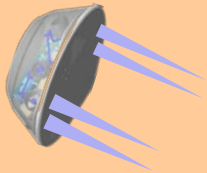

Supersonic Retropropulsion (SRP) for Robotic Mars Landers

Aron Wolf, with material from Rob Manning and help from Joel Benito, Ashley Karp, Eddie Lau, Marcus Lobbia, Barry Nakazono, Connor Noyes, Dan Scharf, Robert Shotwell, David Vaughan

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8/24/16

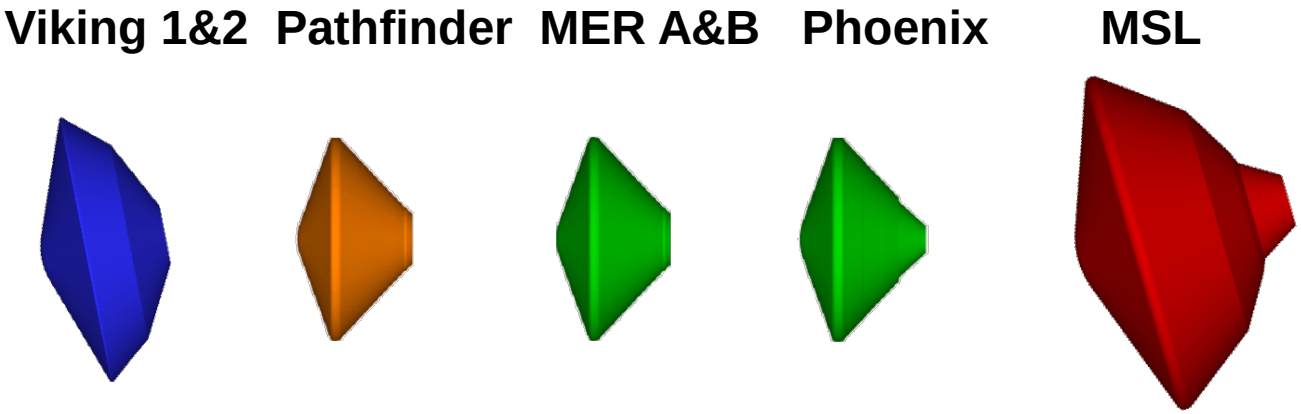
Main Drivers for a Sample Return Lander (post-2020)

- **Increased "landed payload" mass**
  - Payload: 1200-1500 kg? (includes MAV and rover)
    - MSL rover: 900 kg
- **Lowest possible cost**
  - Sub-SLS launch performance / accommodation, e.g. up to "Heavy" class of Falcon, Delta / Vulcan Families (anticipated to exceed Atlas V…) – 5m fairing max
  - Retain "legacy" roll-control "capsule" hypersonic approach, if feasible
- **Improved landing accuracy**
  - Less driving distance for rover to get to the cached sample => save rover cost?

artist's concept

Aeroshell/Entry Comparison

Ref: Braun & Manning IEEE AC Paper 0076-8, Updated December 2005

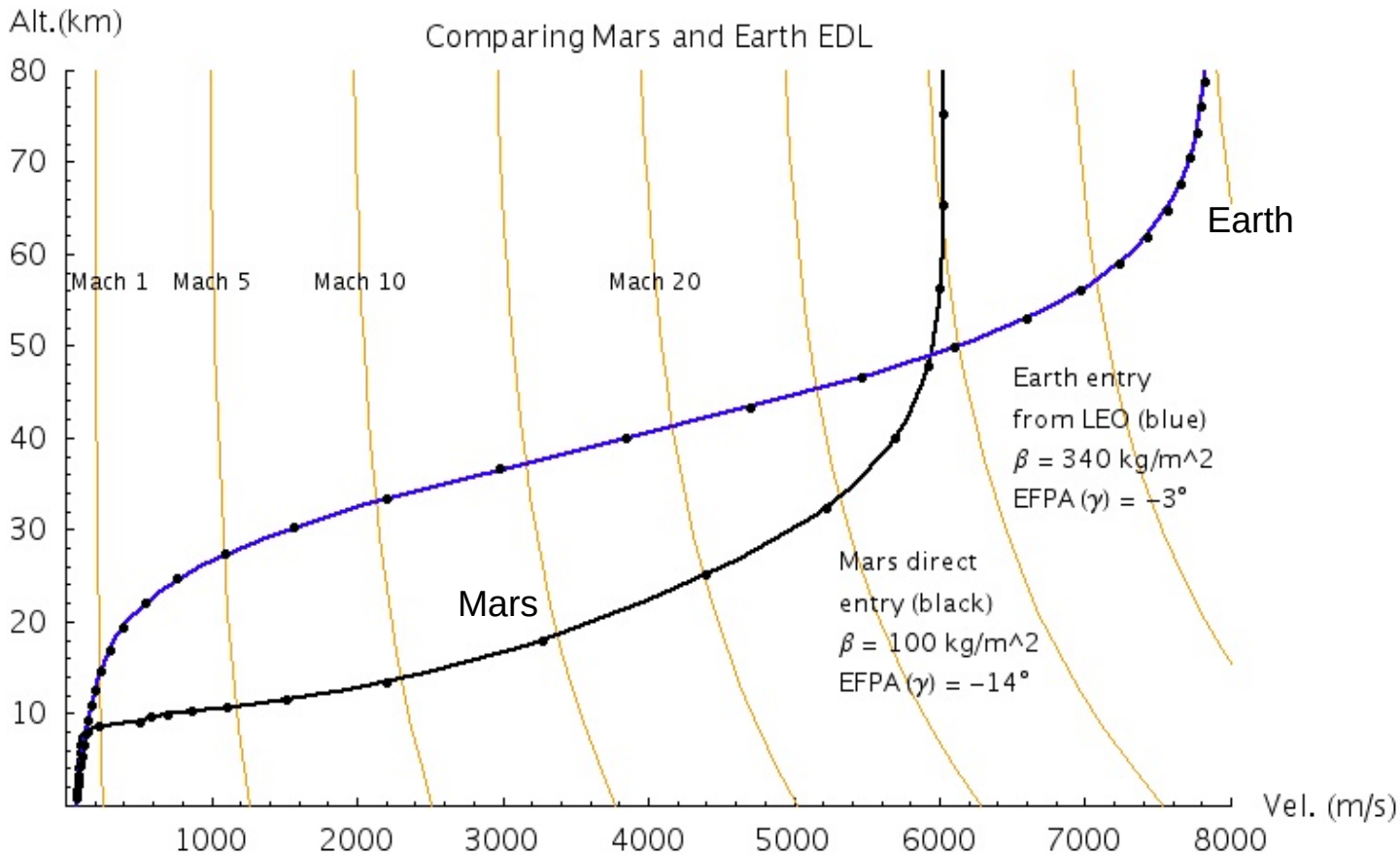


Diameter, m	3.5	2.65	2.65	2.65	4.5
Entry Mass, kg	930	585	840	602	3151
Entry Ballistic Coeff, kg/m^2	***Ballistic Coefficient = mass / (Cd * area)*** 63	62.3	88	71	128
Landed mass, kg	603	360	539	364	1541
Landing Accuracy, km	420x200	100x50	80x20	75x20	10x10
Entry Guidance	None	None	None	None	Yes (Apollo)

Earth vs Mars Entries

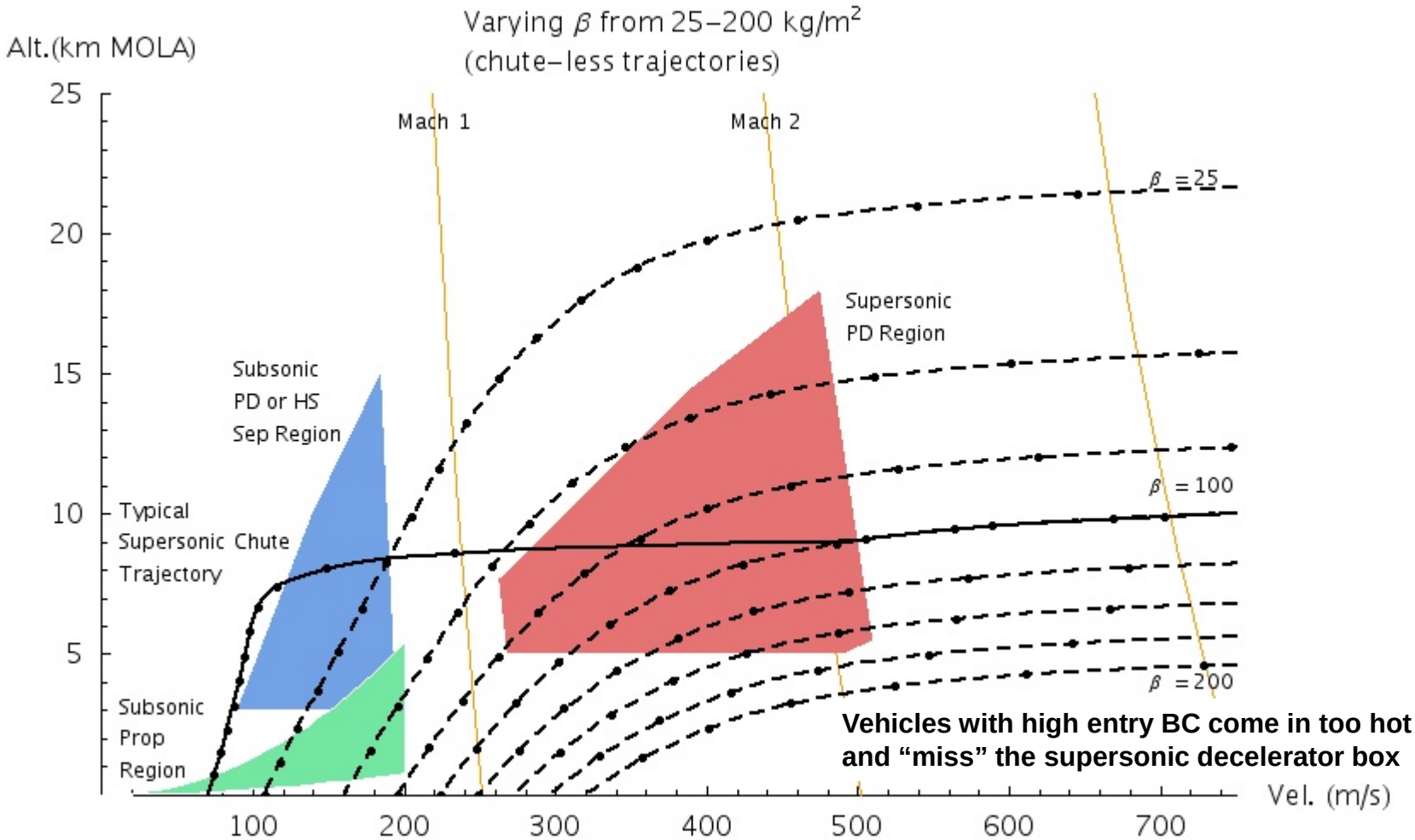
Ref: Braun & Manning IEEE AC Paper 0076-8, Updated December 2005

- Even with a faster entry speed at earth, the earth's atmosphere slows down the vehicle to below Mach 1 way up high without additional help.
- Without a supersonic decelerator of some sort, Mars missions hit the ground > Mach 1 (see next chart)



The “Viking Heritage” ballistic number limit

Ref: Braun & Manning IEEE AC Paper 0076-8, Updated December 2005



Vehicles with high entry BC come in too hot and “miss” the supersonic decelerator box

A Radical Departure

- **Although blunt body entry vehicles using supersonic parachutes are the norm for Mars, these were constrained to entry ballistic coefficients less than about 150-200 kg/m^2 .**
  - Any higher, and the conditions for supersonic parachute deployment can not be achieved unless very low elevation sites are selected.
- **Removal of the supersonic parachute deployment constraint enables much larger entry masses for a given entry body diameter**
  - The use of high thrust-to-weight SRP (initiating between Mach 3 and 4) couples elegantly with this approach.
- **With SRP (and no parachute), we are free to fly "below" the parachute "Mach-Q box" and decelerate at a lower altitude (<5 km vs 20 km) where the atmospheric density is thicker and less uncertain.**
- **Removal of the parachute eliminates a key constraint on "scalability" of important design parameters from smaller to larger vehicles.**

SRP effectively removes a key limitation on our Viking-heritage entry/descent architectures

Notional EDL Sequence & Selected Assumptions

Entry
R:3522.2 km

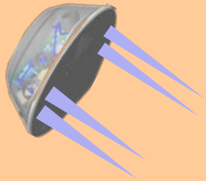
Peak Heating

Hypersonic
Aeromaneuvering

Aerodynamics:
MSL-equivalent
(L/D = 0.24)

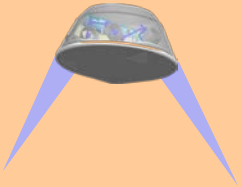
Start Ground Acquisition

T/W at ignition:
3 – 5 Mars G's

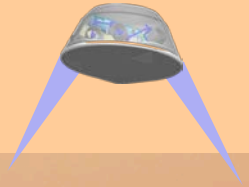


SRP ignition

Powered Descent:
Const. Vel Phase
Ground Sensing



Powered Descent:
Const. Decel.
Phase



Entry BC:
150, 300, 450

Aeroshell
diameter:
4.7m (fixed)

No jettison of backshell or heatshield
(both kept to touchdown)

Touchdown

Site elevation:
-0.5 to -2.5 km MOLA
(range of Mars 2020 sites)

Pre-decisional. For Planning and Discussion Purposes Only.

Ballistic Coefficient Envelope

Main region of interest: BC=300 - 450

Human Mission Concept: Entry BC ~650
(entry mass 75000 kg, 10m aeroshell, SLS LV)

~MSL

Entry ballistic coeff (kg/m^2)	150	300	450	600
Entry mass w/4.7m aeroshell	3813	7627	11440	15254

Notional maximum launch masses for launch vehicles other than SLS in 2026 and 2028 opportunities

	2026 best	**2028 best**
Minimum C3=>	**9.14**	**8.93**
Falcon Heavy	12800	>12800
Delta IV H (NLS II)	9005	9040

Assuming a 4.7 m aeroshell, launch mass constraints probably limit entry ballistic coeff to ~450ish (maybe less), unless launching on SLS

Selected Study Assumptions

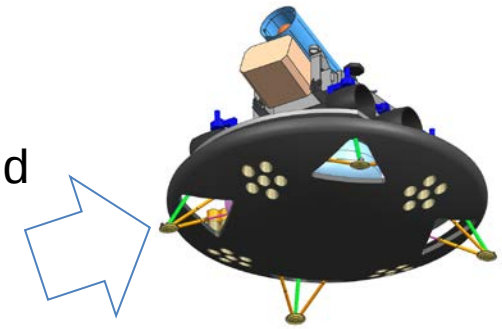
- **Biprop system**
  - Isp=300 sec
  - Preliminary prop system design shows Isp greater than ~300 is difficult, due to limitations on nozzle expansion ratio and aeroshell height
- **T/W at ignition: 3 – 5 Mars G's**
- **T/W prior to touchdown: ~1 Mars G**
  - Throttle engines or turn engines off
- **Propellant mass fraction = 20% (all consumed between ignition and touchdown)**
  - Representative number obtained from parametric study of EDL trajectories optimized from entry to touchdown
- **Engines canted at 20 deg. for control and mitigation of plume effects on planet surface**

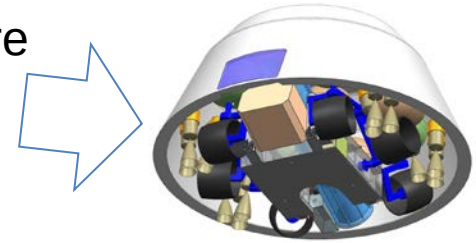
Notional Example Design Parameters

	Entry ballistic coeff = 300						Entry ballistic coeff = 450					
Entry ballistic coeff, kg/m^2	**300**	**300**	**300**	**300**	**300**	**300**	**450**	**450**	**450**	**450**	**450**	**450**
Entry mass w/4.7m aeroshell, kg	7627	7627	7627	7627	7627	7627	11440	11440	11440	11440	11440	11440
T/W at ignition	**3**	**3**	**3**	**5**	**5**	**5**	**3**	**3**	**3**	**5**	**5**	**5**
Thruster cant angle (deg)	20	20	20	20	20	20	20	20	20	20	20	20
At ignition												
Total required thrust, N	84910	84910	84910	141516	141516	141516	127365	127365	127365	212275	212275	212275
# thrusters	12	16	20	12	16	20	12	16	20	12	16	20
Required thrust / thruster, N	**7530**	**5647**	**4518**	**12550**	**9412**	**7530**	**11295**	**8471**	**6777**	**18825**	**14119**	**11295**
Pre-touchdown (T/W=1)												
Total required thrust, N	21227	21227	21227	21227	21227	21227	31841	31841	31841	31841	31841	31841
# thrusters	4	8	8	4	4	4	4	8	8	4	4	4
Required thrust / thruster, N	**5647**	**2824**	**2824**	**5647**	**5647**	**5647**	**8471**	**4236**	**4236**	**8471**	**8471**	**8471**
Throttle % required	**75%**	**50%**	**63%**	**45%**	**60%**	**75%**	**75%**	**50%**	**63%**	**45%**	**60%**	**75%**

Notional Configurations

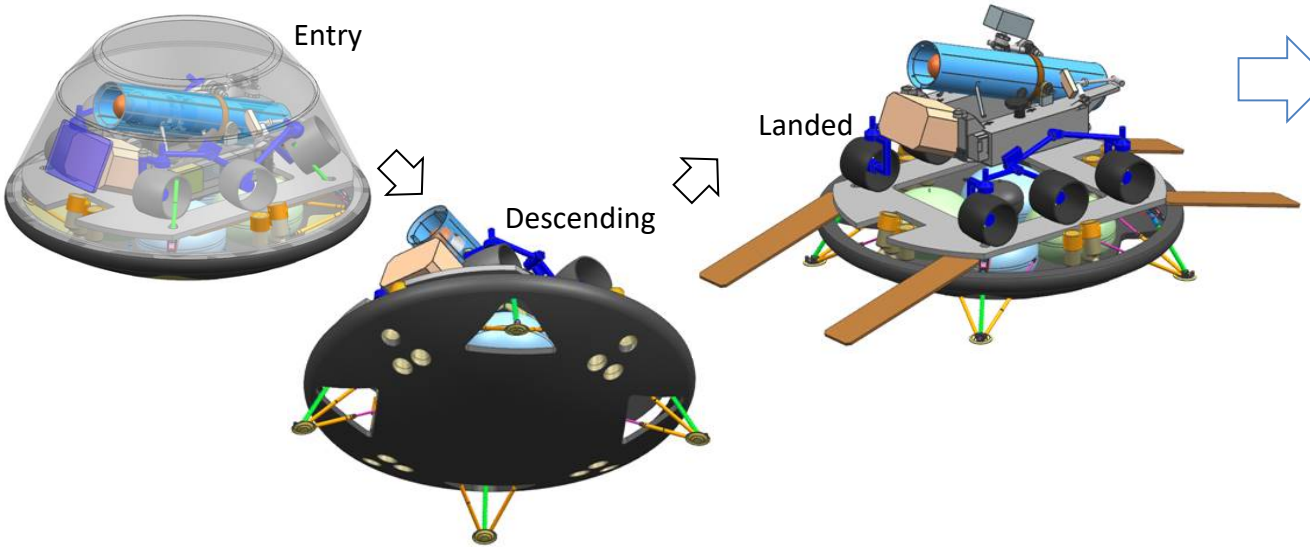
- **Initial SRP configurations assessed**
  - Legged lander
    - Propulsion system integrated into heatshield structure below rover
    - Rover drives off landed platform
  - Skycrane system
    - Propulsion system integrated into backshell structure
    - Heatshield jettisoned; skycrane used to land rover





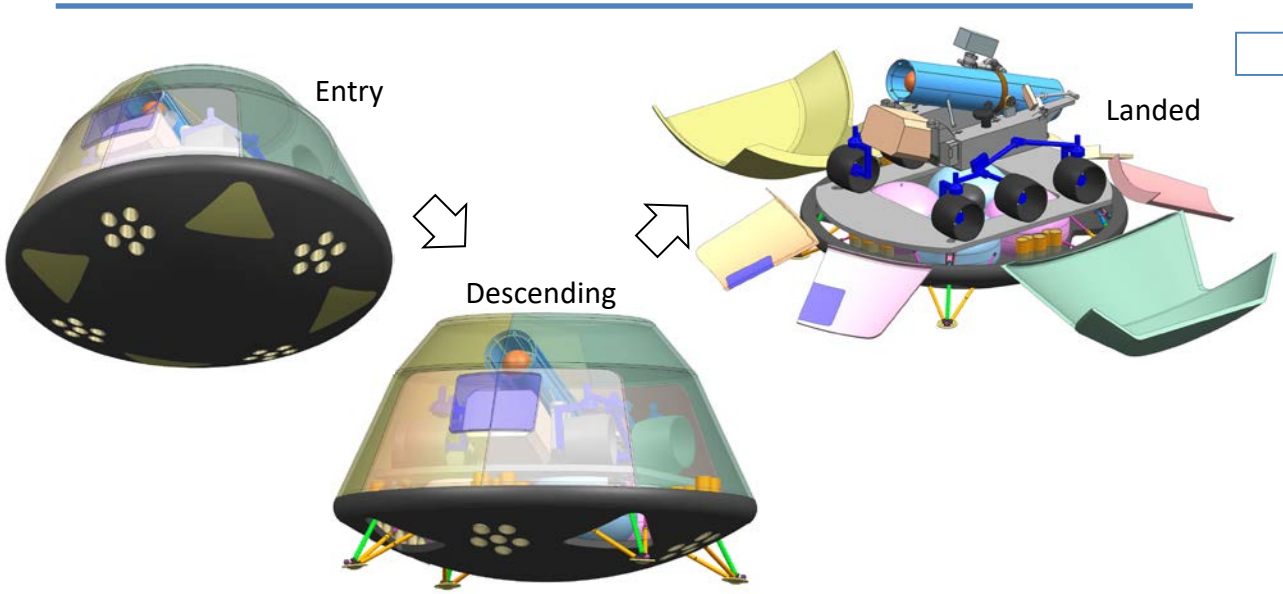
- **Current focus on Legged Lander configuration**
  - Better packaging / payload volume envelope
  - Avoids potential CG location issues
  - Avoids complexity of heatshield jettison & SRP integration
  - Will investigate skycrane in more detail in future

Legged Lander Options



BACKSHELL JETTISON OPTION

Potential for lower propellant mass requirement and simplified egress, but adds jettison event/system complexity



BACKSHELL NON-JETTISON OPTION

Protects payload from engine plume/debris during final landing, but adds complexity to backshell design

Summary

- **Range of ballistic coefficient of interest for a future MSR SRP Sample Return Lander on a non-SLS LV is ~300-450** (upper bound could be < 450)
- **Vehicles with BC in this range with biprop and T/W ~3-5 at ignition can be flown with ~20 - 25% PMF** (**P**ropellant **M**ass **F**raction, = prop mass / wet mass at ignition)
  - Compares to MSL PMF of ~19% (parachute + monoprop)
- **Reduction of thrust is required during powered descent to produce T/W = ~1 prior to touchdown**
  - Can be accomplished by throttling or shutting down engines, or a combination of the two
  - Motivates design concepts with larger numbers of thrusters to facilitate shutting down some thrusters while throttling remainder to reasonable levels

Backup