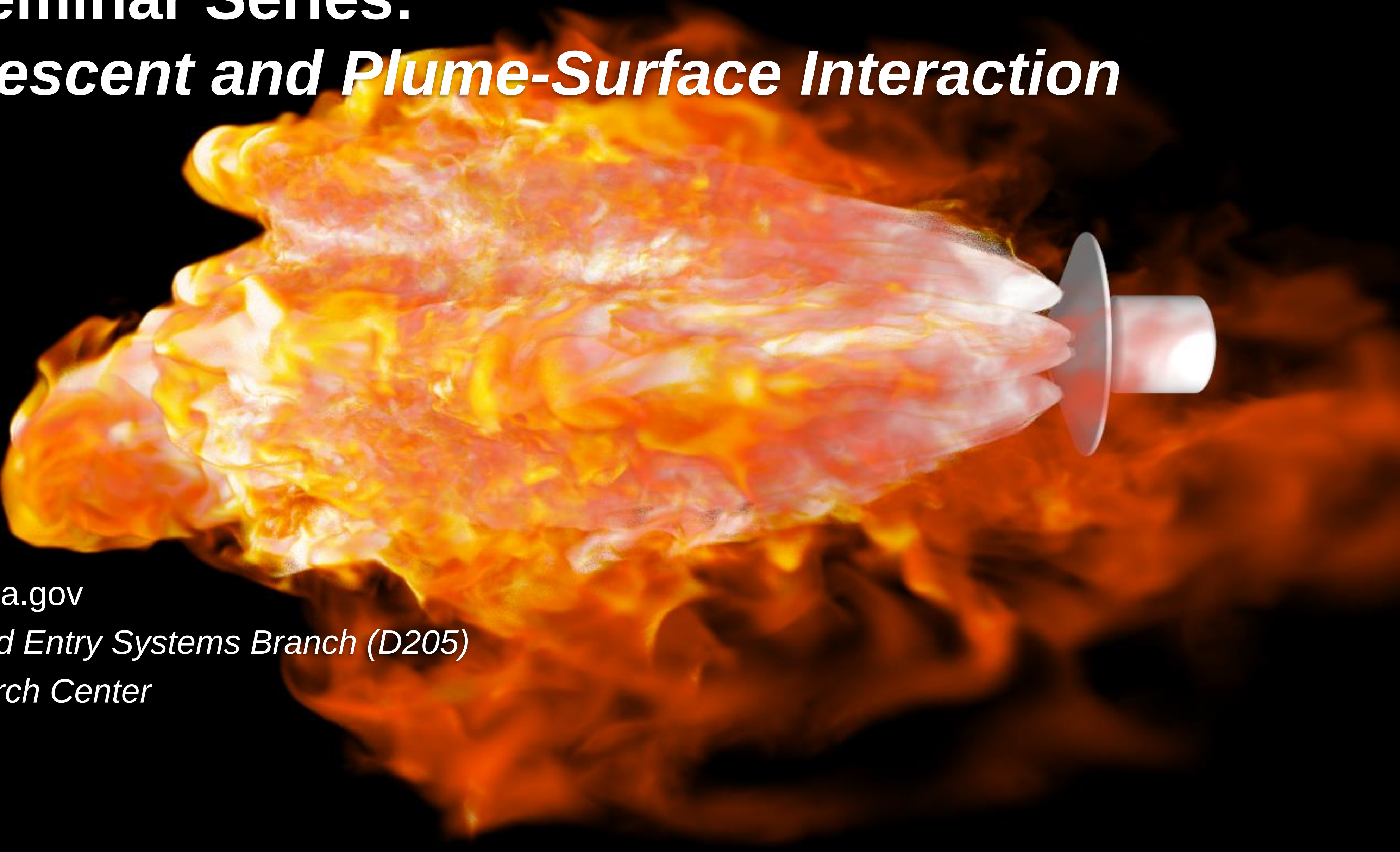
National Aeronautics and Space Administration

Summer Seminar Series:
Powered Descent and Plume-Surface Interaction



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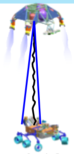
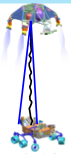
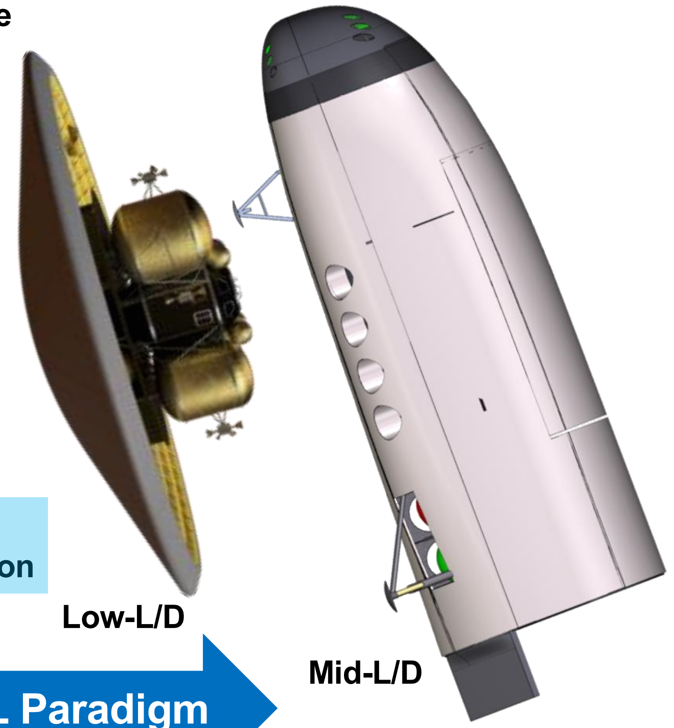
Introduction

- Viking-heritage Entry, Descent, and Landing (EDL) technologies 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								
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.5	16 - 19
Entry Mass (t)	0.930	0.584	0.832	0.573	3.153	0.608	3.440	49 - 65
Parachute Diameter (m)	16.0	12.5	14.0	11.8	19.7	11.8	21.5	N/A
Parachute Deploy (Mach)	1.1	1.57	1.77	1.65	1.75	1.66	1.75	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	0
Terminal Descent and Landing Technology	 Retro-propulsion	 Airbags	 Airbags	 Retro-propulsion	 Skycrane	 Retro-propulsion	 Skycrane	Supersonic Retropropulsion

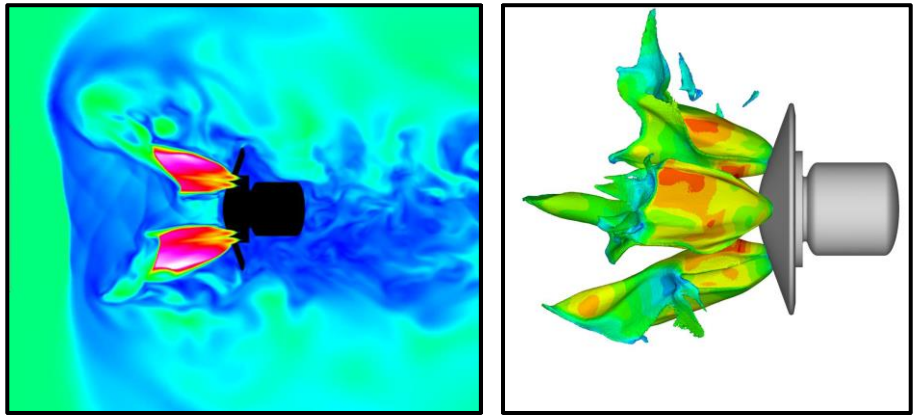


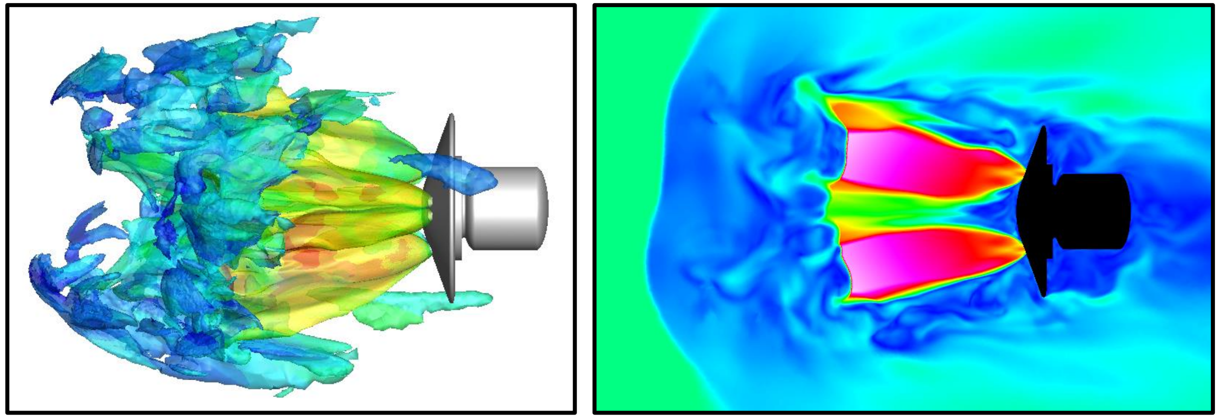
Steady progression of “in family” EDL

New EDL Paradigm

Powered Descent in an Atmosphere

- **Aerodynamic effects can be significant during powered descent**
- **Principal technology challenge is in aerosciences characterization and reduction of uncertainties**
- **Legacy ground test data (1960s) and modern NASA investments form the current basis of experience**
- **Inability to fully simulate relevant physics in ground testing requires strong reliance on high-fidelity computational analyses**
- ***Infeasible* to continue with conventional resources, given the computational expense of single solutions (>300,000 CPU-hours)**

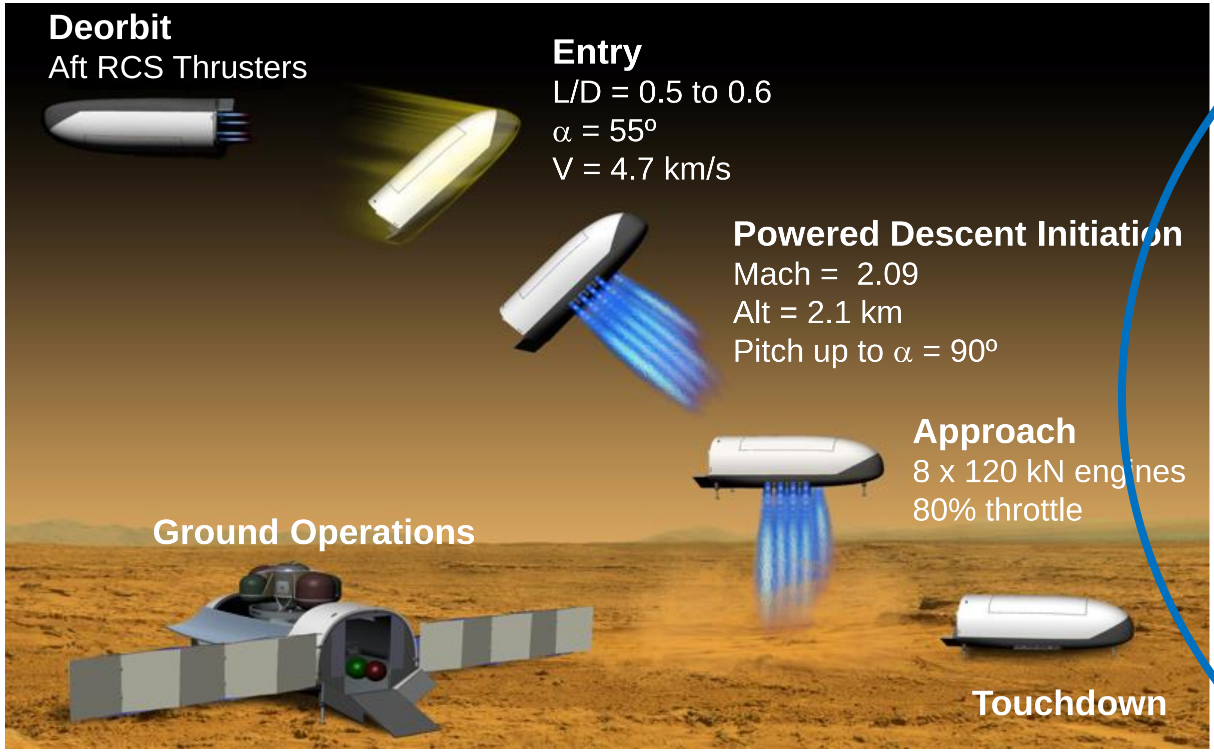




Examples of unsteady RANS solutions with insufficient spatial and temporal resolution (AIAA 2020-1510)

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

Human-Scale EDL Concept of Operations



Deorbit
Aft RCS Thrusters

Entry
L/D = 0.5 to 0.6
$\alpha = 55^\circ$
V = 4.7 km/s

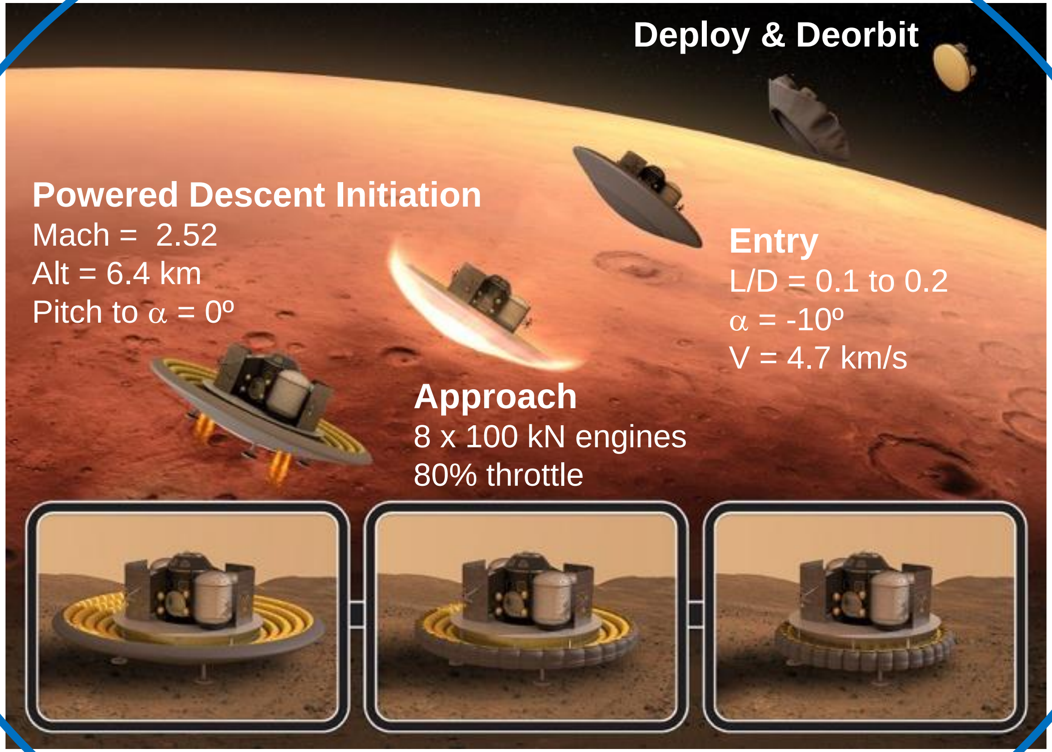
Powered Descent Initiation
Mach = 2.09
Alt = 2.1 km
Pitch up to $\alpha = 90^\circ$

Approach
8 x 120 kN engines
80% throttle

Ground Operations

Touchdown

Mid-L/D



Deploy & Deorbit

Powered Descent Initiation
Mach = 2.52
Alt = 6.4 km
Pitch to $\alpha = 0^\circ$

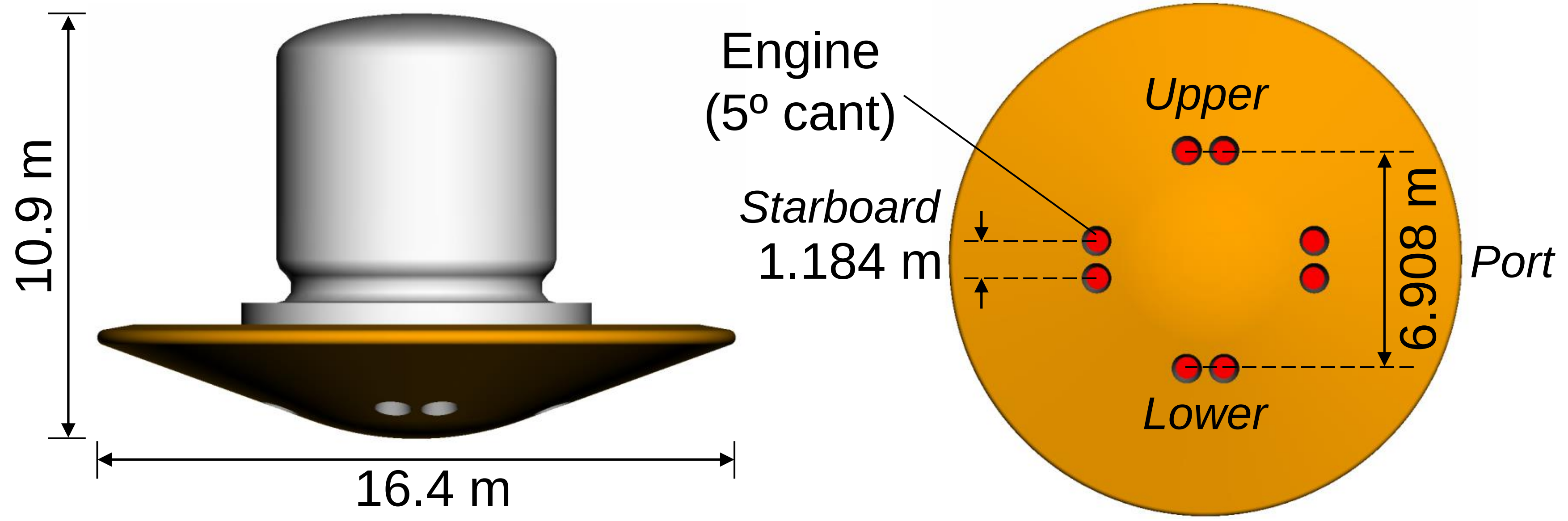
Entry
L/D = 0.1 to 0.2
$\alpha = -10^\circ$
V = 4.7 km/s

Approach
8 x 100 kN engines
80% throttle

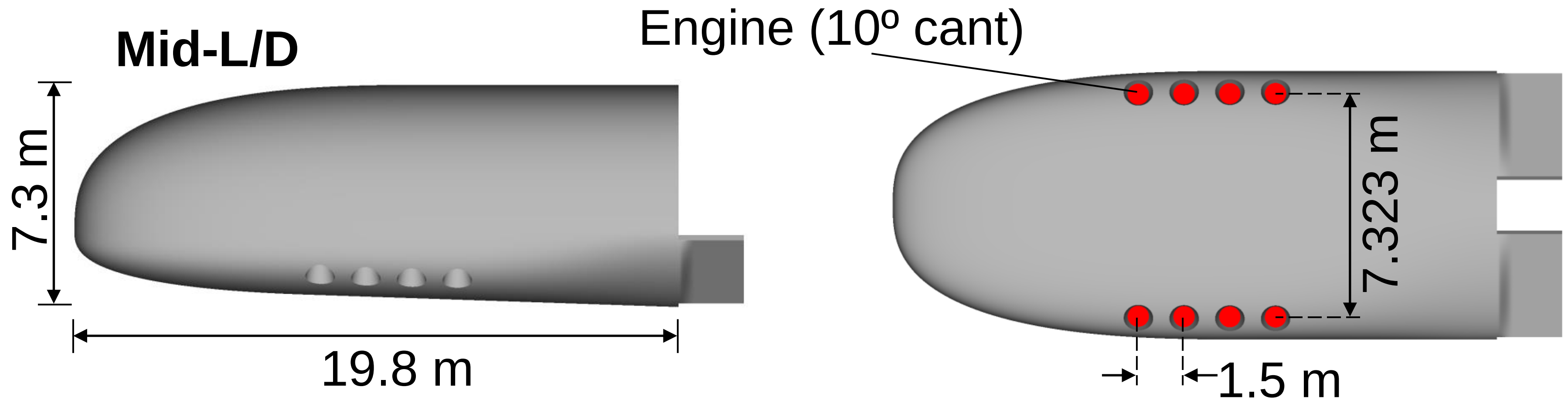
Low-L/D

Vehicle Geometries

Low-L/D



Mid-L/D



- 8 O_2/CH_4 gas generator cycle engines
- 100 – 120 kN thrust per engine at max throttle
- $A_e/A^* = 177:1$
- O/F = 3.5
- Nozzles scarfed to be flush with vehicle OML

Aerosciences Impacts to Other Disciplines

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

Flight Mechanics

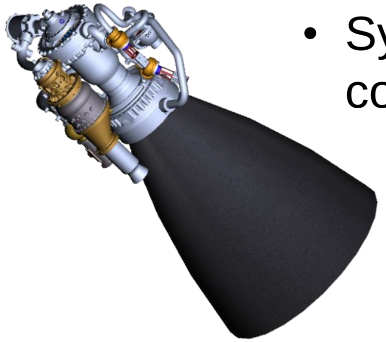
- GN&C (sensors, controllability, targeting)
- Engine operating conditions
- Integrated aero effects models
- RCS effectiveness
- Propellant usage

Navigation Sensors

- Sensor requirements, integration, performance
- Vehicle accommodation, look angles

Propulsion

- Engine operating conditions
- System performance and controllability

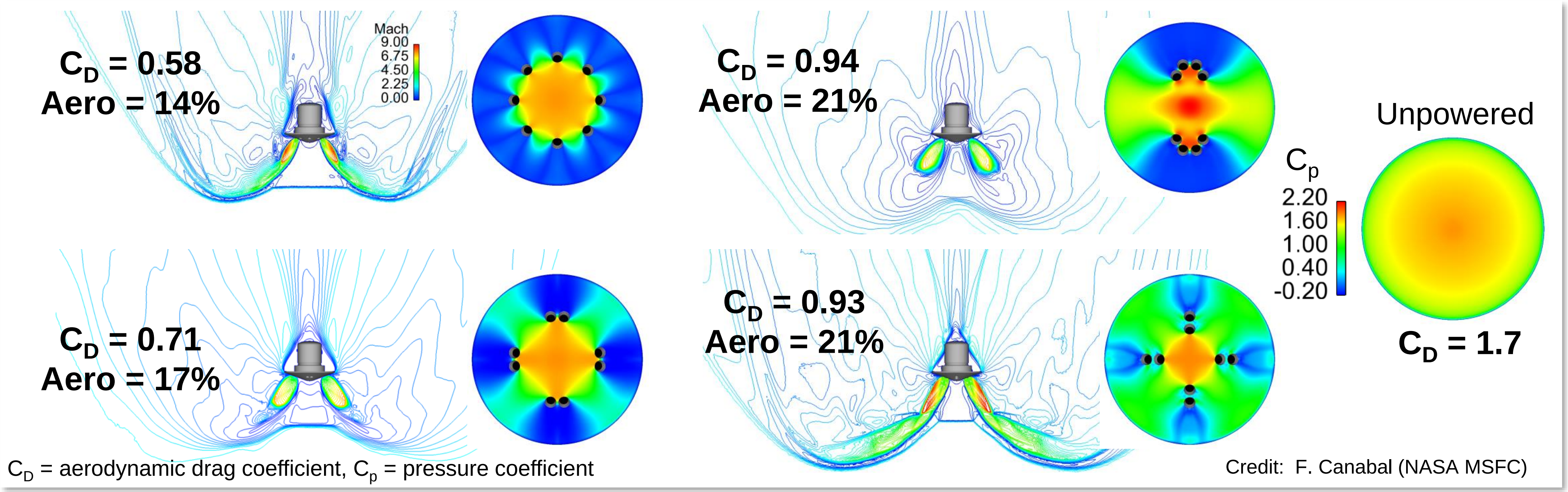


Notional
CAD Model

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

Example: Engine Configuration



C_D = aerodynamic drag coefficient, C_p = pressure coefficient

Credit: F. Canabal (NASA MSFC)

Mach 2.7, time-averaged CFD solutions, engines canted outboard 20º, angle of attack = 0º

- **Powered C_D ranges from 40% to 70% of the unpowered C_D *at these conditions***
- **Over-expanded plumes are less steady and more difficult/expensive to predict**
- **Engine cant and arrangement emphasize variation with configuration**
- **Governing behavior well-understood for one nozzle, less understood for multiple nozzles whose plumes may interact (AIAA 2020-0039)**

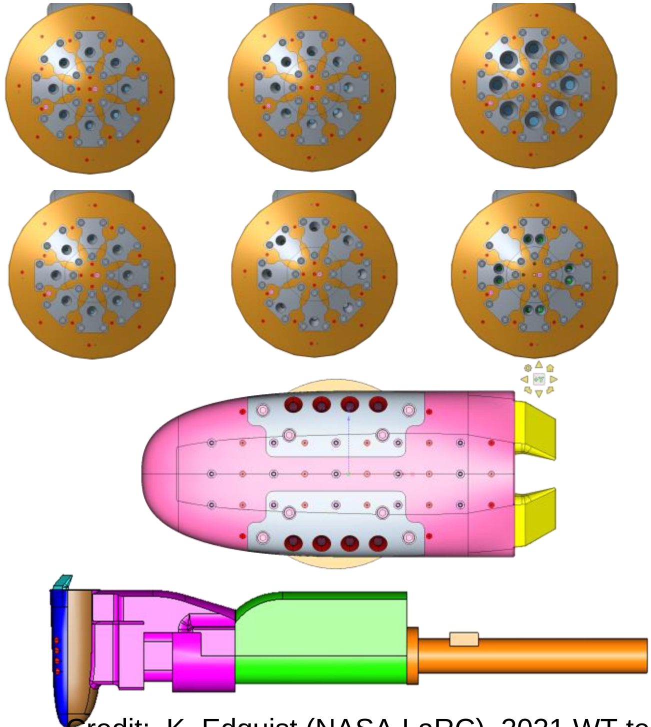
Ground Testing

State of the Art

- Inert gas simulant, subscale models, limited configurations with multiple nozzles at supersonic conditions
- Discrete surface pressures and pressure sensitive paint (PSP) for force and moment data
- High-speed schlieren visualization

Challenges

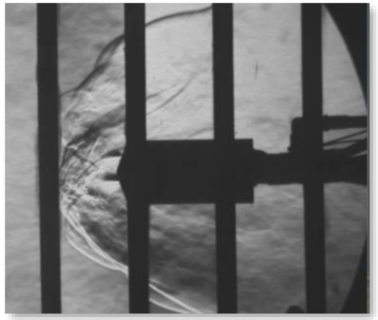
- Limited environments and facilities
- Limitations on model scale
- Hot-fire testing complex and expensive
- Direct force and moment measurement (steady and unsteady)



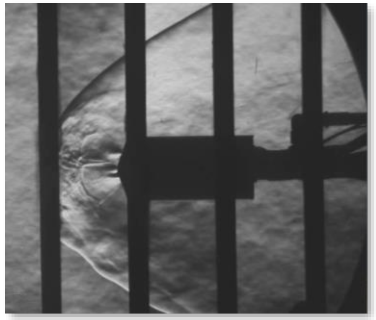
Credit: K. Edquist (NASA LaRC), 2021 WT testing (AIAA 2020-2230)

Zero nozzles

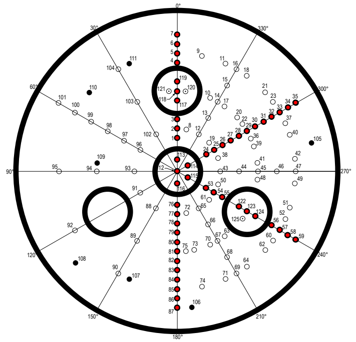
One center nozzle



Three nozzles



Four nozzles



Credit: S. Berry (NASA LaRC), 2010/2011 WT testing

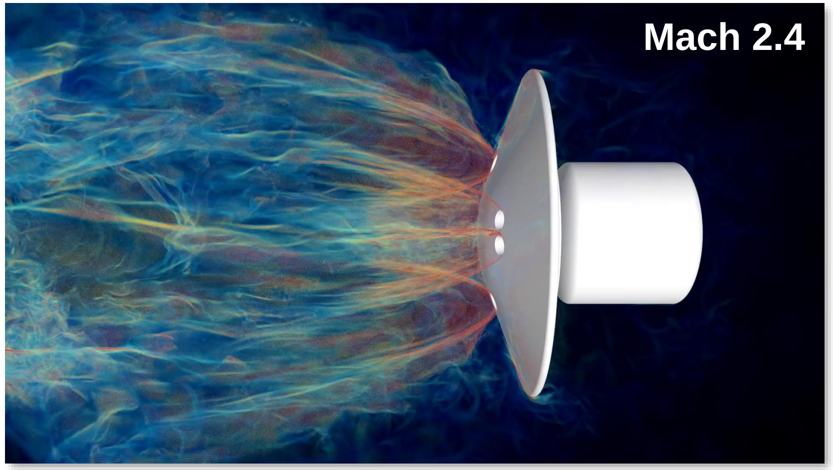
Computational Modeling

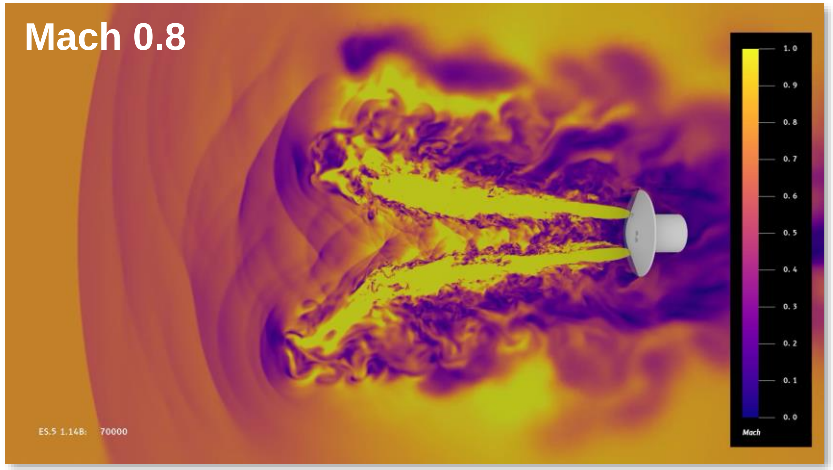
State of the Art

- **Full-scale vehicle with Detached Eddy Simulation (DES) methods on GPU-based computing resources**
- **Inert gas (air, semi-validated), full chemistry (unvalidated)**
- **Capture of most major flowfield features for limited scenarios**

Challenges

- **Large range of physical scales**
- **Complex, unsteady, viscous-dominated flow physics**
- **Computationally expensive for even individual solutions**
- **Insufficient validation data from ground testing**
- **Limitations of ground test environments will increase reliance on predictive computational capability**
- **Minimal (validated) work exists for plume-induced aerothermal environments during powered descent**

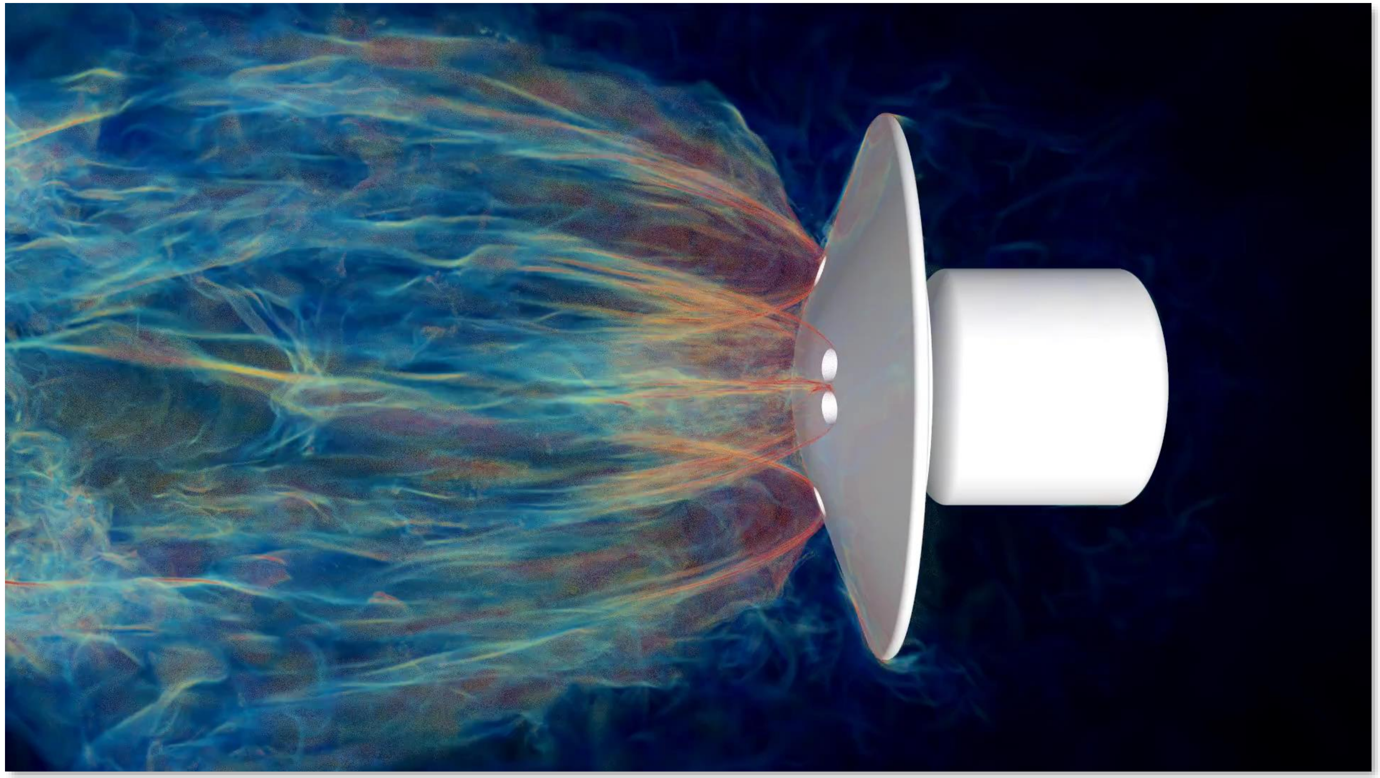




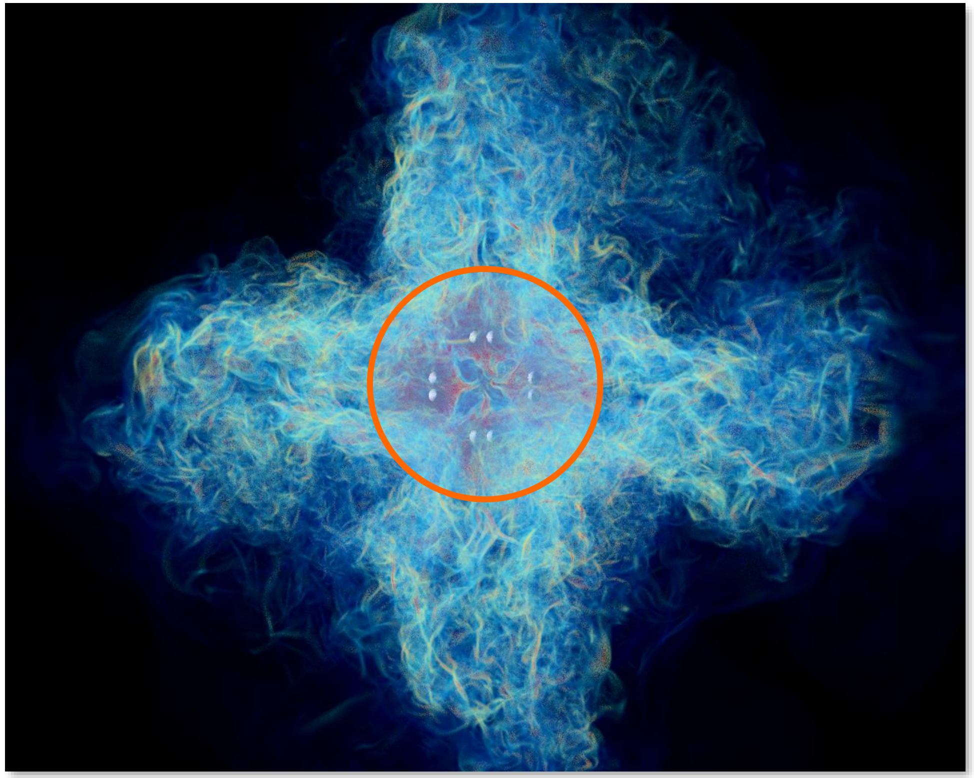
Credit: A. Korzun (NASA LaRC) and T. Sandstrom (NASA ARC), ORNL Summit supercomputing resources

Results: Mach 2.4

All engines at 80% throttle (individual engines are under-expanded)
Vorticity magnitude contours



Side view

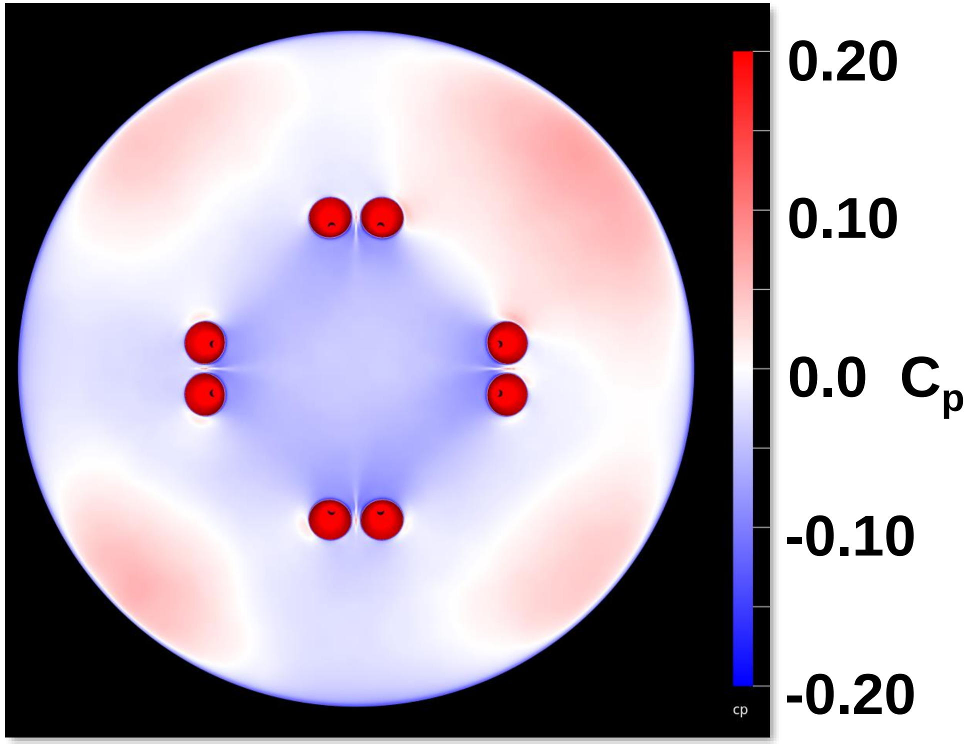


Facing the heatshield

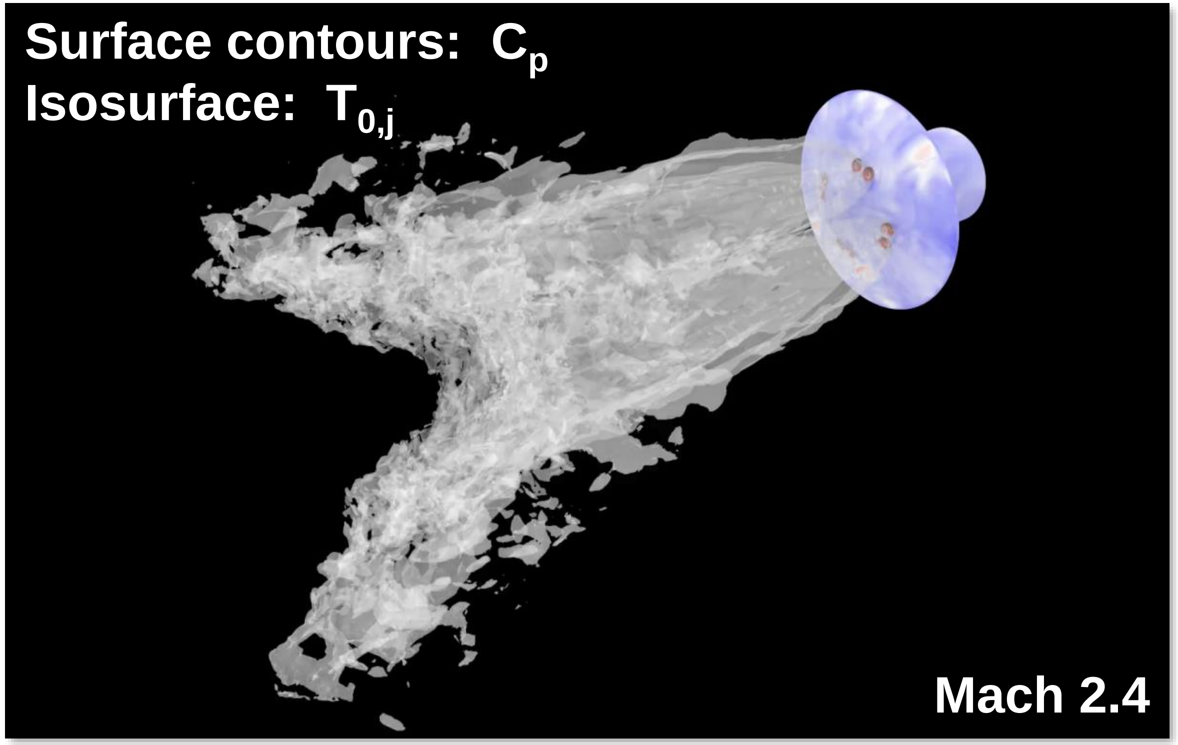
Vehicle-level design decisions are directly impacted by the ability to characterize and bound aerodynamic-propulsive interference effects

Results: Mach 2.4

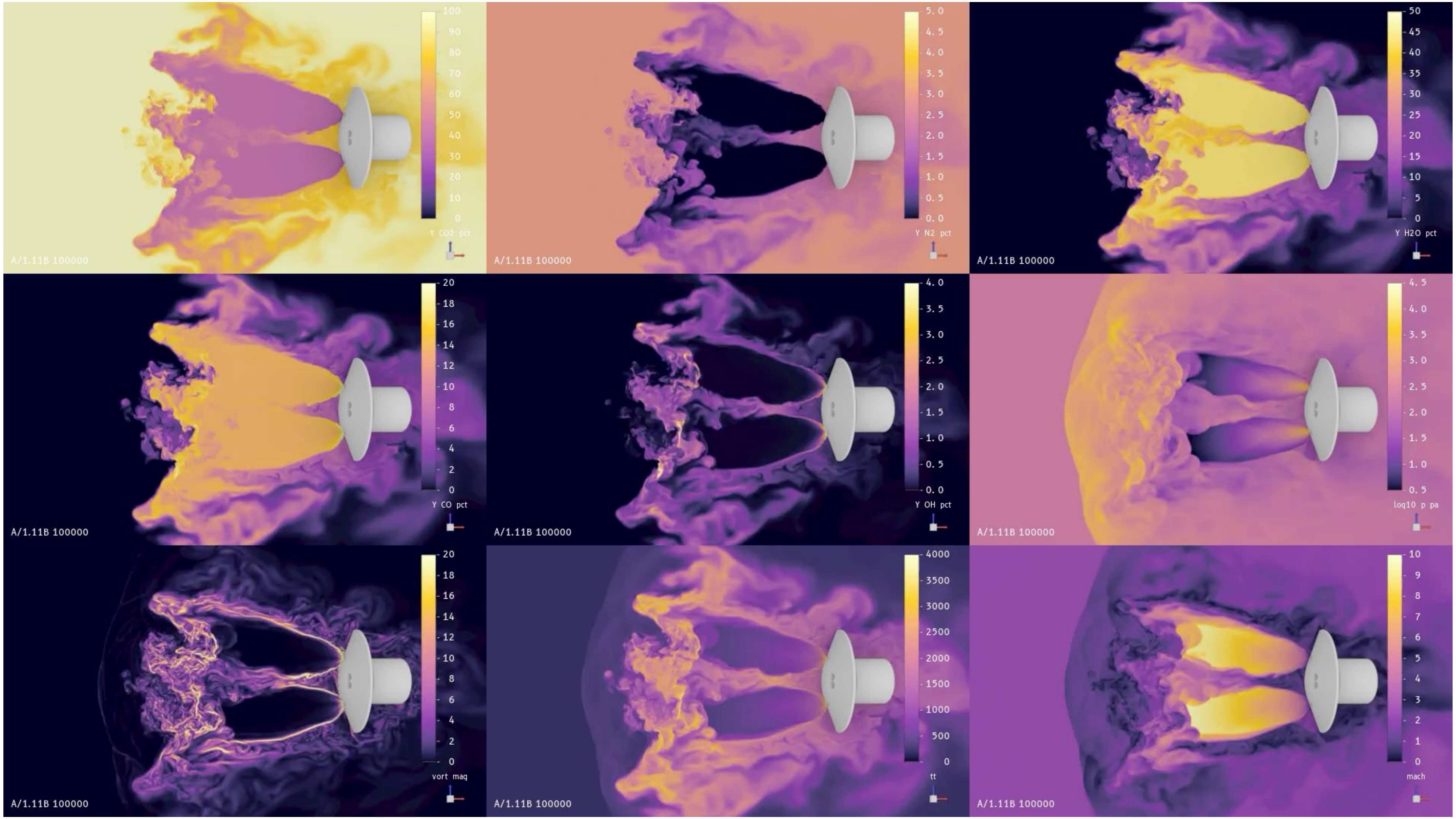
All engines at 80% throttle ($p_e/p_{0,2}$ = 1.25)



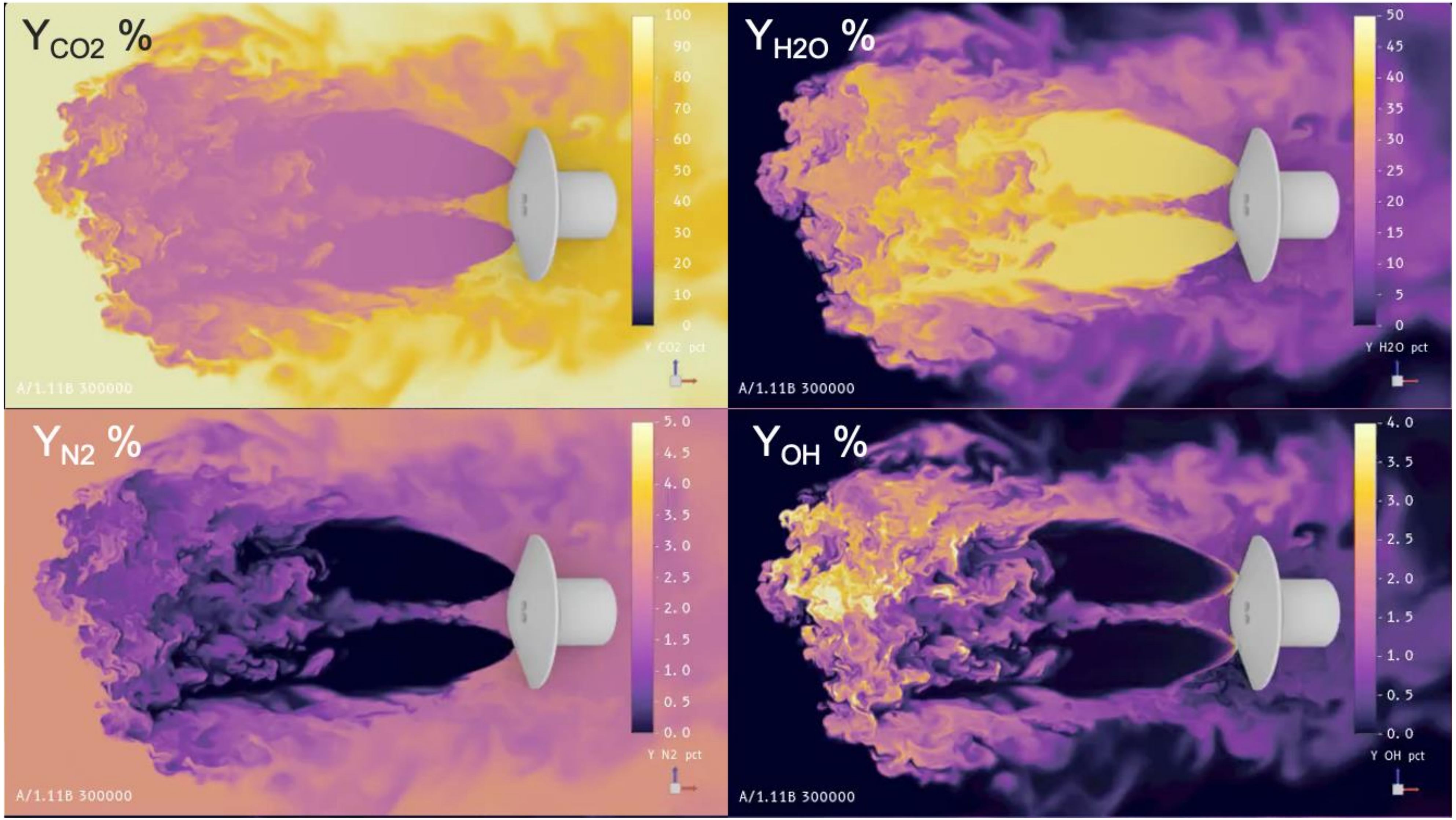
Time-averaged C_p contours



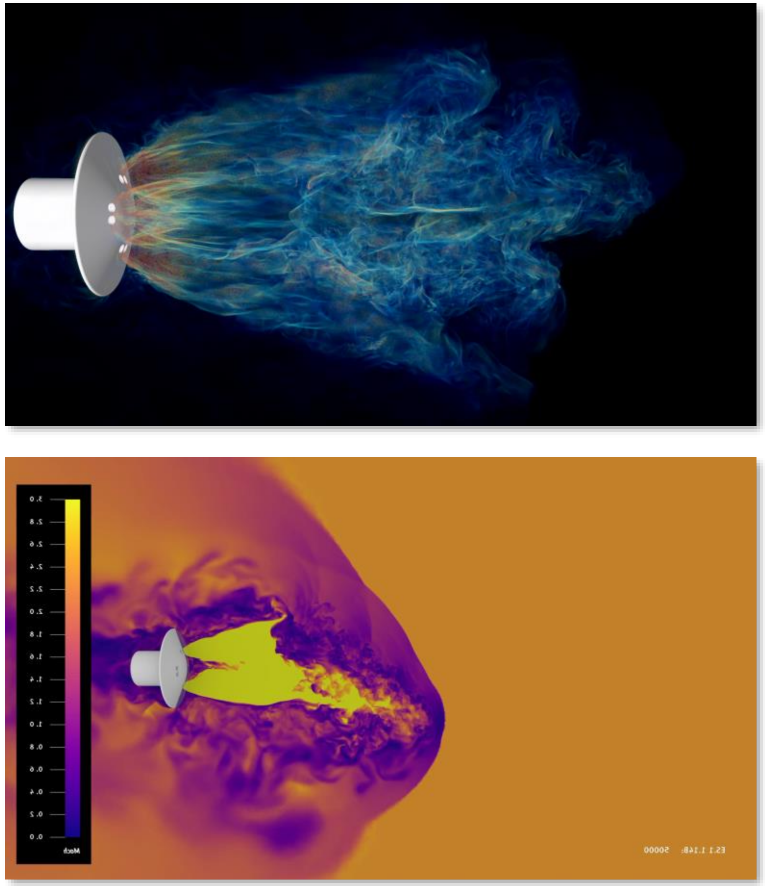
Results: Mach 2.4 (10-species)



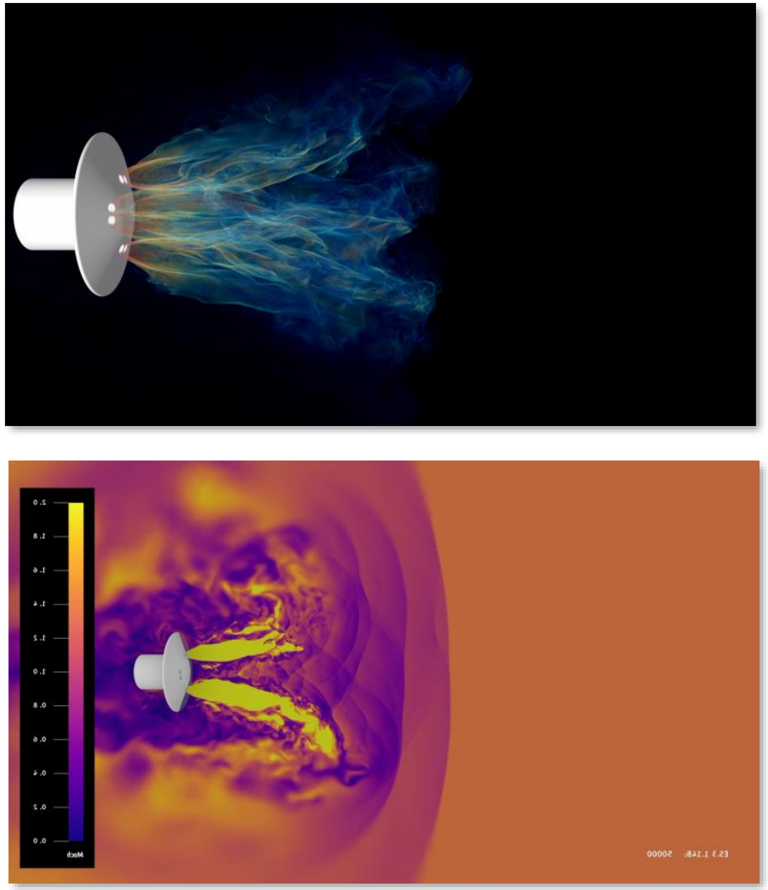
Results: Mach 2.4 (10-species)



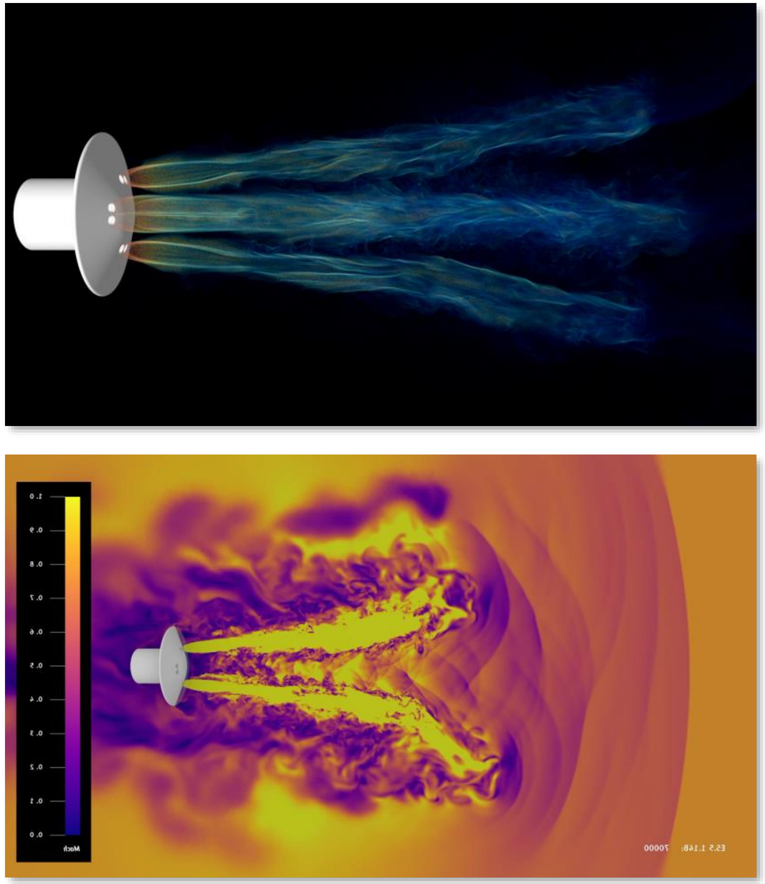
Results: Freestream Mach Number



M_∞ = 2.4



M_∞ = 1.4

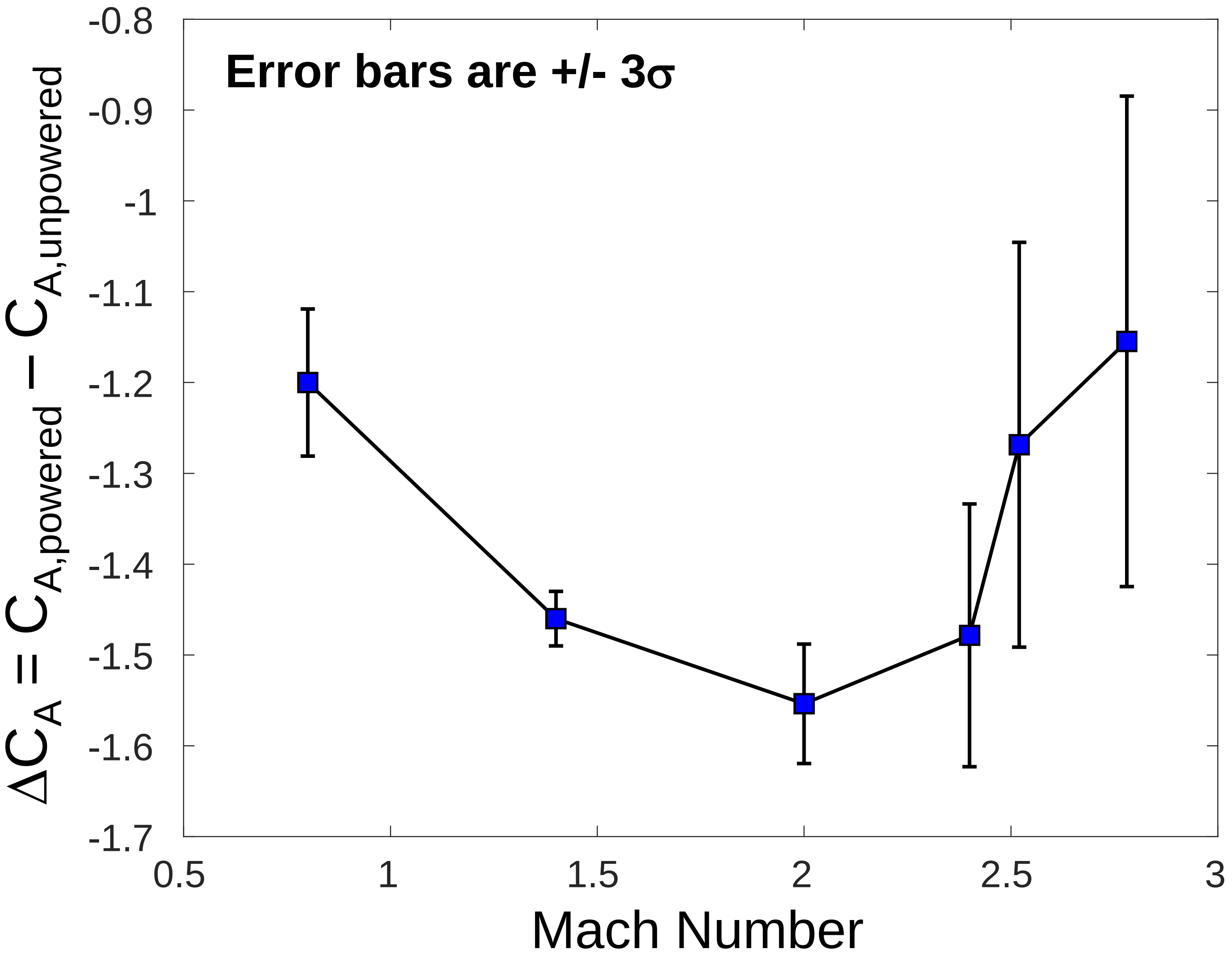


M_∞ = 0.8

→

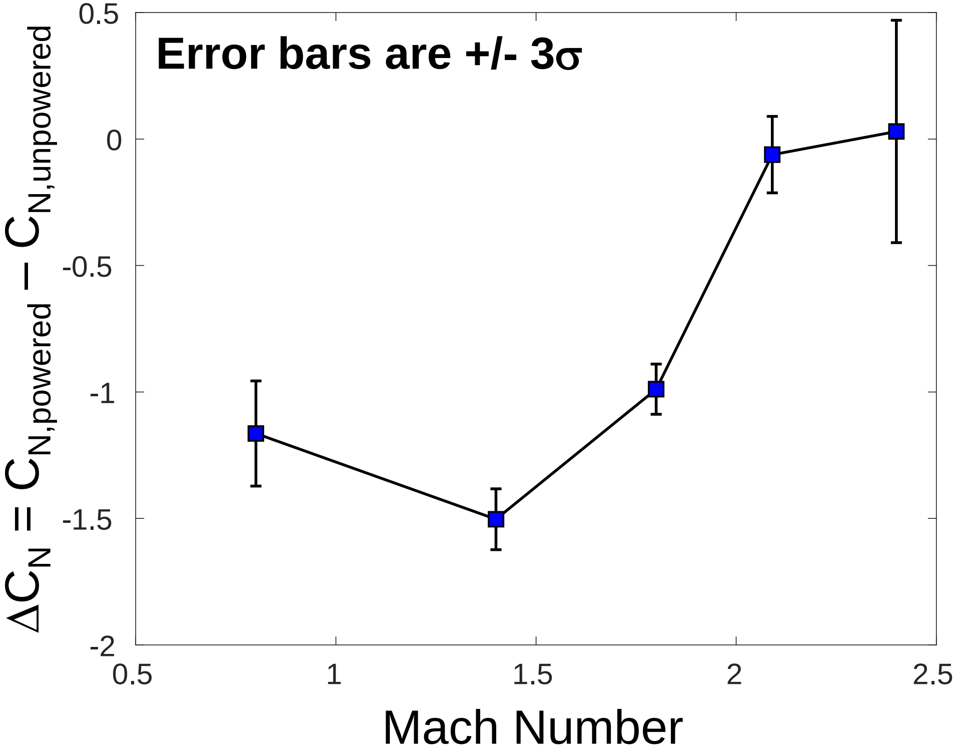
Vehicle decelerates along the descent trajectory

Low-L/D Aerodynamics Model

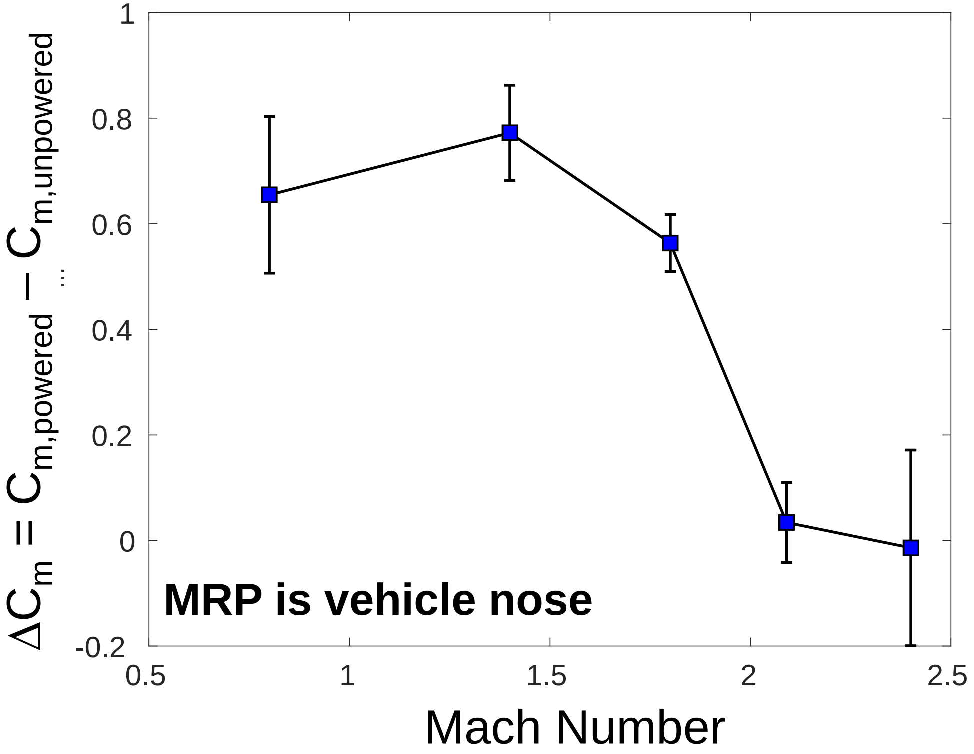


- Prior analyses turned aero off when engines are turned on
- Uncertainties account for variation in individual solutions and code-to-code differences
- Uncertainties are largest for over-expanded and marginally under-expanded engines

Mid-L/D Aerodynamics Model



Error bars are +/- 3σ



MRP is vehicle nose

- Uncertainties account for variation in individual solutions and code-to-code differences
- Uncertainties are largest for over-expanded and marginally under-expanded engines
- Investigation of C_m behavior, particularly for other AOAs, is ongoing

Flight Testing

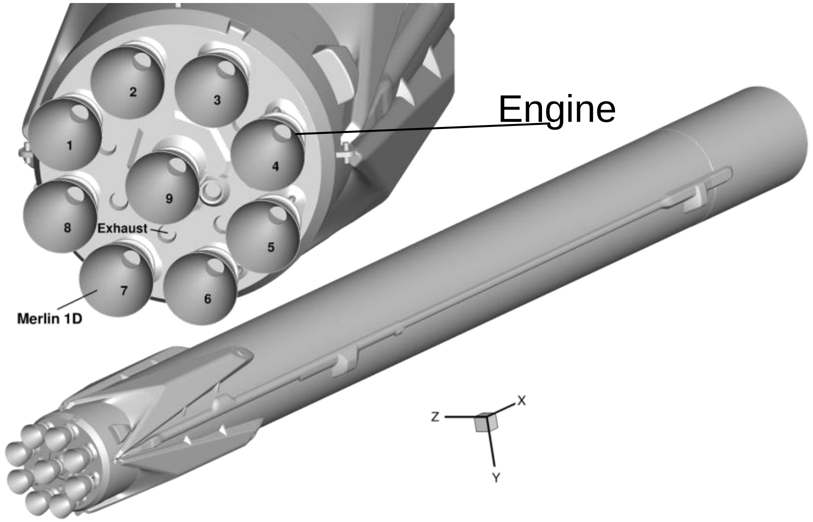
State of the Art

- Falcon 9 1st stage booster recovery
- Minimal aerodynamic surface area relative to engine area
- High C_T, low A_e/A^*
- Initial test flights through Mars-relevant conditions

Challenges

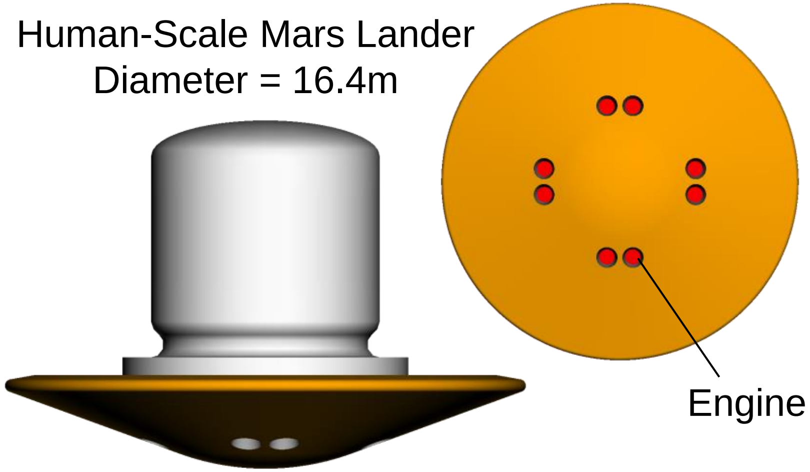
- Mars-relevant conditions: ~ 30.5 km (Earth) altitude
- Costly, complex, integrated systems
- Limited to validation of extrapolated simulations

Credit: SpaceX



Falcon 9 Launch
Vehicle 1st Stage
Diameter = 3.7m

Credit: K. Edquist,
AIAA 2017-5296



Human-Scale Mars Lander
Diameter = 16.4m

Lunar Exploration

- Coming years will see uptick in lunar landing attempts, all of which will use powered descent
- Points of departure for:
    - Long-term cryogenic storage
    - Engine performance
    - GNC with retropropulsion
    - Plume-surface interaction

With no atmosphere, lunar exploration will not reduce aerosciences risks for powered descent at Mars

But what about propulsive landing on the Moon…?

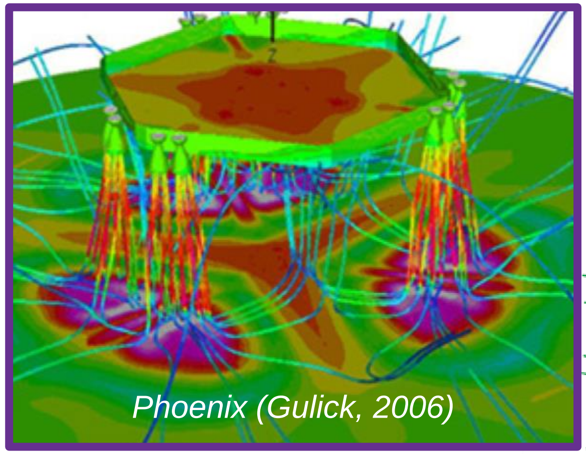
Plume-Surface Interaction (PSI)

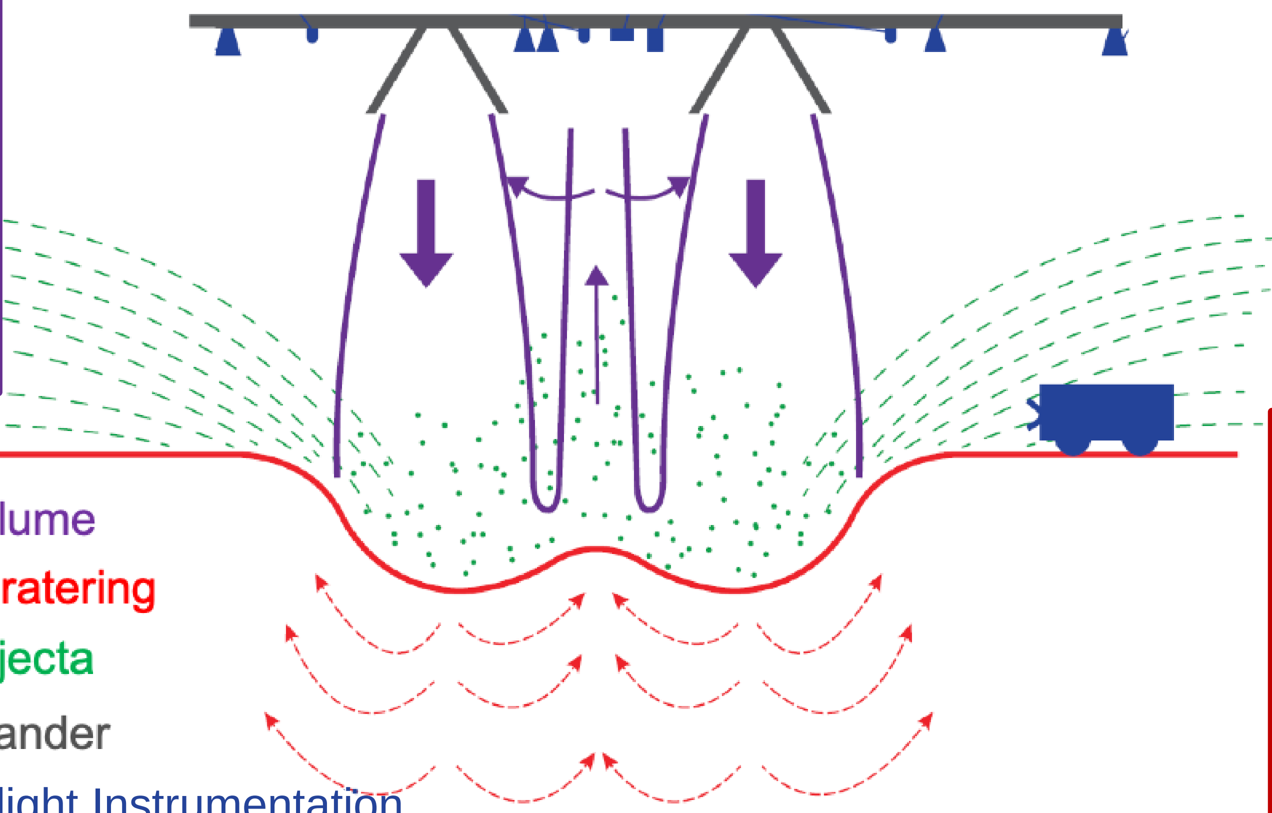
18 February 2021: Jezero Crater, Mars

Image Credit:
NASA, JPL

Plume-Surface Interaction (PSI)

Rocket **plume-surface interaction (PSI)** is a multi-phase and multi-system complex discipline that describes the lander environment due to the impingement of hot rocket exhaust on regolith of planetary bodies.


Phoenix (Gulick, 2006)


Plume

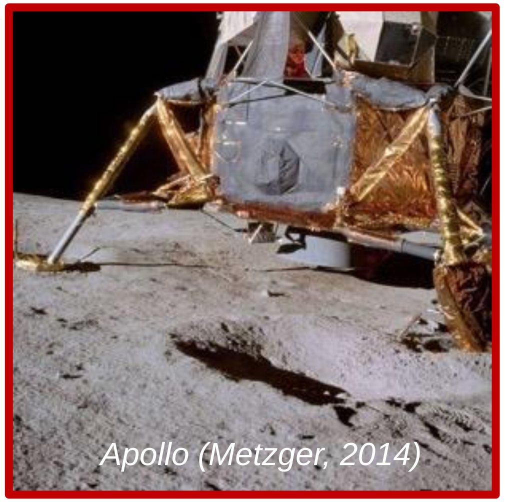
Cratering

Ejecta

Lander

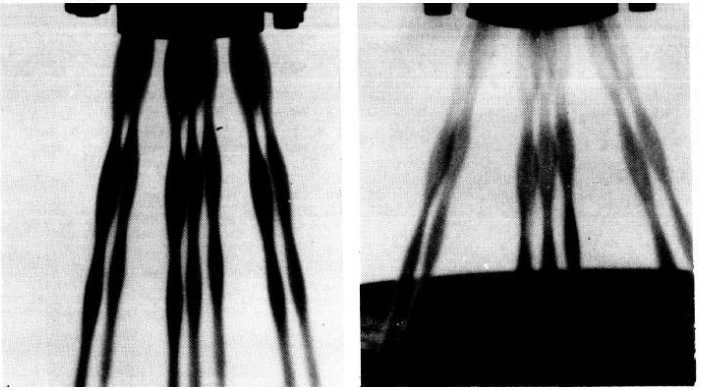
Flight Instrumentation
and Surface Assets


InSight Mars Lander

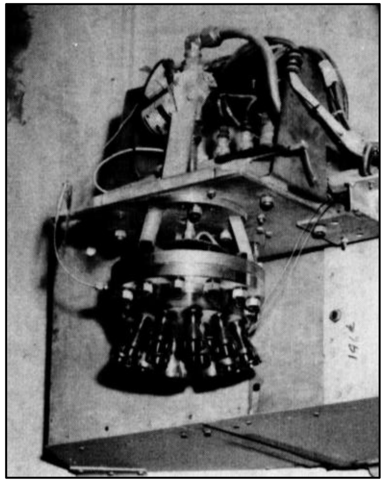

Apollo (Metzger, 2014)

Viking (1976)

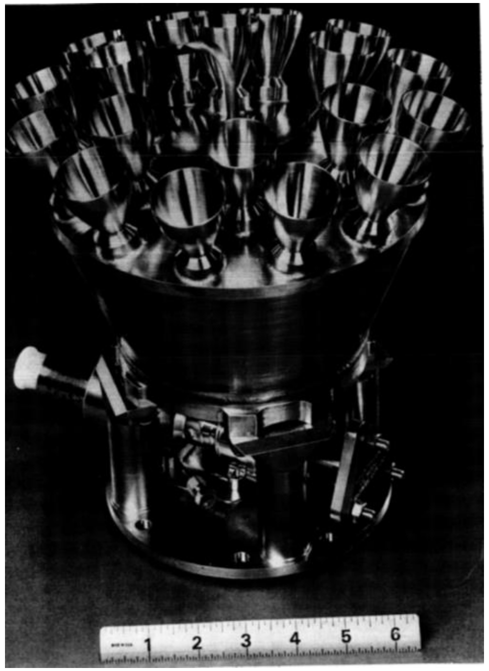
- Viking was concerned with PSI and conducted testing that is still heavily relied upon today
- Special 18-bell 'showerhead' nozzle developed to keep direct impingement pressure below 2 kPa



Columnated plumes at different cant angles with 7-bell Viking engine



Viking landing engine PSI test at White Sands Test Facility



18-bell Viking landing engine

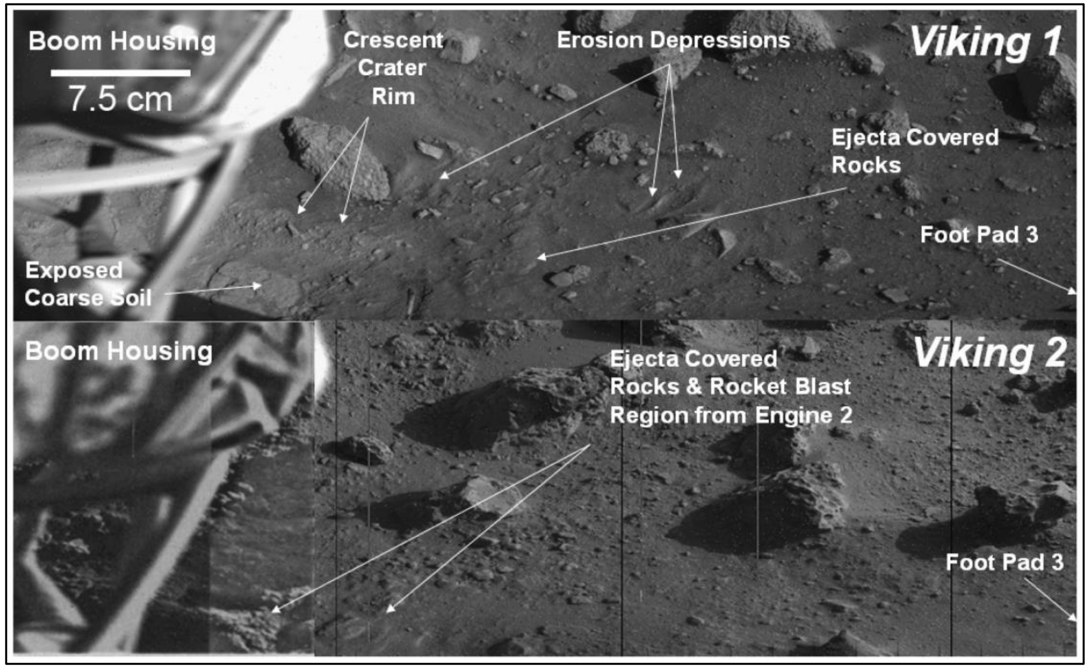


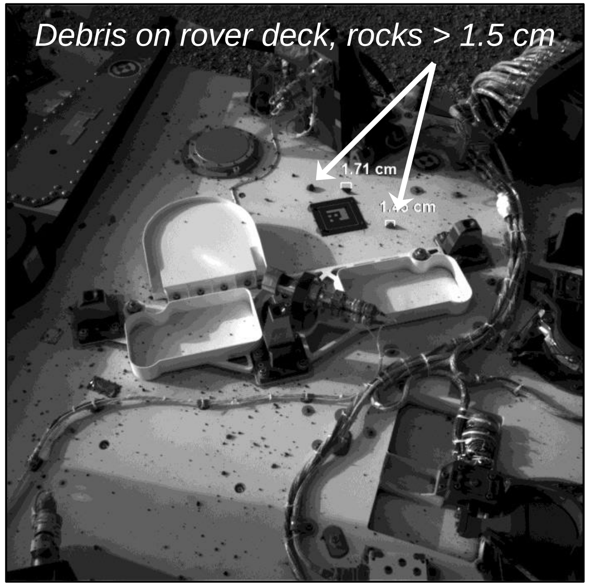
Image Credits:

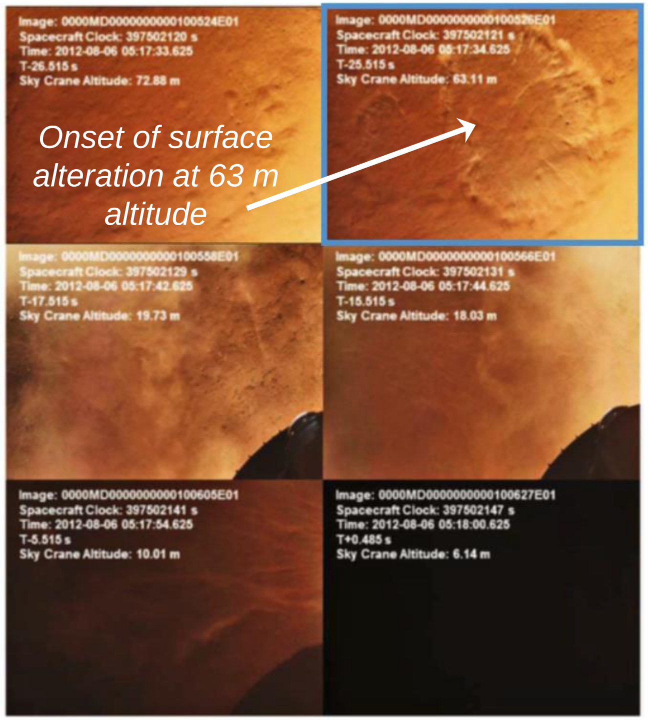
(1) Romine, G., Reisert, T., and Gliozzi, J., "Site Alteration Effects from Rocket Exhaust Impingement During a Simulated Viking Mars Landing", NASA CR-2252, 1973.

(2) Mehta, M., "Plume-Surface Interactions due to Spacecraft Landings and the Discovery of Water on Mars", Ph.D. Dissertation, Univ. of Michigan, 2010.

Mars Science Laboratory (2012)

- Skycrane designed to mitigate PSI effects and damage to science payload
- Surface erosion observed to begin at ~ 63 m above the surface
- Crater depth estimates range from 5 to 20 cm before exposing bedrock
- Damaged wind sensor (hypothesized to be damaged by PSI)


Debris on rover deck, rocks > 1.5 cm



Onset of surface alteration at 63 m altitude

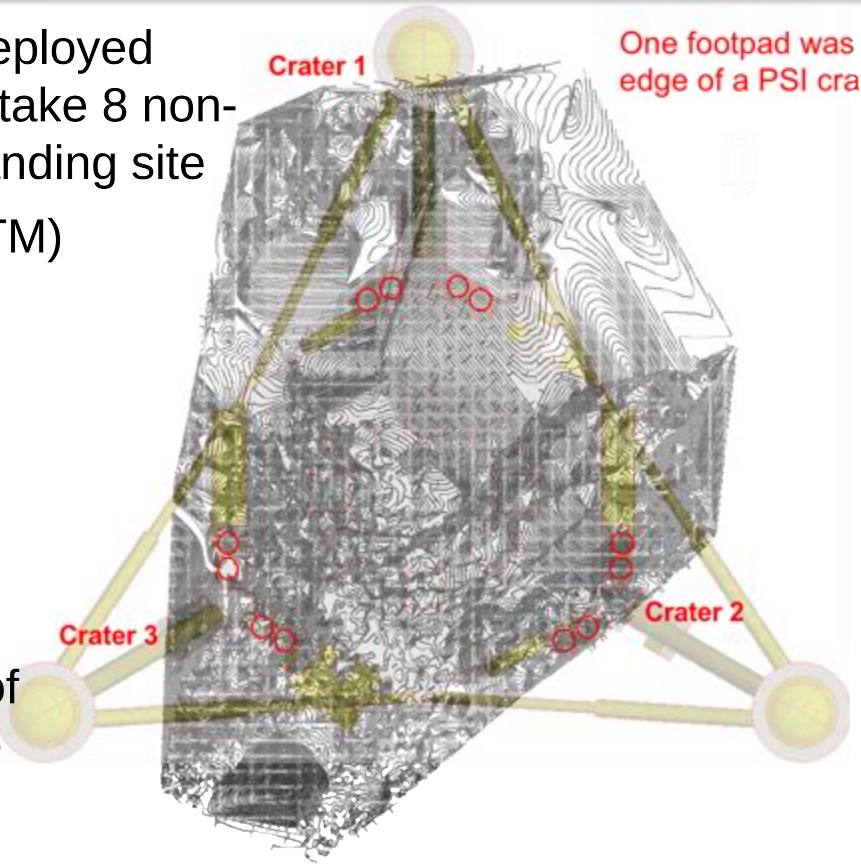
MARDI images showing progression of surface alteration

Panorama with MSL plume impingement craters

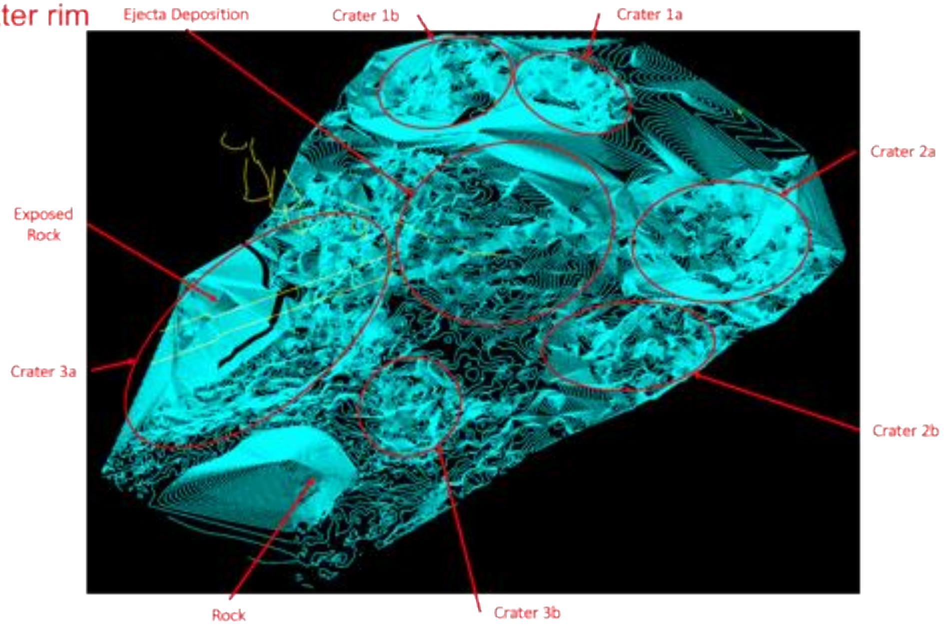
Image Credits:
(1) Bradford, E., Rabinovitch, J., and Abid, M., "Regolith Particle Erosion of Material in Aerospace Environments", IEEE, 2019.
(2) Vizcaino, J. and Mehta, M., "Quantification of Plume-Soil Interaction and Excavation due to the Skycrane Descent Stage", AIAA 2015-1649, 2015.

InSight (2018)

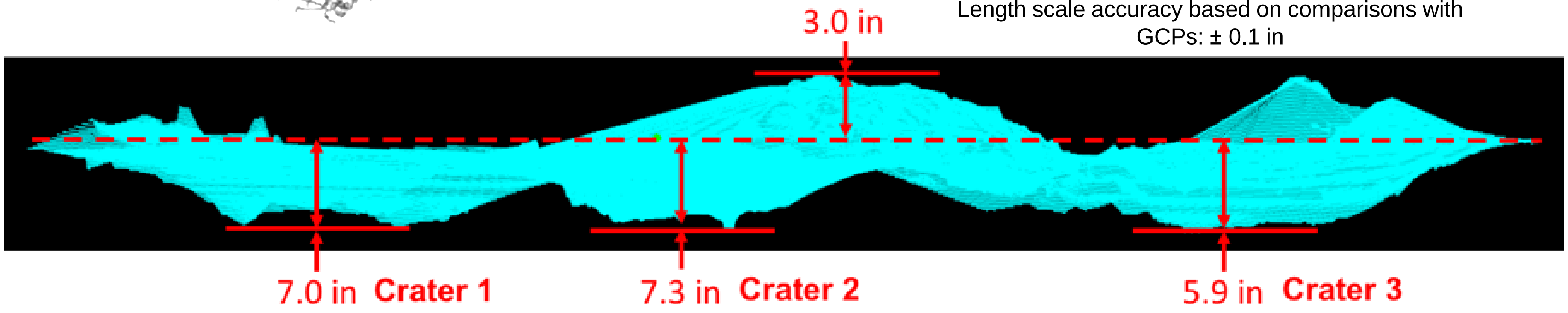
- InSight's Instrument Deployed Camera (IDC) used to take 8 non-stereo images of the landing site
- Digital Terrain Map (DTM)
- Crater volume
- Erosion rate
- Avg. crater diameter:
  - 20 inches wide
  - 7 inches deep
- One footpad on edge of crater rim – could have led to a ~5º tilt of the lander



One footpad was on the edge of a PSI crater rim

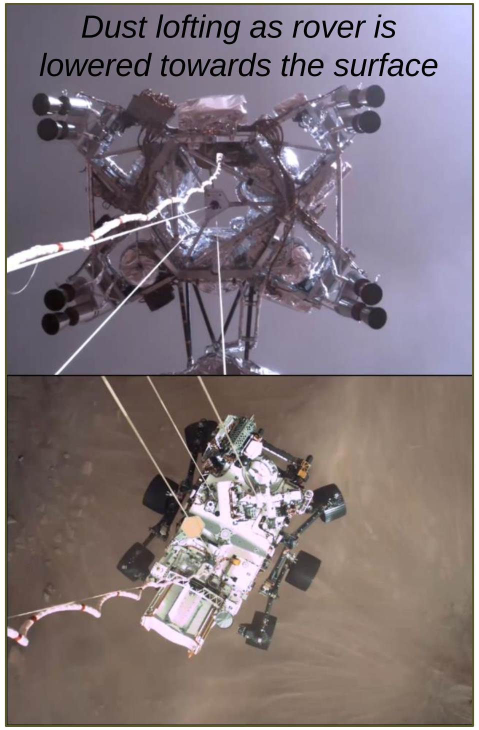


Length scale accuracy based on comparisons with GCPs: ± 0.1 in



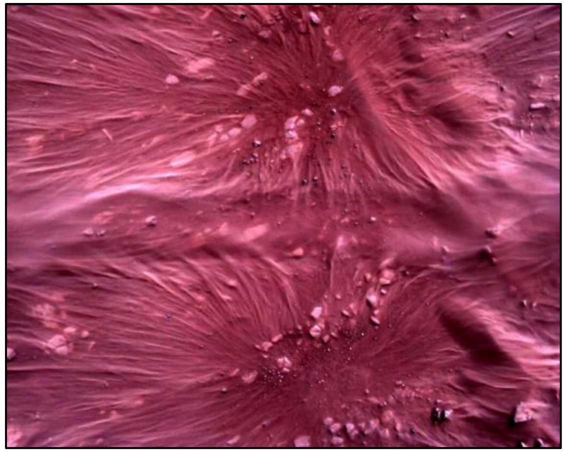
Mars2020 (2021)

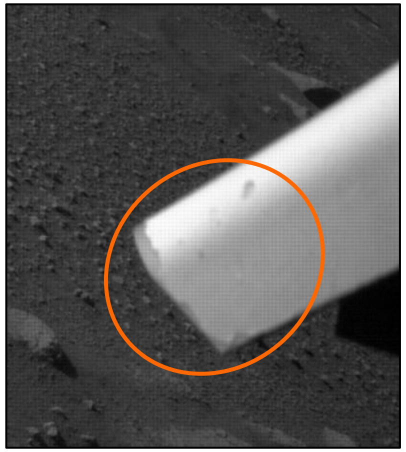
- Similar to MSL, M2020 also used the Skycrane to mitigate PSI effects
- For the first time, data from uplook and downlook cameras on the descent stage and rover provided visualization of PSI


Dust lofting as rover is lowered towards the surface


Nearly complete visual obscuration of the rover by touchdown


Skycrane begins to depart and dust begins to dissipate


Mars Lander Engine surface impingement and flow patterns


Paint erosion on the RIMFAX instrument

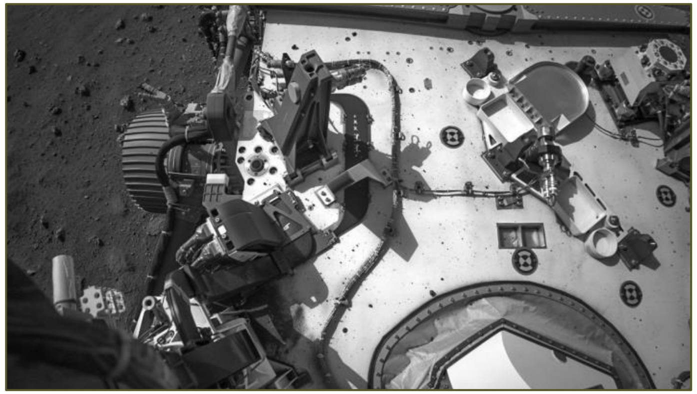
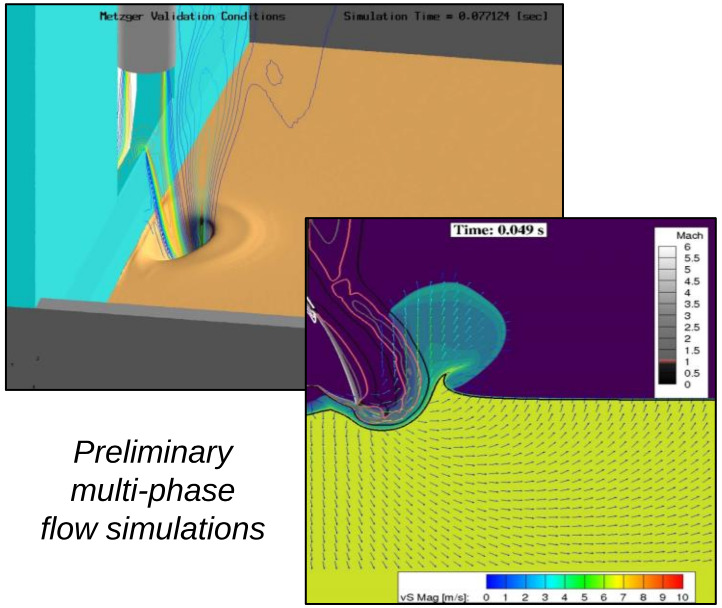

Debris on the Perseverance rover deck

Image Credit:
NASA, JPL

NASA's PSI Project

Computational Modeling & Simulation

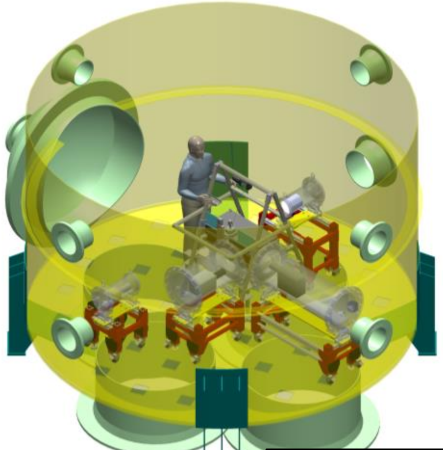
- Plume flow in low-pressure environments
- Effect of mixed continuum/rarefied flow on erosion and ejecta
- Regolith particle phase modeling
- Gas-particle interaction modeling



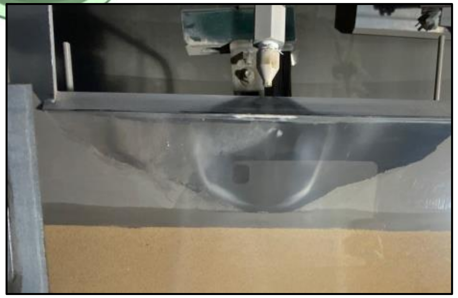
Preliminary multi-phase flow simulations

Ground Testing

- NASA MSFC TS300 sub-scale, inert gas regolith test
- NASA GRC ISP flight-scale hot-fire regolith test



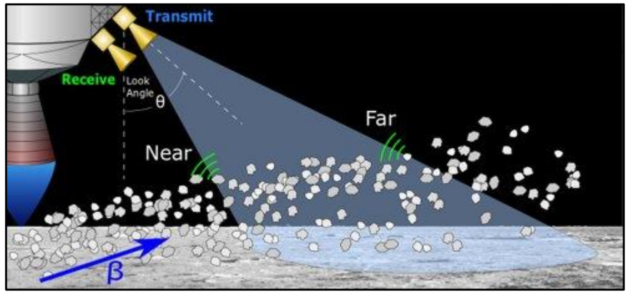
MSFC TS300 test setup



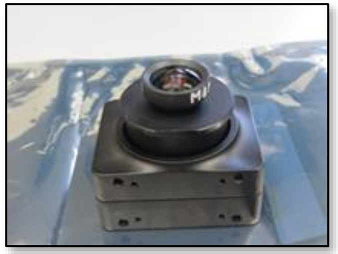
BP-1 crater generated under near-vacuum ambient pressure

Flight Instrumentation

- Improve TRL in relevant testing:
    - Stereo camera (SCALPSS)
    - mm-wave doppler radar
- 3D flight reconstruction with photogrammetry



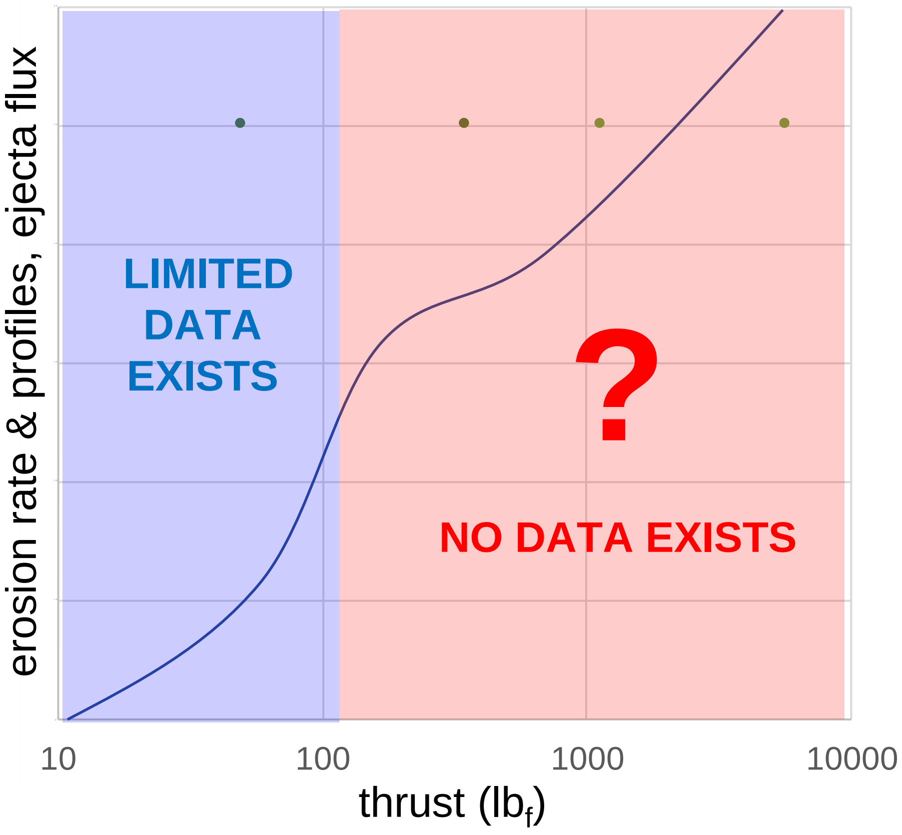
mm-Wave Doppler Radar



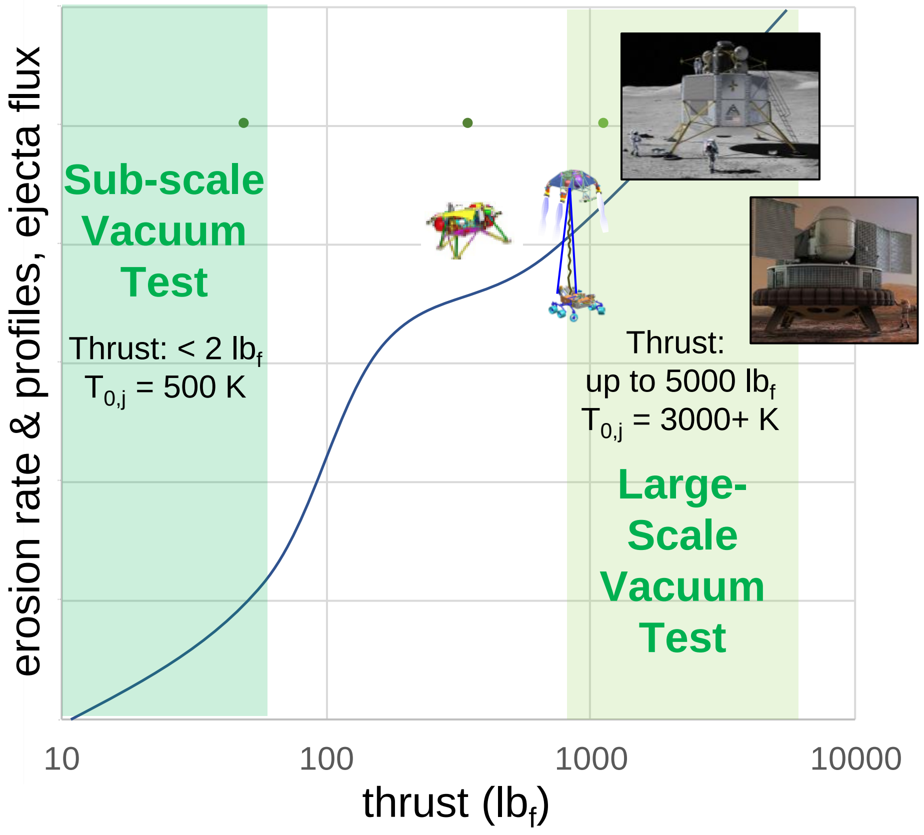
SCALPSS

Need for Relevant Test Data

Current Situation



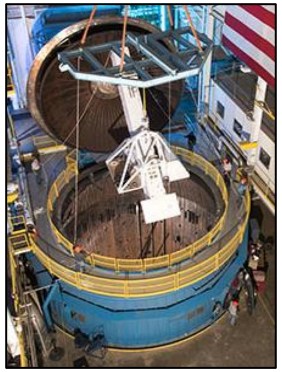
PSI Project



These two ground tests are the first opportunity since Viking to obtain flight-relevant PSI data through controlled, well-characterized ground testing

Sub-scale Inert-gas Test

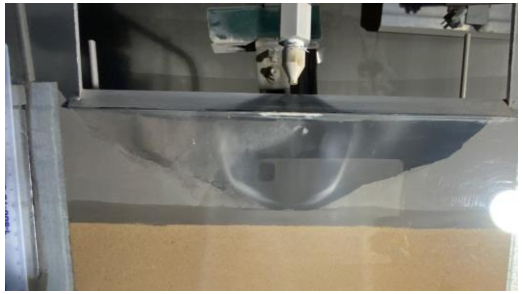
Large-scale Hot-fire Test



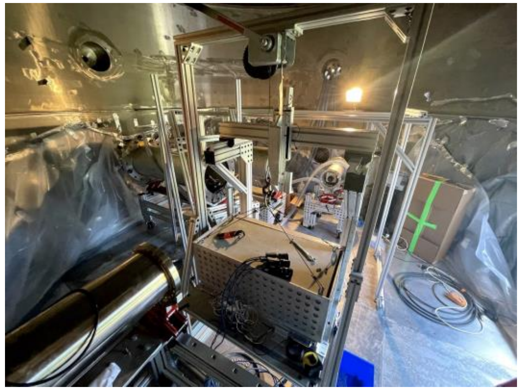
- Relevant ground test data are necessary to validate predictive tools and quantify uncertainty in predictions: *qualitative* → *quantitative environments and impacts*
- No direct measurements of flight-scale data presently exist to inform large-scale landing systems

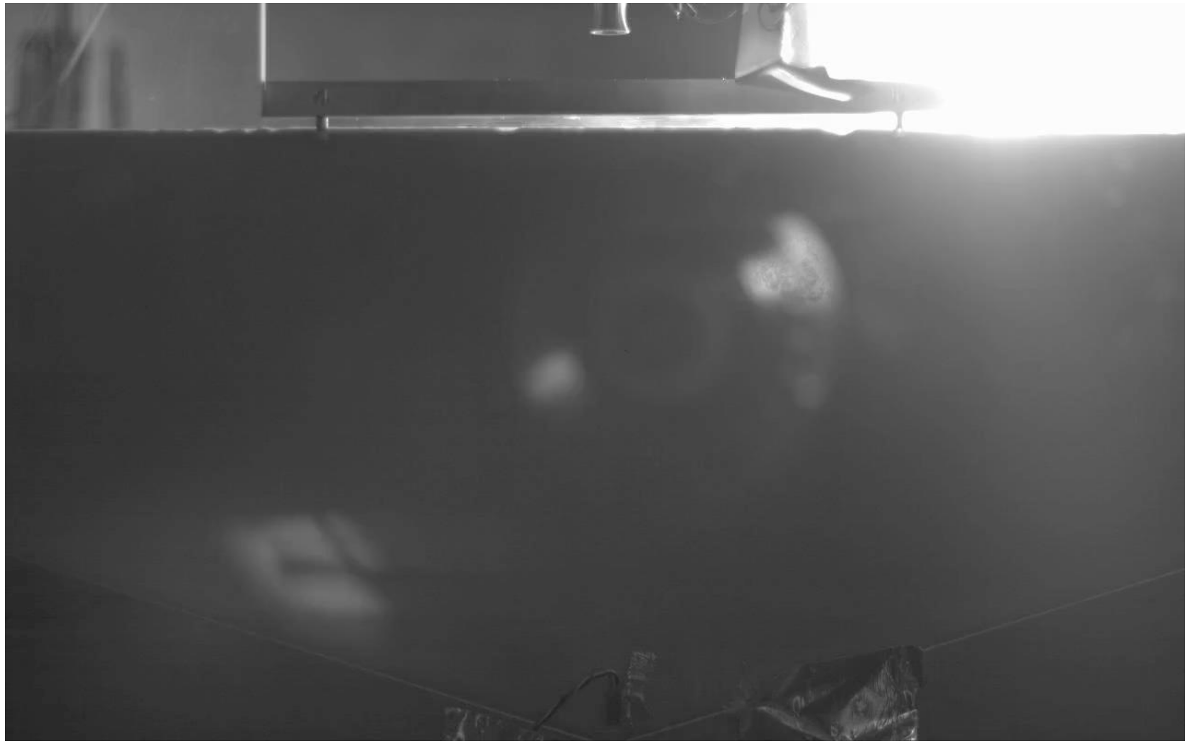
PSI Ground Testing: August 2021

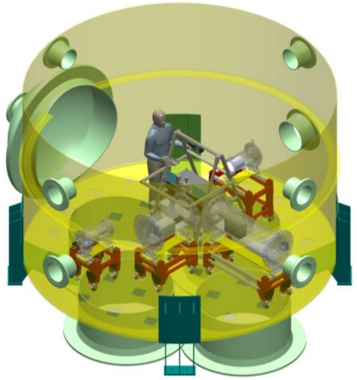
- The Physics Focused Ground Test (PFGT) will collect experimental data of sufficient quality to validate computational simulation and empirical modeling of relevant physics for PSI
- Subscale, inert gas test with heated, supersonic N_2 flow impinging onto a prepared regolith bed and onto an instrumented plate
- Intrusive, half-plane experiment
- Novel high-speed visual diagnostics to capture temporal evolution of 2D crater profile and ejecta behavior

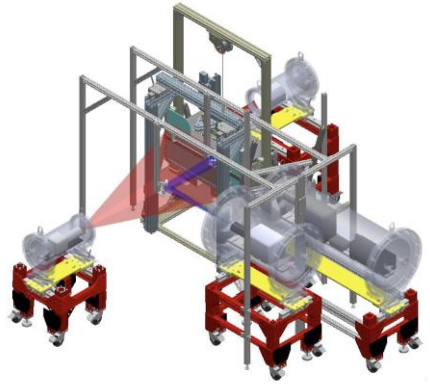

BP-1 crater generated under near-vacuum ambient pressure during pathfinding site visit work


BP-1 dust coating over entire 15-foot vacuum chamber after pump-down outgassing






Diagnostics integration in TS300


CAD showing cratering test integration

Closing

- Vehicle performance evaluation is only as good as the lowest fidelity of the underlying models
- Powered descent aerosciences are inherently coupled to EDL system performance and must be a key player at the conceptual design level
- Due to limitations in ground testing and terrestrial flight environments, development of powered descent for Mars will be heavily reliant on computational modeling and simulation

All propulsive landers are affected by PSI

- It's E, D, ***and L***: When landing paradigms change, PSI returns to the risk list
- Sustainable exploration necessitates looking beyond immediate, near-field vehicle effects
- Lunar landing experience will directly feed forward to Mars

Questions?