National Aeronautics and Space Administration

Development Status of Powered Descent for High-Mass Mars Entry, Descent, and Landing Systems

Ashley Korzun and Karl Edquist

NASA Langley Research Center

Hampton, Virginia, USA

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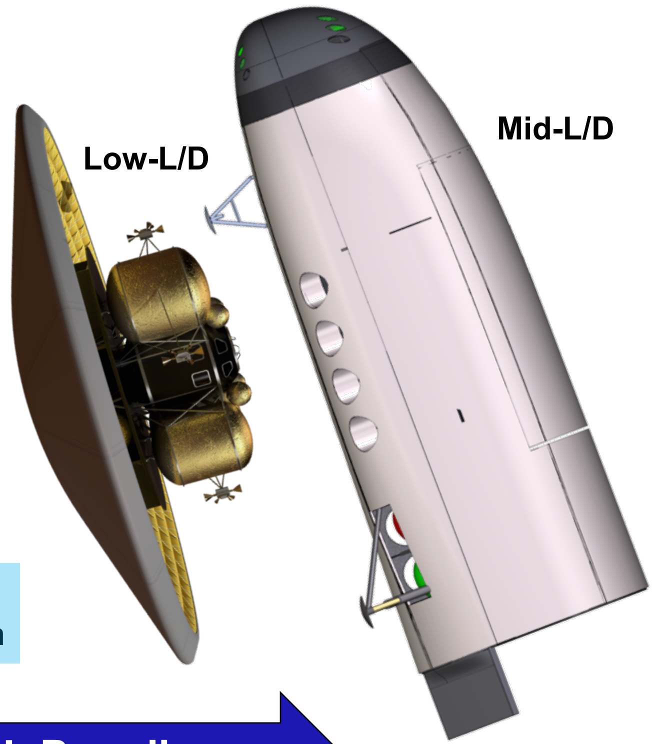
Introduction

- Heritage Entry, Descent, and Landing (EDL) systems cannot land masses required for human Mars exploration
- Supersonic parachutes cannot be extended to high-mass EDL
- Propulsive descent and landing are enabling for human-scale EDL at Mars

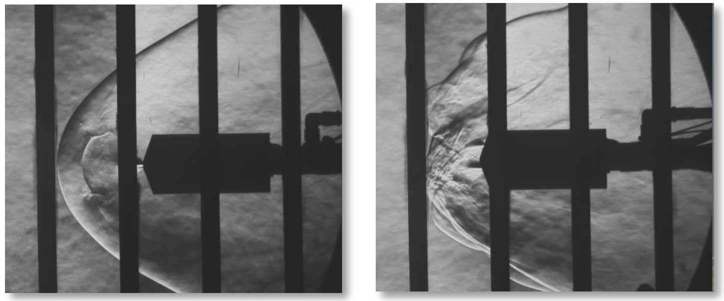
	Viking	Pathfinder	MERs	Phoenix	MSL	InSight	M2020	Human-Scale Lander (Projected)
Entry Capsule (to scale)								
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.52	16 - 19
Entry Mass (t)	0.930	0.585	0.840	0.573	3.153	0.608	3.368	49 - 65
Parachute Diameter (m)	16.0	12.5	14.1	11.8	21.5	11.8	21.5	N/A
Parachute Deploy (Mach)	1.1	1.71	1.67	1.65	1.75	1.66	1.8	N/A
Landed Mass (t)	0.603	0.360	0.539	0.364	0.899	0.375	1.050	26 - 36
Landing Altitude (km)	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5	+/- 2.0
Terminal Descent & Landing Technology	 Retro-propulsion	Airbags	Airbags	Retro-propulsion	Skycrane	Retro-propulsion	Skycrane	Supersonic Retropropulsion



Steady progression of “in family” EDL → **New EDL Paradigm**

Motivation

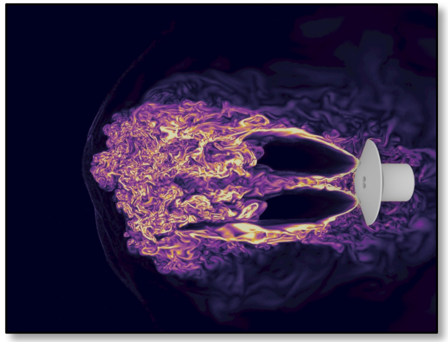
- Legacy ground test data (1960s – early 1970s) and modern NASA investments form the current basis of experience



2010 NASA wind tunnel testing

- Inability to fully simulate relevant physics in ground testing leads to increasing reliance on high-fidelity computational analyses

AIAA 2020-4228



AIAA 2022-2299

- Principal technology challenge is in aerosciences characterization and reduction of uncertainties

Infusion for Mars EDL applications requires continuous, multi-disciplinary, long-lead development efforts

Outline

- Characteristics and Relevant Physics
- Technological Maturity
- Current Status
  - Ground Testing
  - Computational Simulation
  - Flight Testing
- Summary

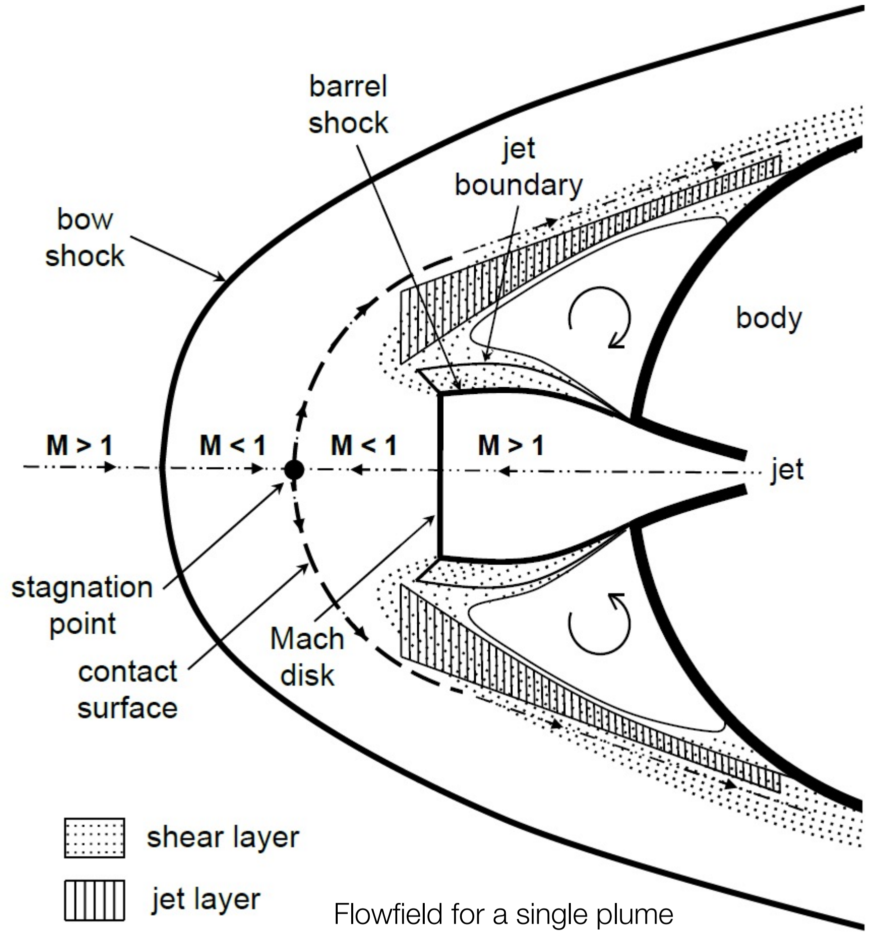
Characteristics and Relevant Physics

- Powered Descent or Supersonic Retropropulsion (SRP)
  - Use of retropropulsion for the primary purpose of decelerating the vehicle
  - Resulting Interference alters the aerodynamic characteristics of the vehicle

- Aerodynamic effects can be significant during powered descent, with strong sensitivity to computational approach and configuration

- Resulting interference characterized by:
  - Complex, unsteady, viscous-dominated flow physics
  - Strong shocks and high-speed shear layers
  - Turbulence
  - Changes in plume expansion condition along descent trajectory

Vehicle-level design decisions are directly impacted by the ability to characterize and bound aerodynamic-propulsive interference effects

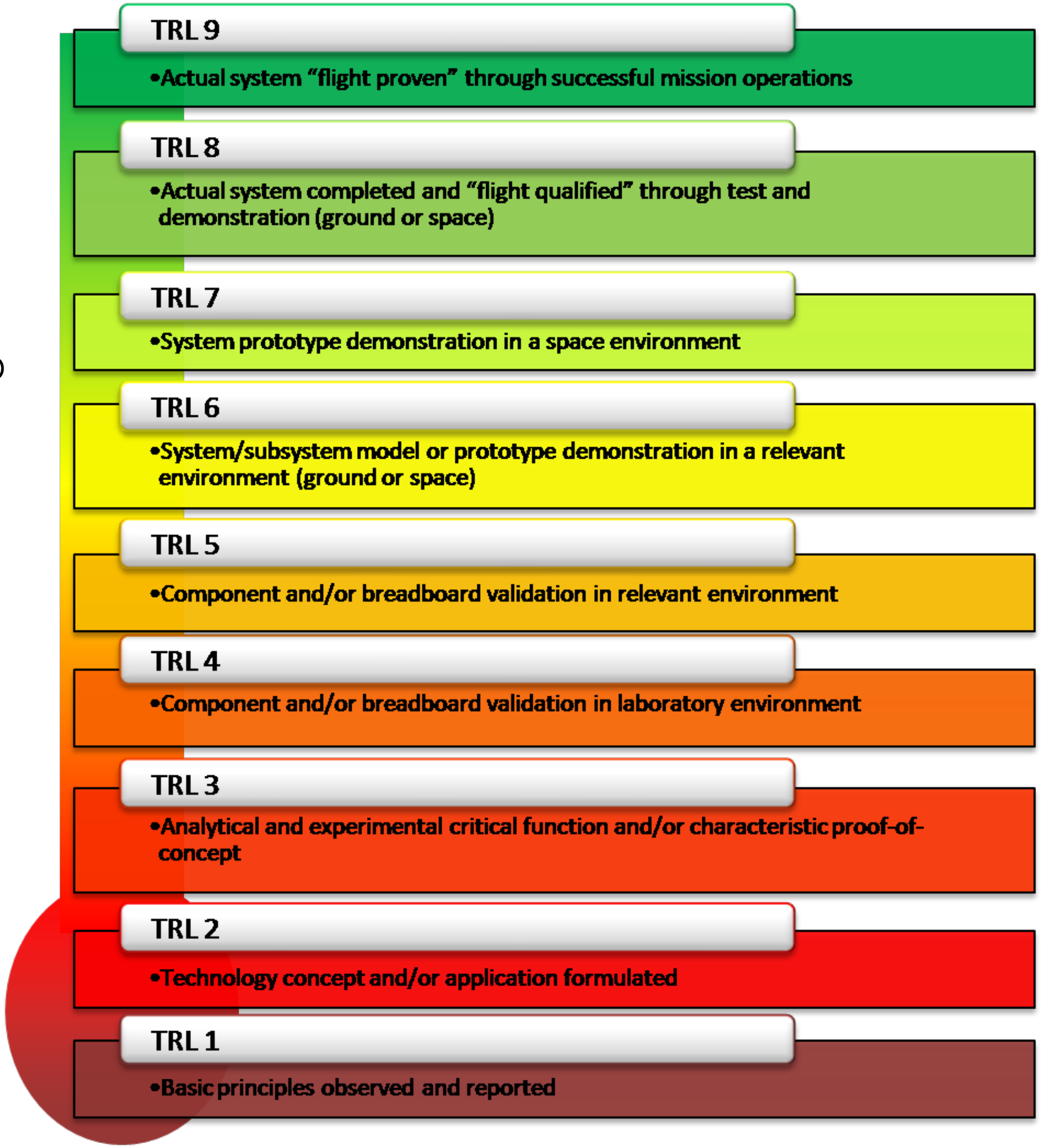


Flowfield for a single plume
(Adapted from Korzun, JSR, 2008)

Technological Maturity

- Overall Technology Readiness Level (TRL) for powered descent for Mars is TRL 3/4
  - TRL scale is from 1 (basic principle observed) to TRL 9 (successful application on a spaceflight mission)
  - TRL 4: Component and/or breadboard validation in lab environment; low-fidelity validation compared to eventual system
  - Achieving TRL 6 will require Earth-based, subscale flight testing to demonstrate aerodynamic performance and acceptable control authority to maintain stable flight

- Component/system technical challenges:
  - **Rocket propulsion for high-mass Mars descent and landing**
  - **Aerodynamics and aerothermodynamics**
  - **Powered guidance and control**
  - **Systems engineering and analysis**
  - **Ground testing**
  - **Flight testing**

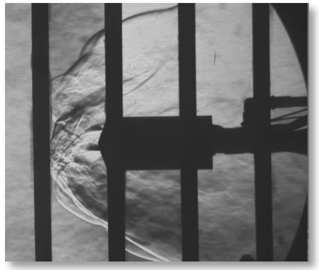


Current Progress – Ground Testing

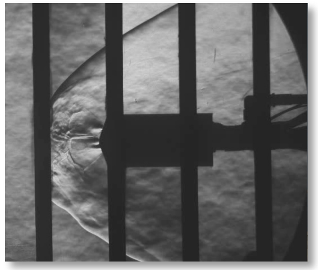
- Upcoming supersonic wind tunnel testing for powered descent in the NASA Langley (4-ft x 4-ft) Unitary Plan Wind Tunnel [now scheduled for Fall 2022]
  - Test subscale versions and variations of NASA's two Mars reference human-scale EDL vehicles
  - Test over a range of Mach numbers, angles of attack, roll angles, nozzle configurations, and thrust levels
  - 6-component flow-through balance, pressure-sensitive paint, high-speed schlieren, oil seeded flow
  - Complete uncertainty quantification and comparisons to pre- and post-test CFD results
- All prior testing limited to inert gas simulant, subscale models, discrete surface pressures and schlieren, few configurations with multiple nozzles, and supersonic freestream conditions

Zero nozzles

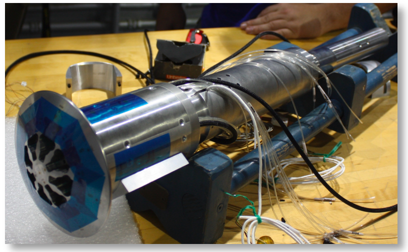
One center nozzle

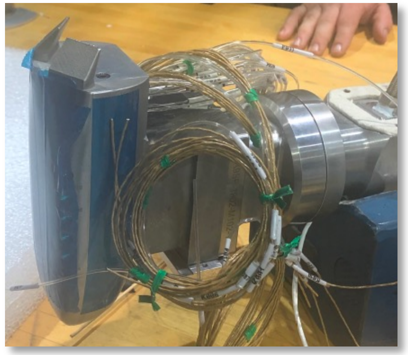


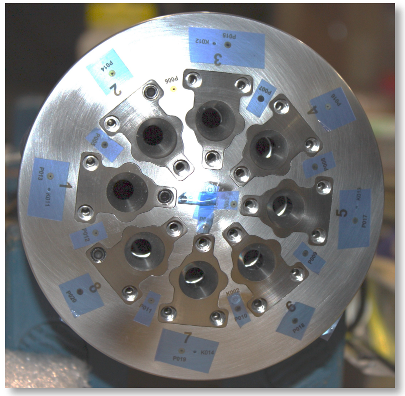
Three nozzles



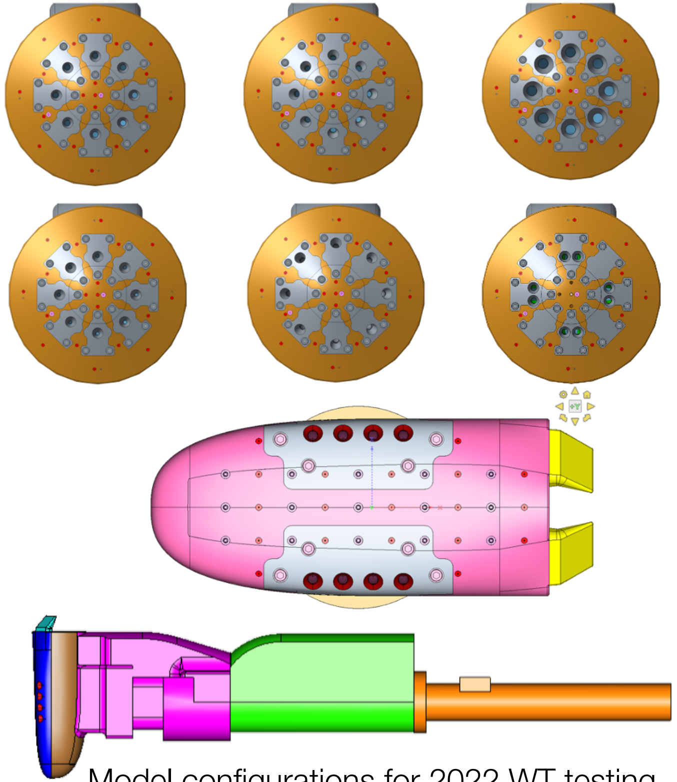
Four nozzles







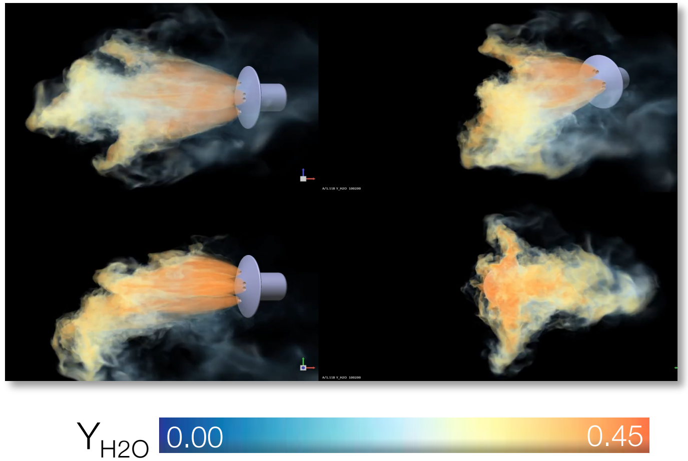
Model hardware for 2022 WT testing



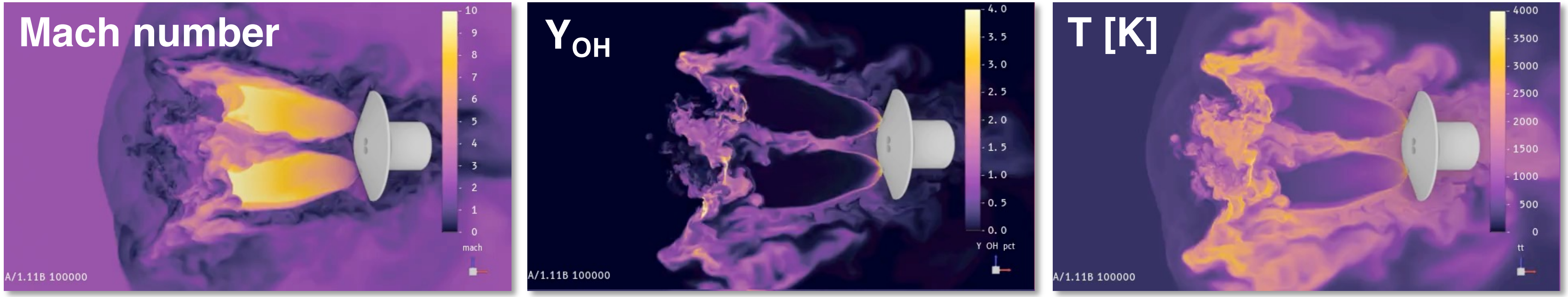
Model configurations for 2022 WT testing (AIAA 2020-2230)

Current Progress – Computational Simulation

- Computational costs are significant for large-scale plume interference, generally requiring trades on the fidelity of modeling approaches
- RANS methods have varying degrees of success in consistent prediction of plume interference aerodynamics, as do non-reacting flow approaches
- URANS, DES, and LES approaches have been applied to powered descent
- Largest simulations to-date completed using GPU-implementation of FUN3D
  - DES approach with 10-species finite-rate chemistry
  - Full-scale, conceptual human Mars vehicle in Martian atmosphere
  - Now fully coupled to POST2 for continuous powered descent from Mach 2.4 to 0.8
  - Thousands of GPUs per simulation, equivalent to several million CPU cores, with simulations executed on Summit (US Dept of Energy, Oak Ridge National Laboratory)
- No quantitative validation for induced aerothermal environments



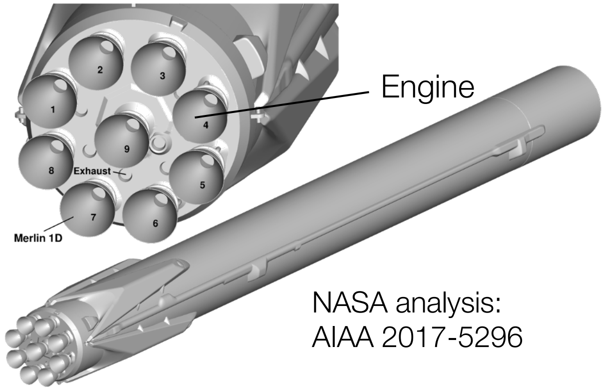
Mach 2.4 flowfield solution animation (AIAA 2022-2290)



Mach 2.4 flowfield solution animation (AIAA 2022-2289)

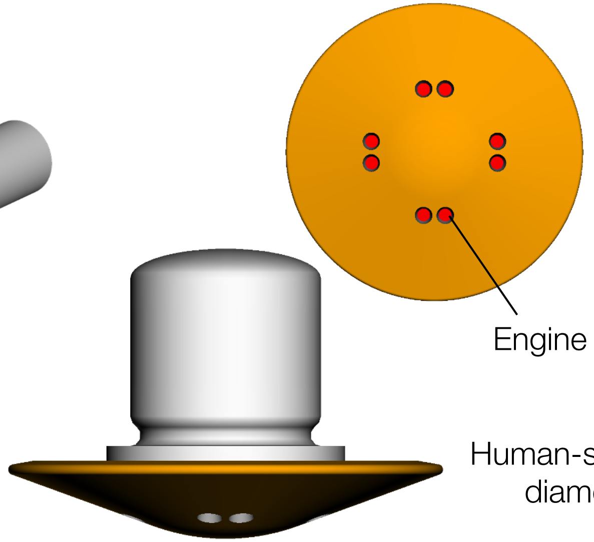
Current Progress – Flight Testing

- No NASA flight testing or development since preliminary sounding rocket design work in 2011-2013
- Long-term planning continues to include a progression of suborbital, Earth-based flight tests
- Dozens of successful commercial launch vehicle booster return flights utilizing retropropulsion for booster recovery are the present state-of-the-art
  - Minimal aerodynamic surface area relative to engine area
  - High C_T, low A_e /A*
- Initial SpaceX Falcon 9 test flights through Mars-relevant conditions
- NASA comparisons (qualitative) to Falcon 9 early test flights showed good agreement for loads and environments

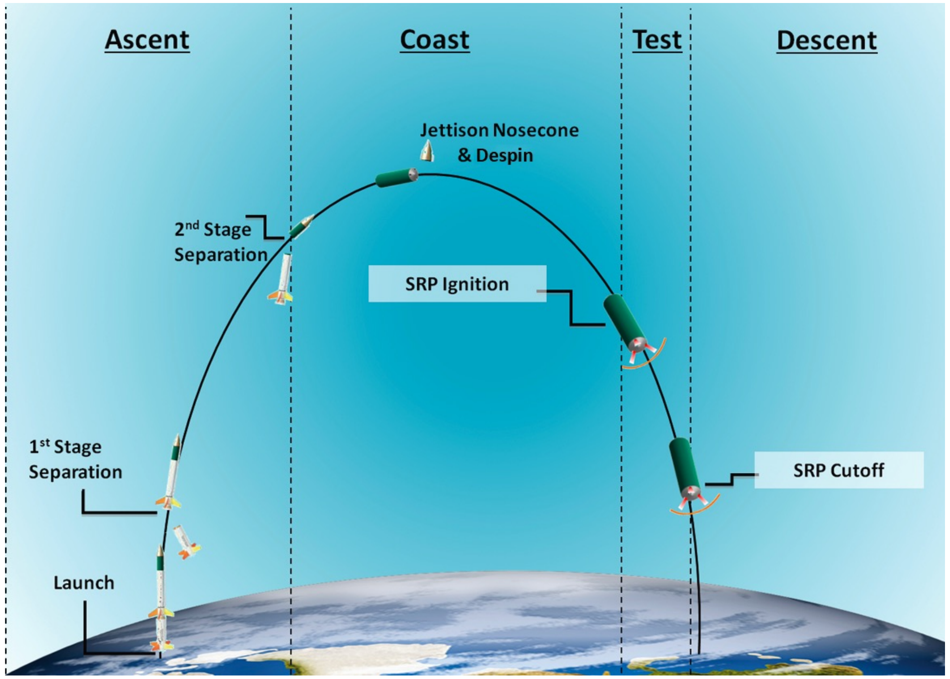


NASA analysis:
AIAA 2017-5296

Falcon 9 launch vehicle 1st stage
diameter = 3.7m



Human-scale Mars lander
diameter = 16.4m



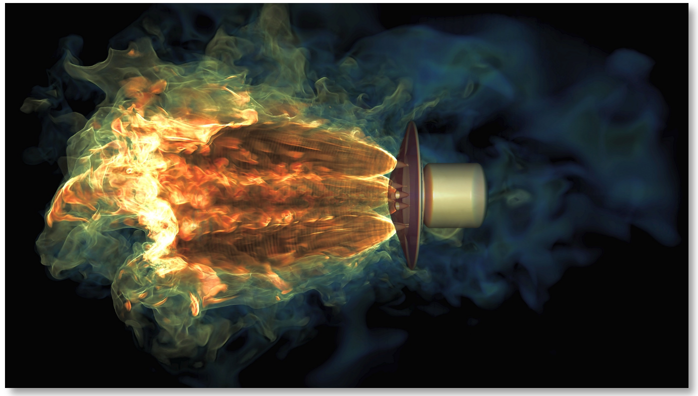
NASA powered descent sounding rocket concept
(Edquist et al., JSR, 2014)

Summary

- Powered descent is enabling for significant increases in payload mass delivery to the surface of Mars
- Principal technology challenge remains in aerosciences characterization and reduction of uncertainties

- Upcoming NASA supersonic wind tunnel test will deliver direct force and moment measurement for highly parametric multiple-nozzle configurations and further benchmark supersonic CFD capabilities
- High-fidelity CFD methods can now simulate powered descent with chemistry and at resolutions previously unattainable, while efforts continue to establish applicability of varying fidelity approaches
- Launch vehicle booster recovery development and now routine flight implementation remain the state-of-the-art for large-scale, Earth-based powered descent with minimal aerodynamic surface area during descent

- Infusion for Mars EDL applications requires continuous, multi-disciplinary, long-lead development efforts
  - Hot-fire ground testing
  - Continued CFD development and validation
  - Progressively complex and relevant scaled flight testing



Credit: Marc Niehaus, NVIDIA (AIAA 2020-2248)