Introduction to Plume-Surface Interaction (PSI)

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2022 NASA EDL Summer Seminar Series

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Motivation

18 February 2021: Jezero Crater, Mars

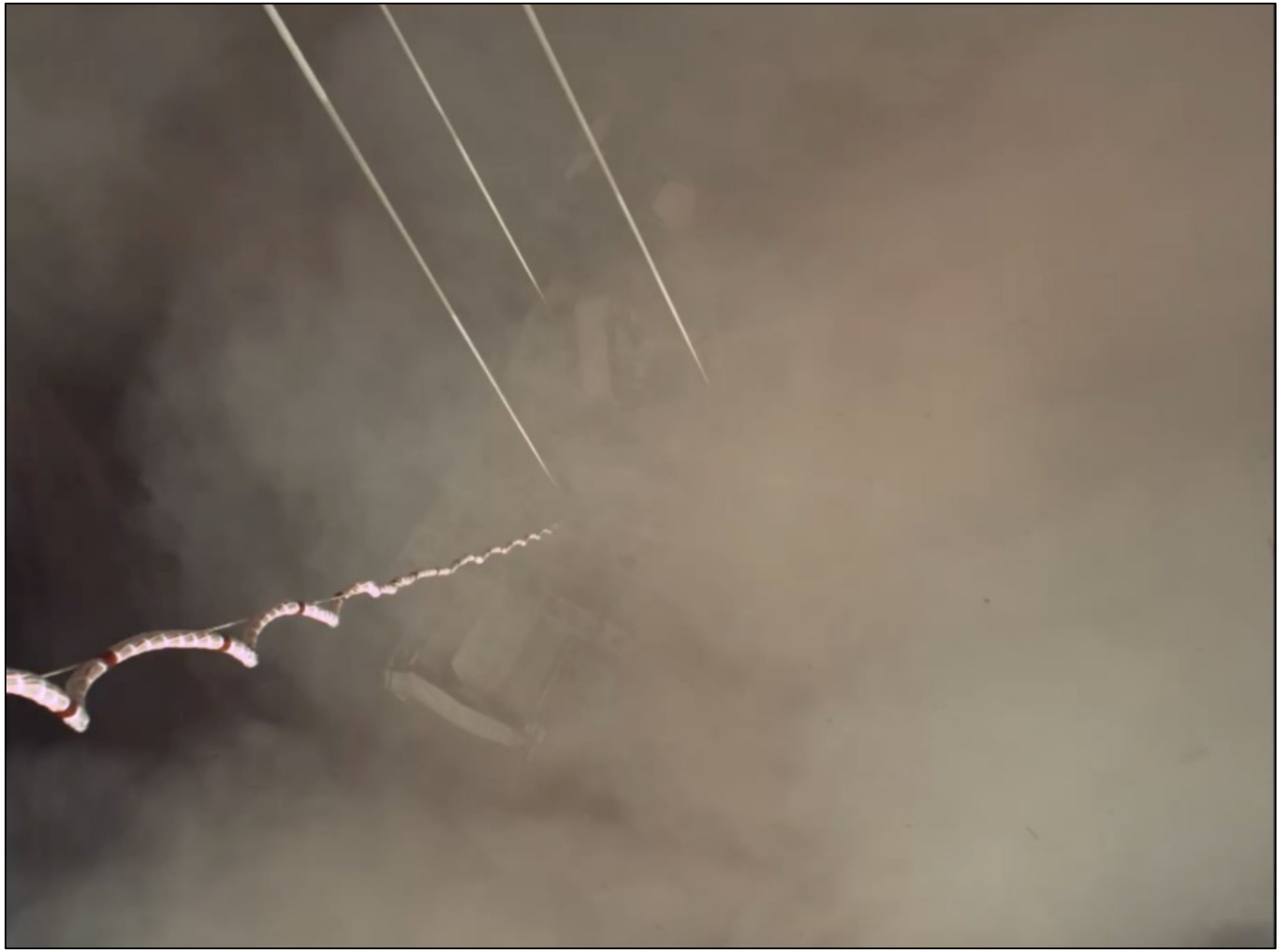


Image Credit:
NASA, JPL

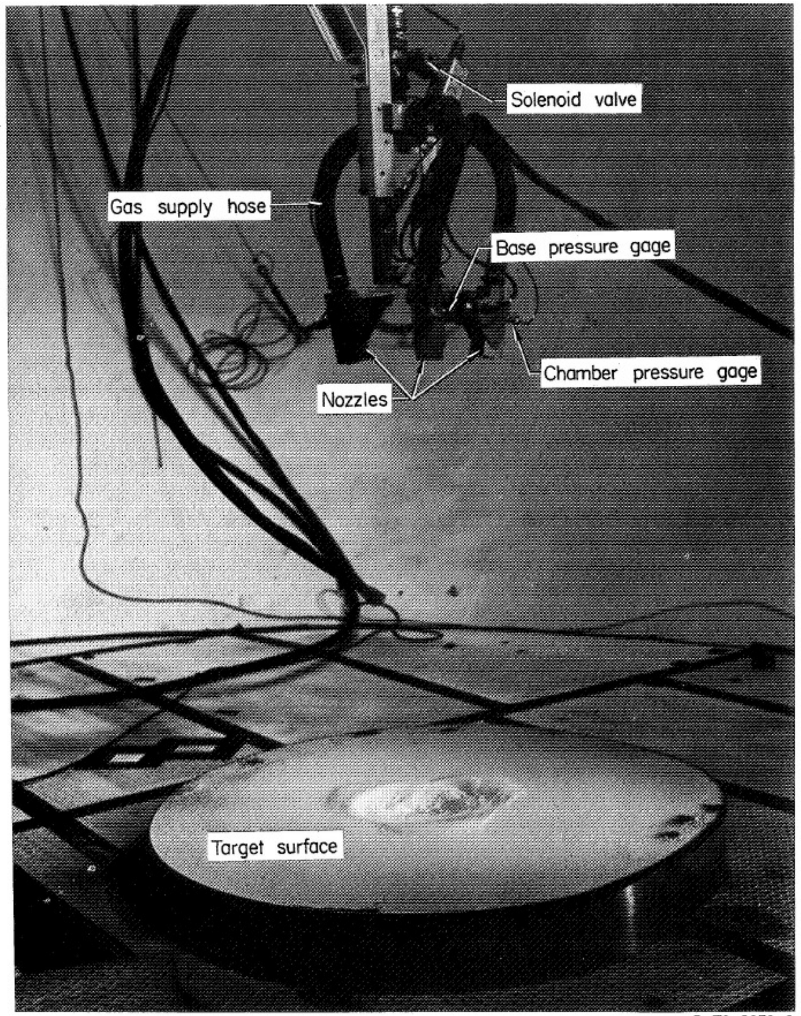
- For both MSL and M2020, visual onset of surface alteration at 65 m AGL
- Skycrane descent stage used 8 Mars Lander Engines (MLEs)
- 1 MLE: 400 – 3100 N thrust

Near total obscuration of Perseverance rover during touchdown with high velocity particulates and debris

Outline

- Introduction
- Historical Work and Flight Experience
- Relevant Physics
- NASA PSI Project Overview
- NASA PSI Ground Testing

Dust obscuration during Apollo 16 Lunar landing (Metzger, 2010)



L-70-2031.1

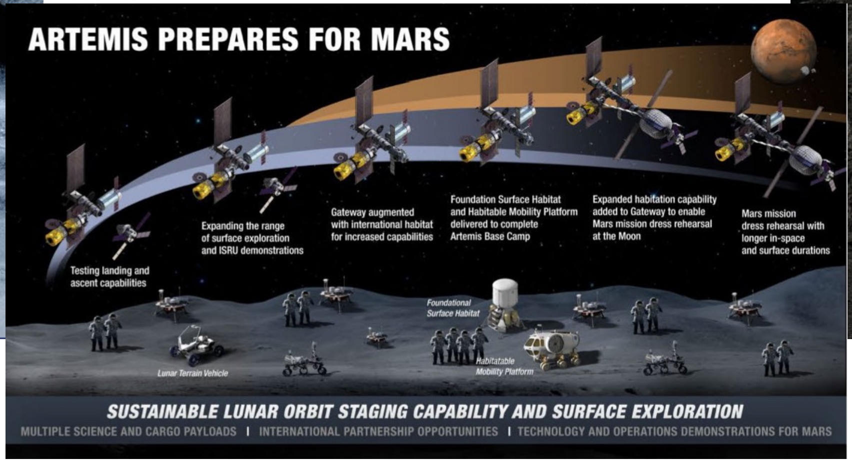
Figure 3.- Photograph of test apparatus installed in Langley 60-foot vacuum sphere.

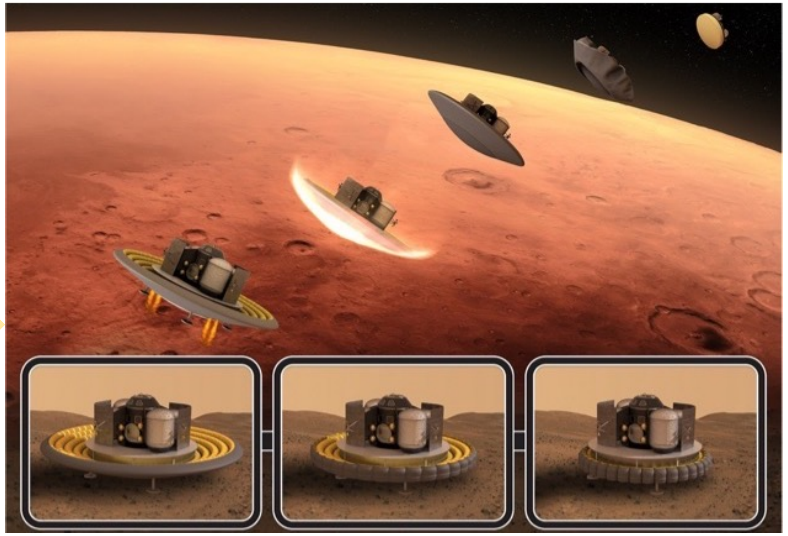
Figure 2.- Jet erosion apparatus in the 55-foot vacuum cylinder at the Langley Research Center. L-67-17

Lunar PSI testing (NASA TN D-5051, 1969)

Future Landing System Evolution

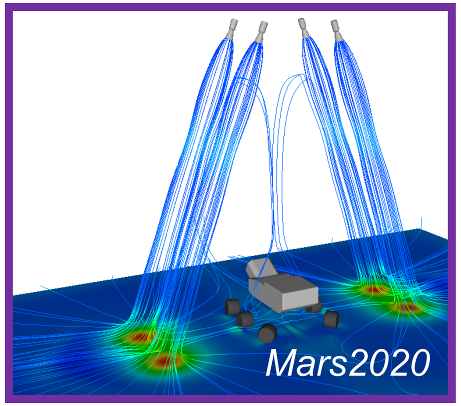
Landers will grow in size and mass to enable sustained human exploration.

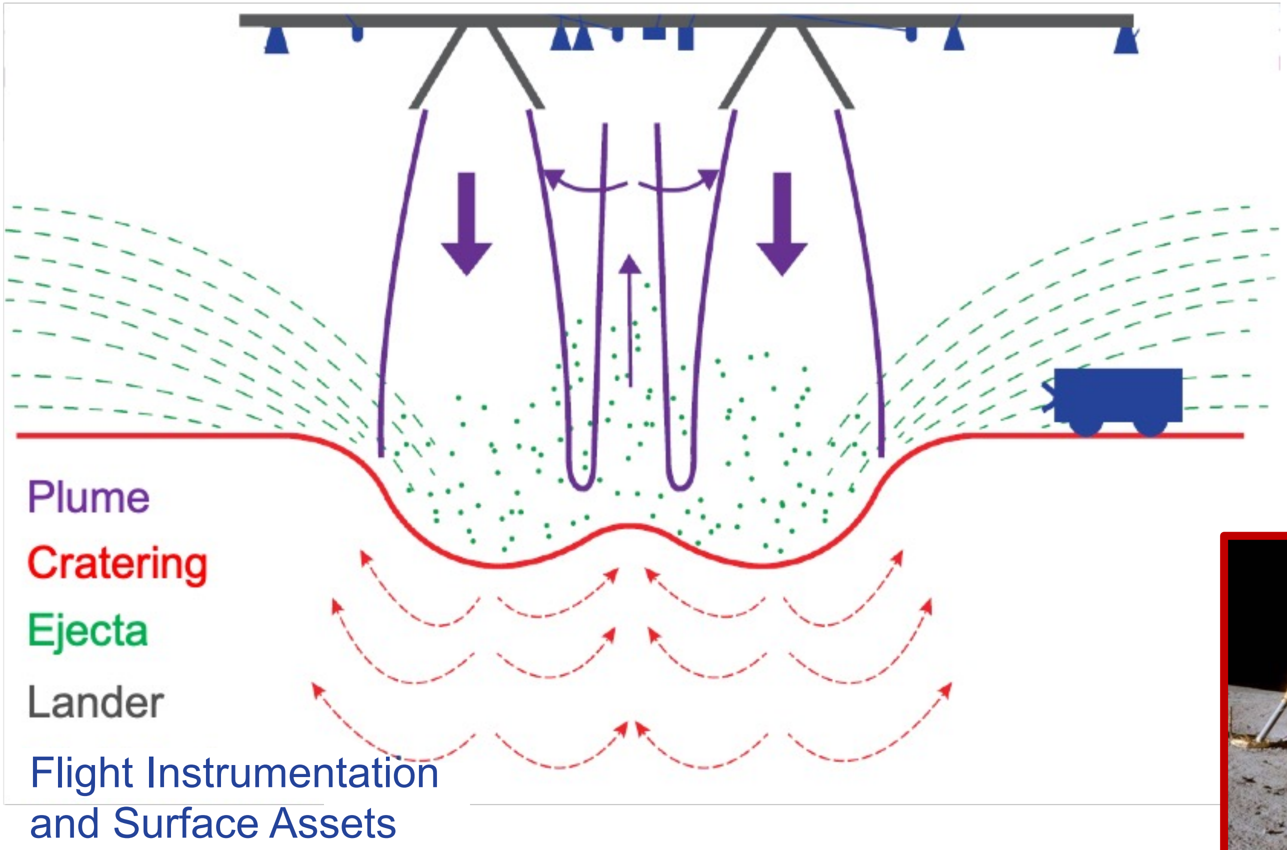




Plume-Surface Interaction (PSI)

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.


Mars2020

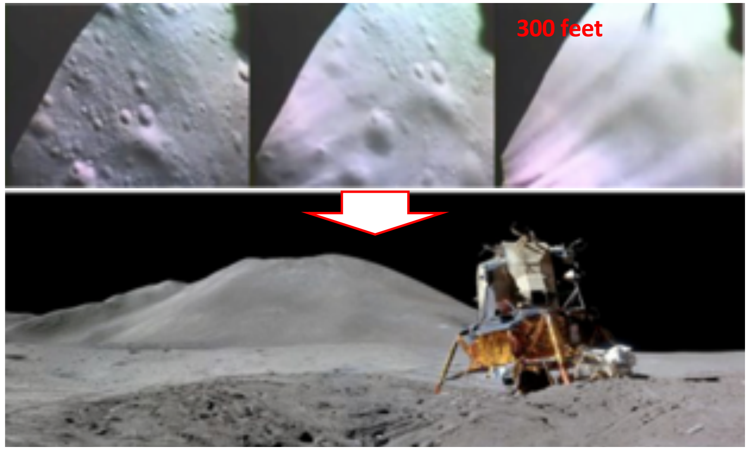



InSight Mars Lander

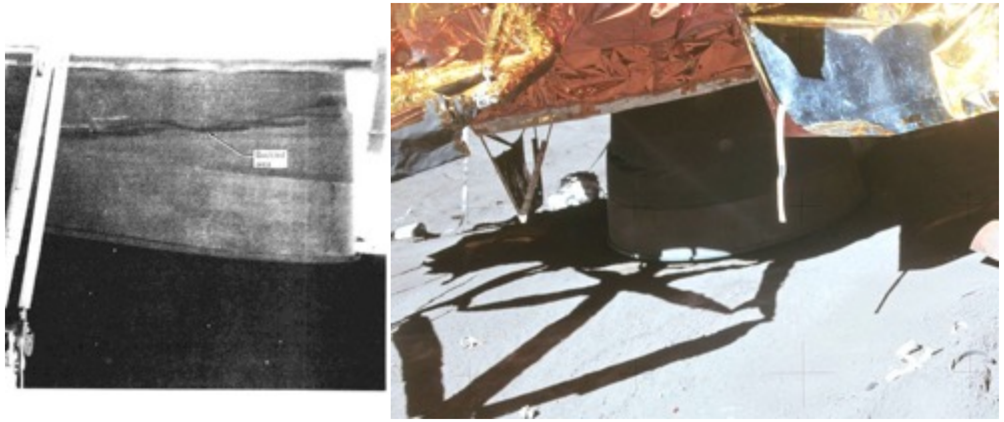

Surveyor 3 'sandblasting' by Apollo 12 Landing


Apollo Lunar Lander

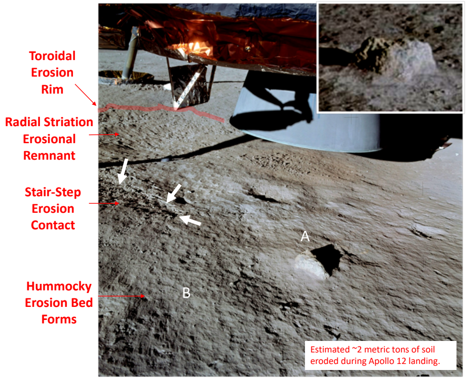
PSI Lunar Flight Impacts



Four out of the 6 Apollo landings had serious visibility problems with lunar plume-induced ejecta during landing - <u>led to flying blind</u>

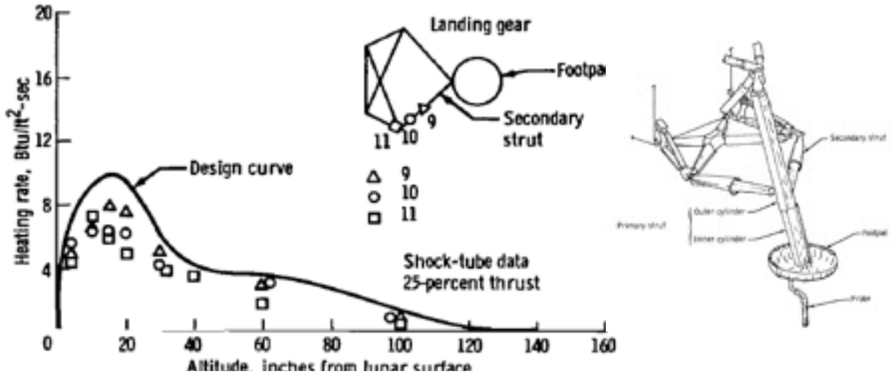


PSI led to the plume exhaust back-filling into the nozzle, overpressurization and buckling of the LEM descent engine nozzle skirt – <u>structural failure</u>

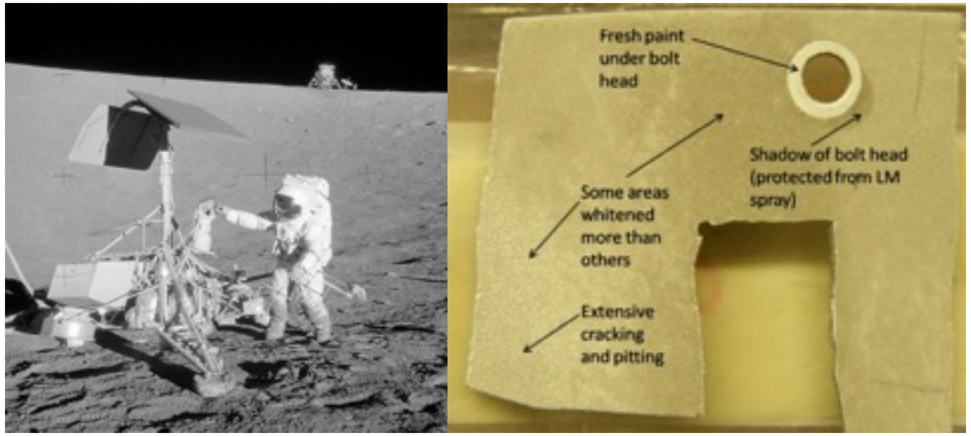


Apollo 12
Metzger (2010)

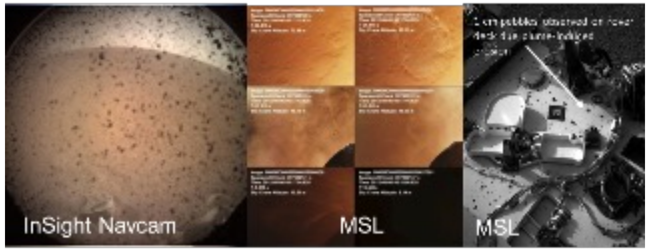
There will be <u>extensive plume-induced erosion</u> during human landings and we have no confident method of predicting these environments.



Plume forces can lead to lander destabilization. Plume heating on the lander struts was above design environments and led to thermal blanket charring for Apollo 11 - <u>led to redesign of LEM TPS and plume shield</u>



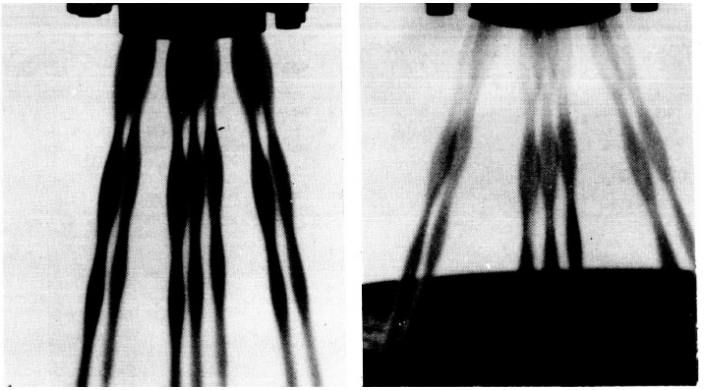
Apollo 12 rocket plume-induced ejecta sandblasting of Surveyor 3 525 feet away <u>led to degradation of nearby surface asset hardware</u>.



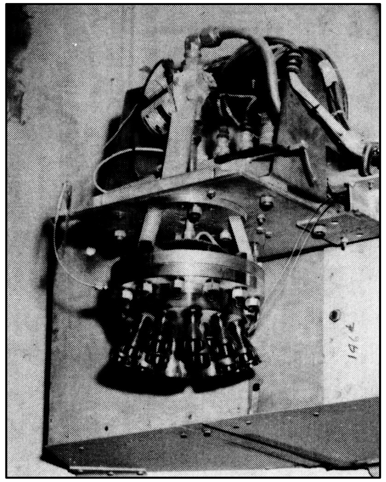
Plume-induced ejecta dynamics led <u>to limited landing visibility and impacts to flight instrumentation resulting in loss of function and damage.</u>

Viking (1976)

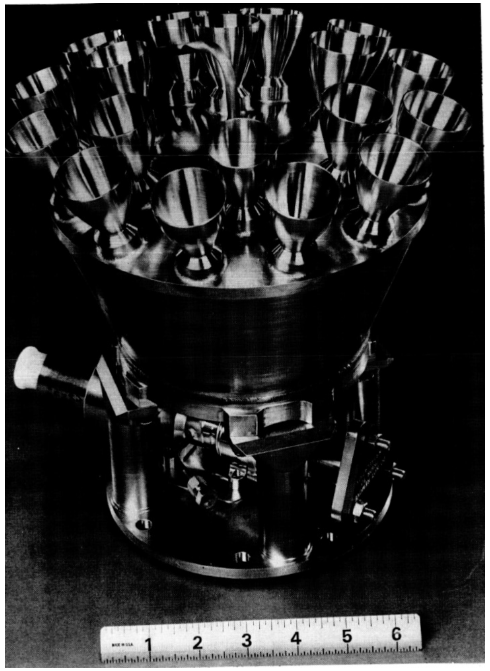
- Viking was concerned with PSI and conducted testing that is still heavily relied upon today
- Special 18-bell 'showerhead' nozzle developed to keep direct impingement pressure below 2 kPa



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

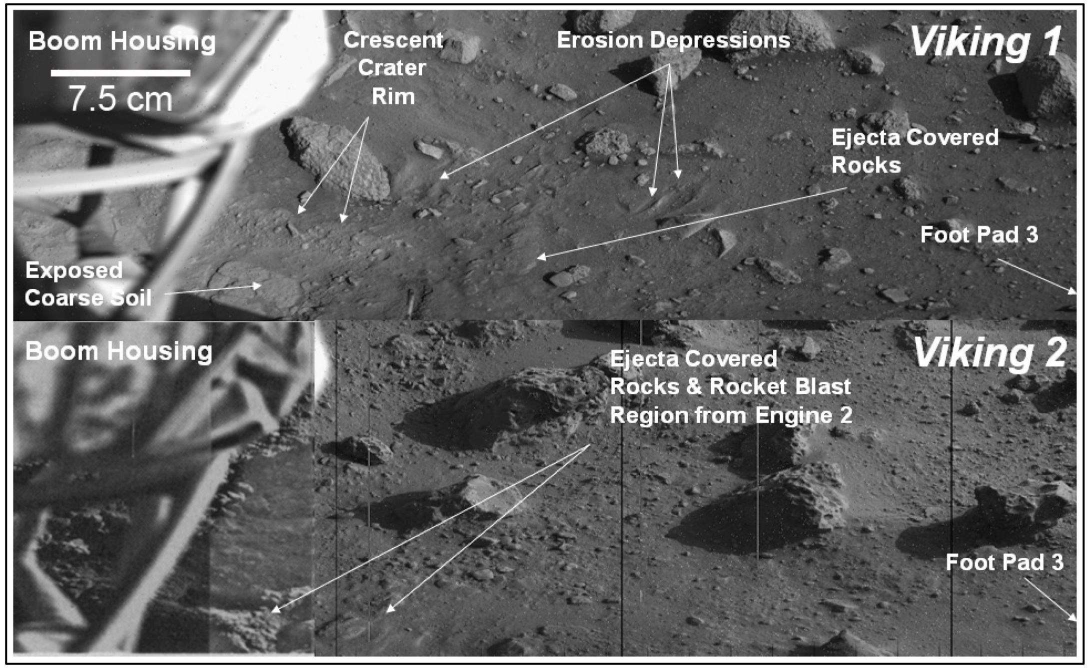


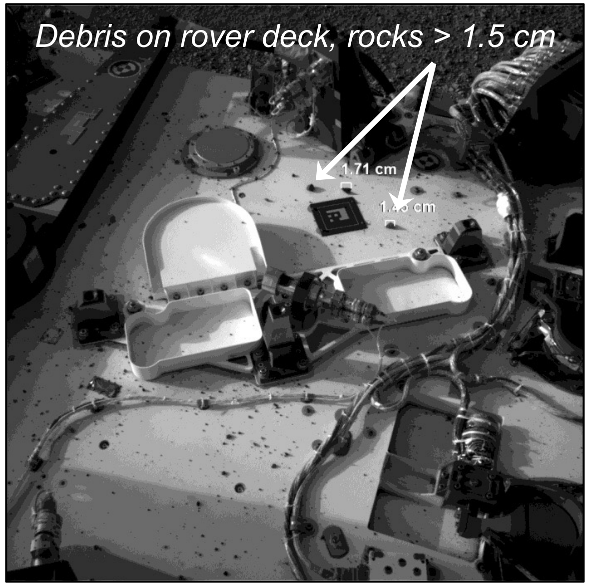
Image Credits:

(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.

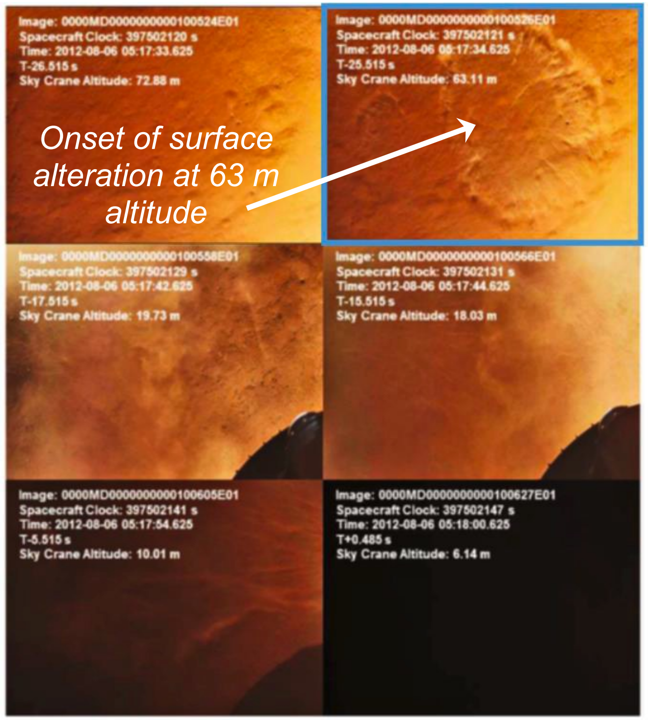
(2) Mehta, M., "Plume-Surface Interactions due to Spacecraft Landings and the Discovery of Water on Mars", Ph.D. Dissertation, Univ. of Michigan, 2010.

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



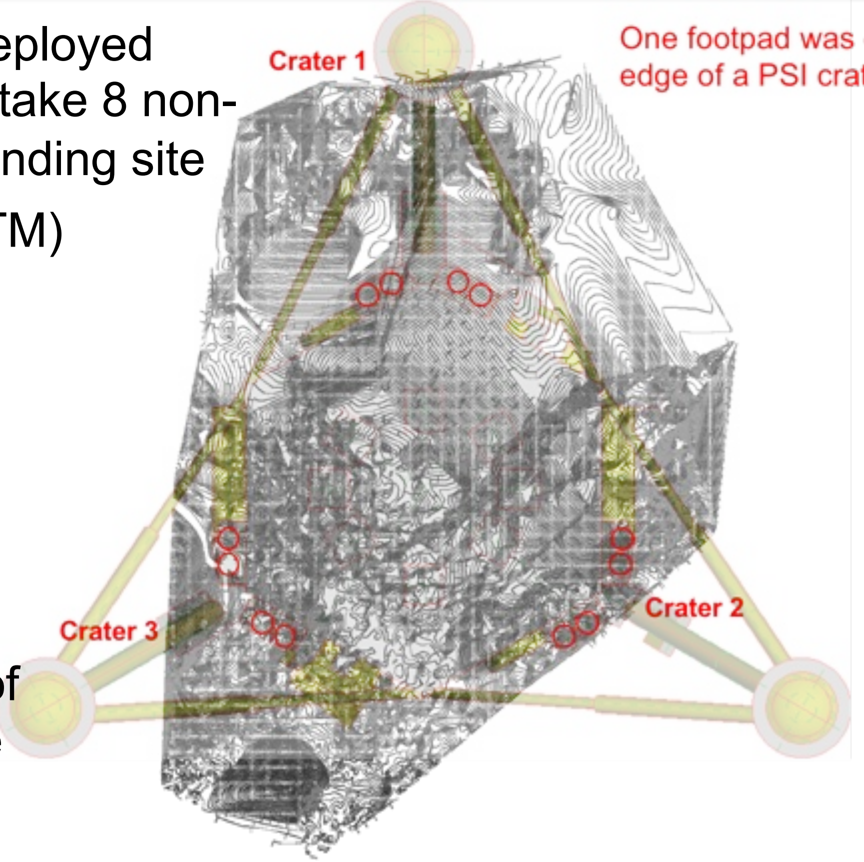
MARDI images showing progression of surface alteration

Panorama with MSL plume impingement craters

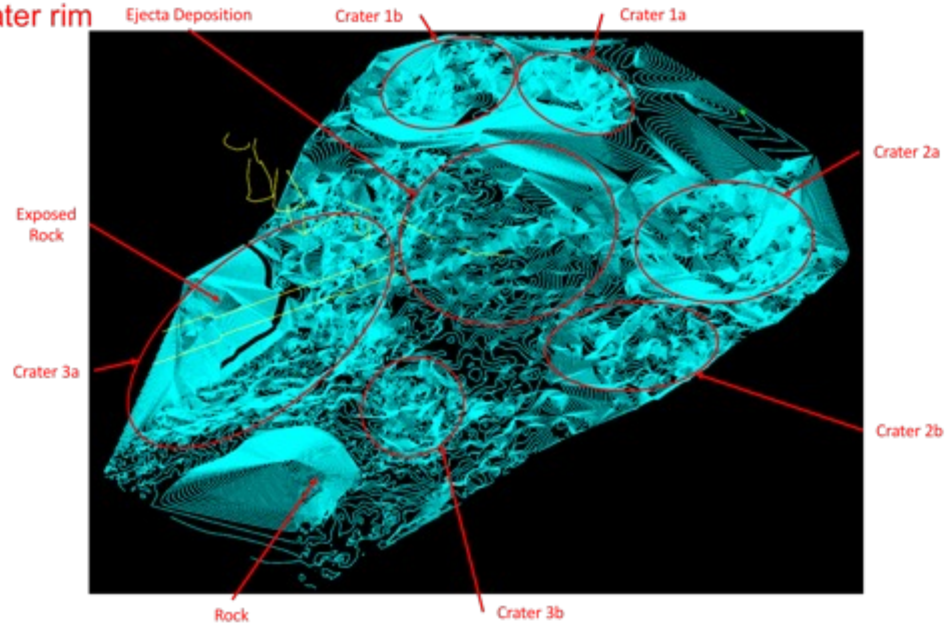
Image Credits:
(1) Bradford, E., Rabinovitch, J., and Abid, M., "Regolith Particle Erosion of Material in Aerospace Environments", IEEE, 2019.
(2) Vizcaino, J. and Mehta, M., "Quantification of Plume-Soil Interaction and Excavation due to the Skycrane Descent Stage", AIAA 2015-1649, 2015.

InSight (2018)

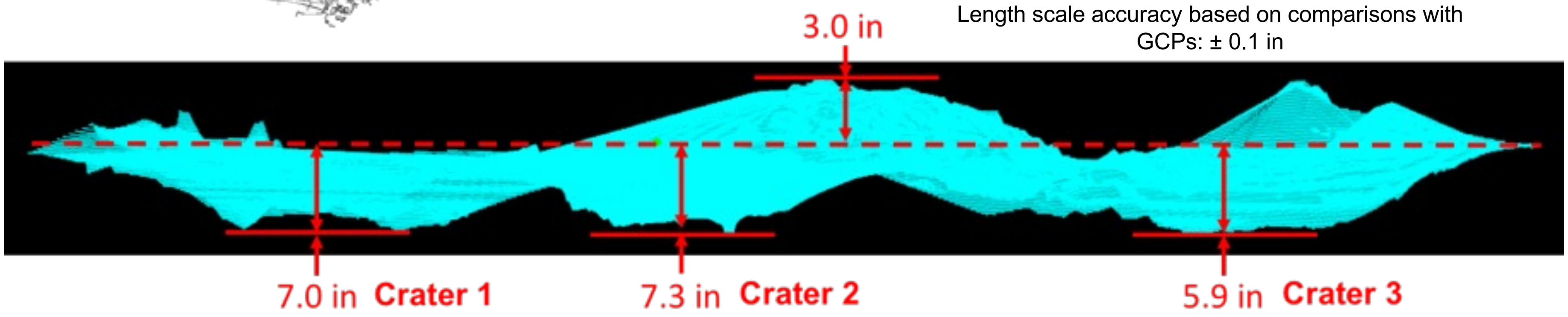
- InSight's Instrument Deployed Camera (IDC) used to take 8 non-stereo images of the landing site
- Digital Terrain Map (DTM)
- Crater volume
- Erosion rate
- Avg. crater diameter:
  - 20 inches wide
  - 7 inches deep
- One footpad on edge of crater rim – could have led to a ~5º tilt of the lander



One footpad was on the edge of a PSI crater rim



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



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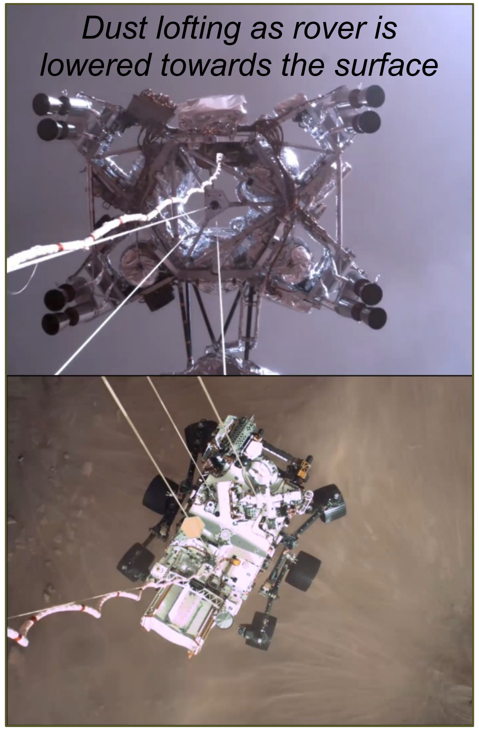
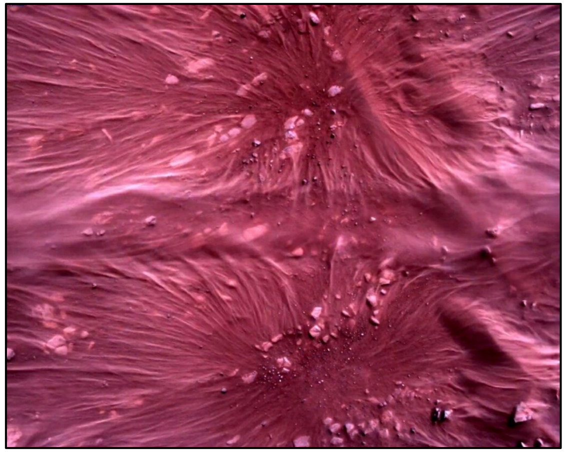
Mars2020 (2021)

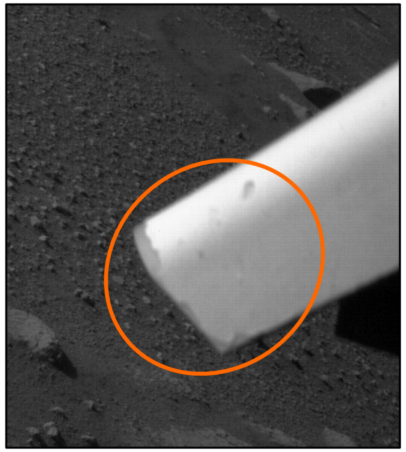
- Similar to MSL, M2020 also used the Skycrane to mitigate PSI effects
- For the first time, data from uplook and downlook cameras on the descent stage and rover provided visualization of PSI


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

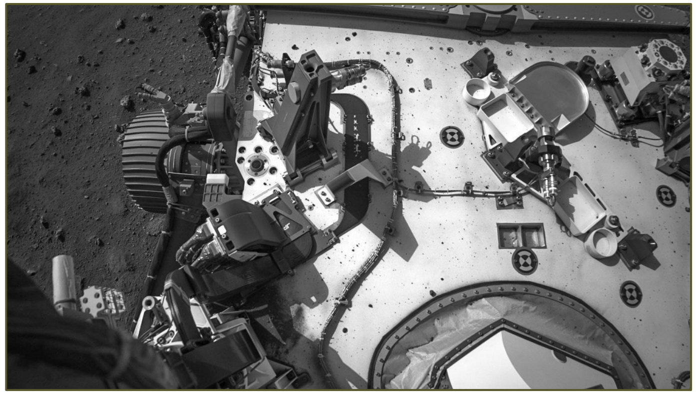
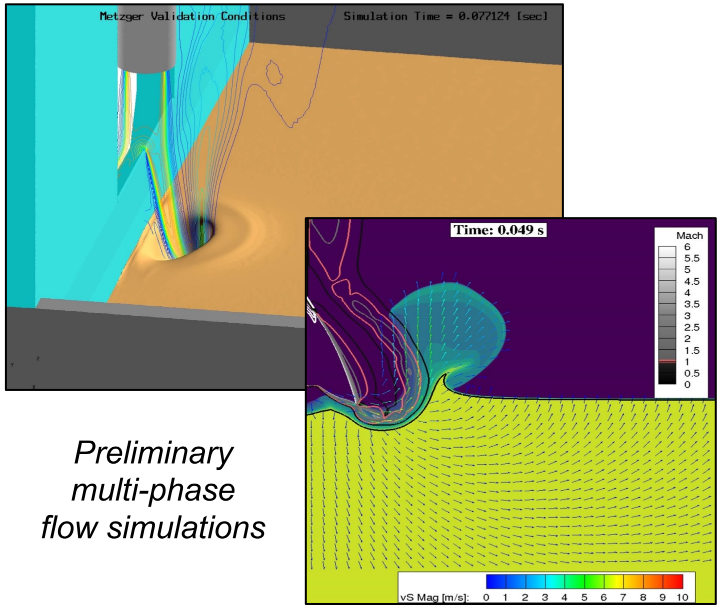

Debris on the Perseverance rover deck

Image Credit:
NASA, JPL

NASA's PSI Project

Computational Modeling & Simulation

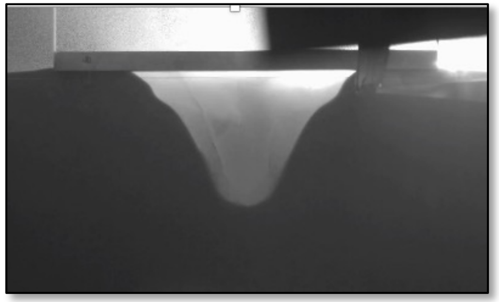
- Plume flow in low-pressure environments
- Effect of mixed continuum/rarefied flow on erosion and ejecta
- Regolith particle phase modeling
- Gas-particle interaction modeling



Preliminary multi-phase flow simulations

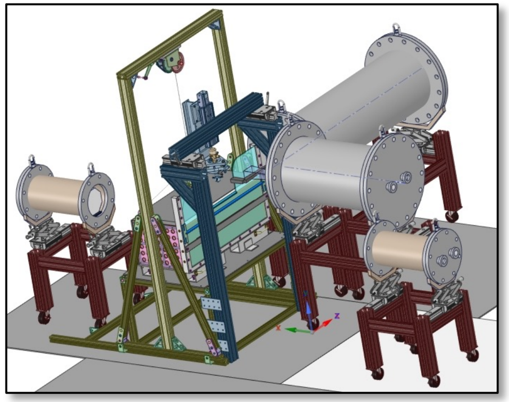
Ground Testing

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



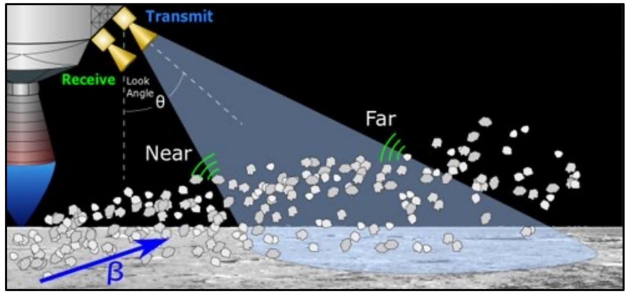
2-D crater profile from 2021 PSI testing

2021 cratering test hardware design

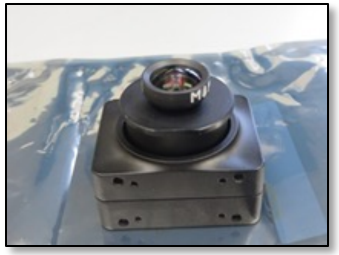


Flight Instrumentation

- Improve TRL in relevant testing:
  - Particle impact detector
  - mm-wave doppler radar
- 3D cratering morphology with photogrammetry
  - SCALPSS, SCALPSS 1.1



mm-Wave Doppler Radar



SCALPSS

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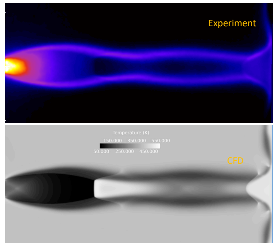
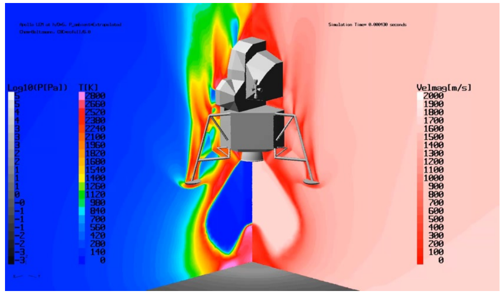
PSI Predictive Simulation Capability Efforts (NASA MSFC)

Task 1: Plume Flow in Low-Pressure Environment

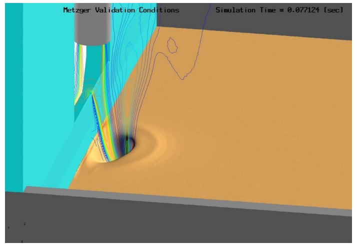
- Lunar vacuum and Mars low pressure environments require mixed continuum-rarefied flow simulation capabilities.
- Production CFD code has mixed continuum-rarefied (NS/Boltzmann) flow solver capability implemented; however, it has not yet been validated.
- JPL Research code is implementing a rarefied (DSMC) solver.
- Plume simulations are progressively validated against existing data and PSI ground test data.

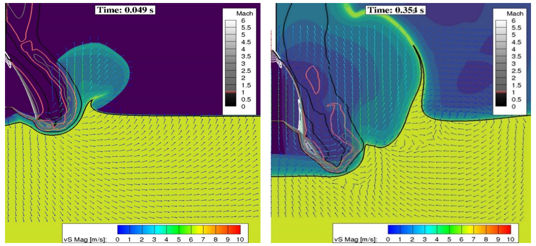




Task 2: Effect of Mixed Continuum/Rarefied Flow on Crater Development and Ejecta Sheets

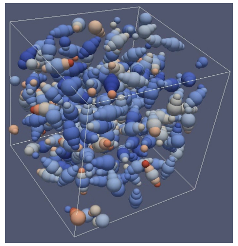
- Strong dependence of plume induced crater size on flow rarefaction effects with first-order effect on ejecta streams and crater size/shape formation for Lunar environment.
- Prediction simulation tool capability is advanced and validated against existing data and new PSI data.
- Delivers a functional and validated mixed continuum/rarefied PSI simulation capability that accurately captures crater formation and ejecta transport.

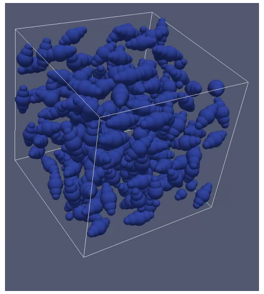




Task 3: Regolith Particle Phase Modeling

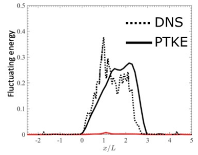
- Regolith particle phase modeling requires resolving complexities particular to extraterrestrial regolith surface material composition.
- Erosion process and crater shape for Lunar regolith demonstrated to be strongly driven by two factors: irregular particle shapes <u>and</u> poly-disperse particle size mixture.
- Particle phase models will be implemented into predictive simulation tools and matured.
- Predictive simulation tools will be validated against data from PSC Task 2 and new ground test data.

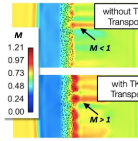


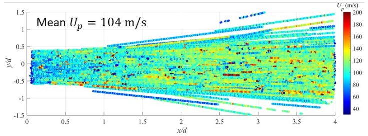


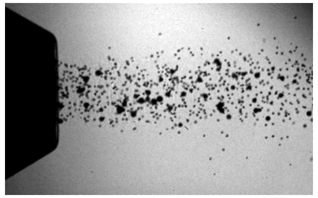
Task 4: Gas-Particle Interaction Modeling

- Large uncertainties exist gas-particle interactions models implemented in current simulation tools.
- The suitability and accuracy of incompressible modeling formulations on modeling the compressible plume-induced erosion must be addressed; a model for gas-particle cloud kinetics has not been found.
- Accurate gas particle interaction modeling is required for lunar environments and will be implemented through unit physics experiments and development of gas-particle interaction models.









Stereo CAmeras for Lunar Plume Surface Studies (SCALPSS)

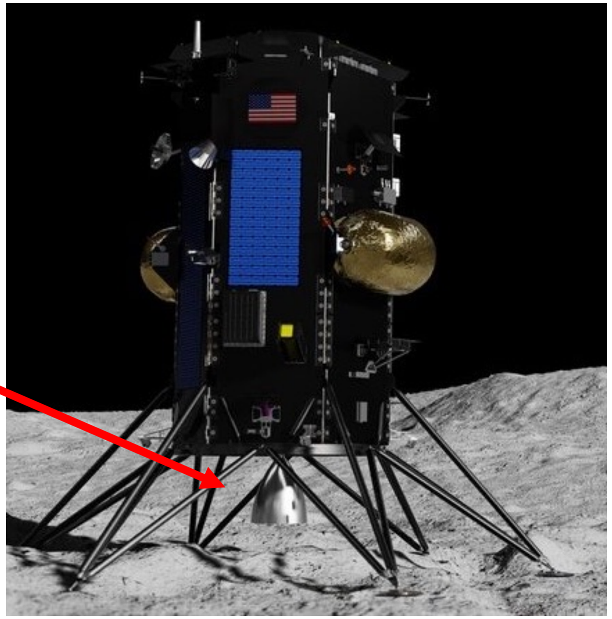
SCALPSS 1.0 – planned Spring 2022 Flight

- One primary engine thruster used for landing: one plume surface interaction centered under the vehicle.
- Photogrammetry system focuses on single crater formed during and after landing.
- No measurement of undisturbed site.

SCALPSS 1.1 – planned Summer 2023 Flight

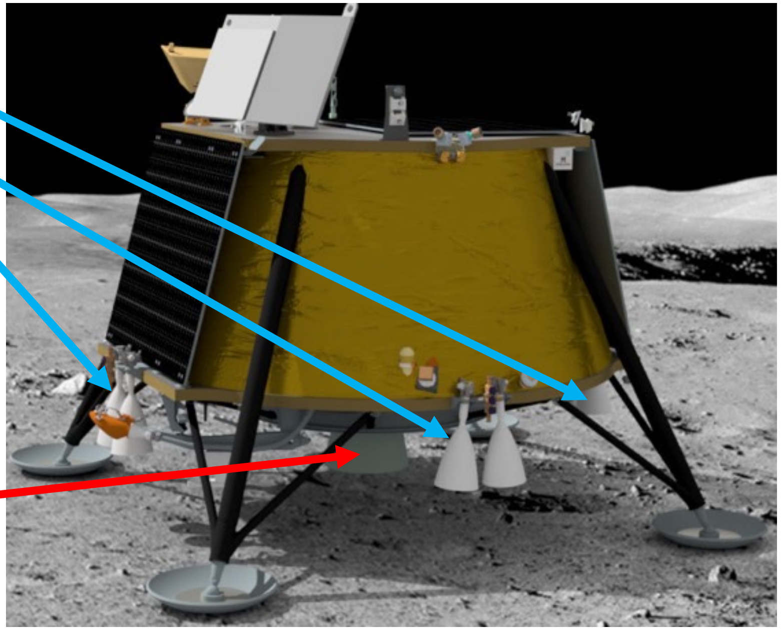
- Main engine will be turned off far above the lunar surface; 8 smaller ACS thrusters placed around the edge of the lander's bottom deck will be used for the landing.
- An added objective is to capture photogrammetry data of the undisturbed regolith prior to erosion (at ~8m altitude).

Intuitive Machines Nova-C



Single main engine used for landing

Firefly Aerospace Blue Ghost

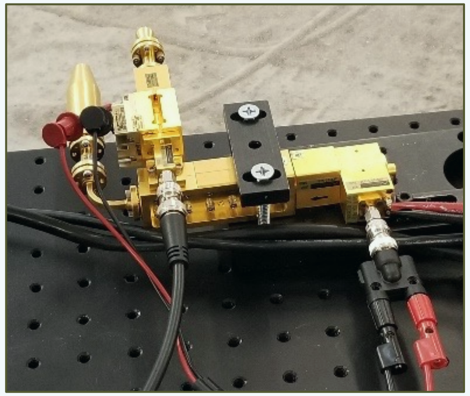


Four pairs of smaller thrusters used for landing

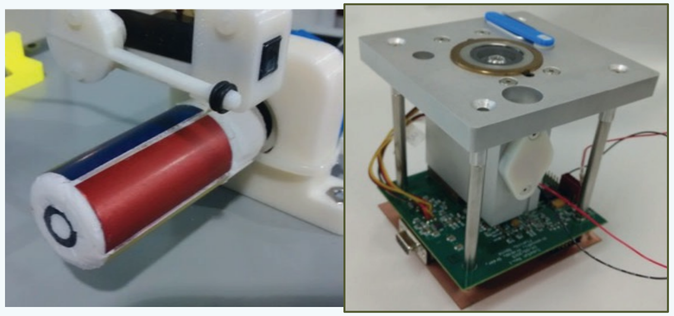
Single main engine (will be turned off far above surface)

PSI Flight Instrumentation

- **We need in-situ data to understand 4 PSI characteristics:**
  - Plume structure
  - Erosion rate
  - Ejecta particle size/speed/energy distributions
  - Environment/effects on lander base/legs
- **SCALPSS can only address erosion rate (mostly)**
- **Planning/development is underway to fly more comprehensive PSI instrumentation on CLPS**



mm-wave radar (MMWR)



Saltation/particle impact detector, optical microscope

SCALPSS 2.0

Lander base instrumentation (heat flux, pressure, other)

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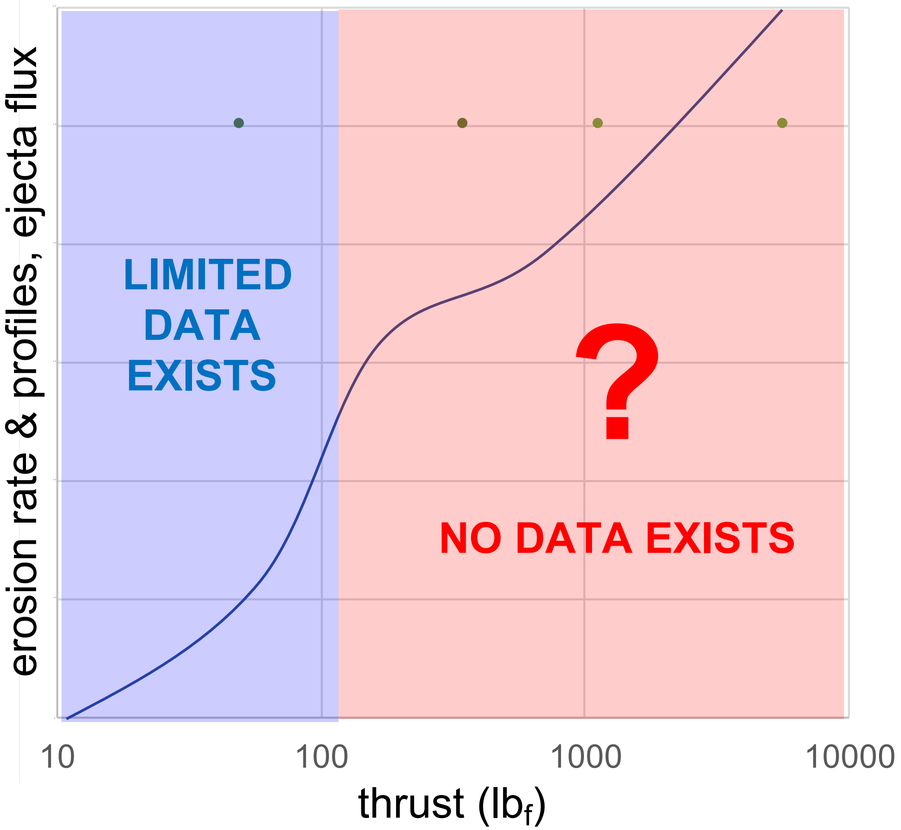
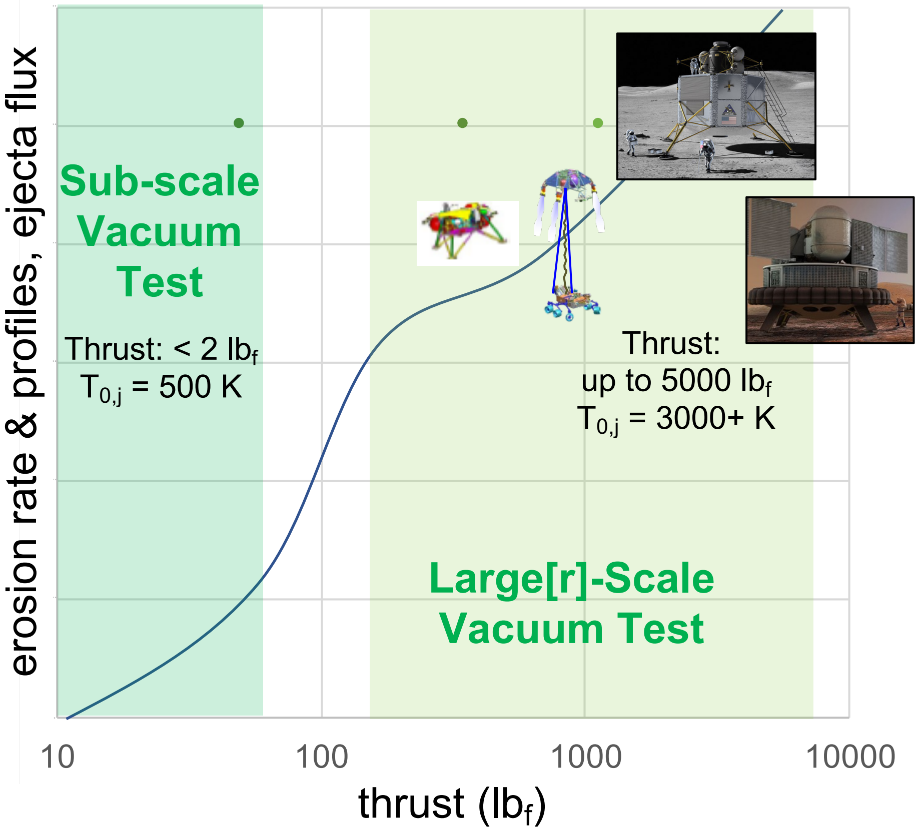
Need for Relevant Test Data

Current Situation



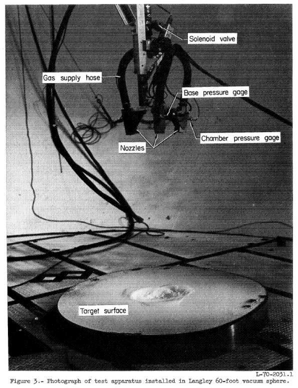
PSI Project



This is one of the first opportunities since Viking to obtain flight-relevant PSI data through controlled, well-characterized ground testing

Sub-scale Inert-gas Test

Mid-scale Warm-flow Test

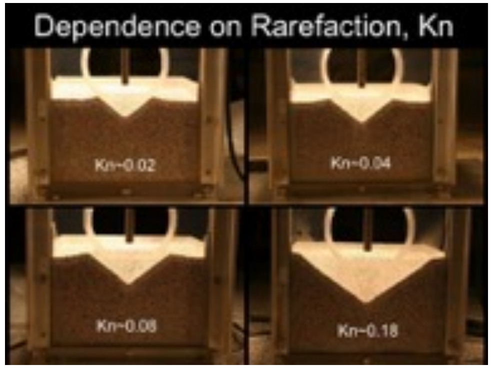


- Relevant ground test data are necessary to validate predictive tools and quantify uncertainty in predictions: *qualitative* → *quantitative environments and impacts*
- No direct measurements of flight-scale data presently exist to inform large-scale landing systems

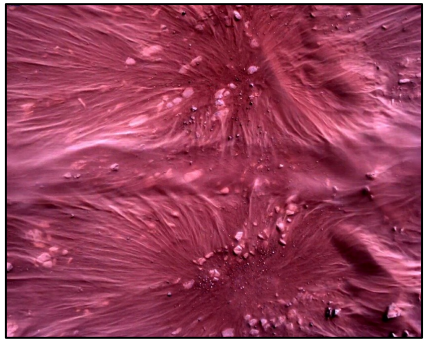
Motivation and Test Objectives

Motivation

- Rocket PSI poses risks to *all propulsive landers*, with current and future large landers increasingly outside of existing data applicability and flight/test experience
- Validation of predictive modeling capabilities requires well-defined, highly-controlled data for plume, erosion, and ejecta physics
- Subscale, inert-gas, half-plane experiments conducted under vacuum limit test complexity, leverage existing experience, and permit well-controlled experiments



Sonic nozzle half-plane experiments under vacuum (Metzger, 2010)



Mars 2020 Mars Lander Engine surface impingement and flow patterns (NASA/JPL)

Test Objectives

- Supersonic Cratering and Ejecta (PFGT1): To measure crater formation and ejecta velocities due to supersonic PSI at ambient pressure conditions ranging from Martian to those approaching the Moon
- Supersonic Plume Structure/Impingement (PFGT2): To visualize supersonic plume structure and to measure impingement pressures at reduced atmospheric conditions

Key Performance Parameters (KPPs)

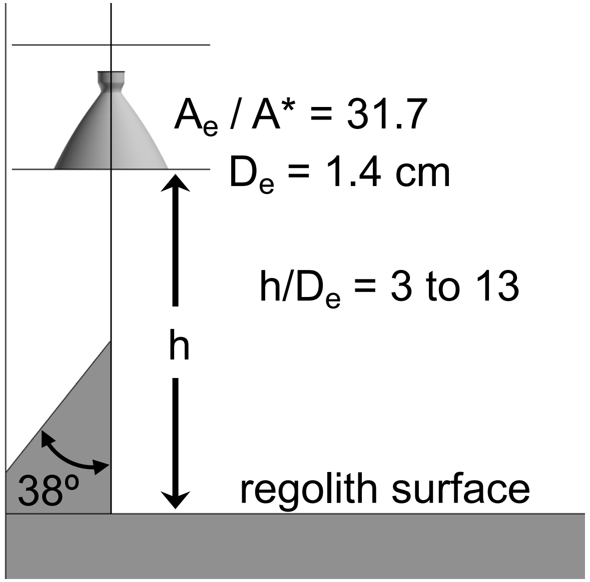
No.	Parameter	Units	Project Goal
1	Prediction of plume-induced pressure distribution	Pa	Predict within +/- 10%
2	Prediction of surface erosion/crater geometry as a function of time	m	Predict within +/- 10%
3	Prediction of ejecta energy flux	$\frac{W}{m^2}$	Predict within +/- 10%

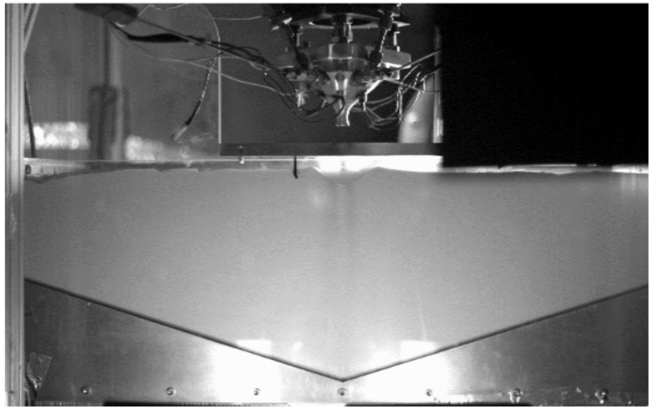
- Ejecta Energy Flux
  - $E_e = 0.5U^2 \frac{\dot{m}}{A}$
  - Dependent on the bulk ejecta velocity and erosion rate
  - An important metric to determine impact energy to lander and surface assets (tangible metric for customers to assess hardware damage)
  - Defines the ejecta energy

Test Parameter Definition

- Supersonic nozzle flow ($M_e > 1$, jet pressure ratio (p_e / p_{amb}), vacuum chamber pressure (p_{amb}), and non-dimensional altitude (h/D_e) are scaled from a NASA reference Lunar lander design
- Intrusive, half-plane experiment allows for observation of time-evolving 2-D crater profile and ejecta
- Discrete h/D_e settings to investigate boundaries between different erosion regimes
- Heated N_2 gas used as plume simulant
- Cannot fully match flight scales and environments with an inert-gas, subscale, intrusive test

Parameter	Range
h/D_e	3.0 to 13.0
p_{amb}	2.67 Pa to 600 Pa (0.02 Torr to 4.5 Torr)
$\dot{m}_j$	0.32 g/s to 8.6 g/s
$T_{0,j}$	500 K (fixed)





Looking towards viewing pane at low h/D_e setting

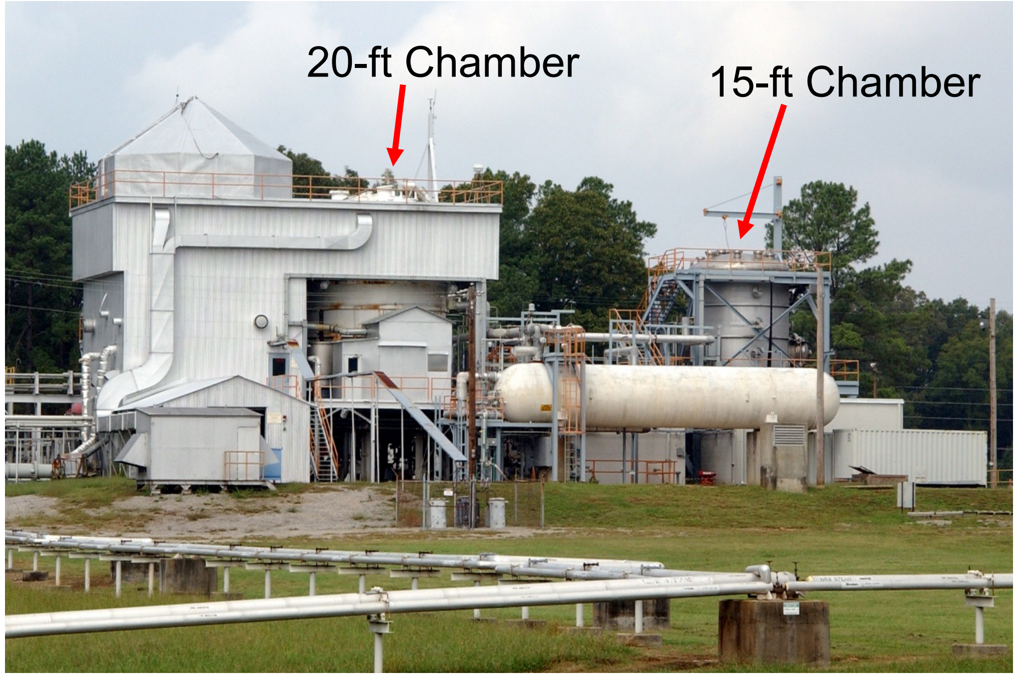
Facility

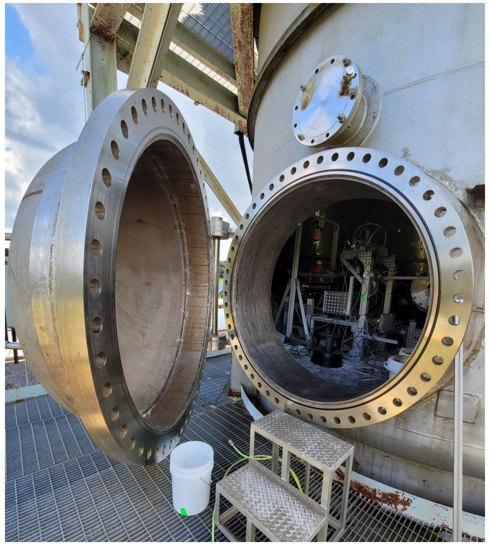
NASA MSFC Test Stand 300

- 15-foot chamber used for cratering and ejecta testing (PFGT1)

Requirement: *Reduced ambient pressure environments and ejection of granular material during testing*

- 15-foot and 20-foot chambers used for plume testing (PFGT2)

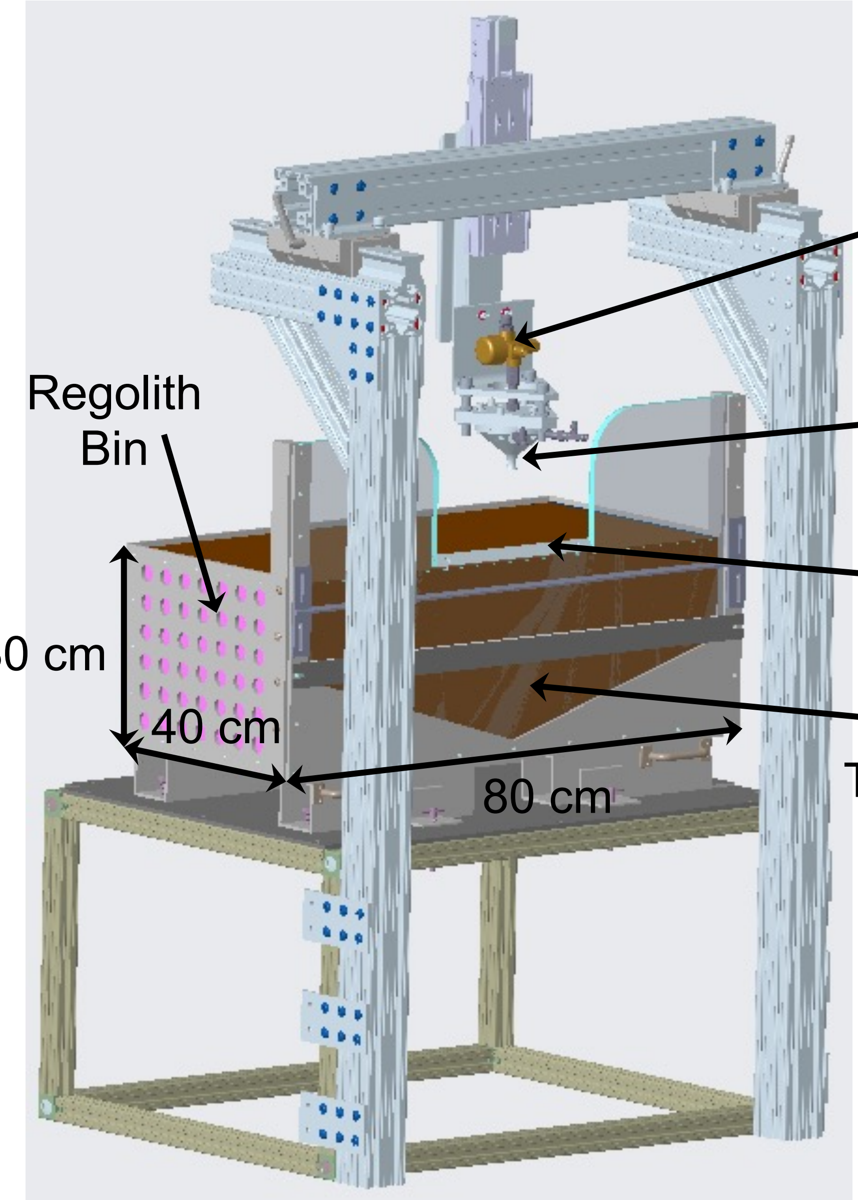


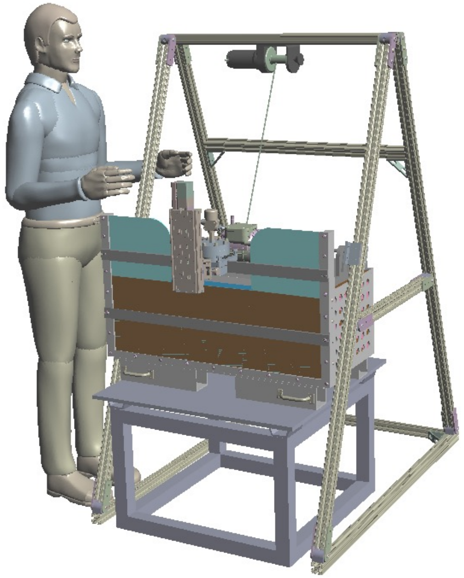


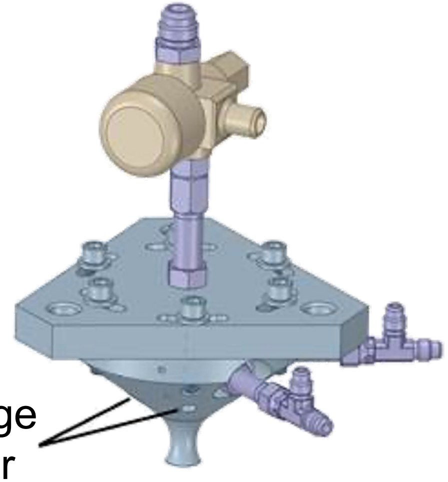
Entrance to 15-foot chamber

- 15-foot chamber: < 0.02 Torr (2.67 Pa)
- 20-foot chamber: 10^{-8} Torr (<< 0.001 Pa)
- Continuous supply of high-pressure gaseous N_2

Cratering and Ejecta Test Article

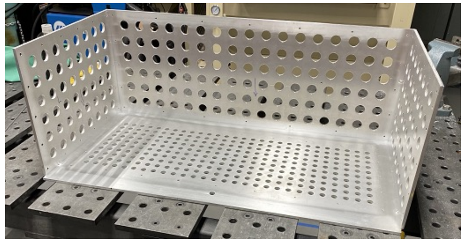


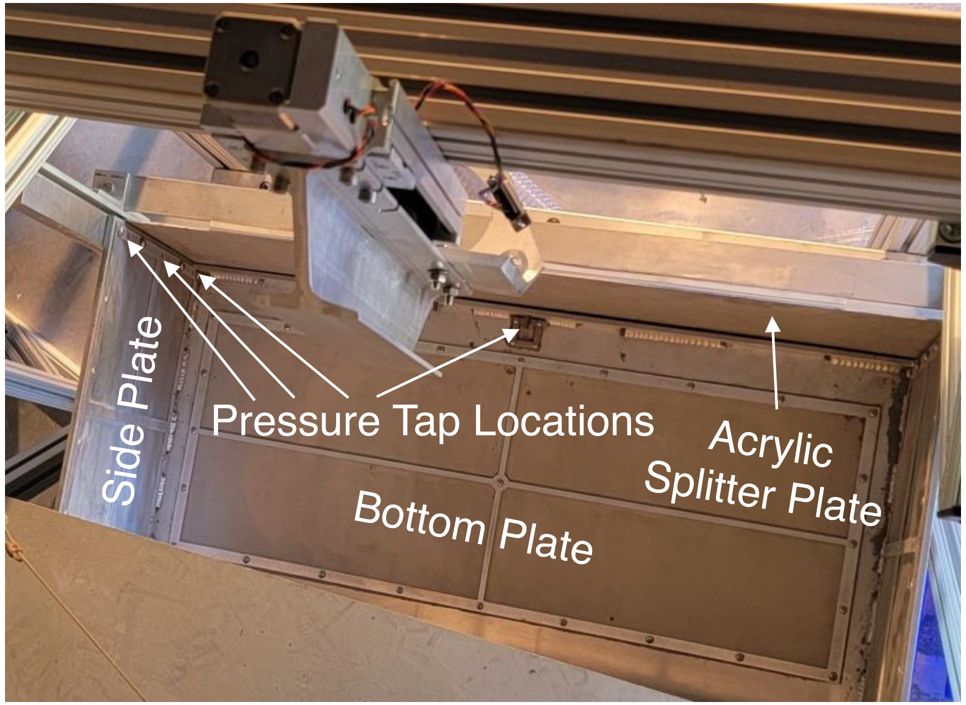




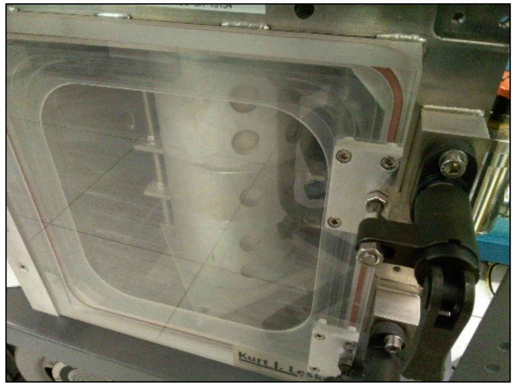
Regolith Bin

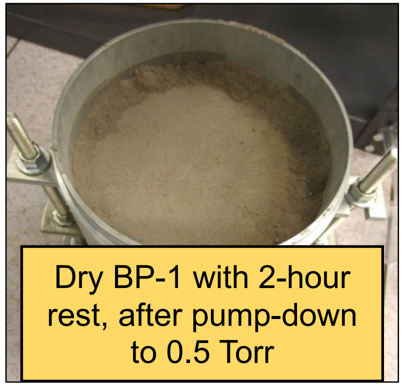
- Unique design to allow outgassing during vacuum pump-down and conventional half-plane experiment
- Significant testing completed with scaled and full-scale regolith bins:
  - Establish vacuum pump-down procedures
  - Verify vented soil bin design
  - Conduct risk reduction testing

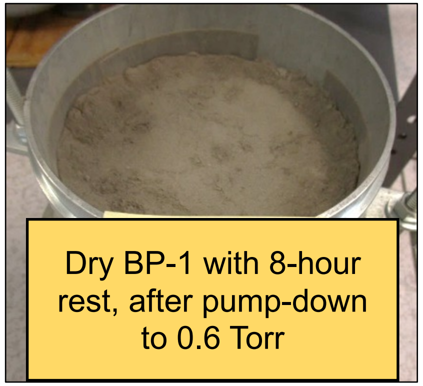




BP-1 dust coating over entire 15-foot vacuum chamber after pump-down outgassing and erosion during pathfinder testing in Jan. 2021

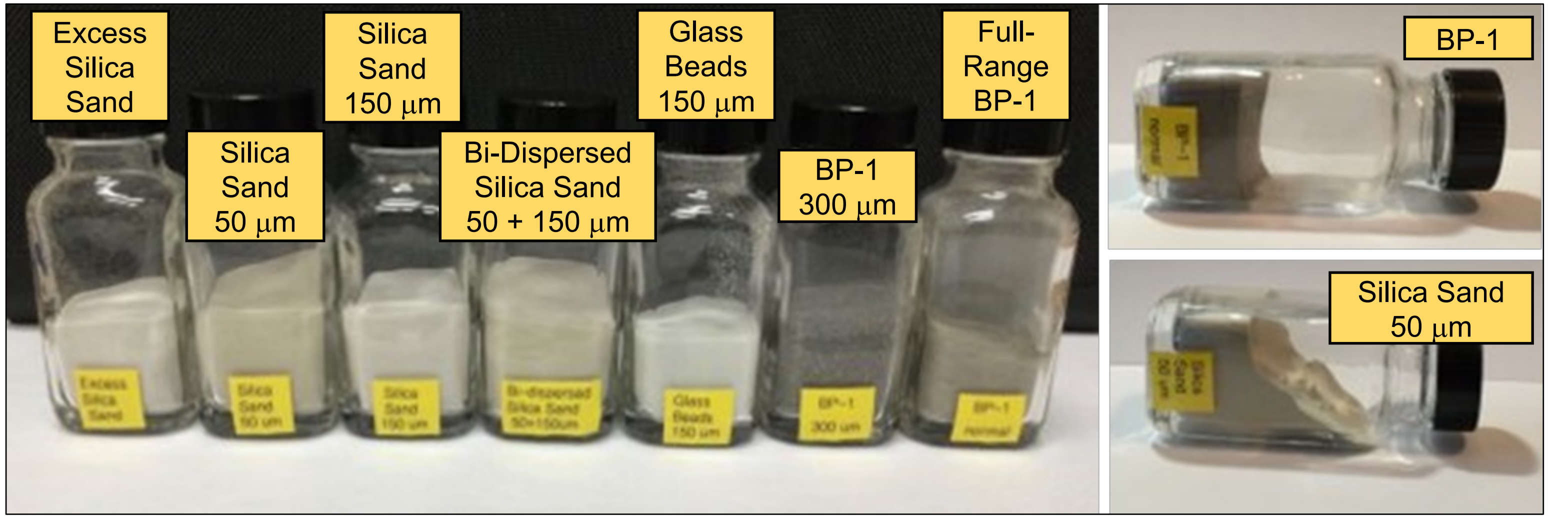






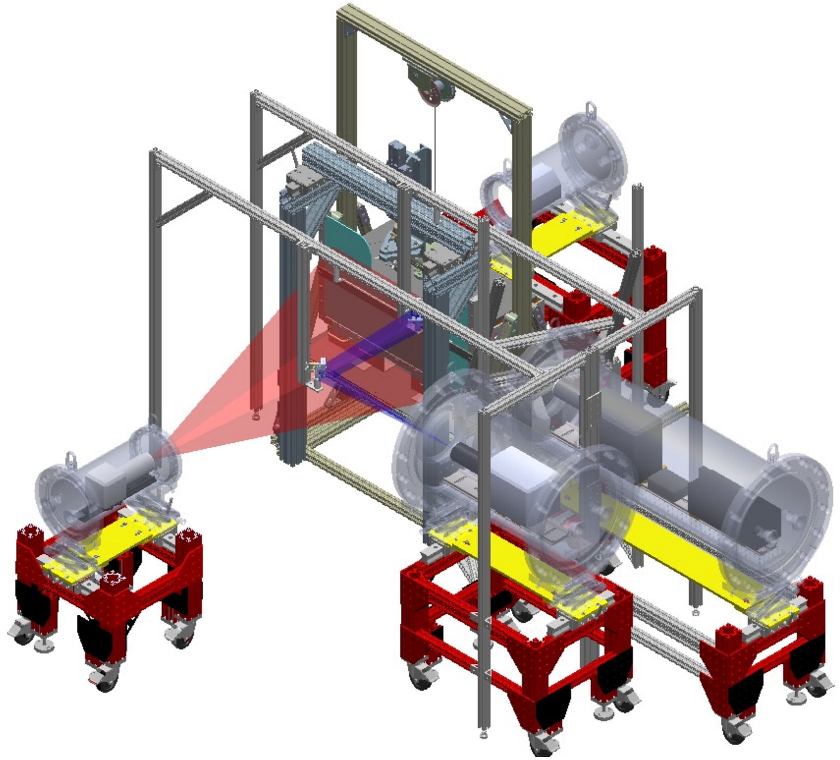
Regolith Simulants

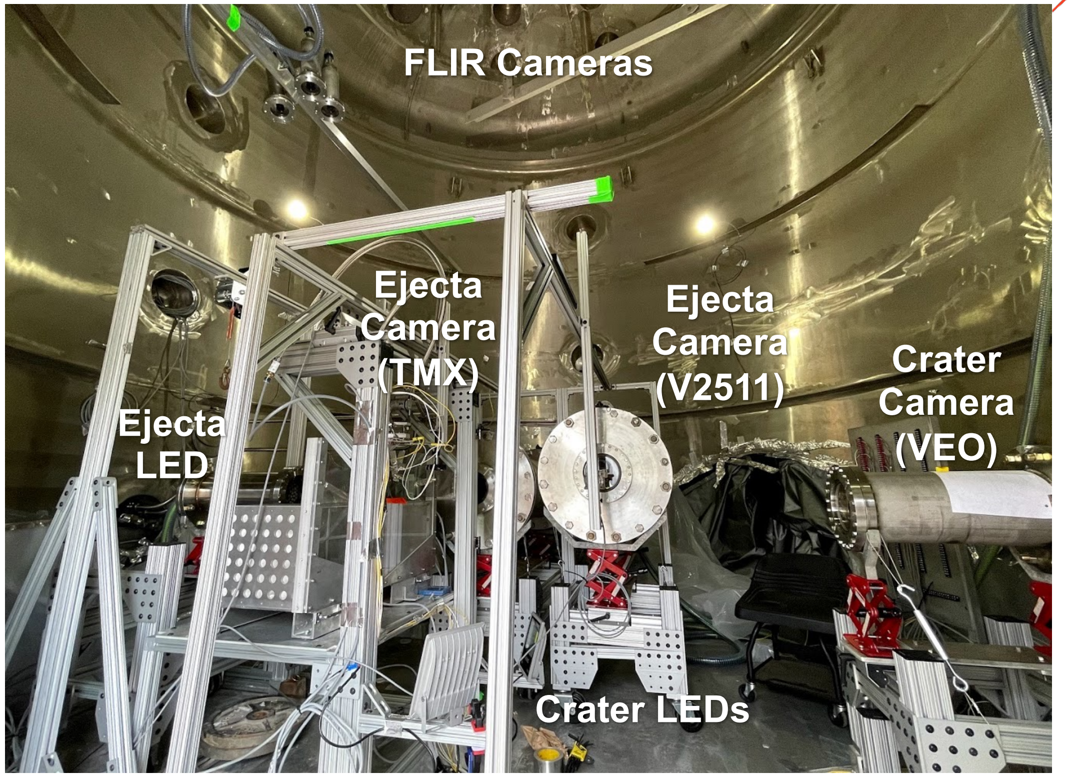
Simulant	Material	Specification
Mono-Disperse Glass Beads	Soda Lime	Nominal diameter 125-177 μm
Mono-Disperse Sand	Silica	Nominal diameter 125-177 μm
Bi-Disperse Sand	Silica	Product 1: Nominal diameter 45-53 μm Product 2: Nominal diameter 125-177 μm Equal mix by volume
Tri-Disperse Mixture	Silica + BP-1	Equal mix by volume of bi-disperse sand particle sizes and BP-1
Irregular Mixture	Sieved BP-1	Nominal diameter 212-350 μm
Full-Range Lunar	BP-1	Particle size distribution varies; Lunar mechanical simulant



- Each regolith simulant requires specific characterization, geotechnical measurements, preparation, and handling procedures, along with specialized PPE
- 4/6 simulants require baking before and over the course of use during PFGT
- Procedures developed to ensure consistency in particle size distribution for regolith simulant mixtures

Cratering and Ejecta Diagnostics





- Primary diagnostics are high-speed cameras:
  - Crater growth, ejecta velocity, ejecta particle behavior
- Facility and flow system conditions
- Regolith bin pressures

- Novel high-speed visual diagnostics:
  - Cratering: Phantom VEO 710L (5 kHz)
  - Ejecta:
    - Phantom V2511 (25 kHz)
    - Phantom TMX7510 (100-775 kHz)
  - LED light sources for both cratering and ejecta

Test Execution

Run Progression for PFGT1

Facility Checkout Runs (Leftover Simulant Mix)
[Occurs before PFGT1 runs begin]

↓

Checkout and Screening Runs to Refine Test Parameters (Mono-disperse sand, BP-1)
[min: 44, max: 50]

↓

Remaining Runs with Mono-disperse sand, BP-1
[min: 6, max: 40]

↓

Targeted Runs with 4 Remaining Simulants
[min: 32, max: 60]

- Screening runs precede additional runs and target the bounds of the test parameters:

$$p_{amb}, \dot{m}_j, \text{ and } h/D_e$$

- Run matrix is blocked by regolith simulant
- Minimum no. of runs: 82
- 10-11 weeks of testing

- Chamber must be opened between runs to reset the regolith bin and to change run parameter settings
- Specific procedures vary with regolith simulant

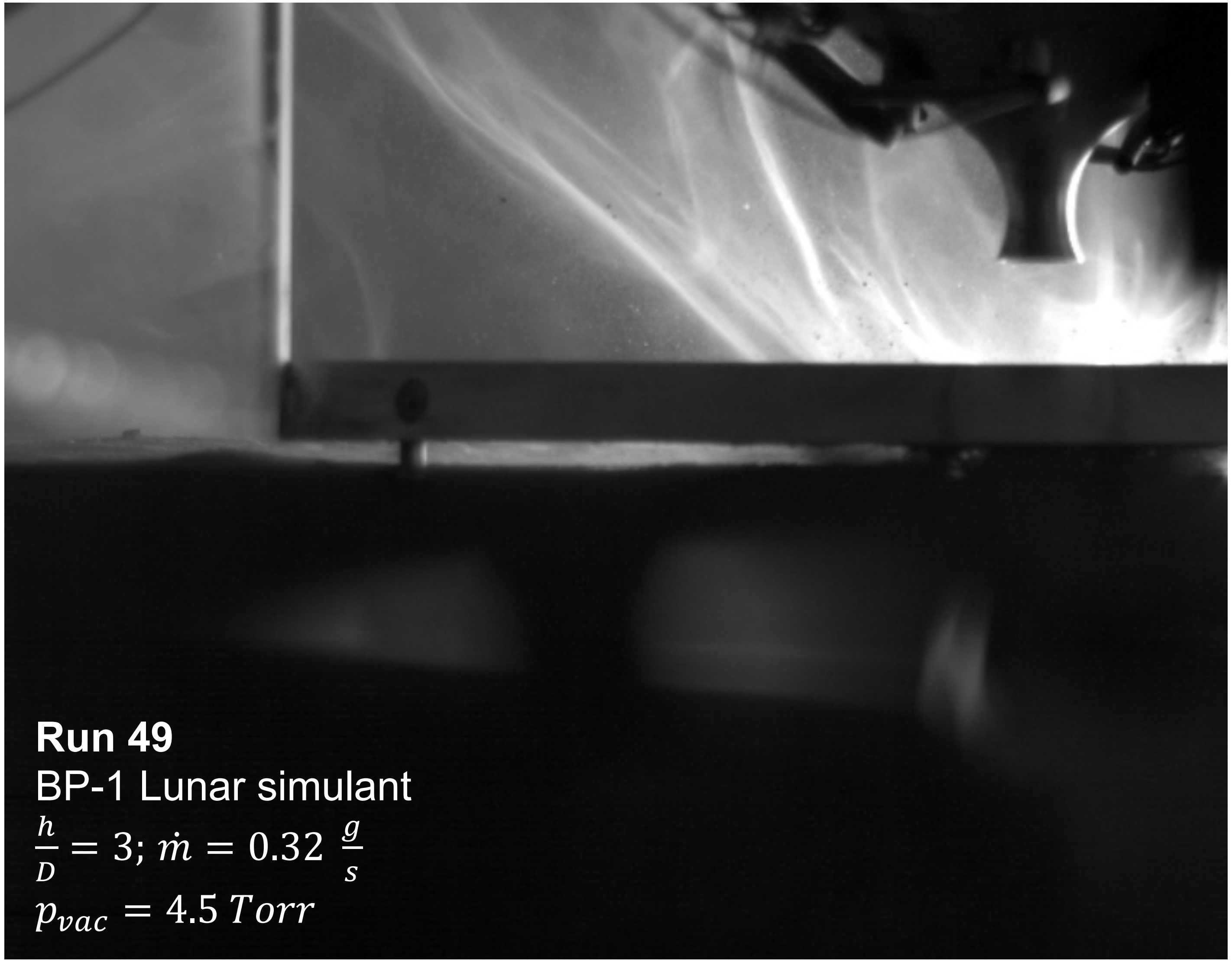
Data Analysis Goals

Measurement Goals

- Locate erosion onset
- Recover transient crater profile
  - Measure depth, diameter, angles, width
- Track ejecta particle / bulk motion
  - Particle velocities
  - Particle masses
- Derived quantities of interest
  - Erosion rate
  - Particle energy

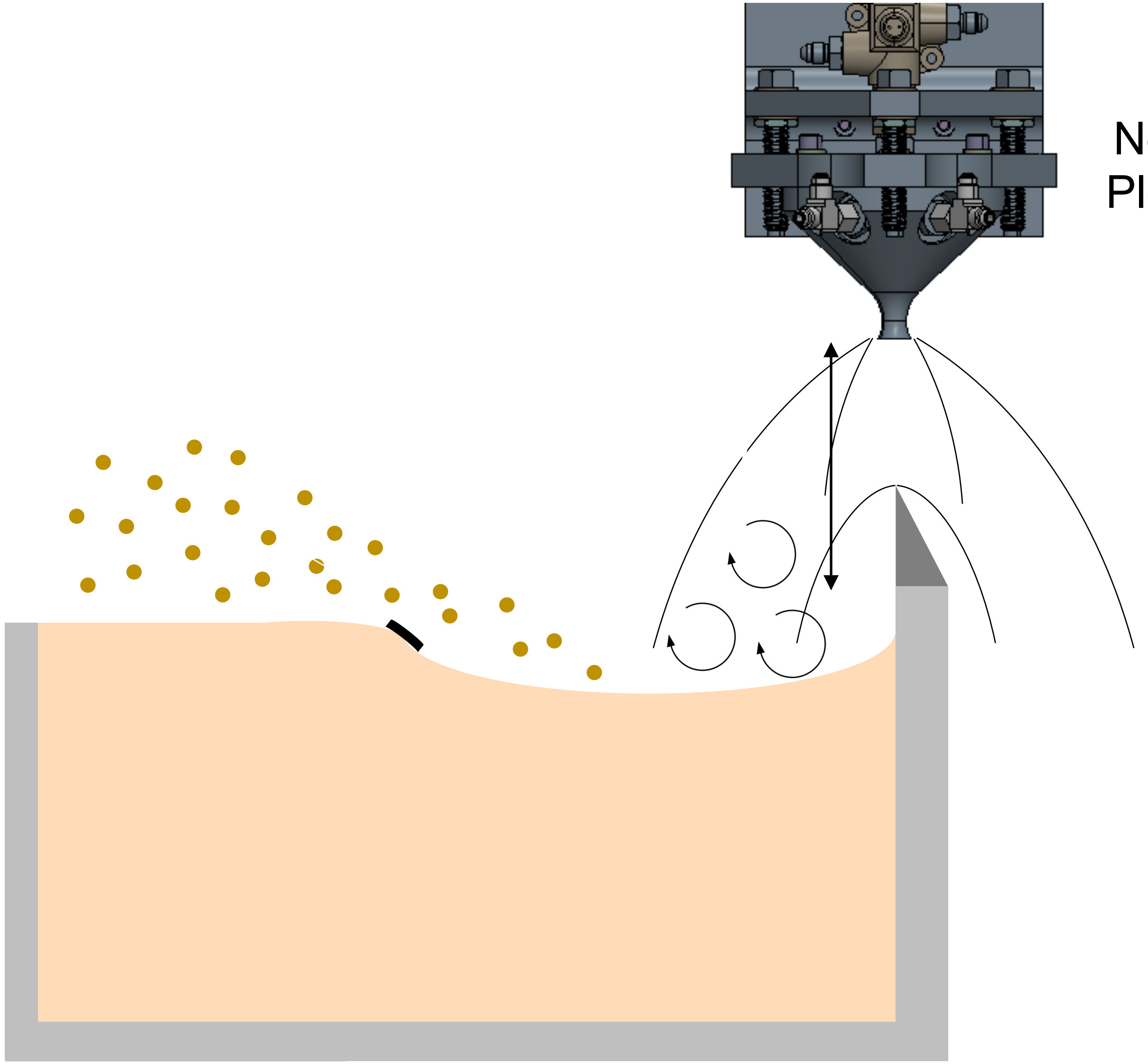
Analysis Goals

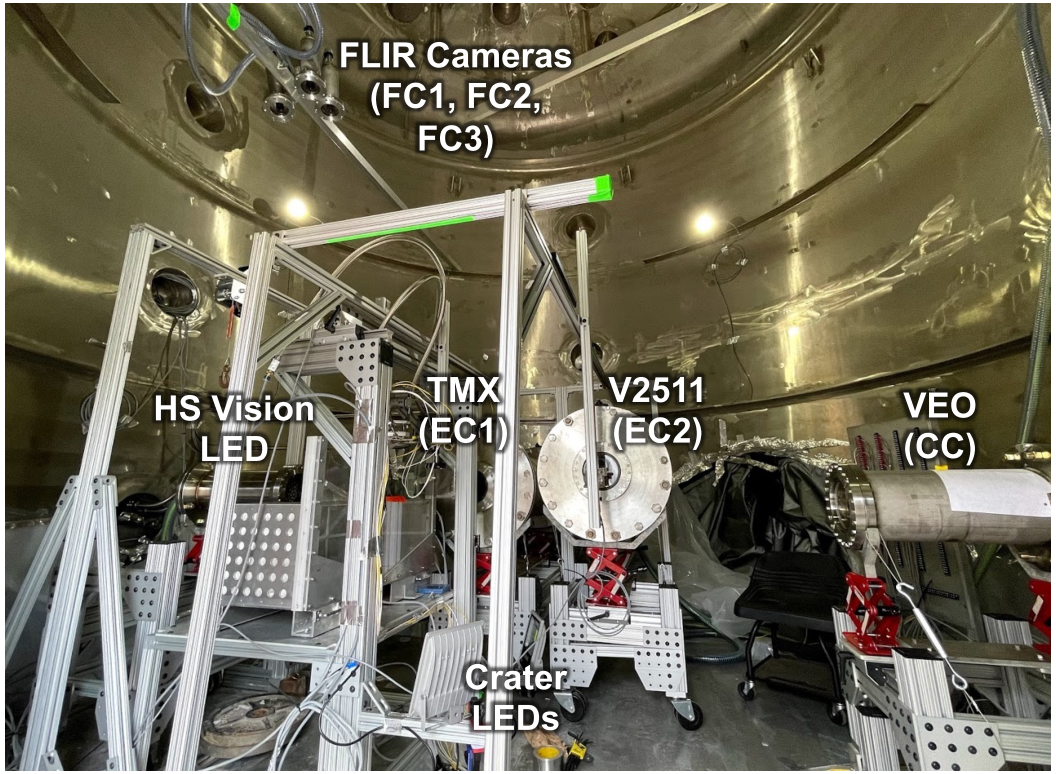
- Describe / quantify phenomena
  - Characterization and comparison with known PSI modes
- Identify scaling relationships
- Understand PSI physics
- Deliver data products to support validation of computational modeling



Credit: Wesley Chambers (MSFC) and JHU Team

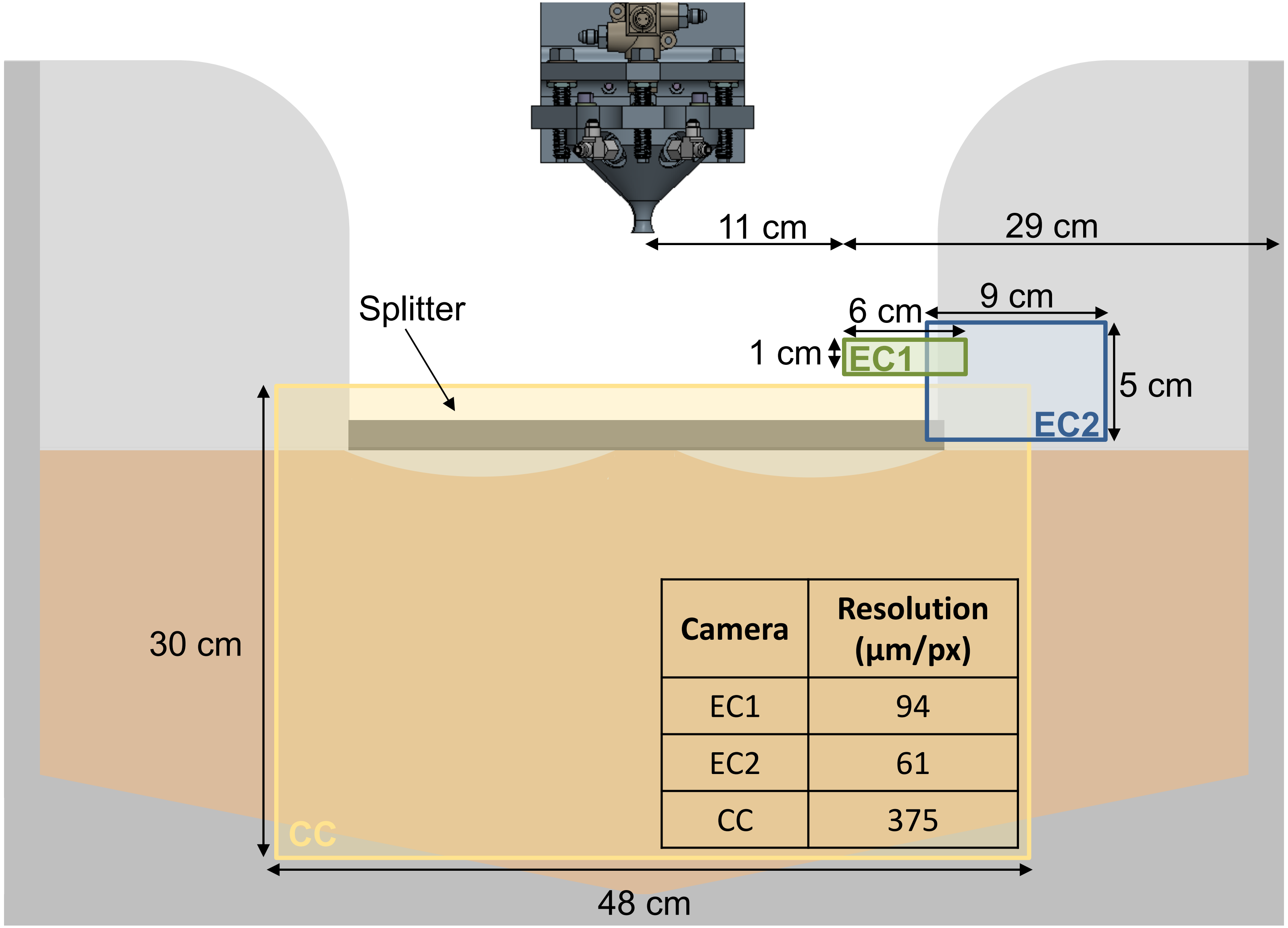
PFGT1 Schematic and Integrated Visual Diagnostics





Credit: M. Diaz Lopez (JHU)

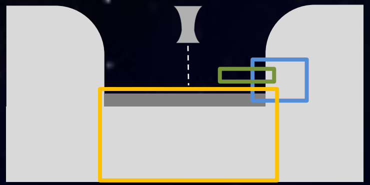
Fields of View

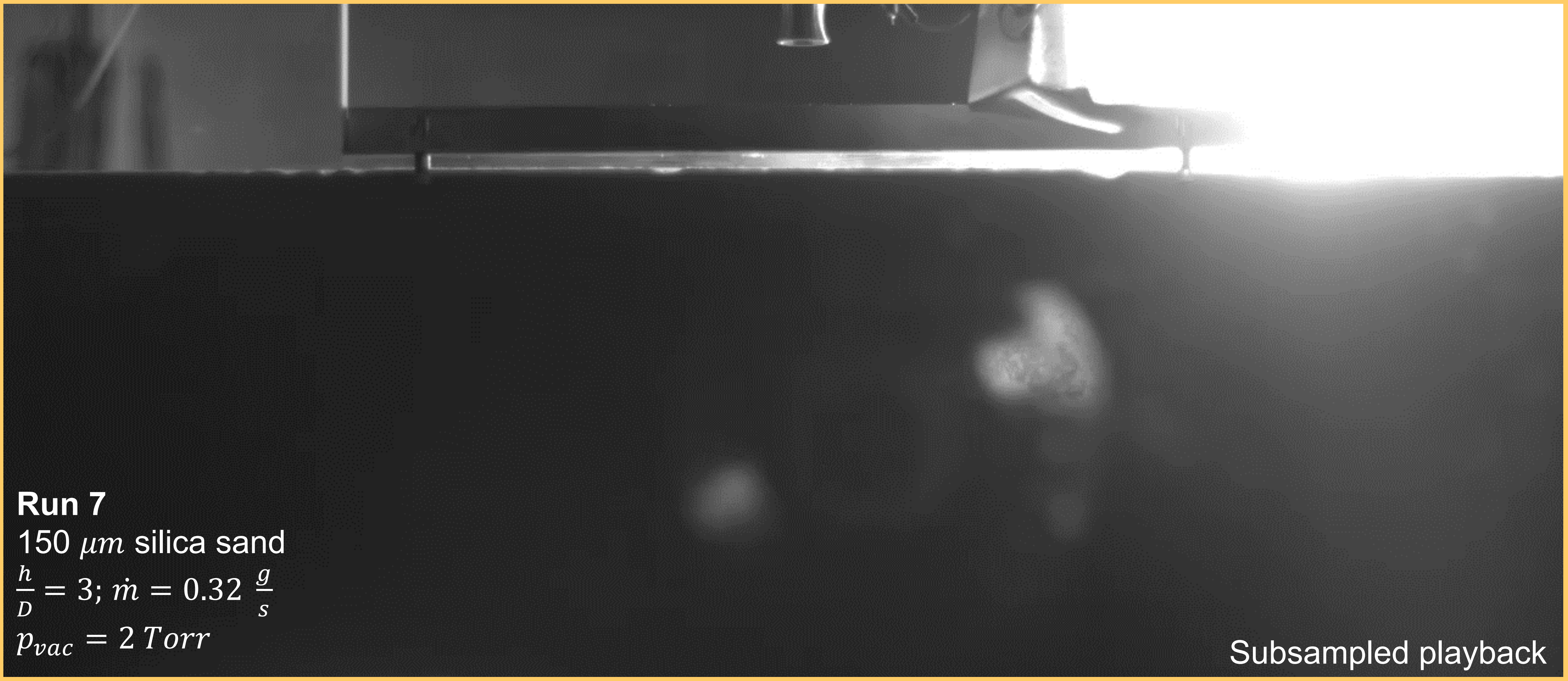


Camera	Resolution (µm/px)
EC1	94
EC2	61
CC	375

Credit: M. Diaz Lopez (JHU)

Example Data

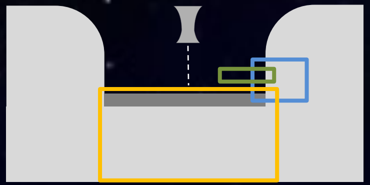


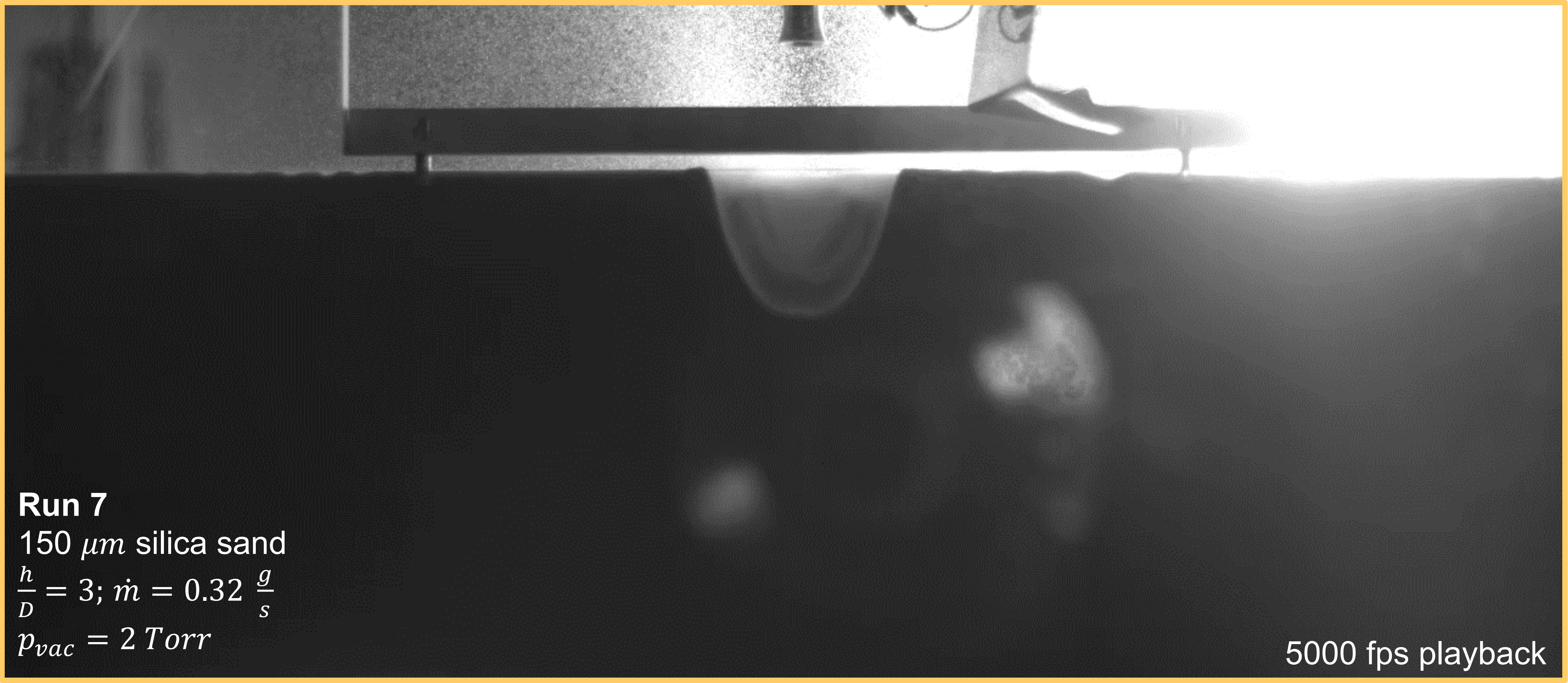


KPP 2

Credit: Wesley Chambers (MSFC) and JHU Team

Example Data

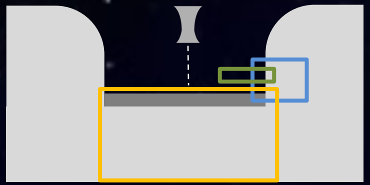


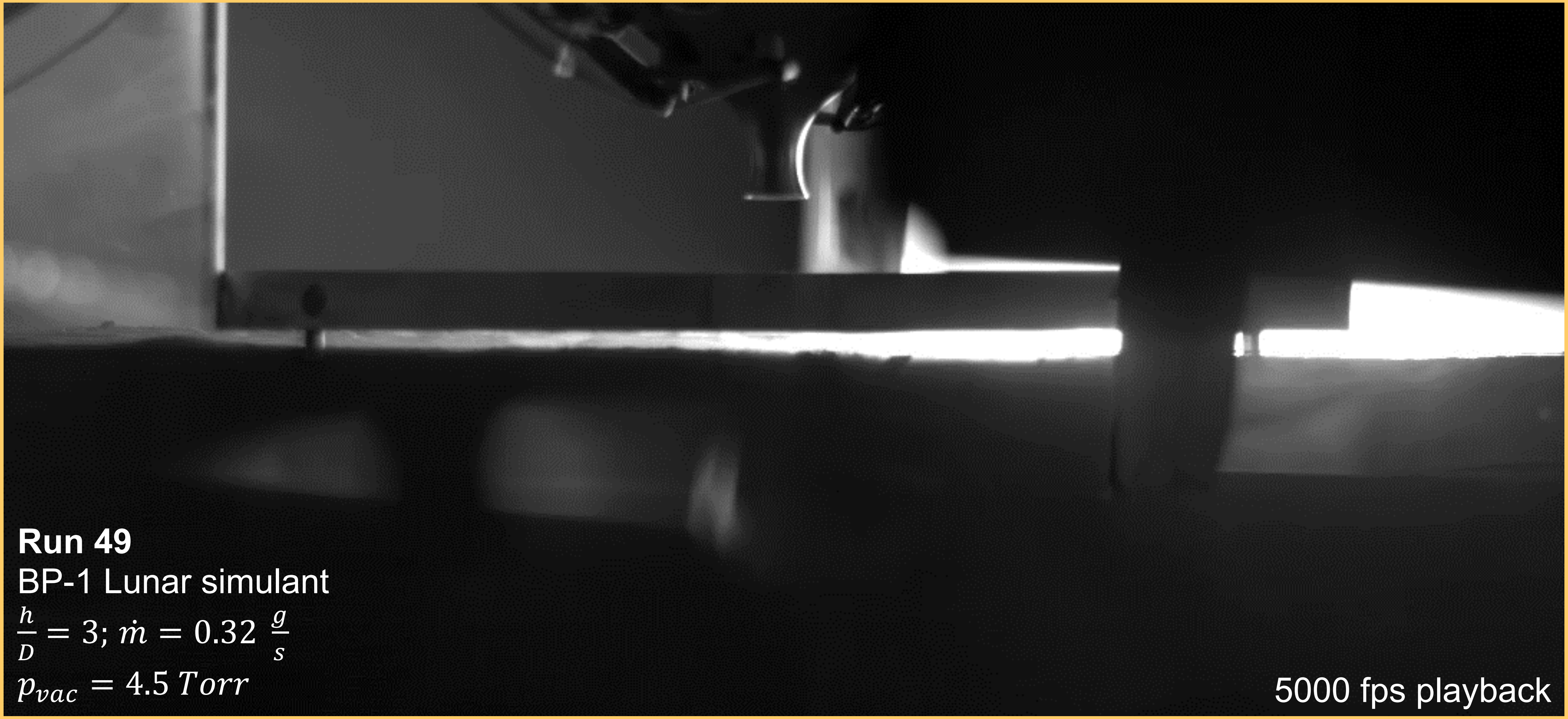


KPP 2

Credit: Wesley Chambers (MSFC) and JHU Team

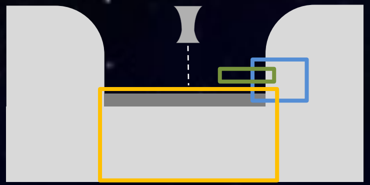
Example Data



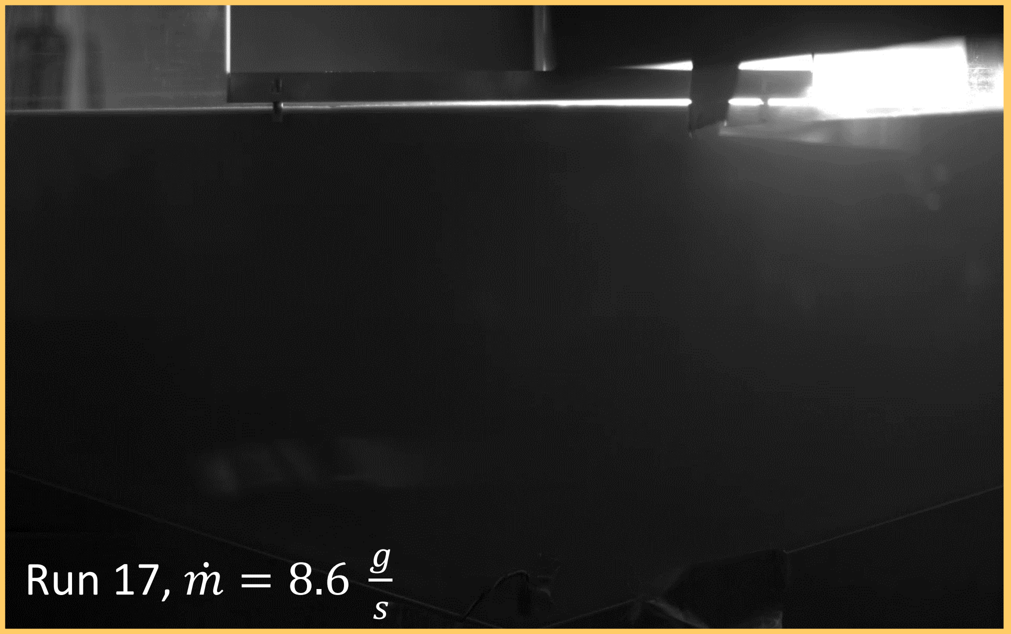


KPP 2

Credit: Wesley Chambers (MSFC) and JHU Team

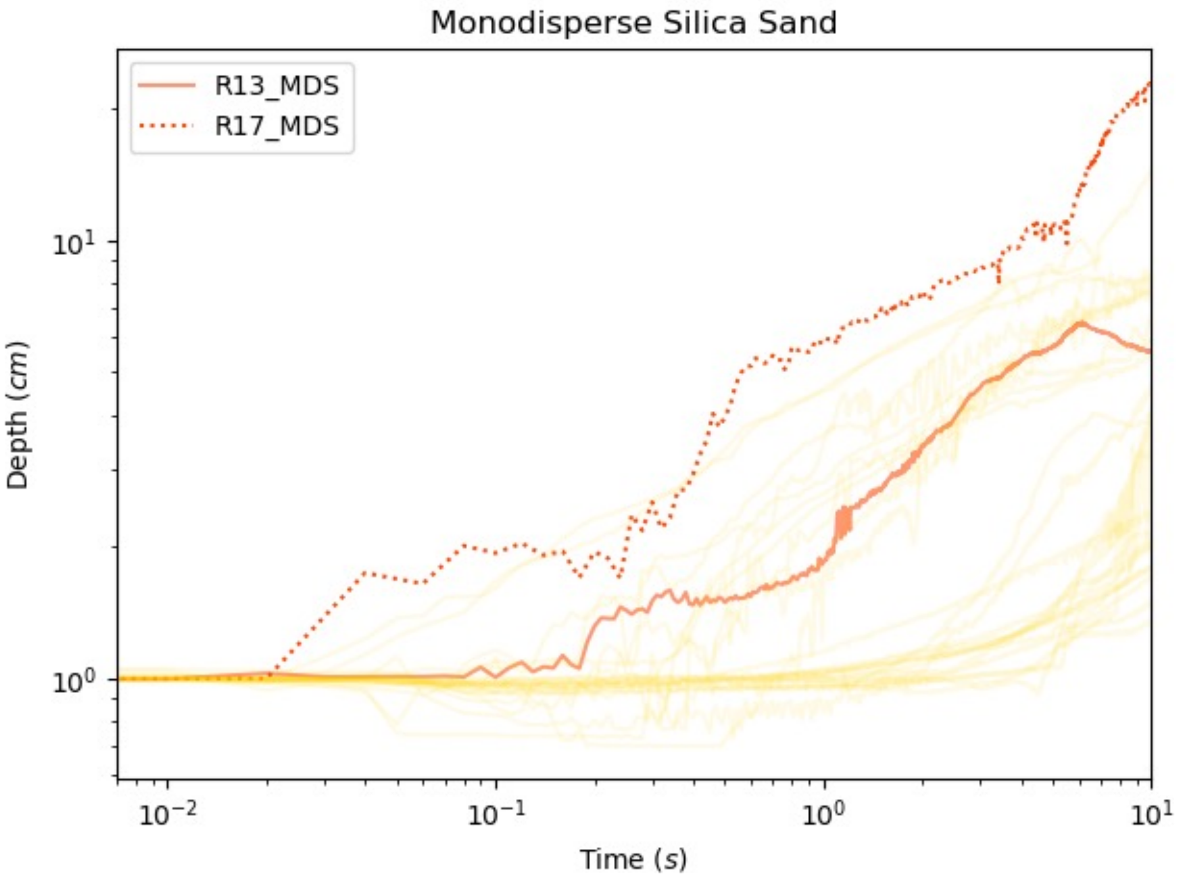


Results and Comparison



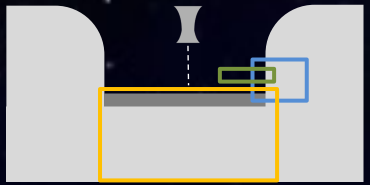
Difference in **mass flow rate**

Runs **13** & **17**, $\frac{h}{D} = 10$, $p_{vac} = 4.5\ Torr$ **(Mars-like)**



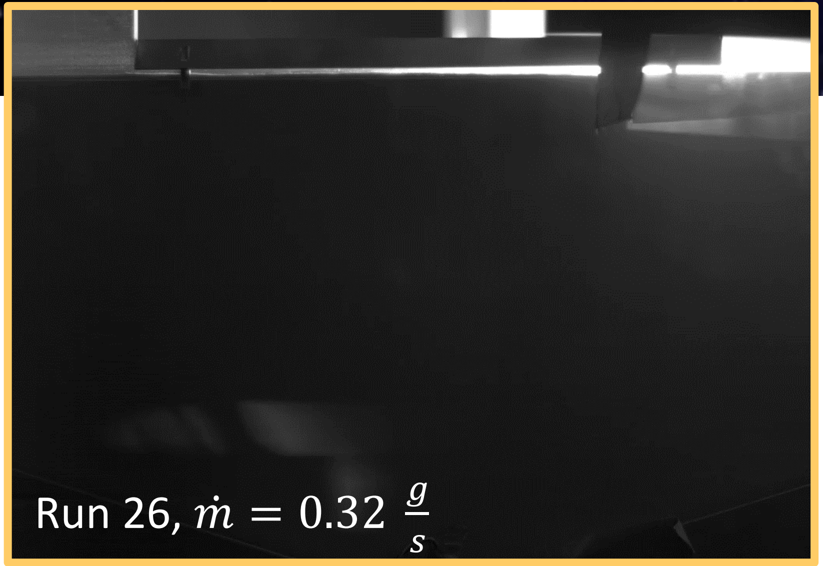
Credit: Wesley Chambers (MSFC) and JHU Team

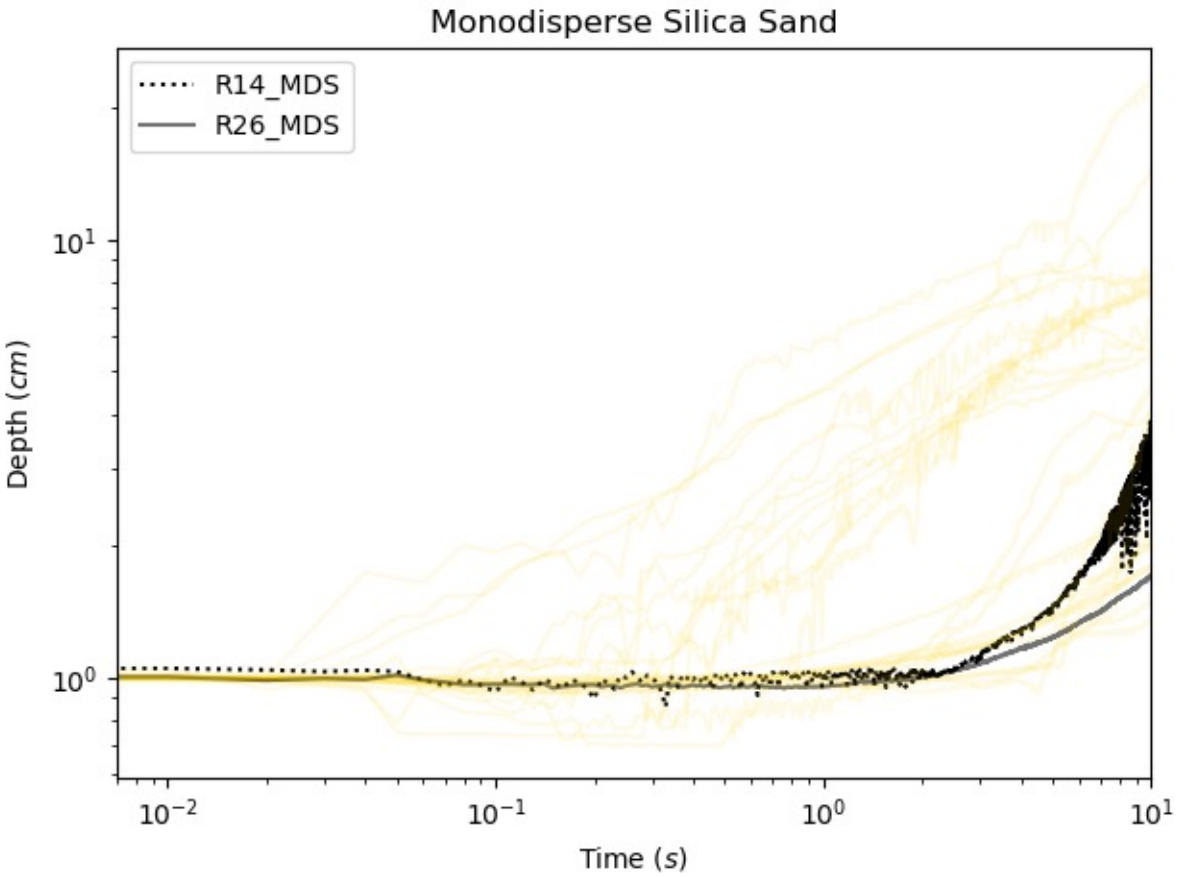
Results and Comparison



Runs **14** & **26**, $\frac{h}{D} = 10$, $p_{vac} = 0.02\ \&\ 0.053\ Torr$ **(Lunar-like)**

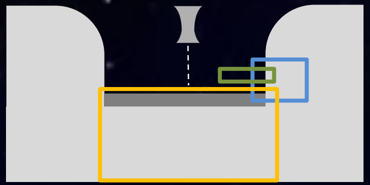
Difference in **mass flow rate**



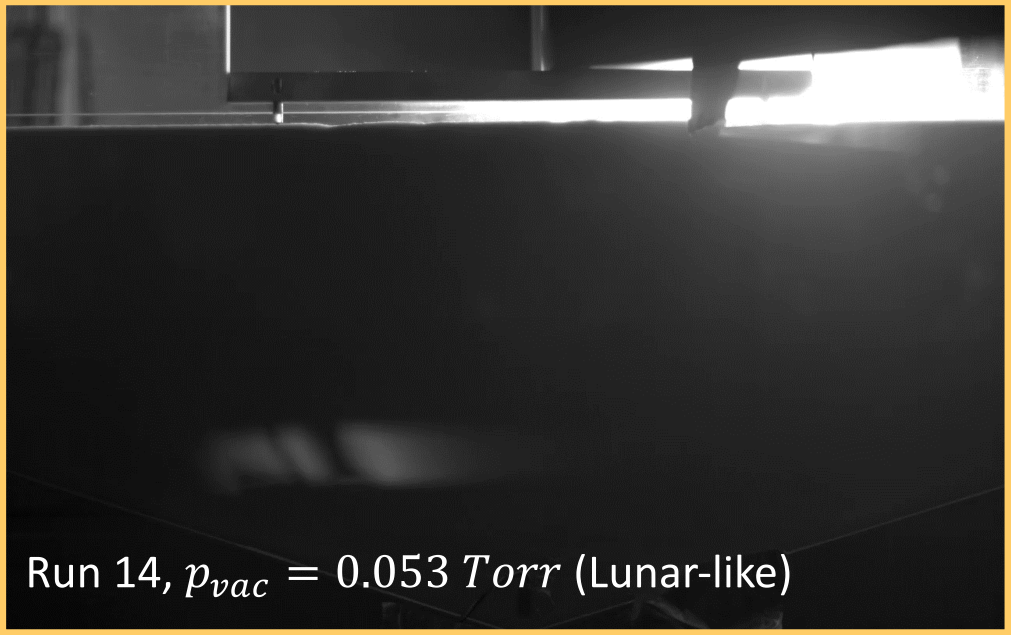


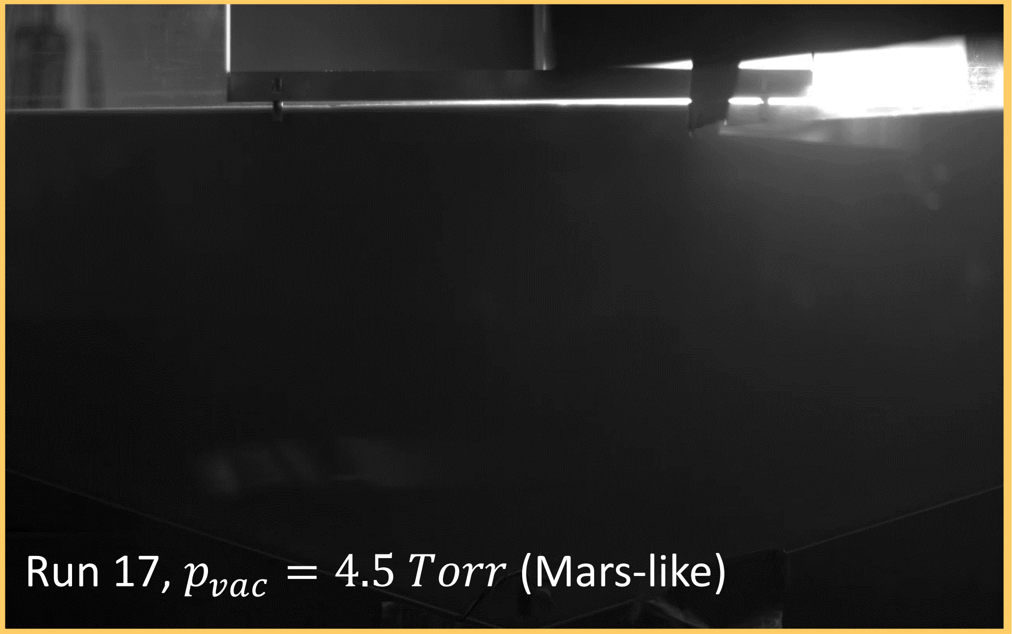
Credit: Wesley Chambers (MSFC) and JHU Team

Results and Comparison

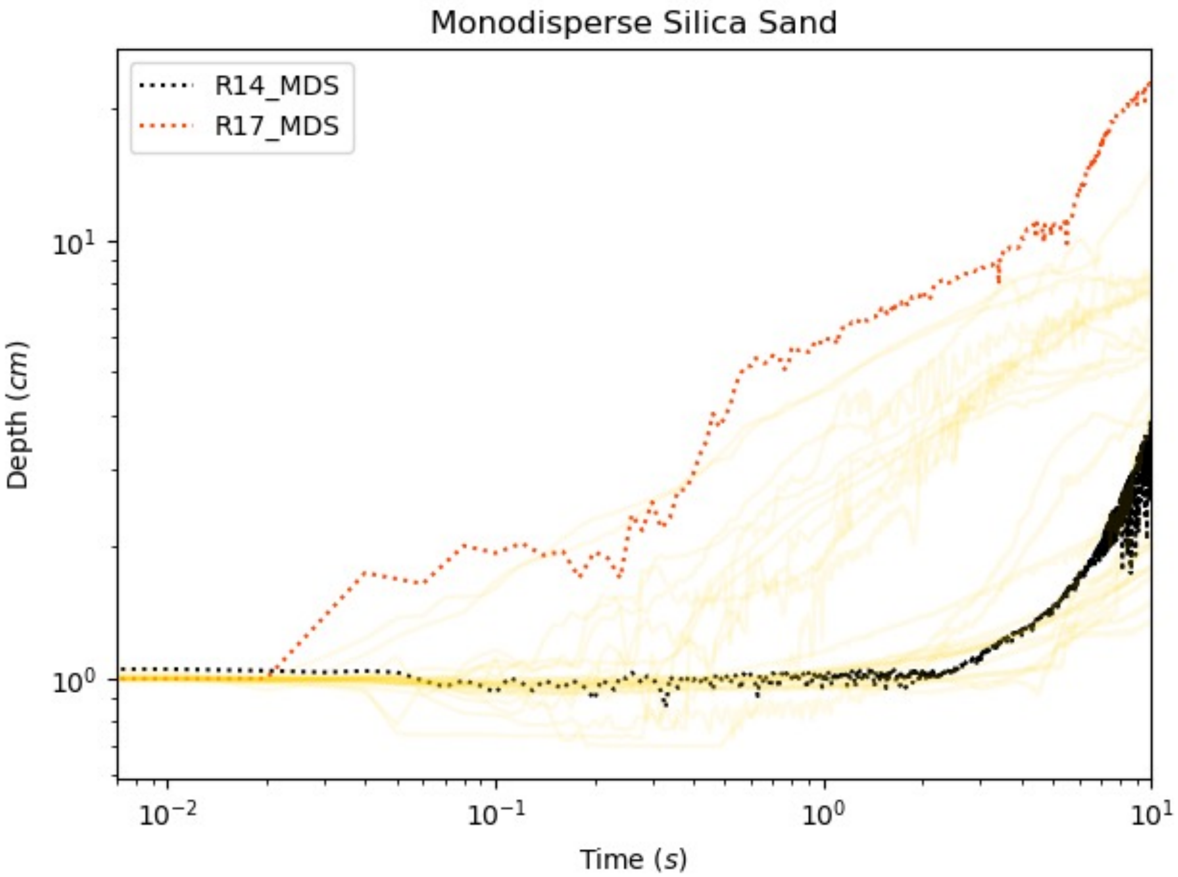


Difference in **vacuum** pressure



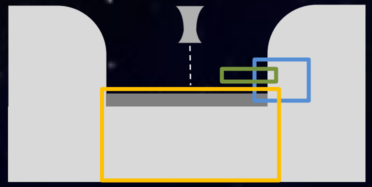


Runs **14** & **17**, $\frac{h}{D} = 10, \dot{m} = 8.6\ \frac{g}{s}$

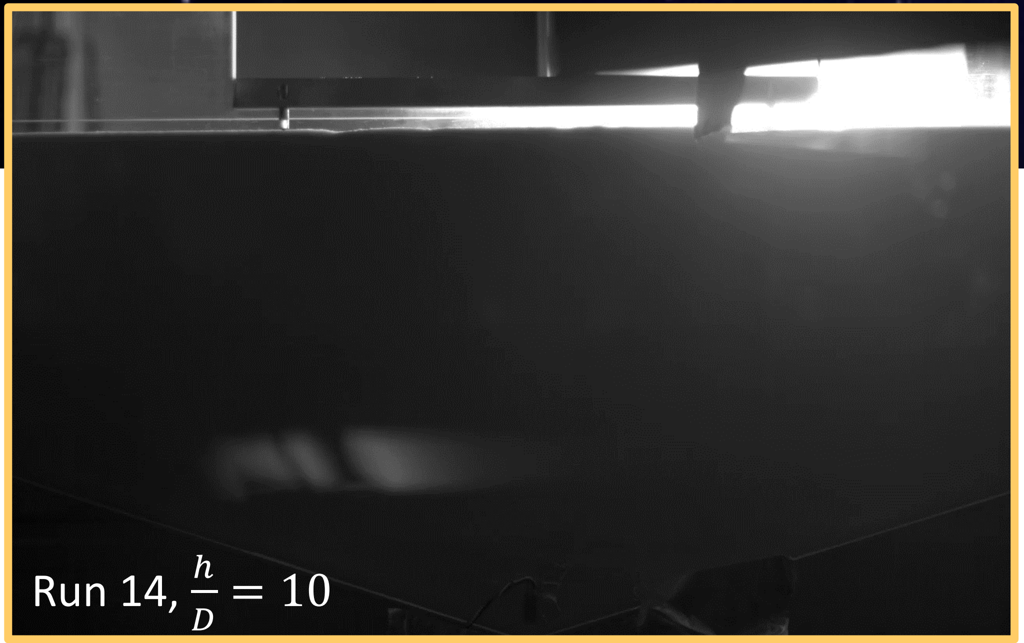


Credit: Wesley Chambers (MSFC) and JHU Team

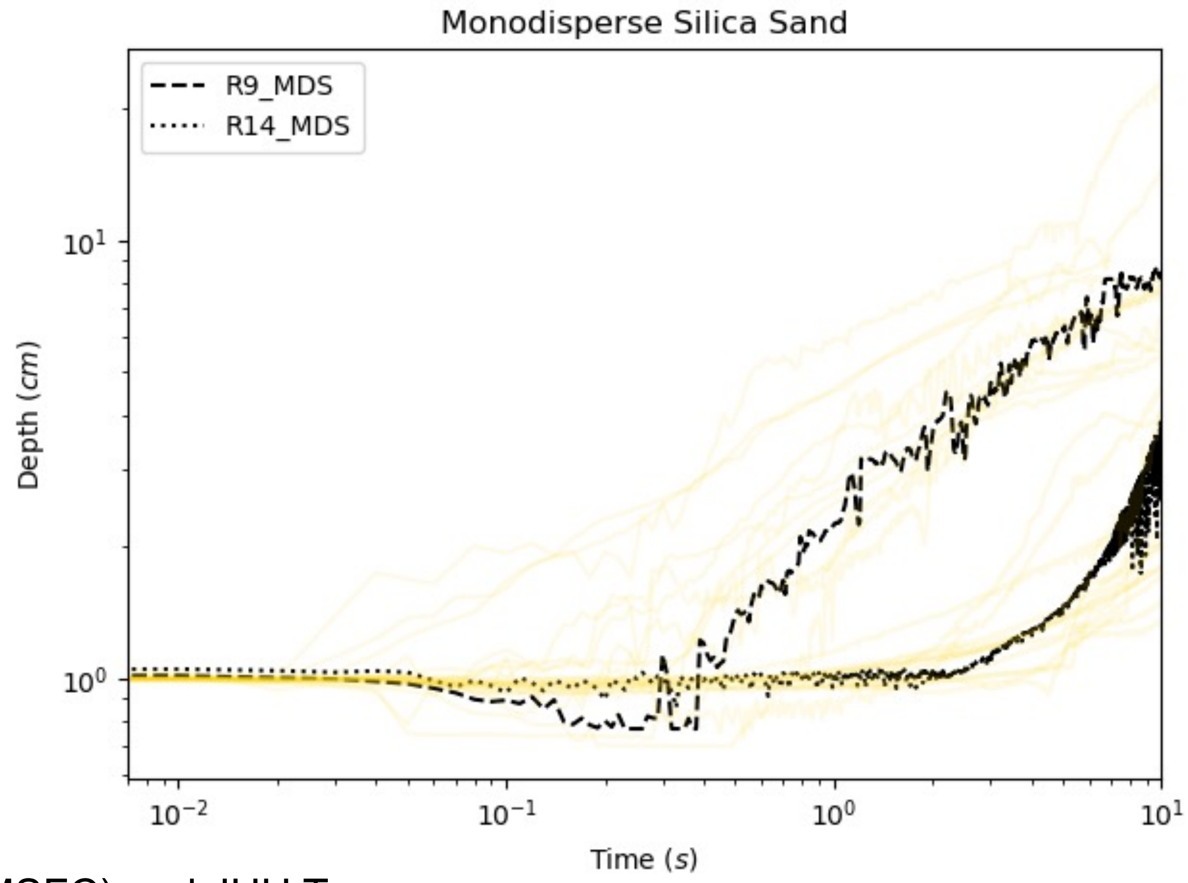
Results and Comparison



Difference in **nozzle height**

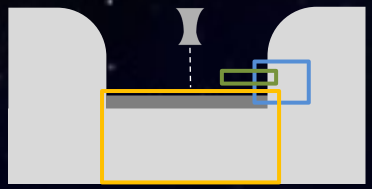


Runs **9** & **14**, $p_{vac} = 0.053\,Torr, \dot{m} = 8.6\ \frac{g}{s}$



Credit: Wesley Chambers (MSFC) and JHU Team

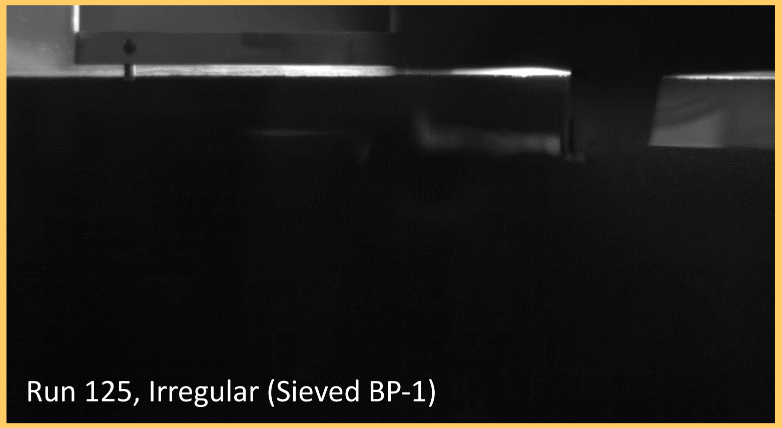
Results and Comparison



$$p_{vac} = 0.02\,Torr, \dot{m} = 0.32\,\frac{g}{s}, \frac{h}{D} = 8 - 10$$

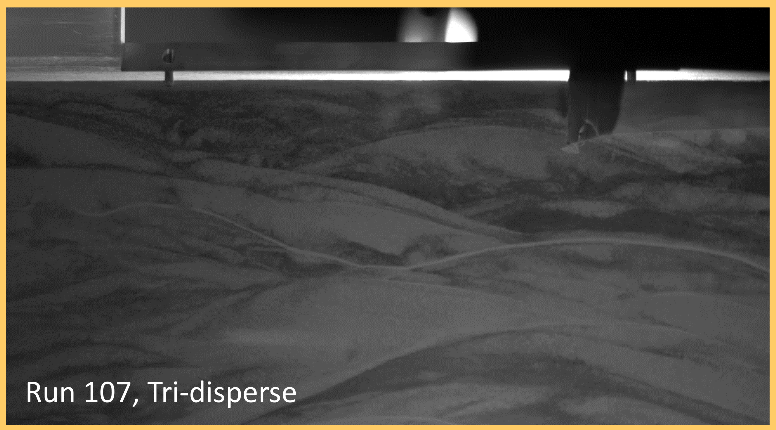
Run 25, Mono-disperse silica sand

Run 139, Mono-disperse glass beads

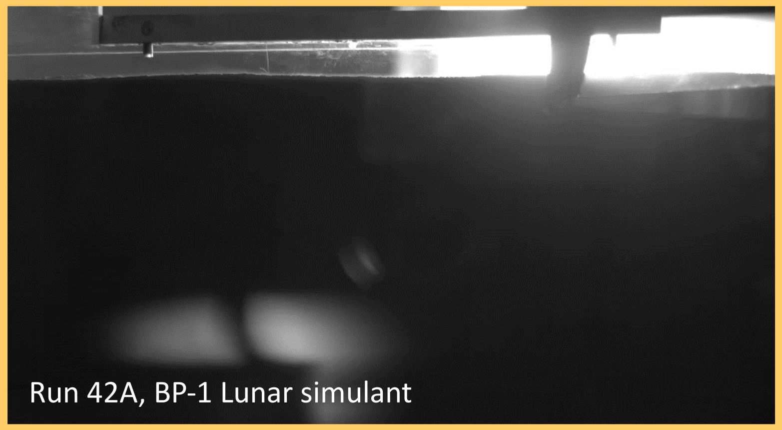


Run 125, Irregular (Sieved BP-1)

Run 93, Bi-disperse



Run 107, Tri-disperse

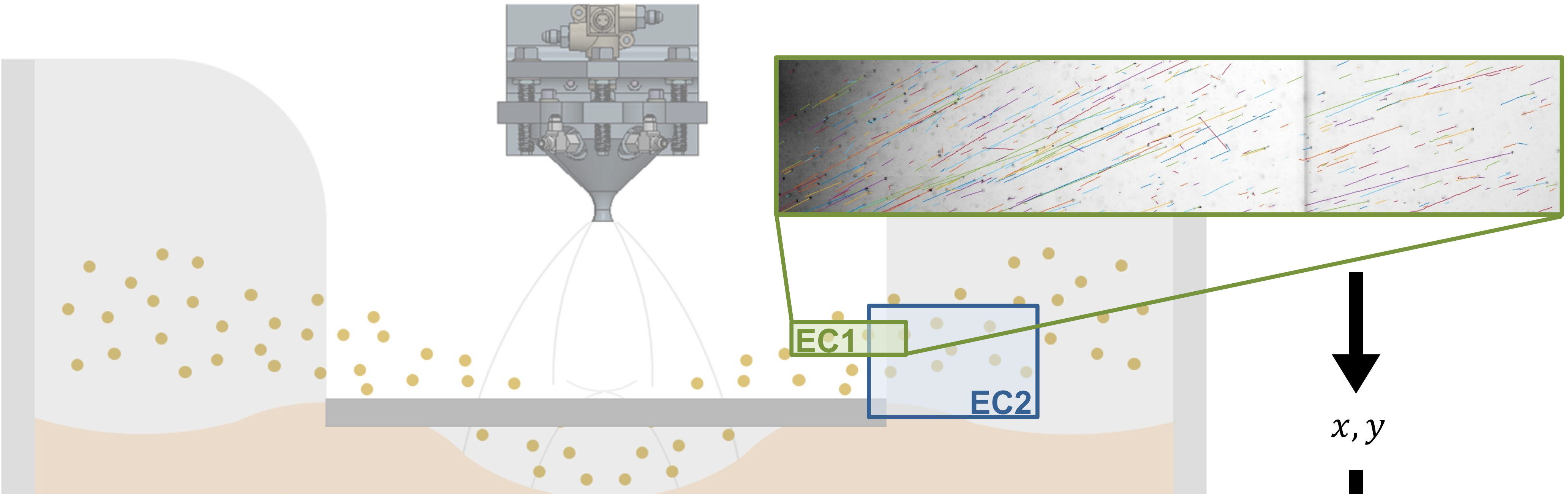


Run 42A, BP-1 Lunar simulant

Credit: Wesley Chambers (MSFC) and JHU Team

Fields of View

Credit: J. S. Rubio (JHU)



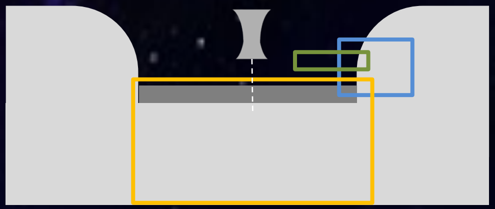
- Lagrangian particle tracking (LPT) algorithm
- First three frames used to determine particles in movement
- Subsequent frames used for following the tracks
- Velocities and acceleration are computed using a convolution filter
- Particle size information extracted

x, y

$U_p, V_p, a_{x_p}, a_{y_p}, \theta_p$

Indirect measurement of **KPP3**

Vacuum Pressure Effects



P_{vac} = 0.02 torr

h/D = 8

$\dot{m}$ = 0.32 g/s

P_{vac} = 4.5 torr

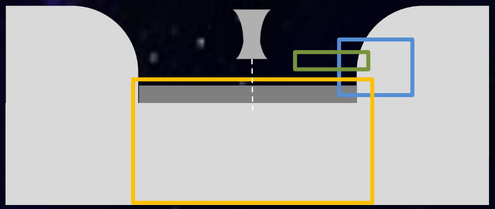
h/D = 10

$\dot{m}$ = 0.32 g/s

KPP 3

Credit: JHU Team

Mass Flow Rate Effects



P_{vac} = 4.5 torr

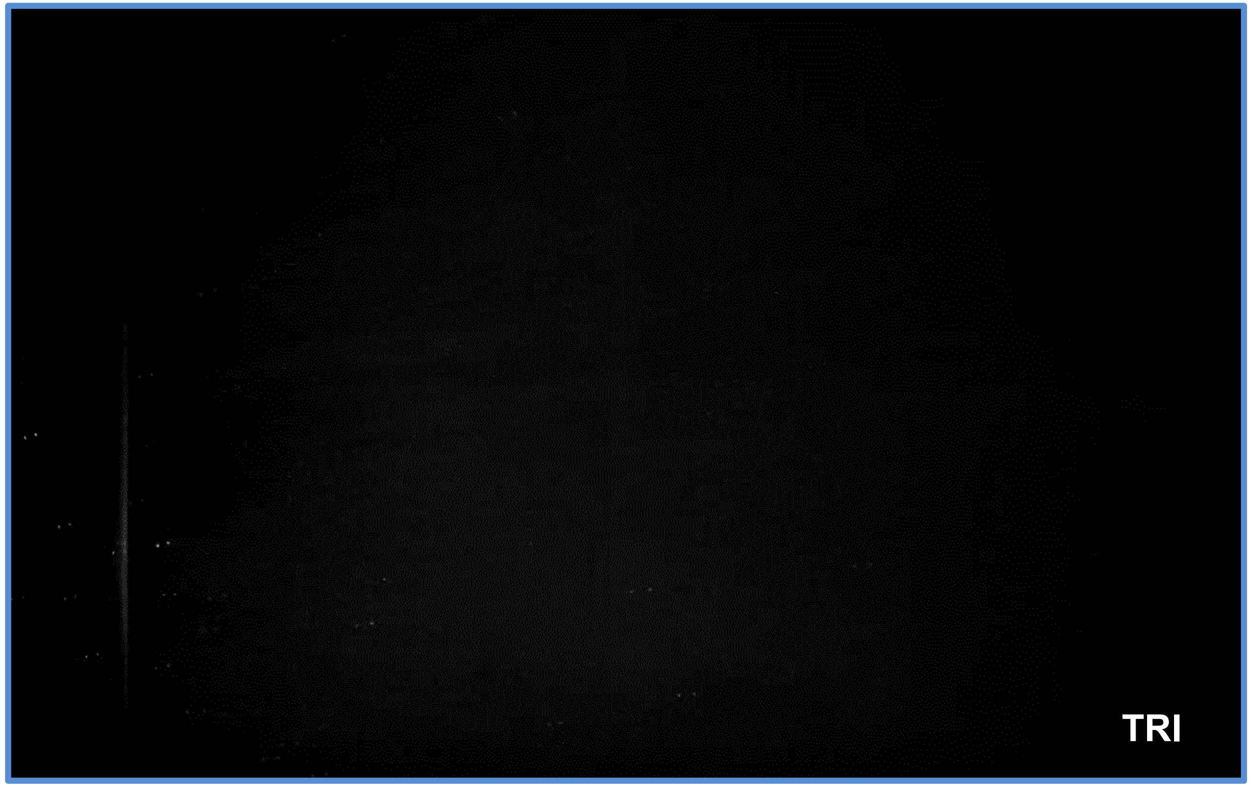
h/D = 10

$\dot{m}$ = 0.32 g/s

P_{vac} = 4.5 torr

h/D = 10

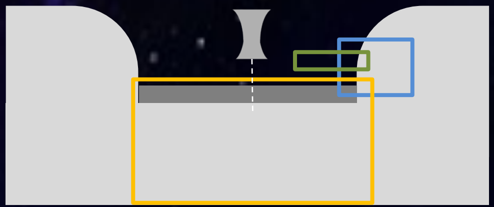
$\dot{m}$ = 8.6 g/s



KPP 3

Credit: JHU Team

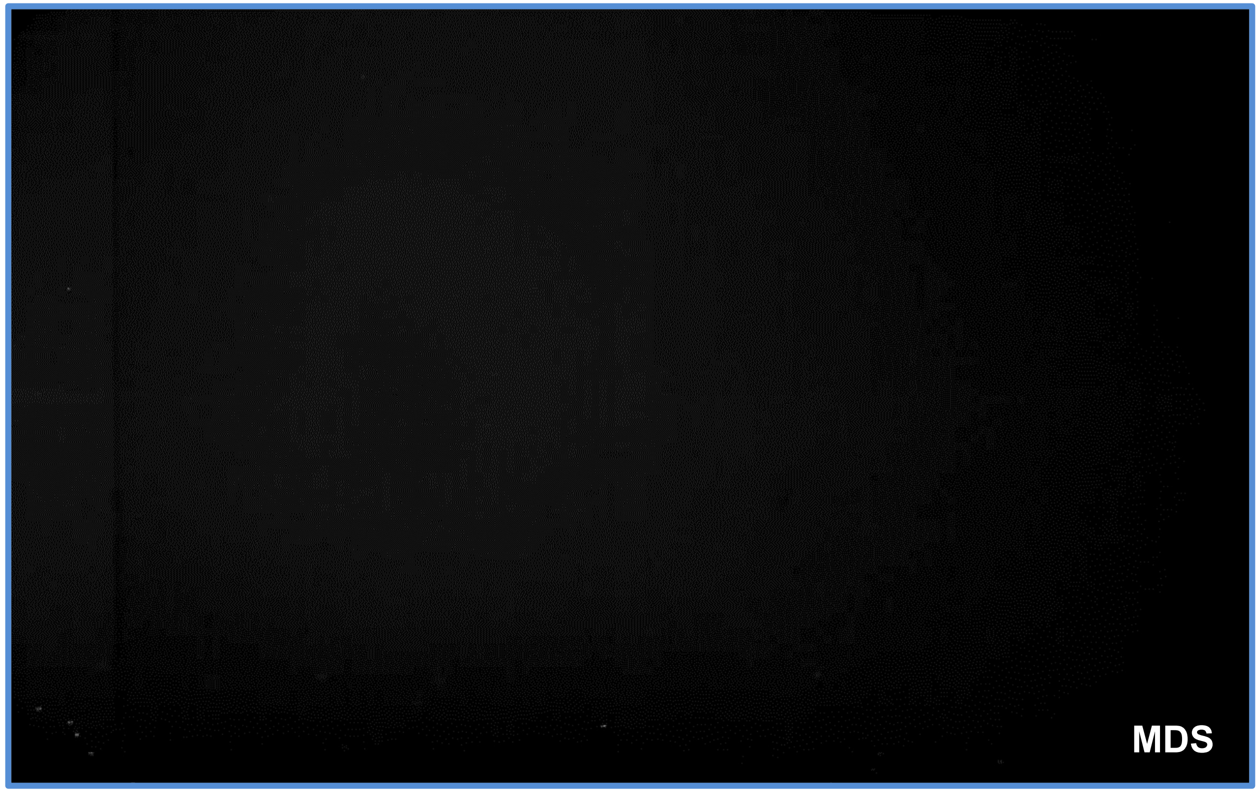
Effect of Nozzle Height



P_{vac} = 0.02 torr

h/D = 8

$\dot{m}$ = 0.32 g/s



P_{vac} = 0.02 torr

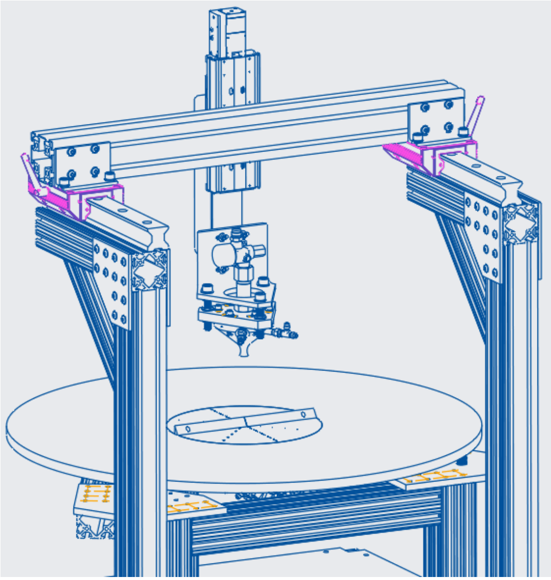
h/D = 3

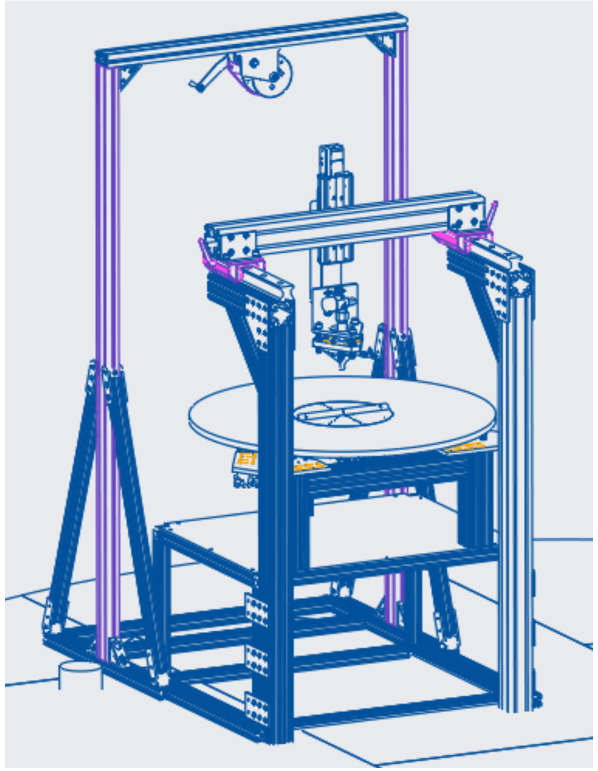
$\dot{m}$ = 0.32 g/s

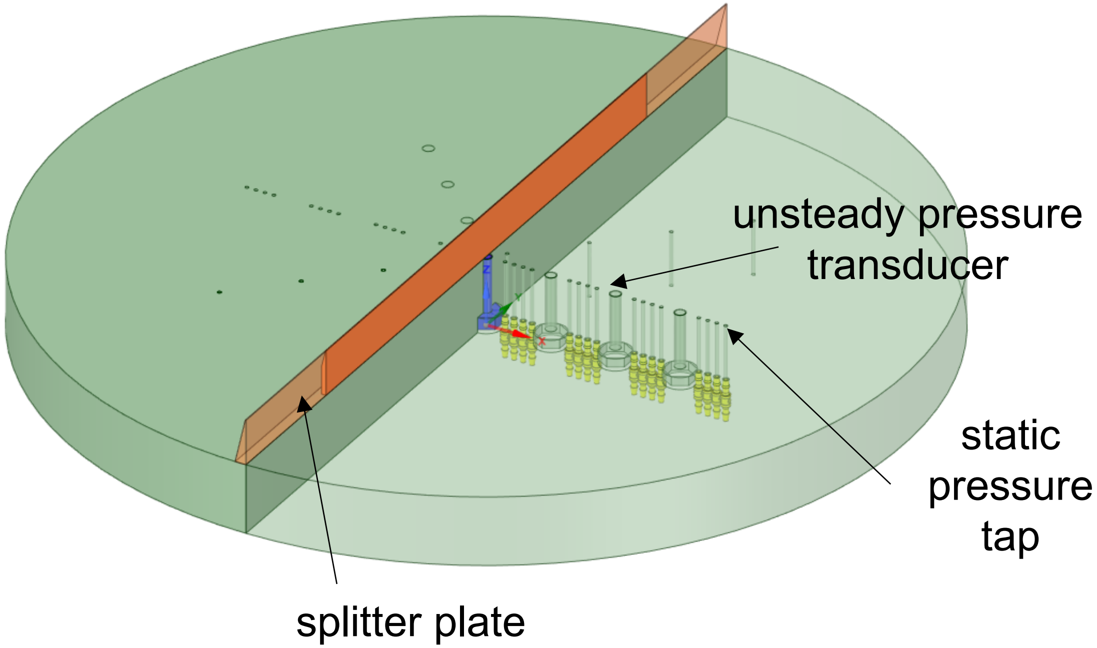
KPP 3

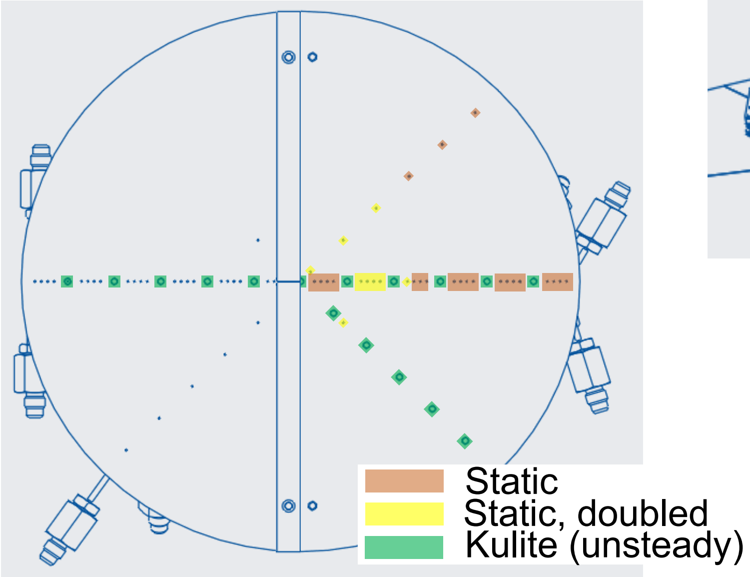
Credit: JHU Team

Impingement Plate Test Article





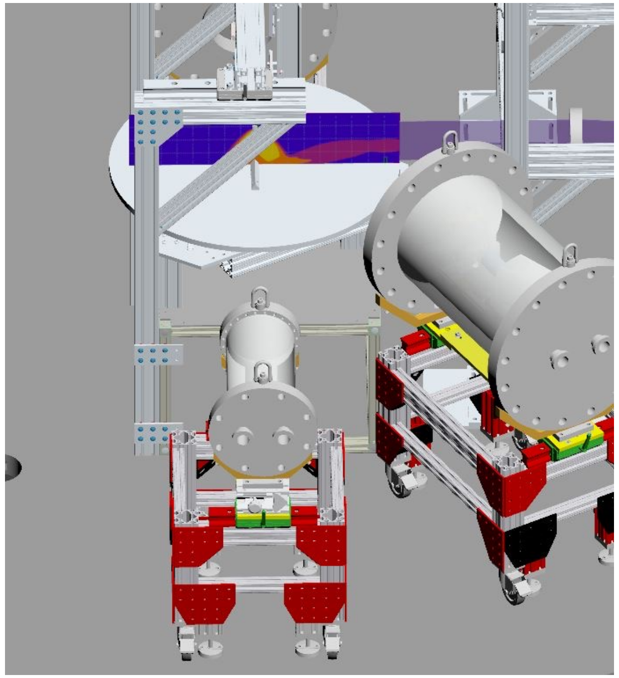


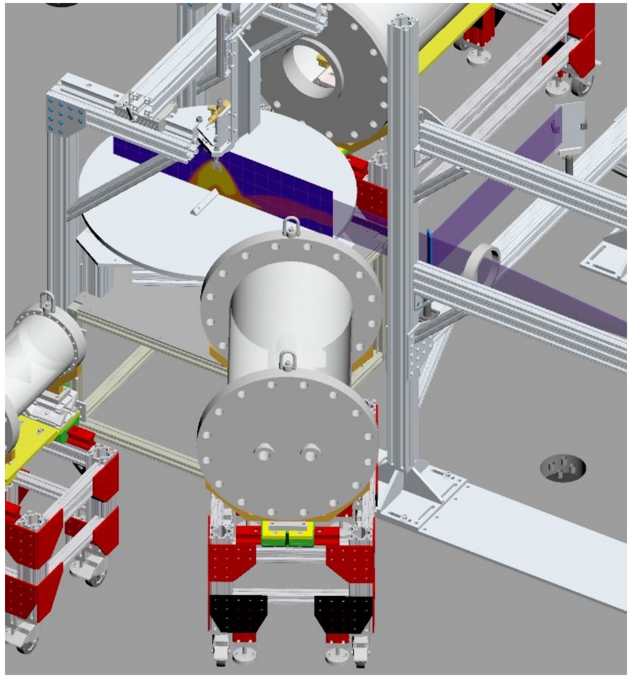


- 31 static taps, with 9 doubly instrumented
  - 10, 20, 100, and 1000 Torr
- 16 Kulites (unsteady pressure)
  - 1 – 10 kPa (7.5 – 75 Torr)
- Same h/D_e settings as in cratering and ejecta testing
- NO PLIF diagnostics will be part of PFGT2 in the 20-foot vacuum chamber

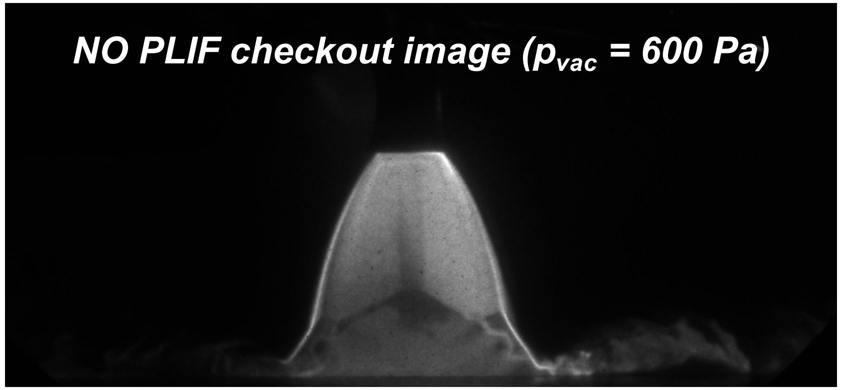
NO PLIF Diagnostics: PFGT2 20-ft Chamber

- PLIF (planar laser induced fluorescence) diagnostics using seeded NO (nitric oxide) will be used to obtain data on plume structure and behavior (NASA LaRC D304)
- 10 Hz NO-PLIF measurements performed within low-pressure gas cell system at Langley
  - Results presented in 2022 AIAA SciTech paper (Rodrigues, Bathel, Danehy).
- 100 kHz NO-PLIF measurements performed on underexpanded jet at ambient pressure at Spectral Energies, LLC (Rodrigues & Danehy visited engineers at Spectral Energies)
  - Results submitted as abstract to 2023 AIAA SciTech (Rodrigues, Danehy, *et al.*).



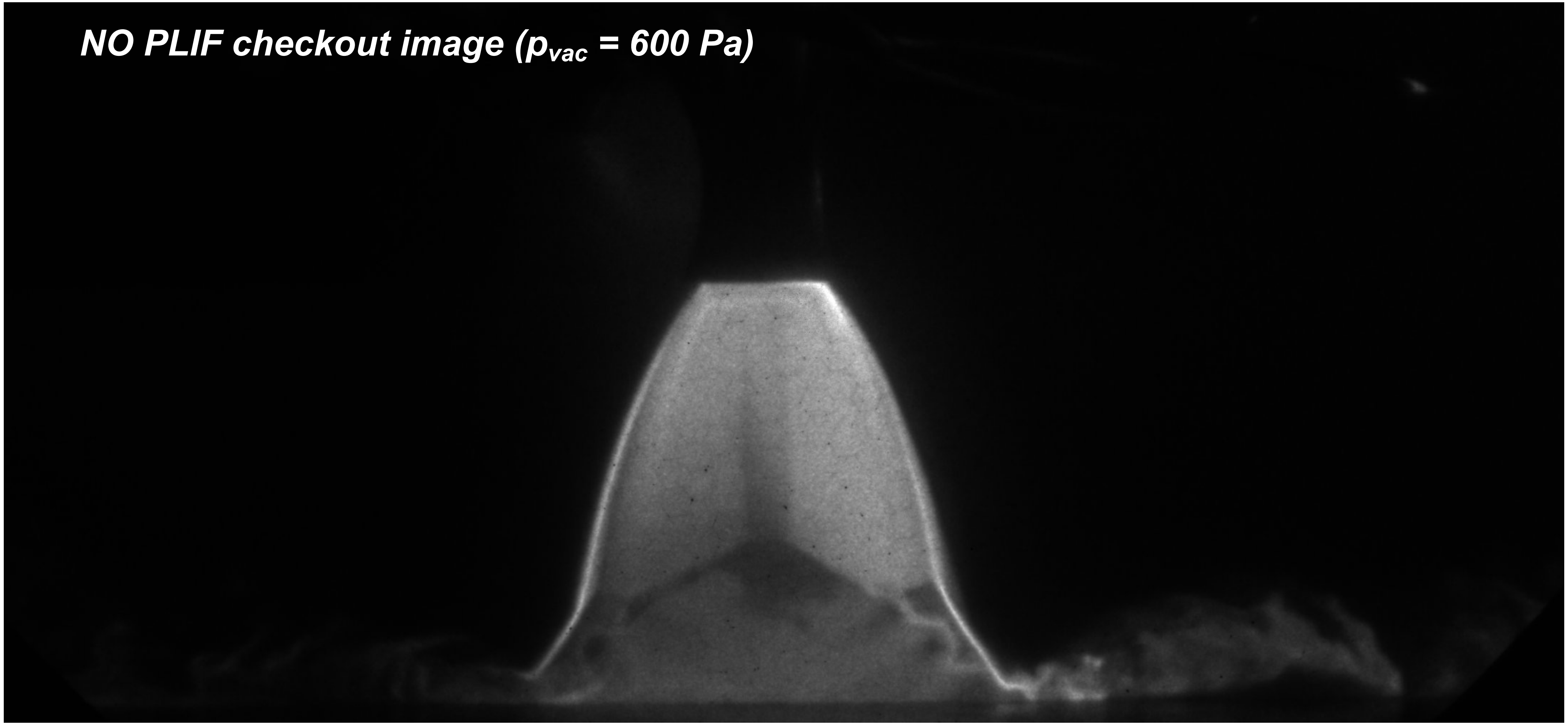


Credit: Neil Rodrigues (LaRC) and PLIF Team



Simulated PLIF field (log-scale) calculated based on temperature and pressure computations performed by NASA MSFC at representative conditions

NO PLIF Diagnostics: PFGT2 20-ft Chamber



Credit: Neil Rodrigues (LaRC) and PLIF Team

Wrap-Up

- Vehicle performance evaluation is only as good as the lowest fidelity of the underlying models
- Powered descent and landing 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, long-term development of powered descent for Mars will be heavily reliant on multiple levels of fidelity in 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

Langley Research Center

Questions?