel tanks (23"x29")
  - 2 pressurant tanks (16"x29")
  - 8 Mars Lander Engines (MLE)
  - 8 entry RCS thrusters
  - Pressurant & Fuel Control Assemblies (PCA & FCA)
  - Two and 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 Design Description – Hardware Layout

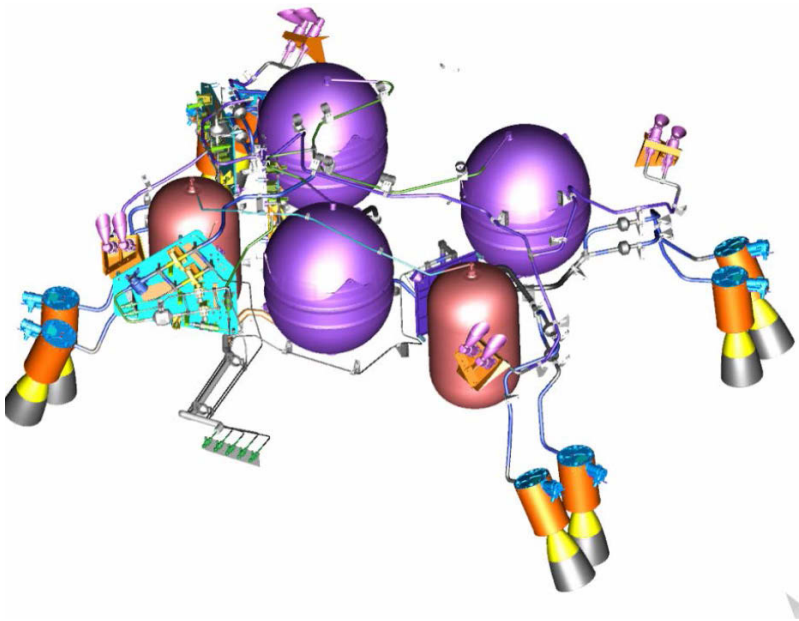


Descent Stage Structural Configuration and Test

- **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



Design Loads Analyses and Structural Analyses of MSL Propulsion Lines



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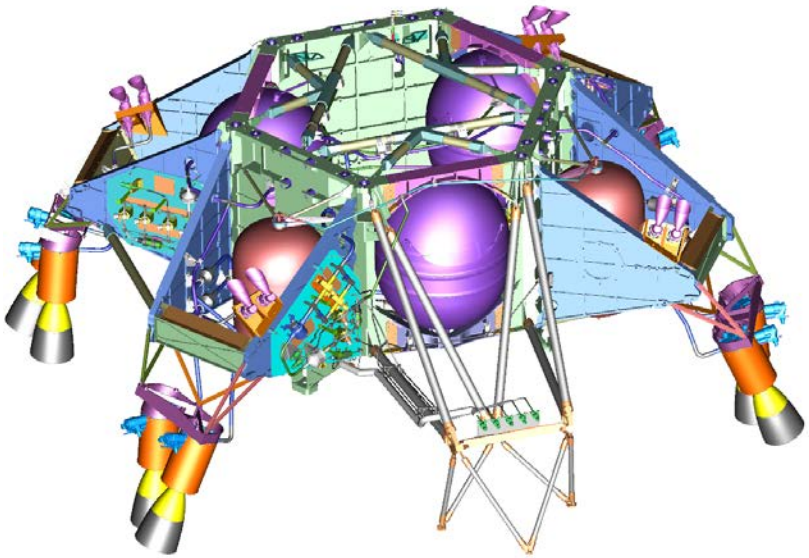
June 10-12, 2008

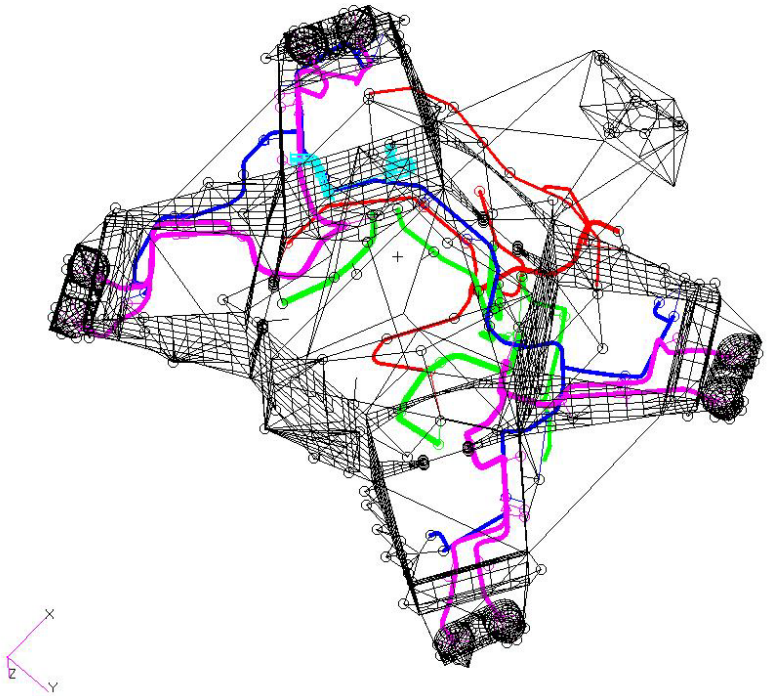
Analyses of MSL Propulsion Lines

- Statement of Concern:
  - **Structural analyses of propulsion lines at JPL follow heritage practices in which line diameters were 3/8” or less**
    - Cassini 3/8” titanium lines, 15” spacing, 100 Hz, 124 g’s design load
    - DS1 ¼” stainless, 100 Hz, 100 g’s design load
    - MER ¼” stainless, assume 100 hz, 100 g’s design load

    →Low flexibility of lines permitted ease of installation. Orders of magnitude stiffer primary structure limited the magnitude of stress which could be developed from structural deflections.
  - **MSL propulsion line diameter are 3/8”, ½”, ¾”, 5/8”, 1”**
    - Bend diameters were designed to 3D with no planned stress relieving → residual stress state is present
    - The primary structural elements supporting the lines have comparable stiffnesses to the 1” lines
    - The normal margins of safety for yield cannot be met

Analyses of MSL Propulsion Lines

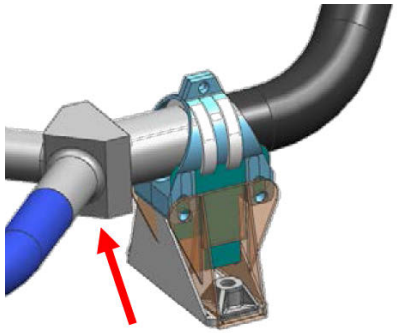




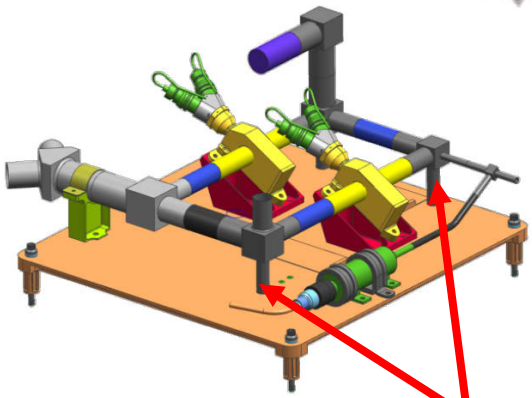
Tubes, Mounts, Fittings

Tubes

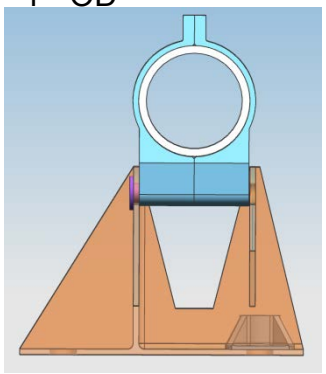
316L Stainless Steel Tubes:
1”, ¾”, 5/8”, ½”, 3/8”, ¼” OD
Titanium 3Al 2.5V Tubes:
1” OD

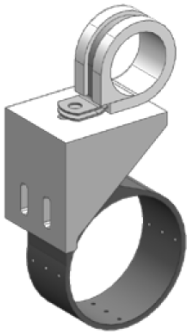


Suspended Fittings (304L)

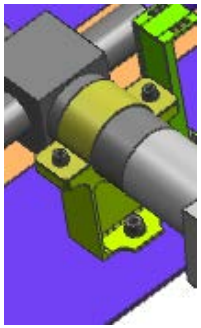


Mounted Fittings (304L)

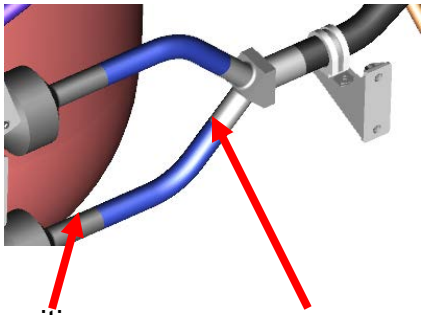




Over 55 brackets support the lines above the primary structure, Torlon provides thermal isolation from the structure



Fixed Tube Mounts

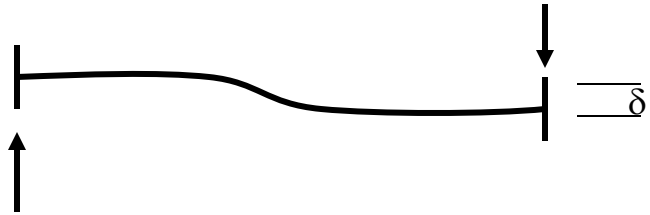


Transition Welds Ti-to-SS

Orbital Welds

Analyses of MSL Propulsion Lines

- **How stiff are MSL lines? Some stiffness comparisons: 15" fixed guided beam**



$d = P \times L^3 / (12 \times E \times I)$ or $k = 12EI/L^3$

- Representative MSL Structural stiffener: aluminum (E = 10.4e6 psi)

  Lower Cap: C section = d x w x t_w x t_d = 1.60" x .32" x .08 x .06, I = 4.453e-2 in^4

  k = 1647 lbs/in
- MER ¼" line: I = 9.628e-5 in^4

  k = 9.6 lbs/in
- MSL 1" line: I = .012367 in^4

  k = 1231 lbs/in

→MSL 1" lines have comparable stiffness to structural elements

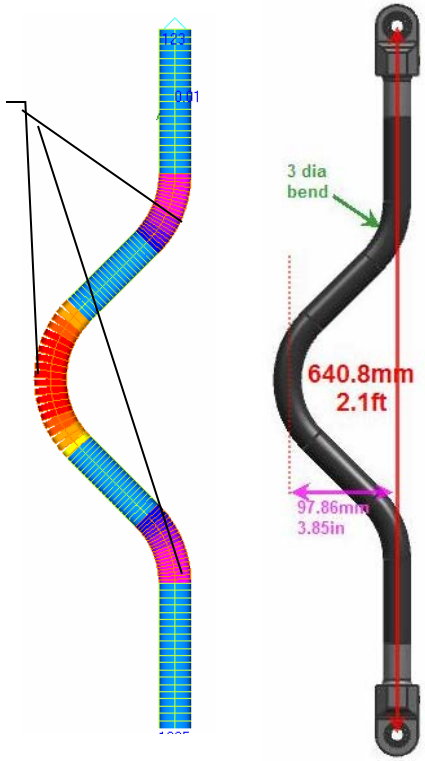
Analyses of MSL Propulsion Lines

- MSL Loads and Structural Analyses Implementation
  - All lines greater than 3/8” diameter have been modeled into MSL Descent Stage loads model: maintain proper coordinate system at each line mount, work within the grid density of the existing DS FEM to connect support bracketry
    - Literature suggests that lines with bends behave with reduced stiffness →utilized Nastran CBEND element
    - Support bracketry modeled with Nastran Rigid Body Elements and coincident translational spring elements. Thermal distortion analyses for the Entry, Descent, and Landing environments developed load magnitudes comparable to acceleration loading → used advanced feature in Nastran to map thermal properties to Rigid Body Elements
    - Lines with bends have different stiffnesses when in compression and tension → practical solution is to perform a bounding linear loads analyses
  - Structural Analyses
    - Detailed modeling predicts highest stress at bends due to ovalization of the pipe cross-section →use of stress intensification factor to account for peak longitudinal stress
    - Replace the nominal strength margins calculation with Fatigue Analyses

Analyses of MSL Propulsion Lines

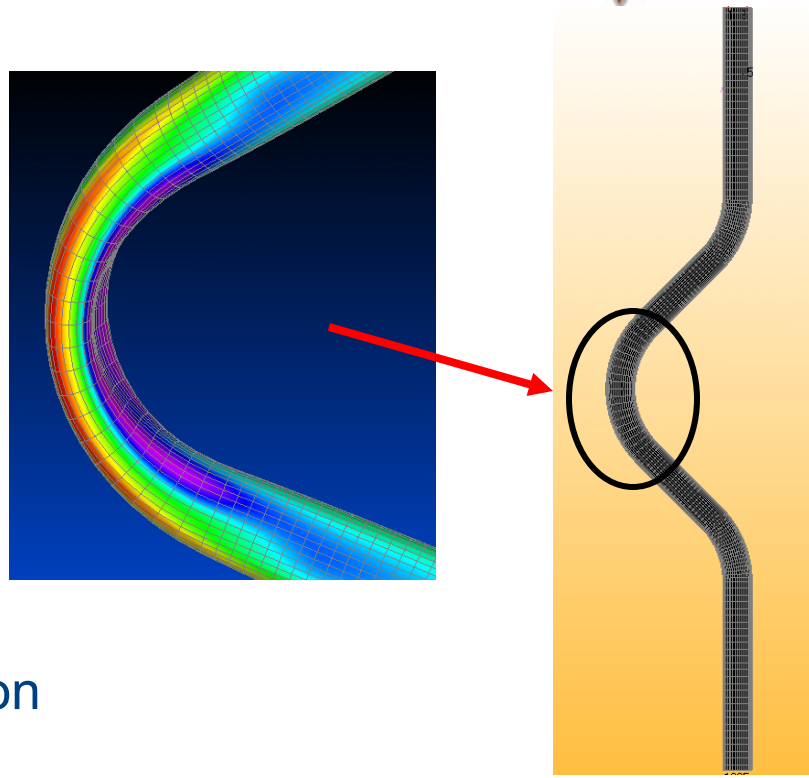
- What is the most accurate stiffness representation of prop line? CBEND/beam model
  - Compare stiffnesses based on Beam, Shell, CBEND/beam models

	@~0-150 lbs **Stiffness**
	lbs/in
SS Bent Tube	
Linear Analyses (Tens = Comp)	
All shell model	1560
All beam model	3930
CBEND/beam model	**1410**
Nonlinear Analyses	
All shell model - compression	1007
All shell model - tension	1655
Test data (use best data or average)	
Compression	1017
Tension	1426



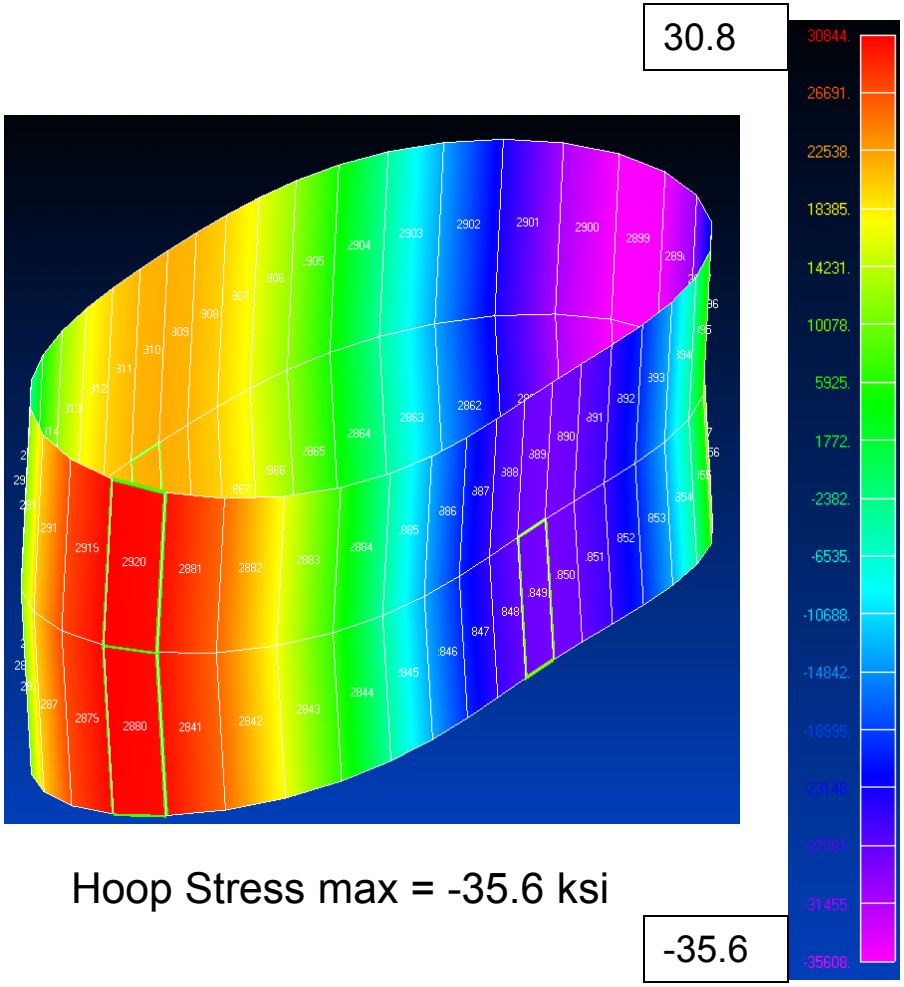
Analyses of MSL Propulsion Lines

- What is the stress state in the bend due to external loading?
  - Finite Element Model: all shell
  - Pinned-Pinned end constraint
  - Enforced deflection (compression)
  - Linear and nonlinear analyses

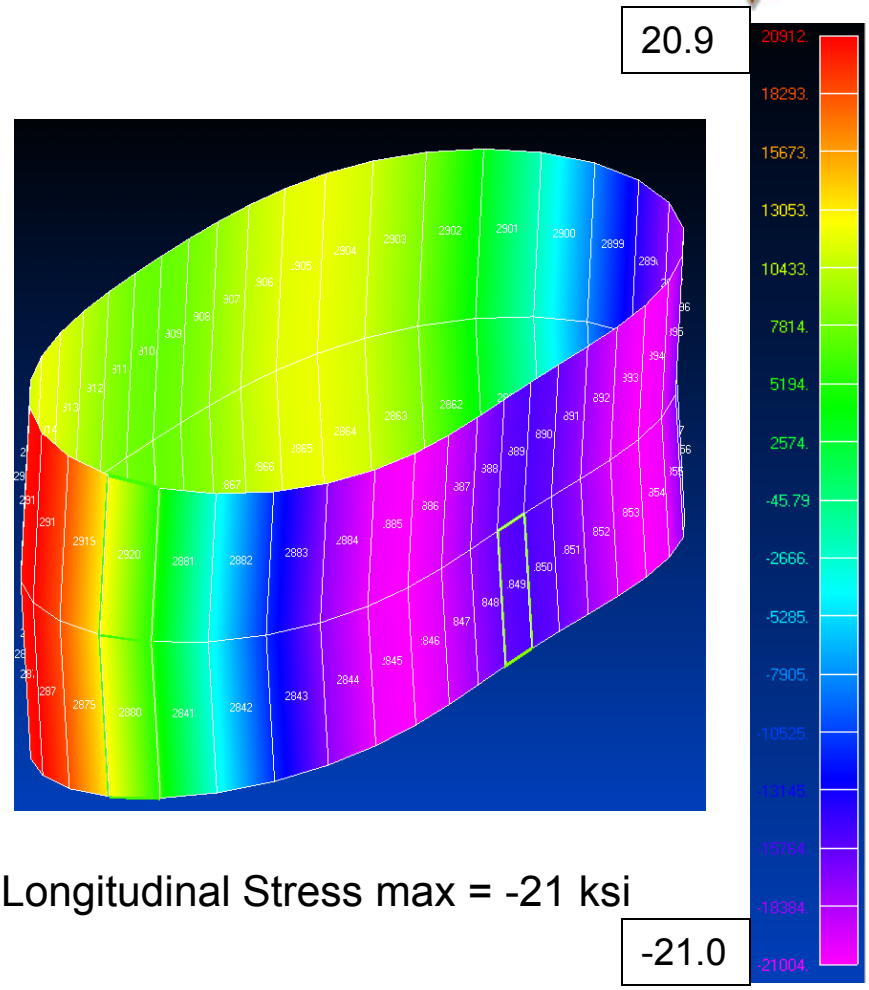


→Notice the ovalization at the cross-section

Analyses of MSL Propulsion Lines



Hoop Stress max = -35.6 ksi

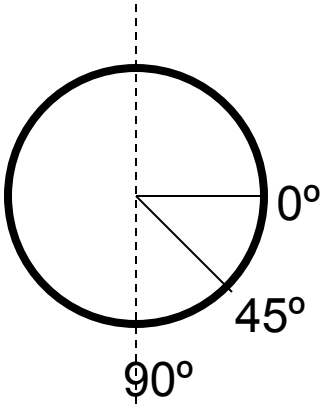


Longitudinal Stress max = -21 ksi

Analyses of MSL Propulsion Lines

Load Case: enforced deflection	Force, lbs	Max Lateral δ, inches	Max Hoop stress, ksi	Max Long. Stress, ksi	Max VonMises stress, ksi	Max Principle Strain, in/in
Nonlinear						
.05"	-74	-0.089	-34.4	-20.5	30.4	0.00110
Static						
.05"	-78	-0.090	-36.6	-21.0	32.5	0.00110

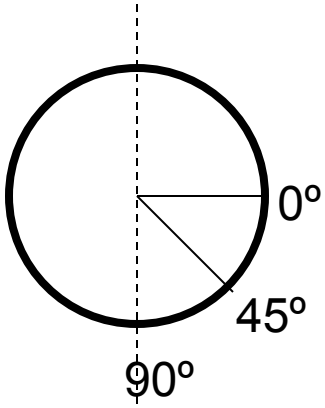
- Key Discoveries:
  - Maximum longitudinal stress occurs at 45º
  - Maximum overall stress occurs at 90º (bending)



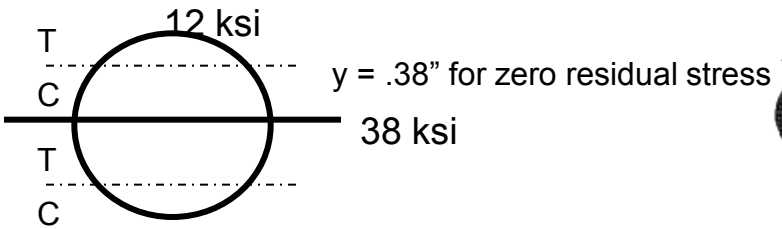
Analyses of MSL Propulsion Lines

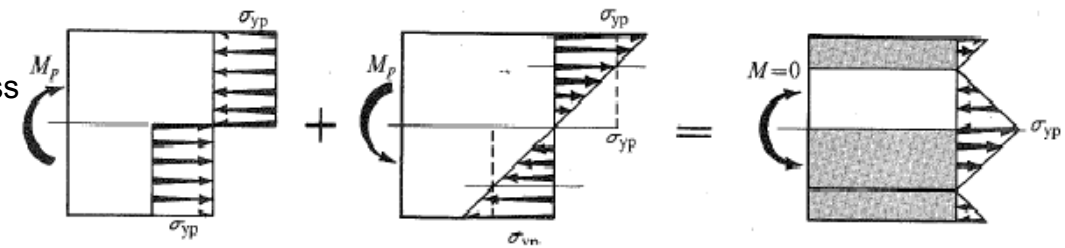
- How to compute maximum axial stress from element loads?
  - Classical hand analyses would produce a P/A + Mc/I stress of 13 ksi
  - Reference Rodabaugh Stress intensification factor
    - $i = .9/(h^{2/3}) = 1.6$
    - $h = t \times R / r^2 = .035 \times 3/ .5^2 = .42$
    - Note R = Radius of curvature of bend
    - Note r = radius of tube
    - Note t = tube wall thickness
  - Peak stress = 1.6 x 13 ksi = 21 ksi

→ Note incorporating the Rodabaugh Stress factor i agrees with the shell model peak longitudinal stress



Analyses of MSL Propulsion Lines

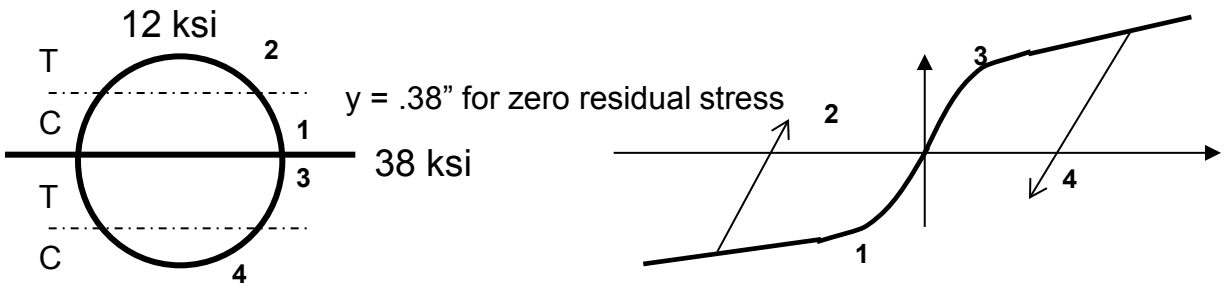


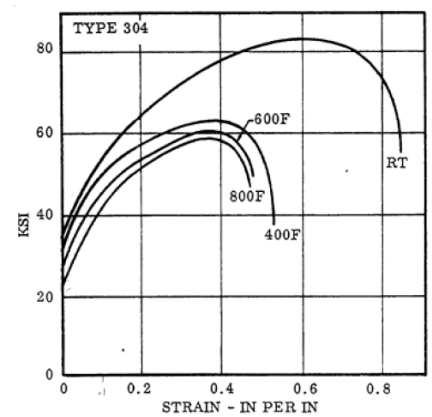


- The Residual Stress State at bends in the 316L Stainless Steel (SS) lines for 1" diameter tube
  - Nominal strain state is geometrically calculated
    - Strain ε = r/R = .167 in/in strain (r = tube radius, R = bend radius)
  - Outer most fibers change sign after the elastic spring back
  - The inner fibers residual stress state is at yield

Analyses of MSL Propulsion Lines

- What is the consequence of the high residual stress state for CRES 316L 1” propulsion line? (min yield = 38 ksi, min ult = 78 ksi, min elongation = .41 in/in strain)

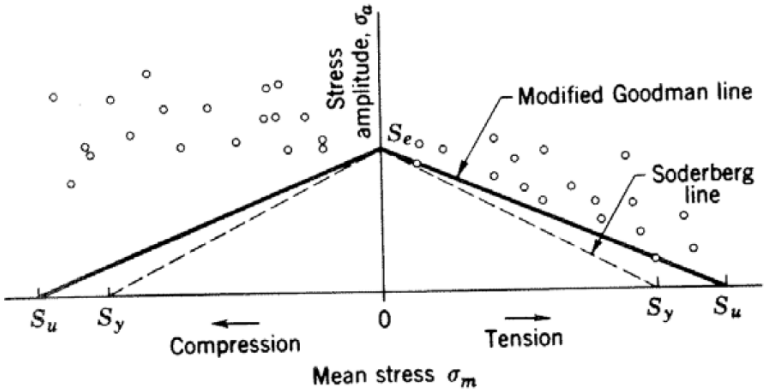


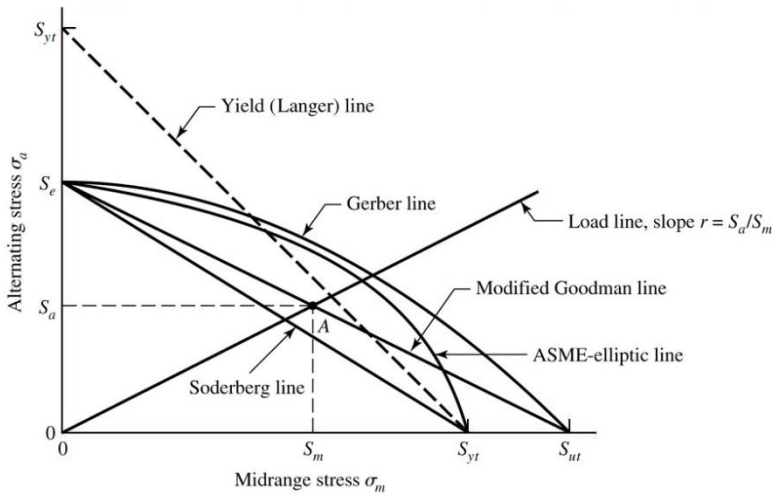


  - Margins of safety for yield cannot be met
  - The initial stress state (mean stress) can be at yield
  - Under loading the material requires only a single cycle of loading to work harden
  - Uncontrolled deformation is limited by the primary structure

Analyses of MSL Propulsion Lines

- The Fatigue Analyses Approach – Modified Goodman Approach

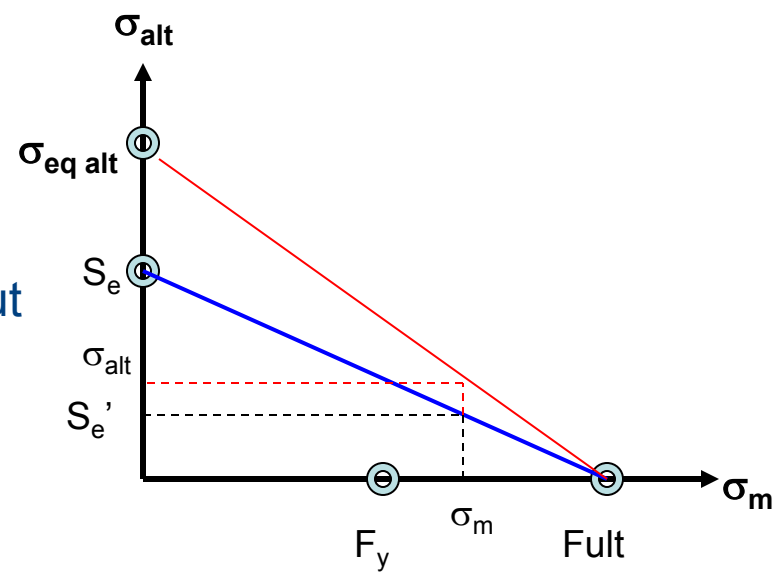




- Stainless Steel known to be conservative to the Modified Goodman line
- Titanium could be unconservative to the Modified Goodman line. Use the Soderberg line, however, due to post-form annealing, the mean stress state could be negligible

Analyses of MSL Propulsion Lines

- Fatigue Analyses – Modified Goodman Approach
  - Use the Goodman curve to estimate alternating stress for a given mean stress level – this $\sigma_{alt} = S_e'$ is the level at which the material can be cycled infinitely without failure
    - $S_e' = S_e(1- \sigma_m/F_{tu})$
  - If the above criteria cannot be met, then compute the fatigue strength for the required cycles



    - Convert the required alternating stress to an equivalent alternating stress, $\sigma_{eq\text{-}alt}$
    - Equivalent alternating stress: $\sigma_{eq\text{-}alt} = \sigma_{alt} / (1- \sigma_m/F_{tu})$
    - Use the nominal S – N Curve with R = -1 and determine life for the equivalent alternating stress level

Analyses of MSL Propulsion Lines

- MSL Implementation
  - Loads Modeling: Use of CBEND to account for reduced stiffness
  - Stress Calculations: Use of Rodabaugh stress intensification factor to account for increased longitudinal stresses
  - Fatigue Analyses: Use of Modified Goodman approach with mean stress equal to yield to account for the residual stress state

	@~0-150 lbs **Stiffness**	**Enforced Deflection**	Axial **Strain, 0 deg**	Axial **Strain, 45 deg**	Hoop **Strain, 90 deg**	**Comment**
	lbs/in		in/in	in/in	in/in	
SS Bent Tube						
Linear Analyses (Tens = Comp)			**Strain at 160 lbs**			
CBEND/beam model	**1410**	**0.11**	**0.0009**	**.0014***	**BLANK**	*Rodabaugh Intens. Factor
Test data (use best data or average						
Compression	1017	0.16	0.00065	0.0016	0.0032	
Tension	1426	0.11	0.0008	0.0014	0.0021	
Test data (use best data or average			**Strain at .11"**			
Compression	1017	0.11	0.00045	0.0011	0.002	~112 lbs
Tension	1426	0.11	0.0008	0.0014	0.0021	~160 lbs

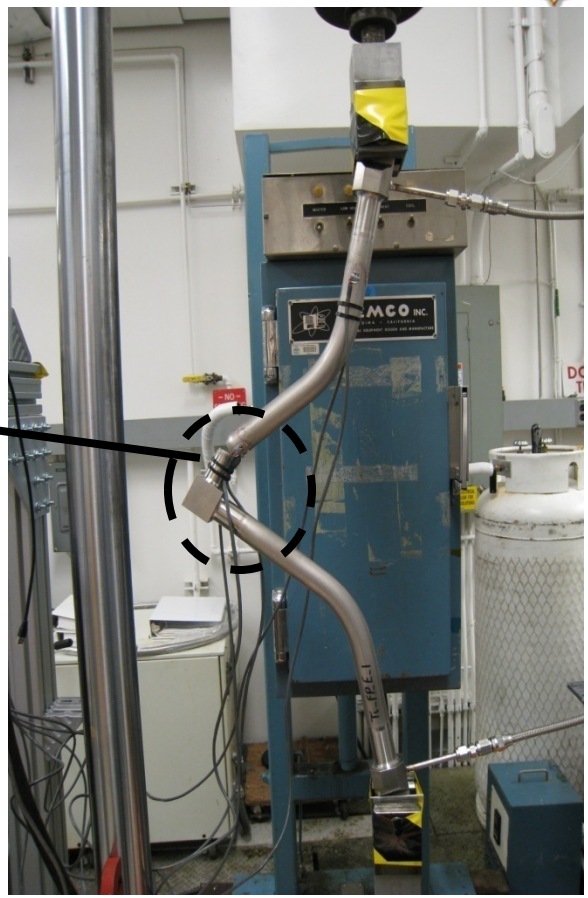
Most appropriate test data is the enforced deflection at .11" (strain in lines are limited by primary structural deflections)

Prop Line Structural Analyses and Verification

Component Strut Fatigue Testing

Ti_FP_B_1 Setup

4/18/08



Failure due to accidental compression over-loading of Ti_FP_E_1 re-test

5/19/08

Prop Line Structural Analyses and Verification

Component Strut Fatigue Testing

Failure of SS_NP_E_1 retest

5/30/08

Failure of SS_FP_B_4

6/12/08

Prop Line Structural Analyses and Verification

Overall Summary (20,000 cycles at peak is 4 lives)

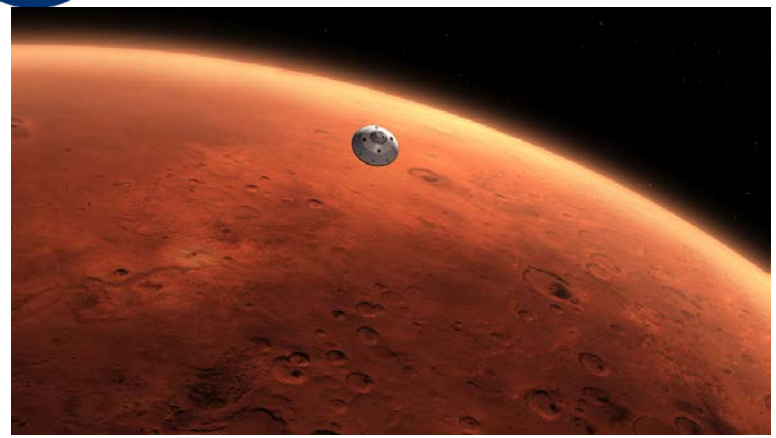
- Testing program demonstrates robust margins over the predicted FLL stress
- Testing in fittings and inertial welds envelope the FLL maximum strains
- The estimated number of cycles at peak is extremely conservative, it assumes that the peak FLL stress will occur during launch and in the random vibration testing

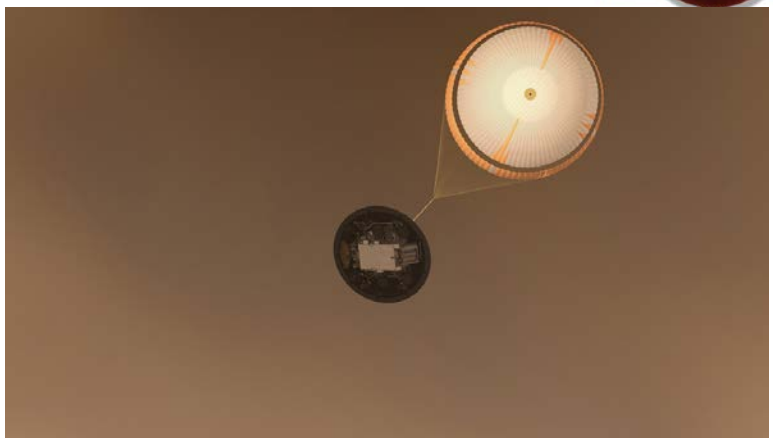
	Flight Limit Load w/o i			Max Fatigue Test Load			
Component	Pressure psi	Stress, ksi	Equivalent Test Load, lbs	Pressure psi	Applied Load	Cycles Achieved	Overtest Ratio
SS Elbow	0	27	138	0	200	19,600	1.45
SS Elbow	550	23	113	550	150	30,000	1.33
SS Bend	0	20	120	0	160	30,000	1.33
SS Bend	550	12.2	74	275	170	22,000	2.30
Titanium Elbow	550	15	66	550	69	72,000	1.05
			66	0	200	8,750	3.03
Titanium Bend	550	23	100	550	225	30,000	2.25

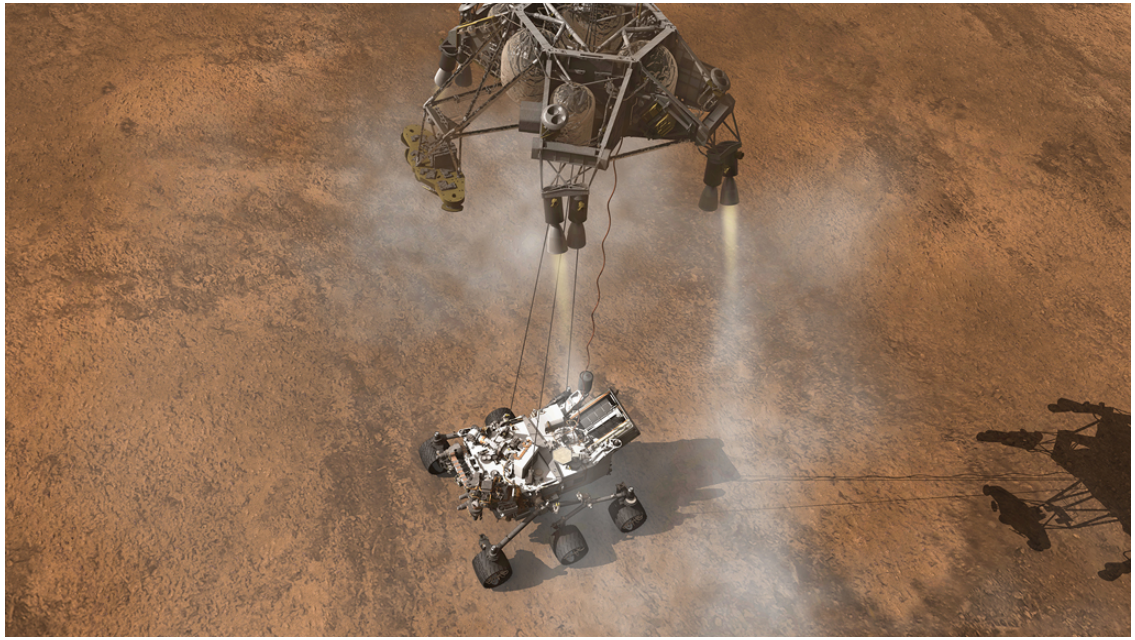
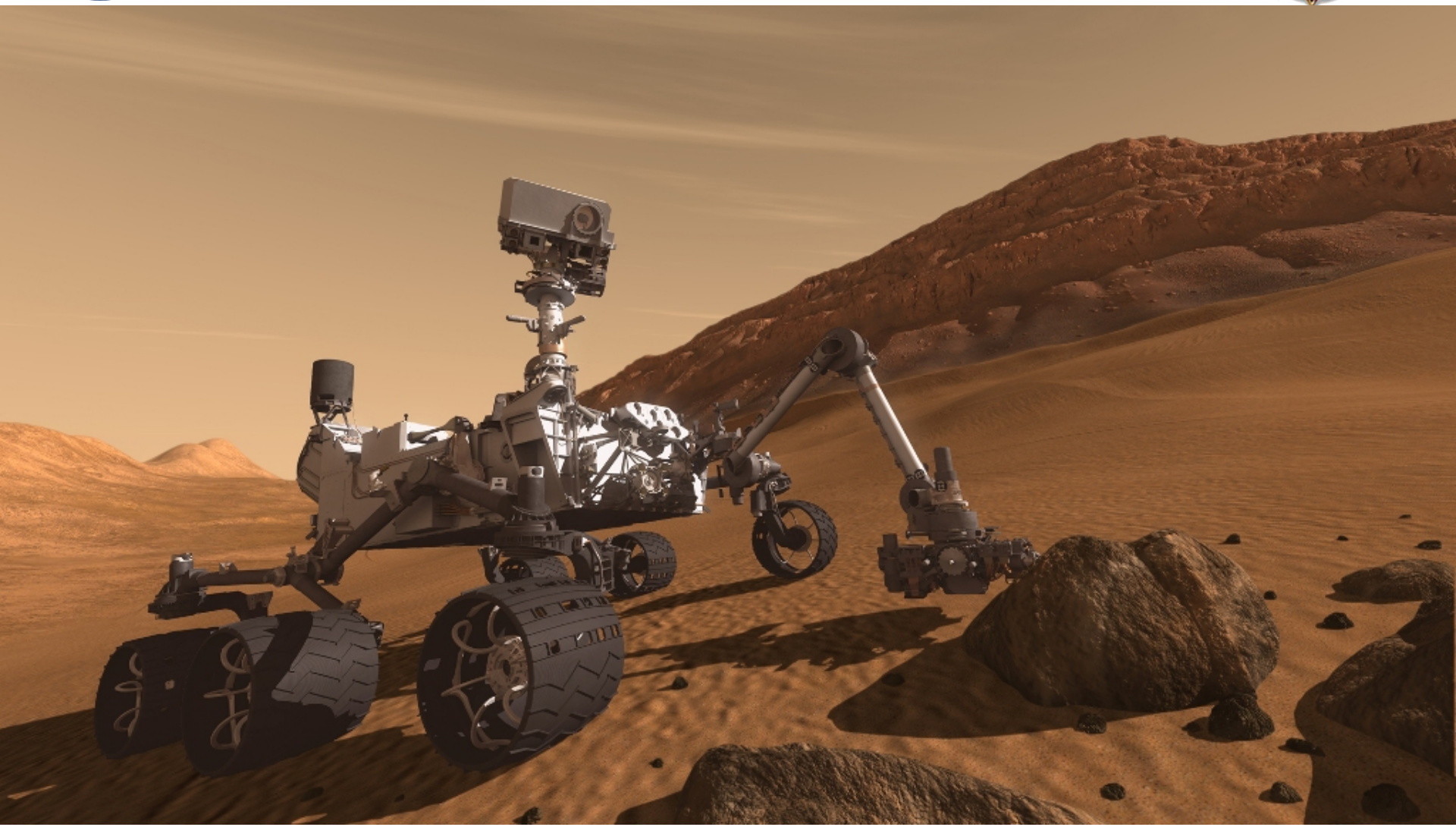
November 26, 2011!

http://mars.jpl.nasa.gov/msl/

August 5, 2012







and Beyond!