Aerosciences Considerations in the Design of a Powered Descent Phase for Human-Scale Mars Lander Vehicles

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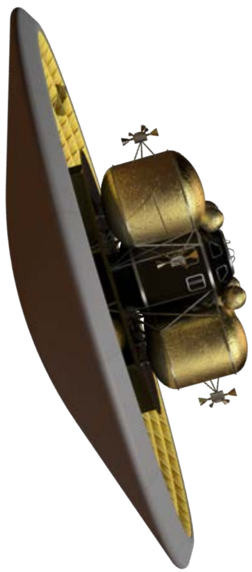
Introduction

- Human-scale Mars landers require a new approach to all phases of Entry, Descent, and Landing
- Propulsive descent and landing are enabling for human-scale EDL at Mars
- Retropropulsion environments and configurations can significantly impact vehicle performance

	Viking	MPF	MER	PHX	MSL	Human-Scale Lander (Projected)
Vehicles to Scale						
Diameter (m)	3.505	2.65	2.65	2.65	4.5	16 - 19
Entry Mass (t)	0.930	0.585	0.840	0.602	3.151	47 - 62
Landed Mass (t)	0.603	0.360	0.539	0.364	1.541	36 - 47
Landing Altitude (km MOLA)	-3.5	-1.5	-1.3	-3.5	-4.4	+/- 2.0
Peak Heat Rate (W/cm^2)	24	106	48	56	~120	~120 - 350



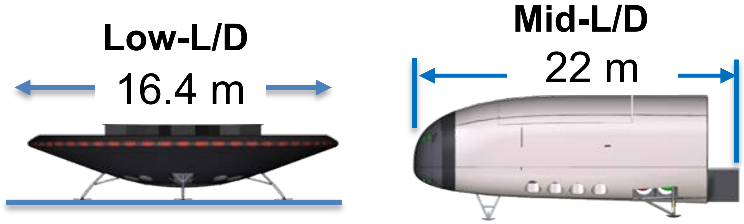
Steady progression of “in family” EDL

Powered Flight in an Atmosphere

- Aerodynamic effects can be significant during powered descent through an atmosphere
- While the idea of propulsive descent and landing dates back to the early 1960s, exploration of retropropulsion aerodynamics resurfaced in the mid-2000s
- Legacy ground test data (1960s, early 1970s) and NASA investments from 2009-present form the current basis of experience

Aerosciences Definition

All aerodynamic and aerothermodynamic interactions and environments during the powered descent phase, beginning with SRP initiation and ending with touchdown.

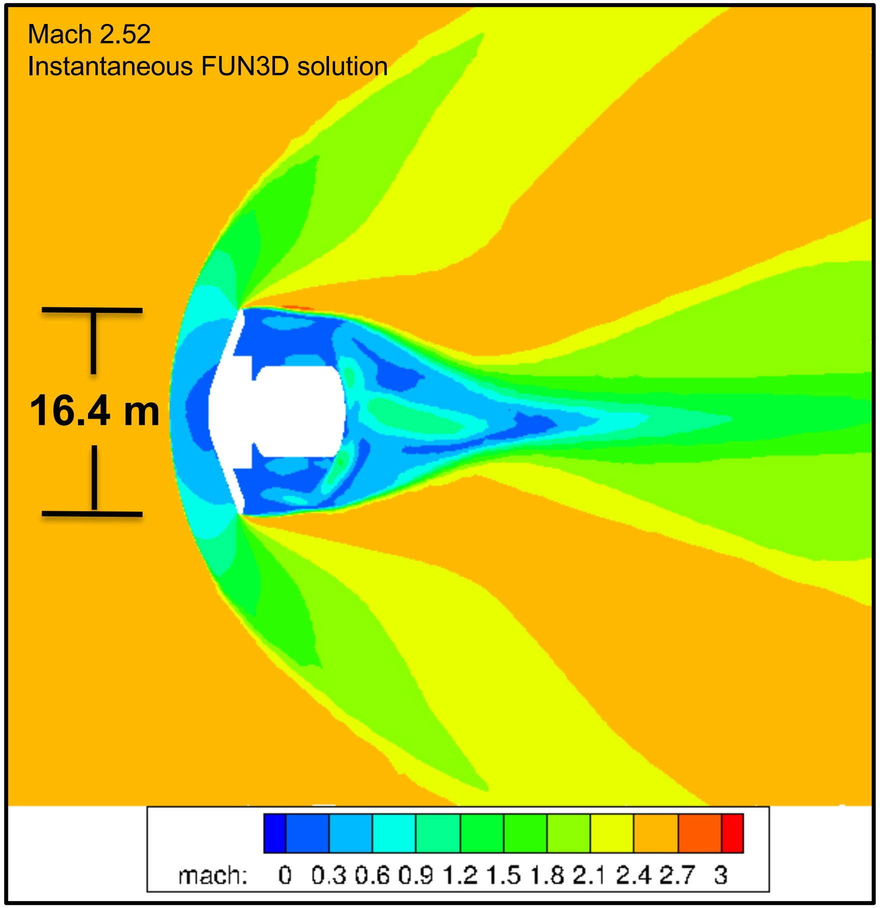


Aerosciences is an important part of performance considerations and compromises across the entire powered descent phase of flight

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

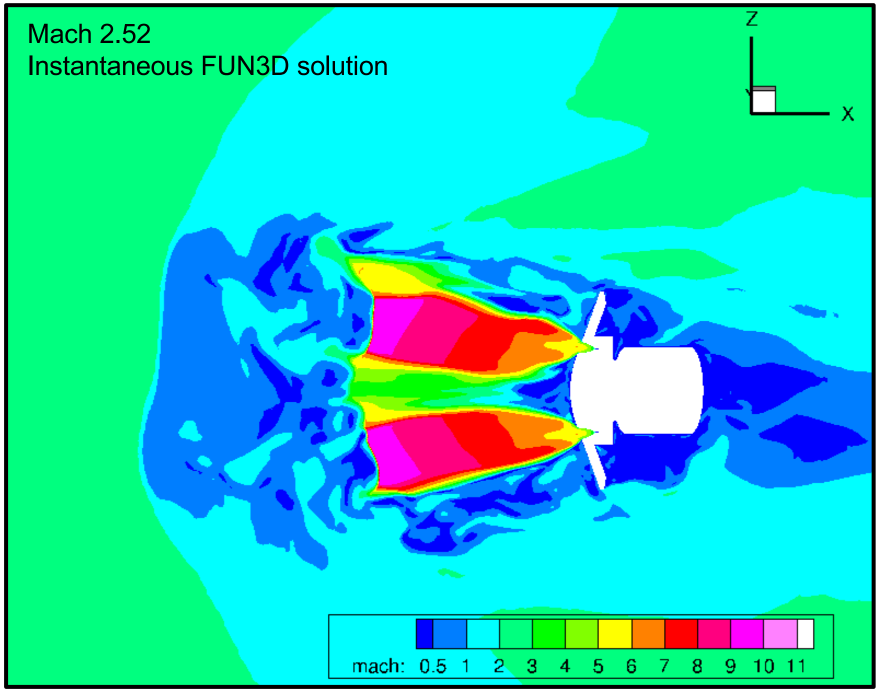
Engines Off vs. Engines On

Engines Off



- Strong, detached shock near vehicle
- Heatshield is the flow obstruction
- Dominant forces and moments are steady
- Well-defined scaling relationships

Engines On

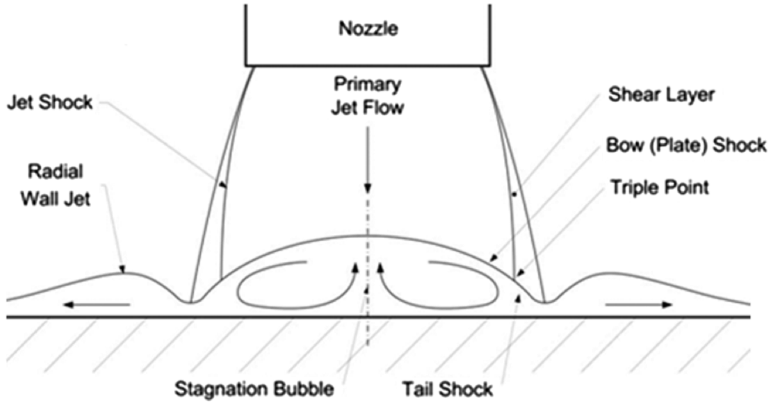


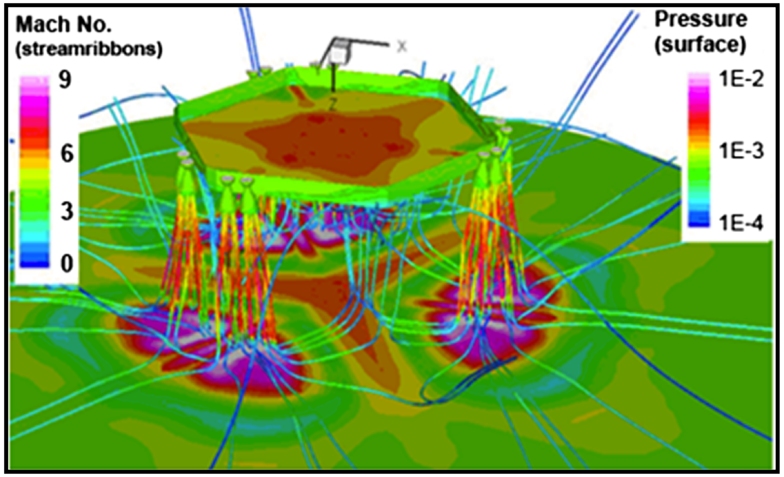
Source: A. Korzun (NASA LaRC), FUN3D solution, 2018.

- Shock displaced far upstream
- Complex, unsteady plume structure is part of the flow obstruction
- Aerodynamic forces and moments can be unsteady
- Less confidence in scaling relationships

Near the Ground vs. Free-flight

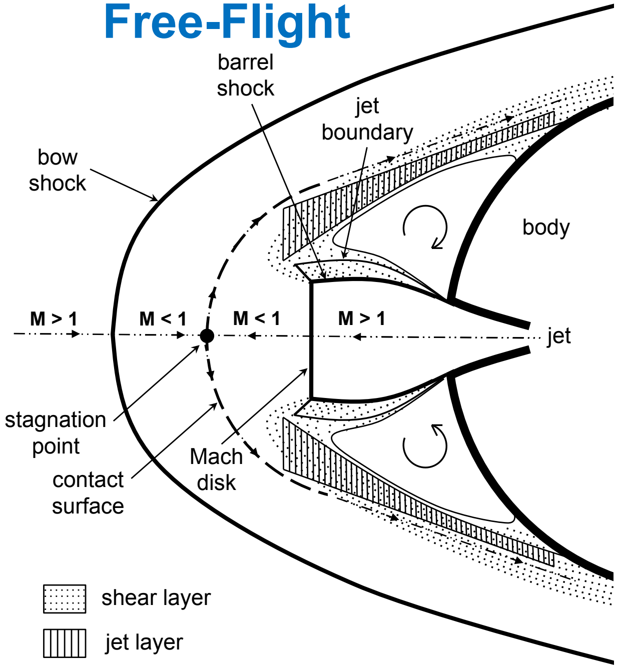
Near the Ground



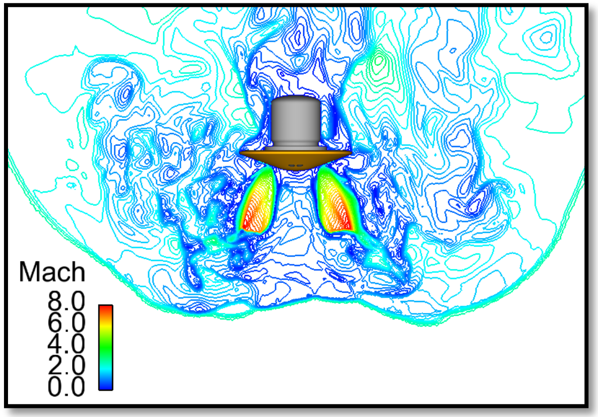


Ref: Mehta, M., et al., (2013), "Thruster Plume Surface Interactions: Applications for Spacecraft Landings on Planetary Bodies", AIAA J., Vol. 51, No.12.

Free-Flight



Ref: Korzun, A. M., Ph.D. Dissertation, May 2012.

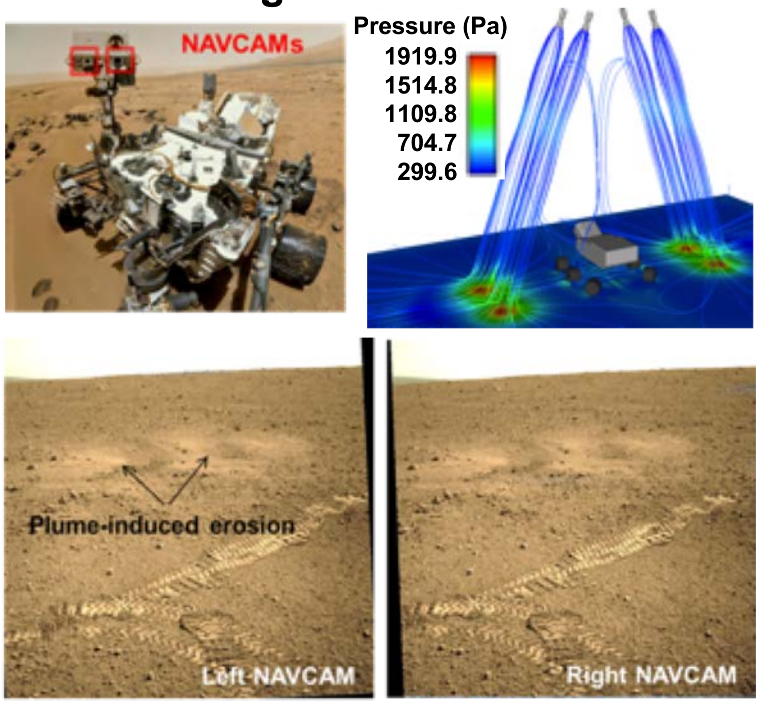


Source: F. Canabal (NASA MSFC), LociCHEM solution, instantaneous Mach number contours, Mach 2.78, 2018.

Surface – Plume Interaction

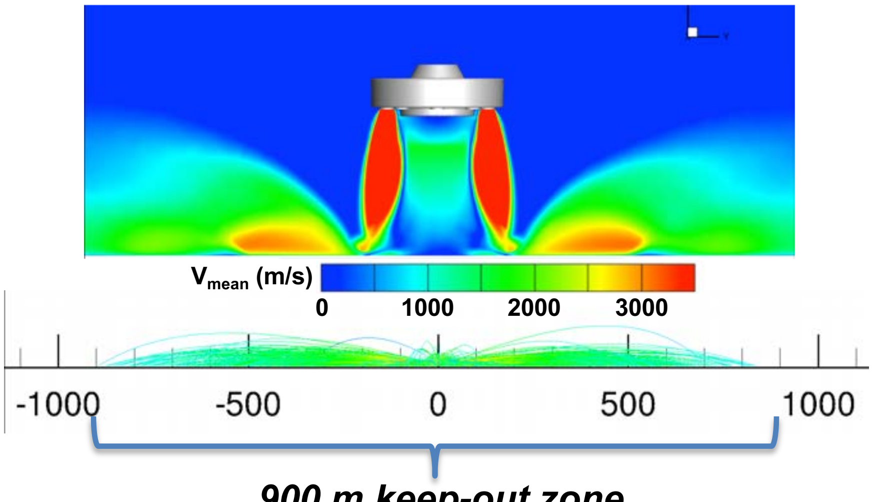
Mars Science Laboratory

24,900 N → 3110 N of thrust,
18+ m from surface
Damaged instrument



Human Mars Lander

800,000 N → 160,000 N of thrust,
3+ m from surface
in proximity to other assets



Source: P. Liever, D. Westra, M. Gale, J. West (NASA MSFC), 2017.

Plumes may be 10s of meters in front of the vehicle on approach.
The total thrust at landing is 50 times more than Curiosity or InSight missions.
Landing on bedrock is preferred, but even that material may be altered.

Aerosciences Impacts on Other Disciplines

Fidelity of vehicle performance simulations is only as good as the fidelity of the underlying models

Flight Mechanics

- GN&C (sensors, controllability, differential throttling)
- Engine operating conditions
- Integrated aero effects models
- RCS effectiveness
- Propellant usage
- Targeting capability

Navigation Sensors

- Sensor requirements
- Look angles
- Sensor integration and performance
- Vehicle accommodation

Propulsion

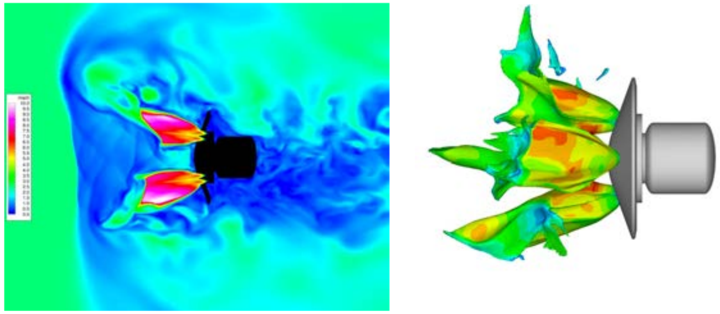
- Engine operating conditions
- System performance and controllability

Notional CAD Model

Mechanical and Structural Design

- Engine configuration and integration
- Balance design for aero effects, controllability, landing, and ability to handle off-nominal scenarios
- Aerothermal considerations may be significant during powered descent

Design Choice Impacts on Aerosciences



Source: J. Van Norman (NASA LaRC), FUN3D solution, 2018.

Propulsion

- ***Nozzle expansion ratio*** **vs. I_{sp} vs. T/W**
- ***Engine operating pressure***
- **Composition (O/F)**

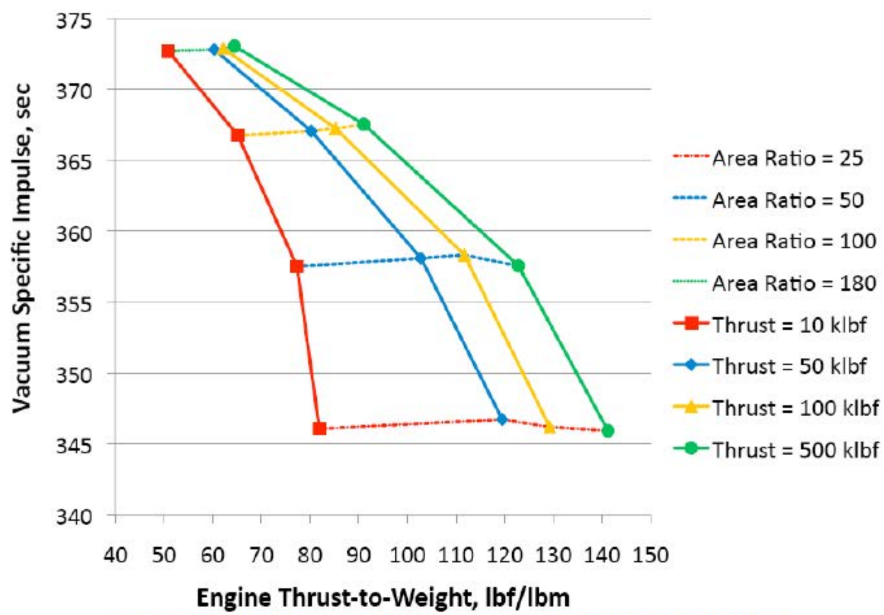


Figure 8. SRP Specific Impulse vs. Engine Thrust-to-Weight

Ref: "Entry, Descent and Landing Systems Analysis Study: Phase 1 Report", NASA/TM-2010-216720, July 2010.

Flight Mechanics

- **Retropropulsion-aerodynamic interactions are most sensitive to:**
  - Engine operating conditions
  - Transients during engine start-up
  - Atmosphere variations
  - Angle of attack

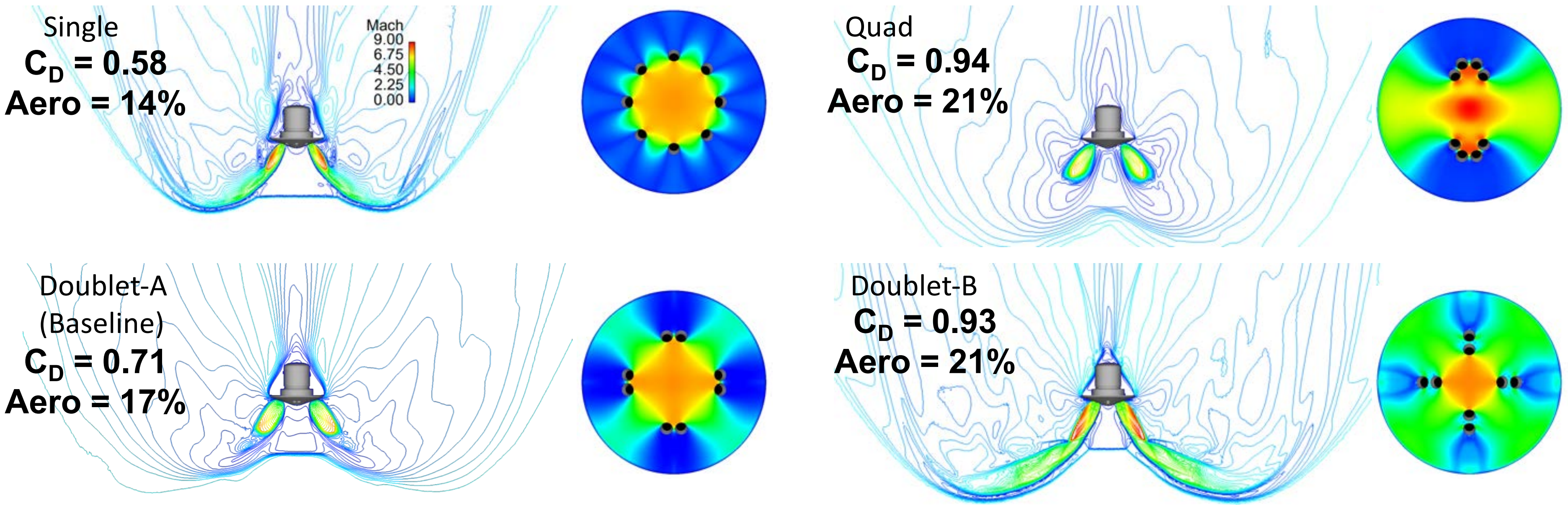
Mechanical and Structural Design

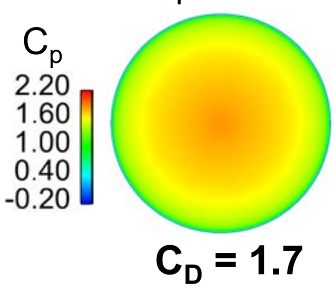
- ***Engine configuration*** **and location on the vehicle**
- **Engine cant angle**

Engine Configuration

High-Fidelity Simulations (F. Canabal, NASA MSFC)

Mach 2.7, time-averaged LociCHEM solutions, engines canted outboard 20º, AOA = 0º

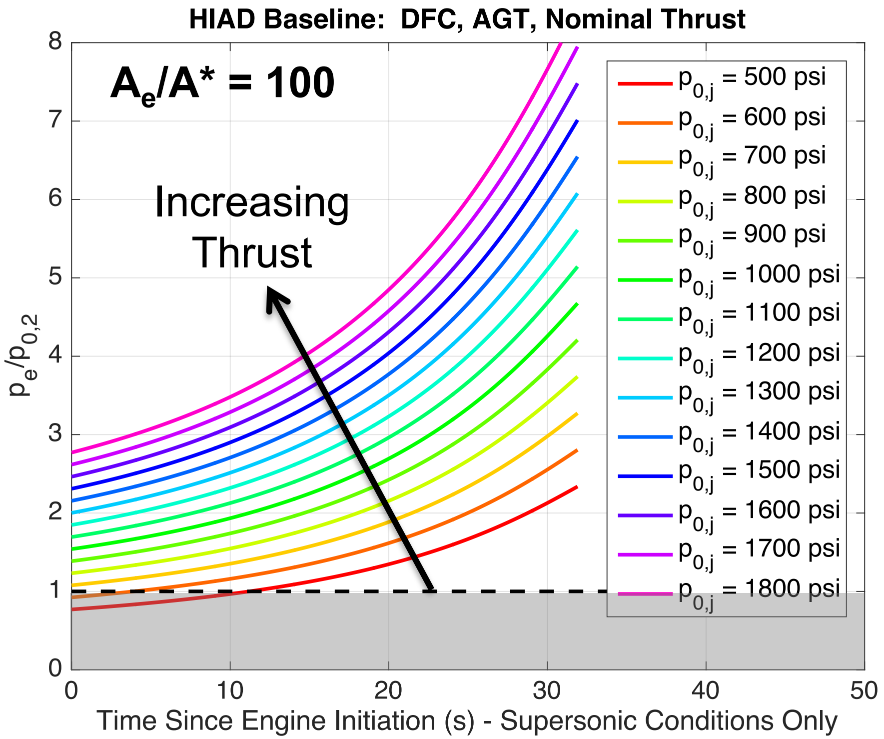


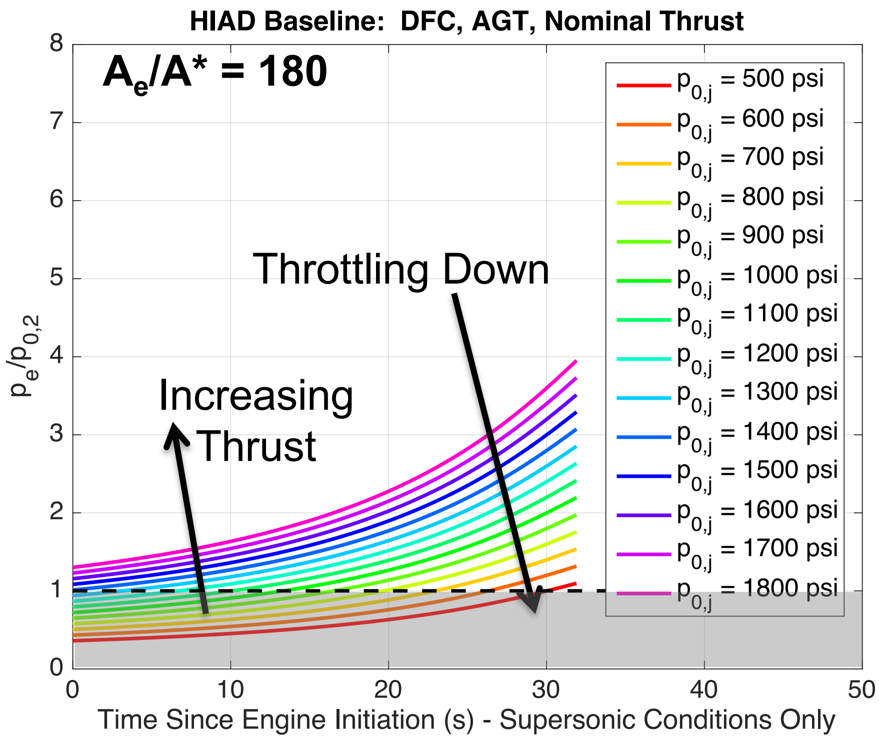


- **Powered C_D ranges from 40% to 70% of the unpowered C_D *at these conditions***
- **Over-expanded composite plumes are less steady and more difficult/expensive to predict**
- **Engine cant emphasizes variation with configuration**
- **Governing behavior well-understood for one nozzle, much less understood for multiple nozzles**

Engine Performance

Variation in Engine Chamber Pressure, with Nozzle Expansion Ratio

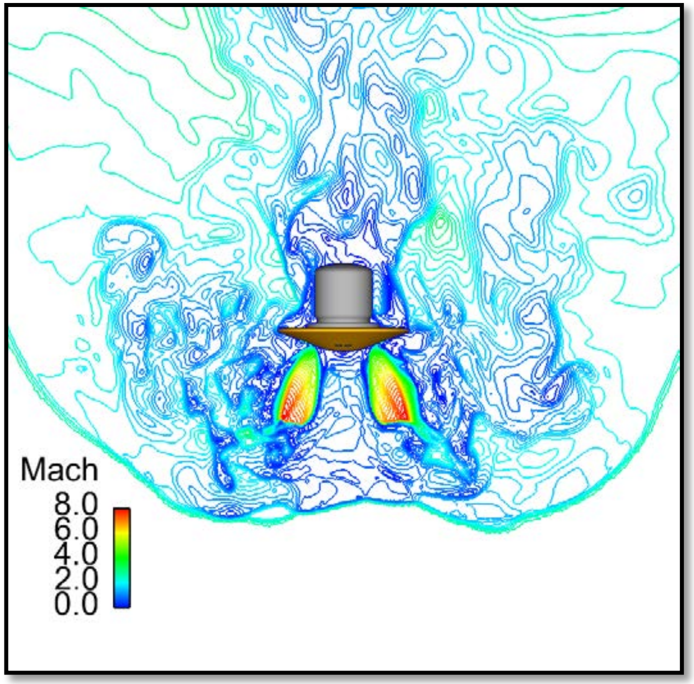




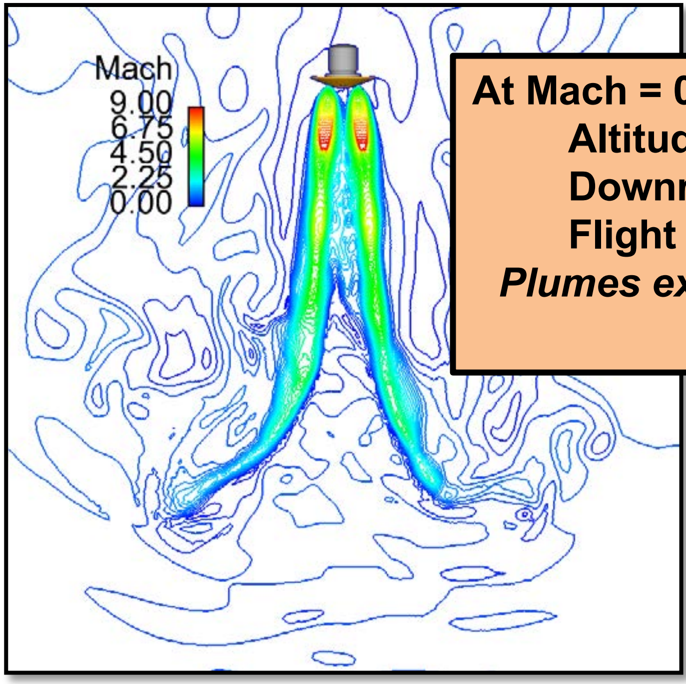
- **$p_e/p_{0,2}$ = 1 represents expansion boundary for a single engine**
  - $p_e/p_{0,2}$: ratio of engine static exit pressure to freestream post-shock stagnation pressure
  - $p_e/p_{0,2} > 1$: under-expanded nozzle, $p_e/p_{0,2} < 1$: over-expanded nozzle
- **Advantageous to minimize the number of times this boundary is crossed**
- **Recent work suggests this boundary to be >> 1 for configurations with multiple nozzles**

Relevant Physics Impacts on Design

Mach 2.78



Mach 0.8



At Mach = 0.8 (20t payload):
Altitude above surface: 975 m
Downrange to target: 1.04 km
Flight path angle: -35˚
Plumes extend ~150 m in front of the vehicle!

Source: F. Canabal (NASA MSFC), LociCHEM solutions, instantaneous Mach number contours, 2018.

- **Unsteady aerodynamics in nominal operation**
- **Transitions through nozzle expansion conditions as the vehicle decelerates**
- **Throttling introduces asymmetry and can significantly alter the resulting aerodynamics**

Closing Comments

- Significant increases in landed mass at Mars requires an extended powered descent phase, generally starting at supersonic conditions
- Atmospheric powered descent is a multidisciplinary design problem, more so than its EDL predecessors
- Aerodynamic-propulsive interference effects are strongly configuration- and condition-dependent
- Vehicle-level design decisions are directly impacted by the ability to characterize and bound aerodynamic-propulsive interference effects