National Aeronautics and
Space Administration

# NASA Plume-Surface Interaction (PSI) Testing to Reduce Risk from Propulsive Landing

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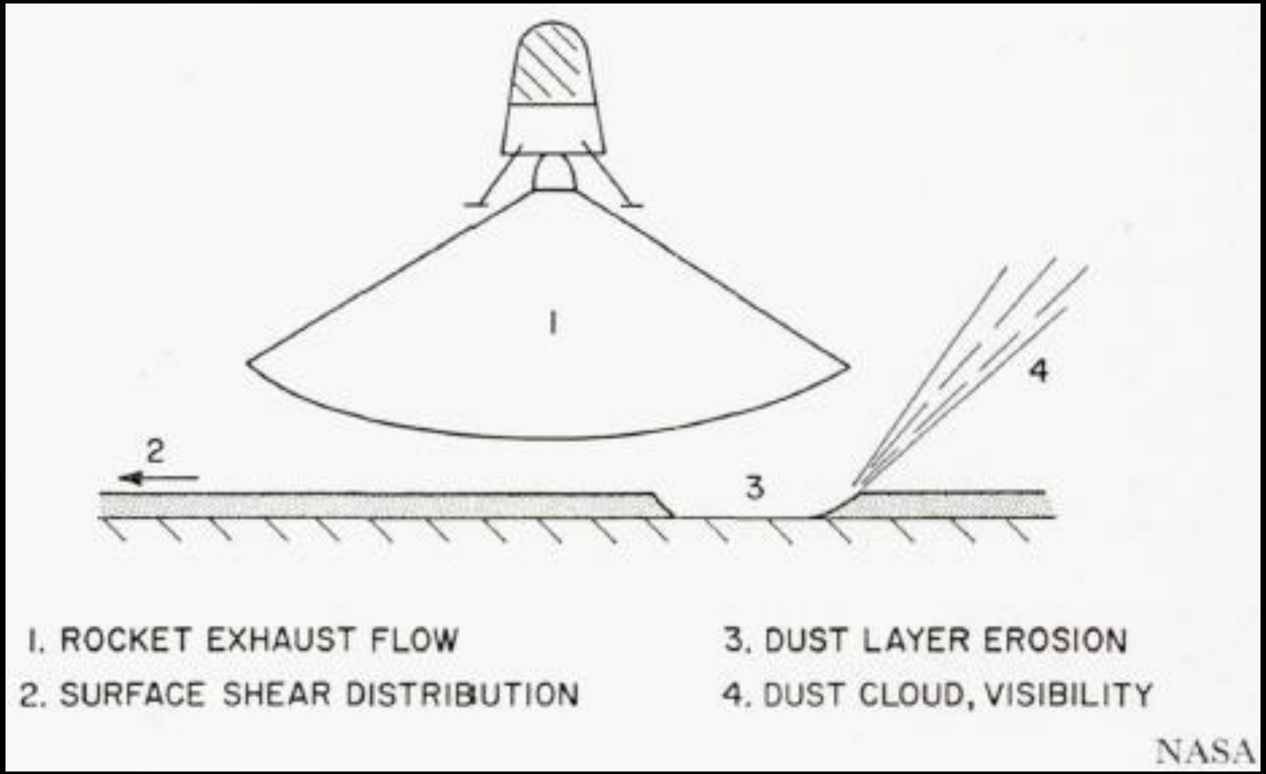
# Outline

- What is PSI?
- PSI risks
- Anatomy of a PSI test
- Large-scale lunar PSI testing
- Impingement plate testing
- Erosion and ejecta testing
- Forward work



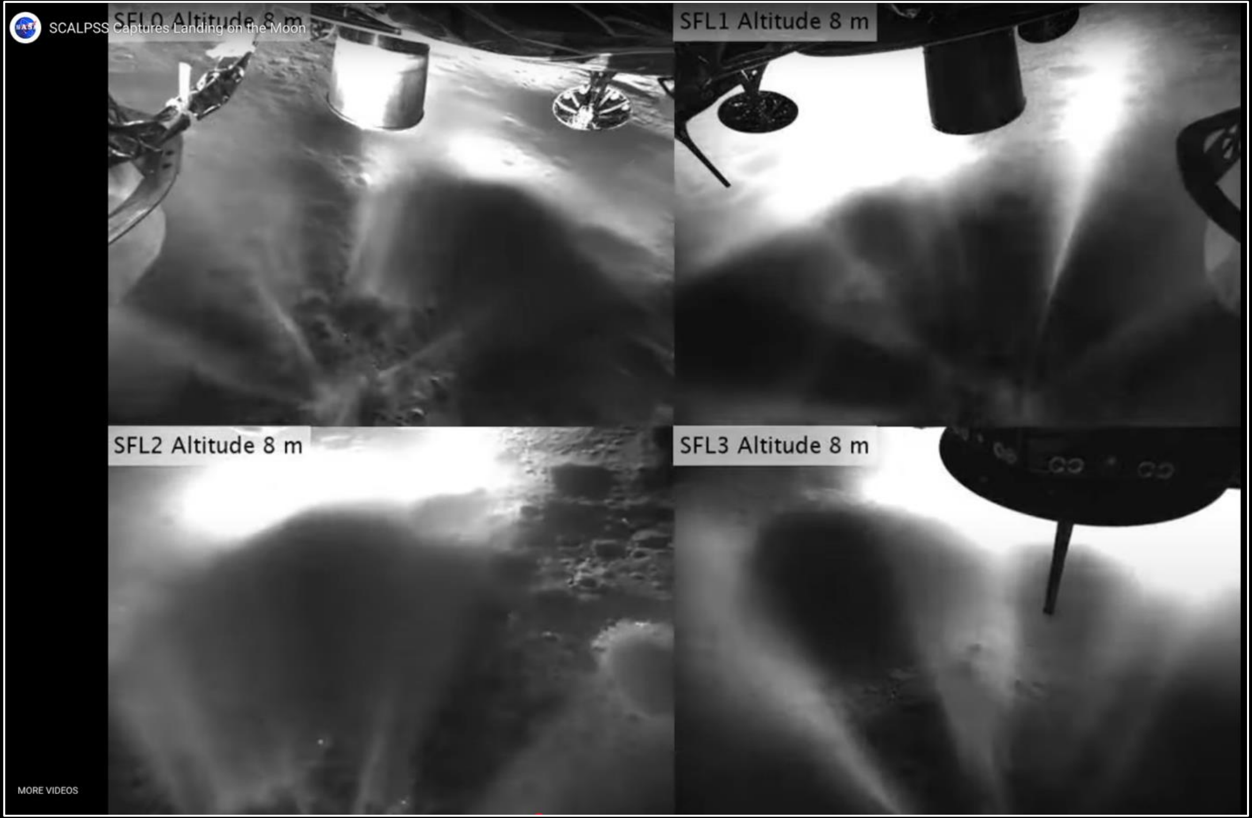

*Roberts, L, AGARDograph 87, 1966*

# Introduction

*Rocket* ***plume-surface interaction (PSI)***

*describes the lander environment induced by impingement of hot rocket exhaust on regolith of planetary bodies*

*Apollo 11 (NASA)*




*SCALPSS Imagery on Firefly Blue Ghost (NASA)*

# Risks Posed to Landers by PSI

Impacts of PSI:

- Visual and sensor obscuration / degraded performance
- Vehicle stability and tilt
- Localized augmentation of heating and/or pressure
- Abrasion damage from debris and ejecta

An understanding of PSI enables the ability to:

- Conduct successful near-surface operations
- Mitigate surface alteration
- Mitigate effects to surrounding assets

*Debris on Curiosity rover deck, rocks > 1.5 cm*

*Image credit: NASA/JPL*

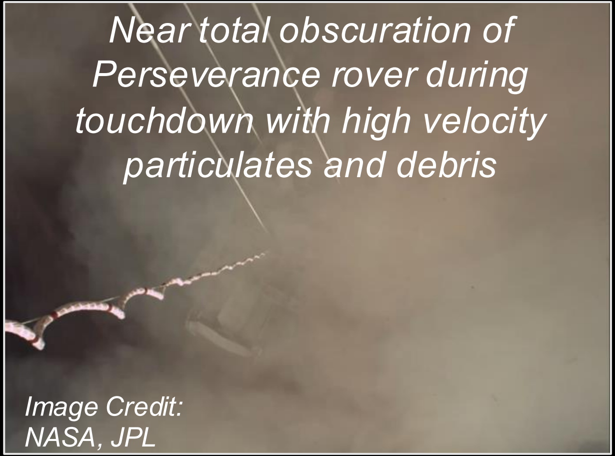
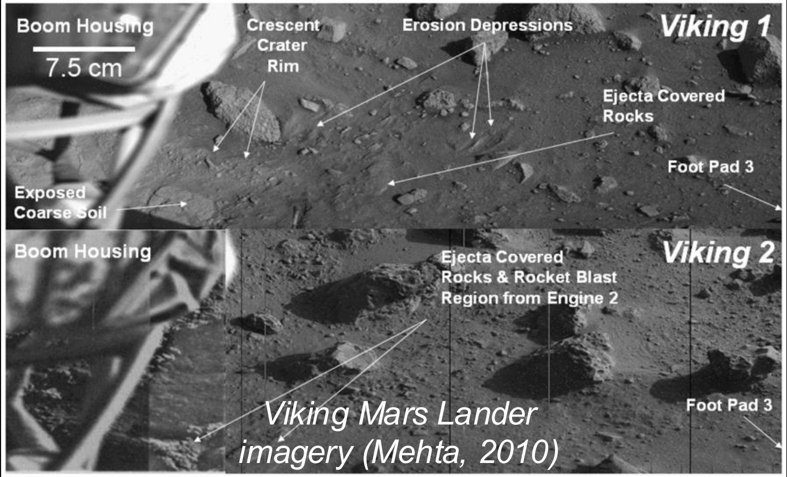

*Near total obscuration of Perseverance rover during touchdown with high velocity particulates and debris*

*Image Credit: NASA, JPL*


*Visual Obscuration During Apollo 16 Landing (Metzger, 2010)*

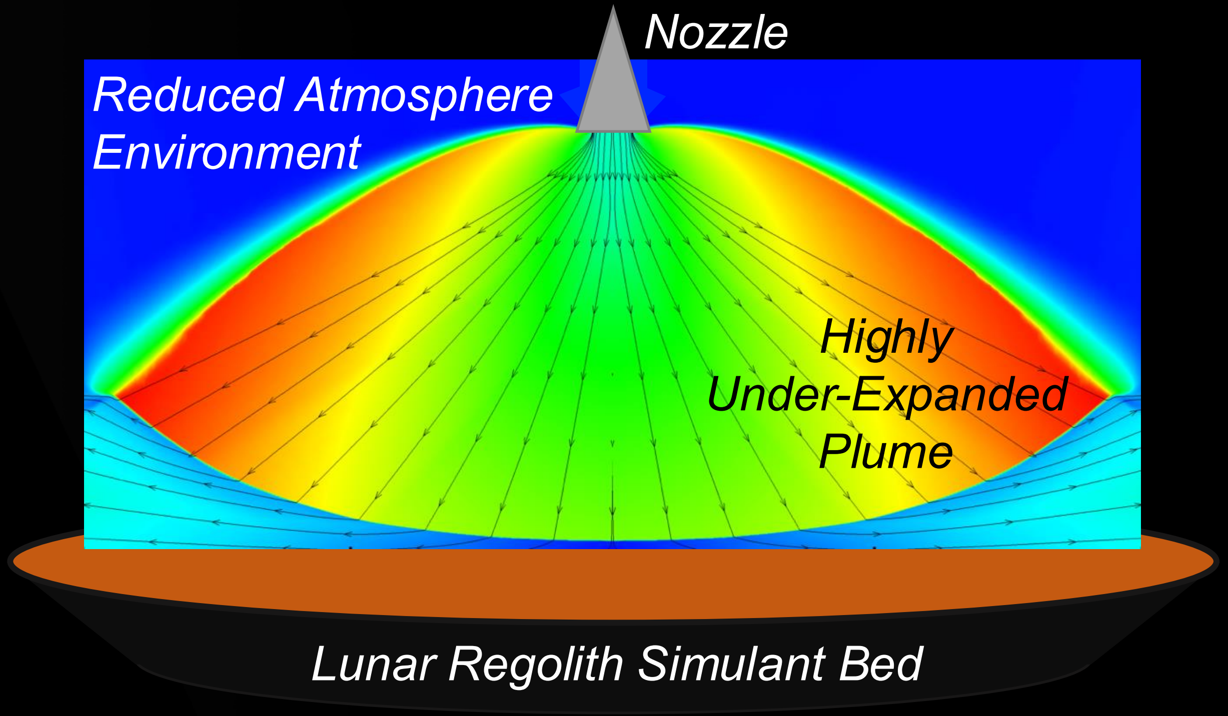


*Viking Mars Lander imagery (Mehta, 2010)*

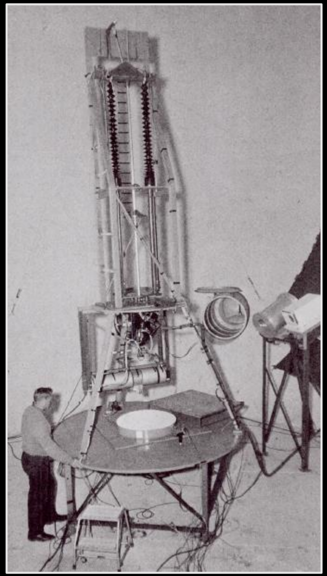
# Anatomy of a PSI Test

**<u>Objective</u>: To reduce risk to large lunar landers through acquisition of lunar-relevant ground test data to quantify and reduce uncertainty in PSI predictions through improvements to and validation of modeling capabilities**

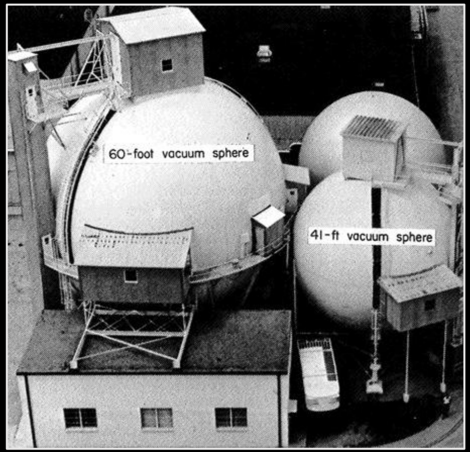
- Target scaled flight conditions and maximize test envelope
- Parameters:
  - Nozzle height above regolith
  - Plume total pressure
  - Plume mass flow rate
- Target 30 runs per propulsion type:
  - Non-combusting Ethane
  - Hybrid Motor (GOX/ABS)



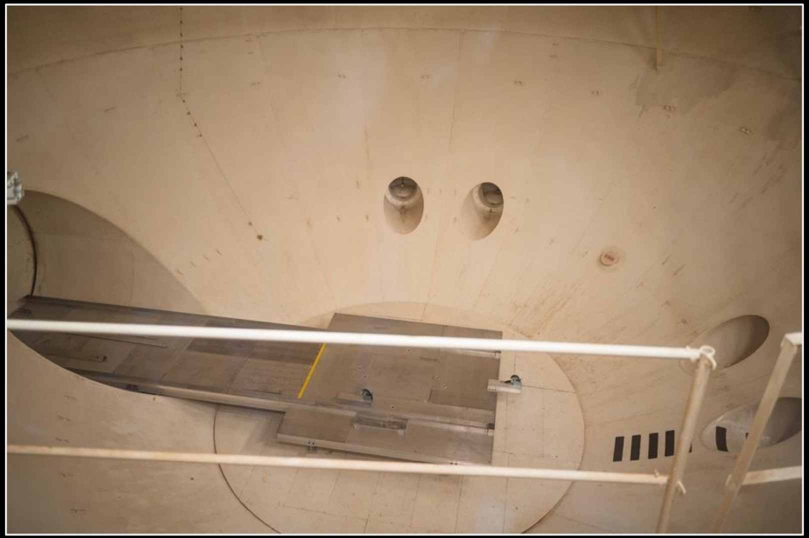
# Vacuum Test Facility



NASA TN D-5051, 1969




- 60-ft vacuum sphere at NASA Langley Research Center
- Historically used to test PSI for Apollo and Viking
- Provides very large volume to minimize ambient pressure rise during PSI testing
- Target test condition (facility capability): 0.75 Torr (100 Pa)



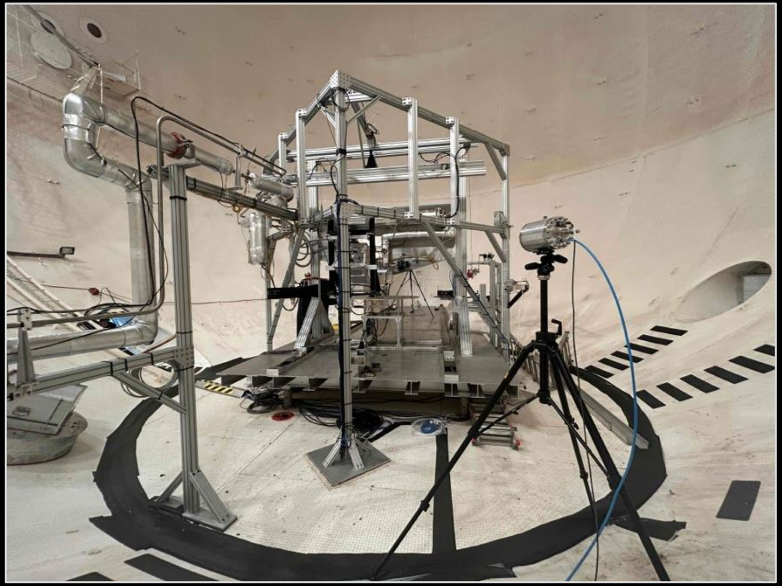
*60-ft Vacuum Sphere (part of the NASA Langley Aerothermodynamics Laboratory Facility)*

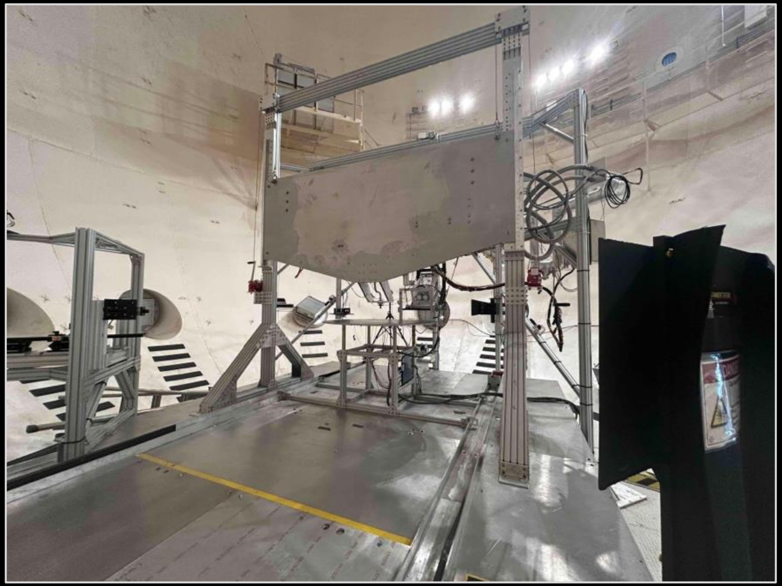
# Large-scale Lunar PSI Testing

- Current scope will conduct testing through Dec. 2026
- Modular design of all hardware
- Multiple fixed nozzle heights above prepared regolith simulant
- Test matrix spans full envelope of pressure system conditions

Regolith bin for PSI testing (2m diameter)

PSI hardware setup

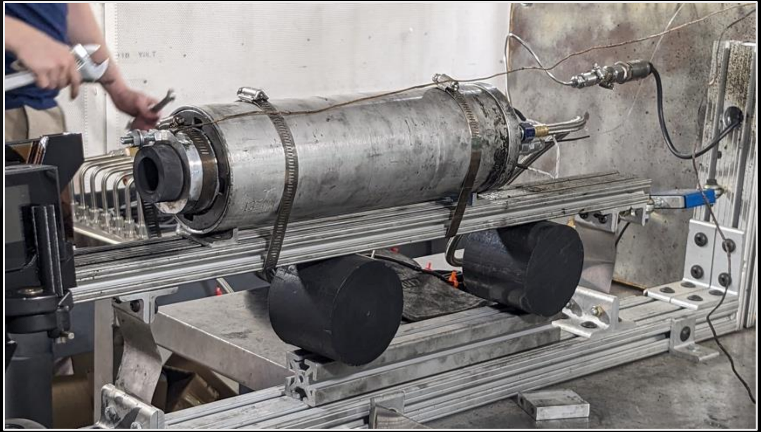




**New NASA PSI test capability to explore erosion and ejecta from PSI under reduced atmosphere – Moon and Mars relevant**

# Propulsion Elements – Rocket Plume Simulants

- Highly under-expanded exhaust plume matching absolute peak and radially scaled distributions for surface impingement pressure and shear
- Firing durations: 6 seconds per test run
- PSI testing using two separate propulsion elements
    - Non-combusting, heated ethane plume (Purdue Univ.)
        - Thrust < 100 $lb_f$
    - GOX/ABS hybrid rocket motor (Utah State Univ.)
        - Thrust < 40 $lb_f$

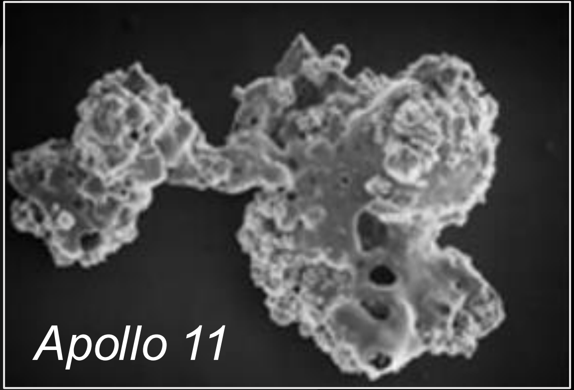


*98 mm GOX/ABS Hybrid Motor (Utah State Univ. / NASA MSFC)*

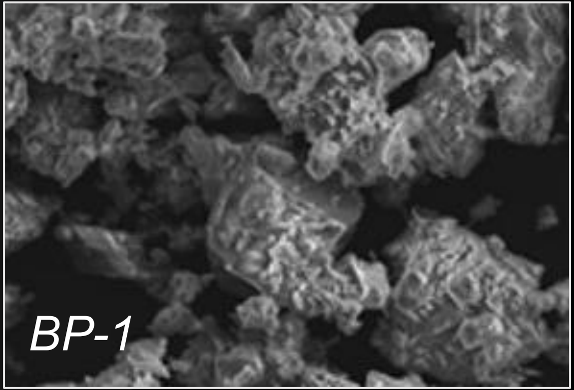
*Ethane Supply Skid (Purdue Univ. / NASA SSC)*

# Lunar Regolith Simulant

- Black Point - 1 (BP-1) crushed basalt lunar regolith simulant with similar geotechnical properties to the lunar South Pole
- Handling, preparation, and hardware design requires drying, venting, PPE, and specialized procedures for use



Apollo 11



BP-1


*Cohesiveness of BP-1 (NASA KSC)*

*Regolith moisture removal*

*Regolith bin for PSI testing (2m diameter)*

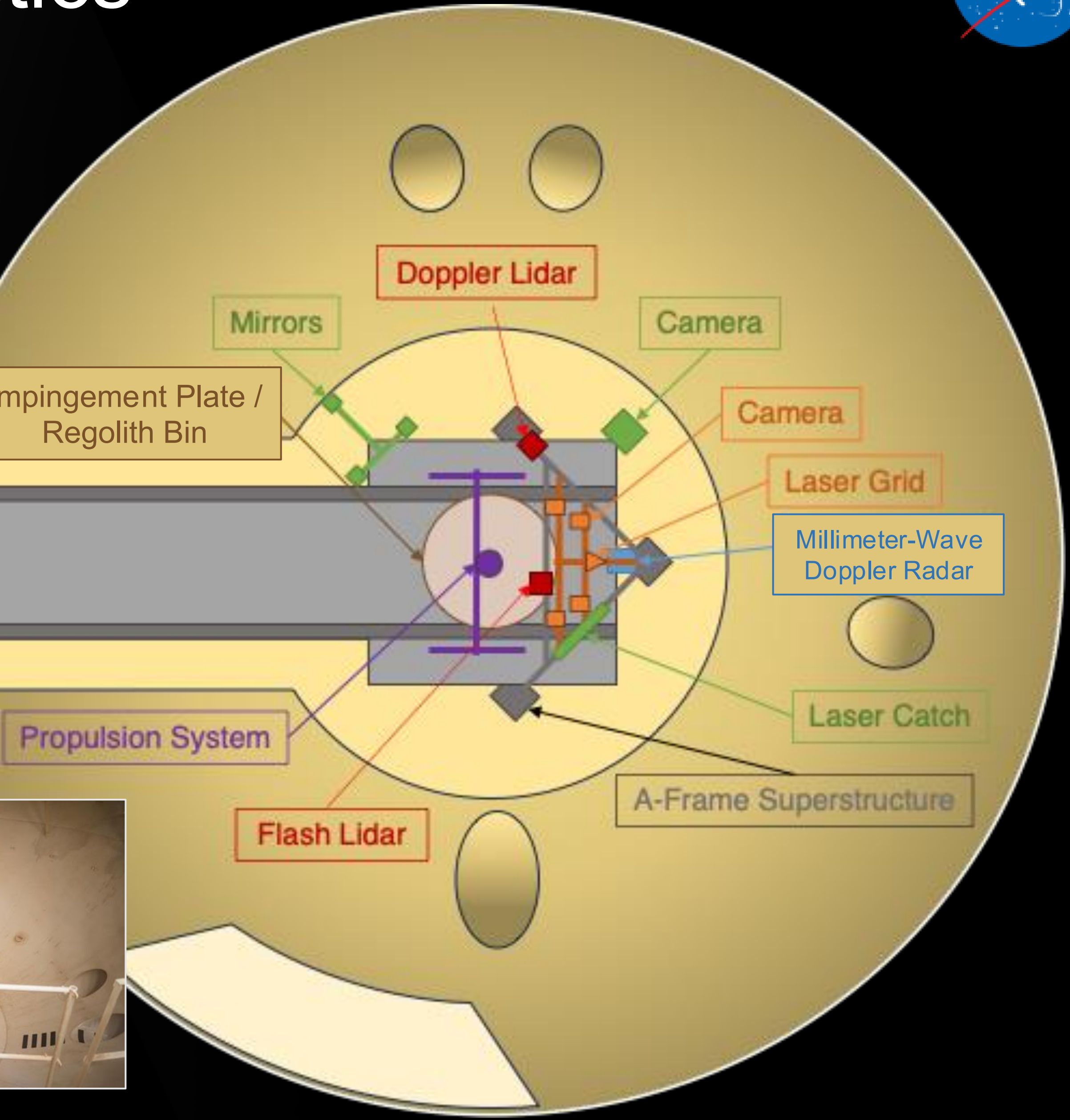
# Instrumentation and Diagnostics

## Primary

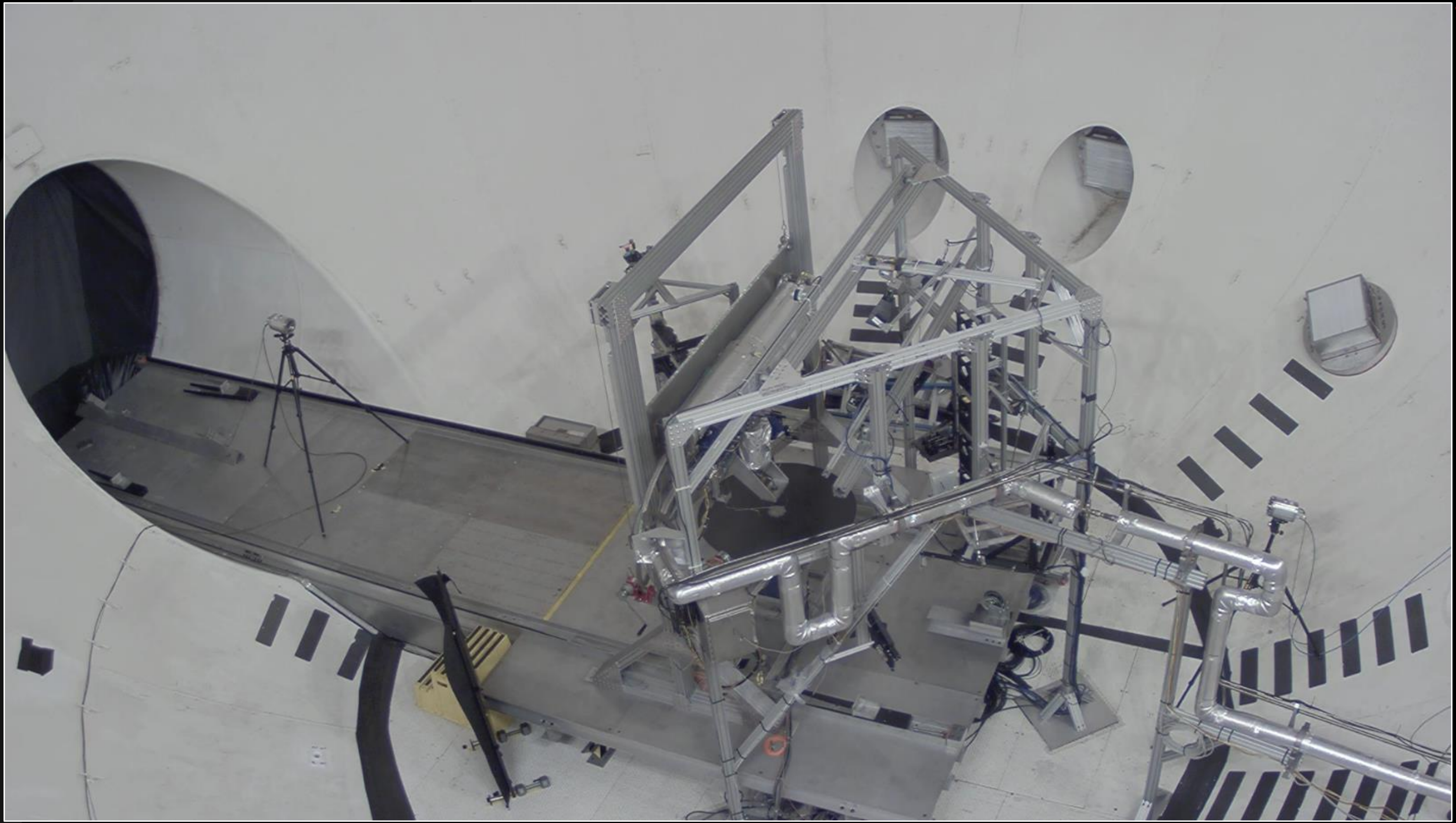
- ***Erosion*** onset; transient and final surfaces in 3D
- ***Ejecta*** energy measurements at discrete locations
- ***Ejecta*** particle velocity and size distributions
- Facility ambient and propulsion system conditions

## Secondary

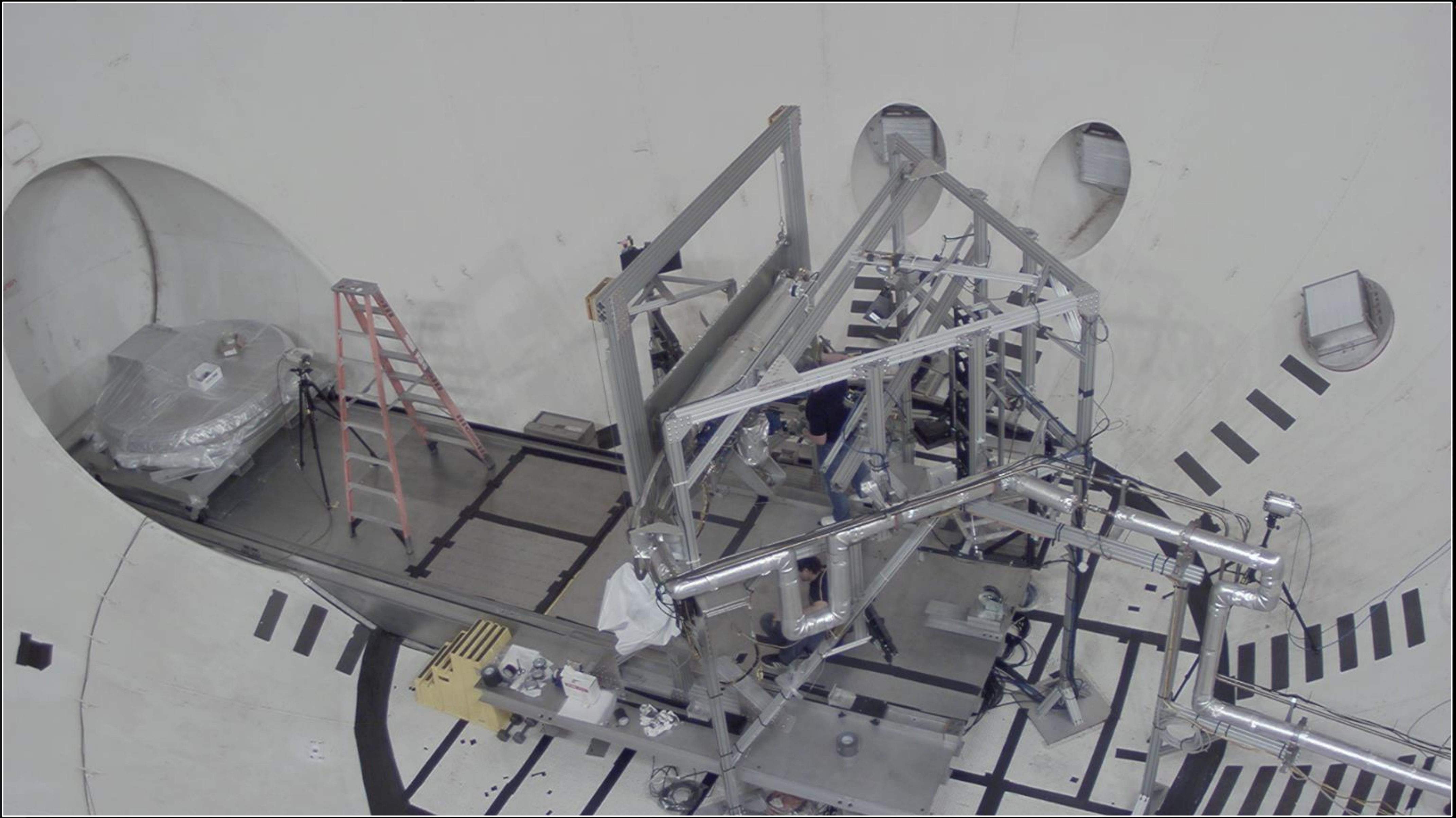
- Direct quantitative verification of ***plume*** impingement conditions (pressure, shear)
- ***Plume*** flow visualization and characterization
- Passively collected data for dust



# Top View of Test Setup (Impingement Plate)

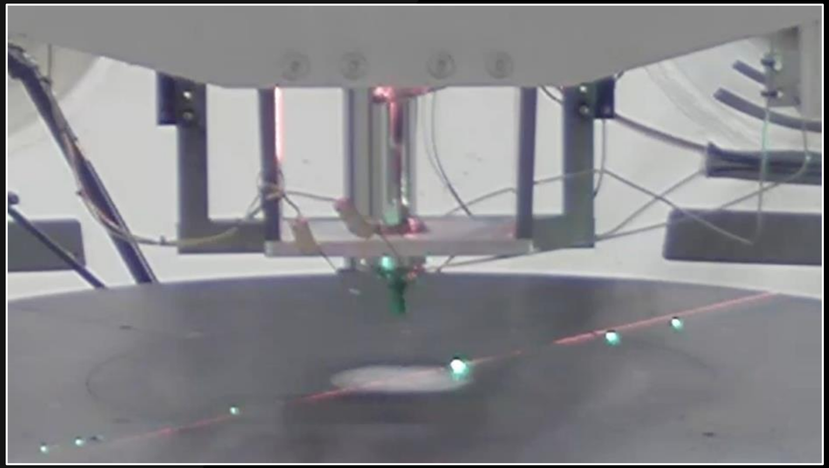


# Top View of Test Setup (Prepping for Regolith)

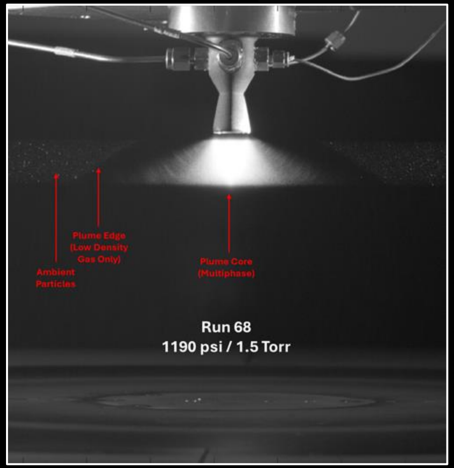


# Impingement Plate Testing

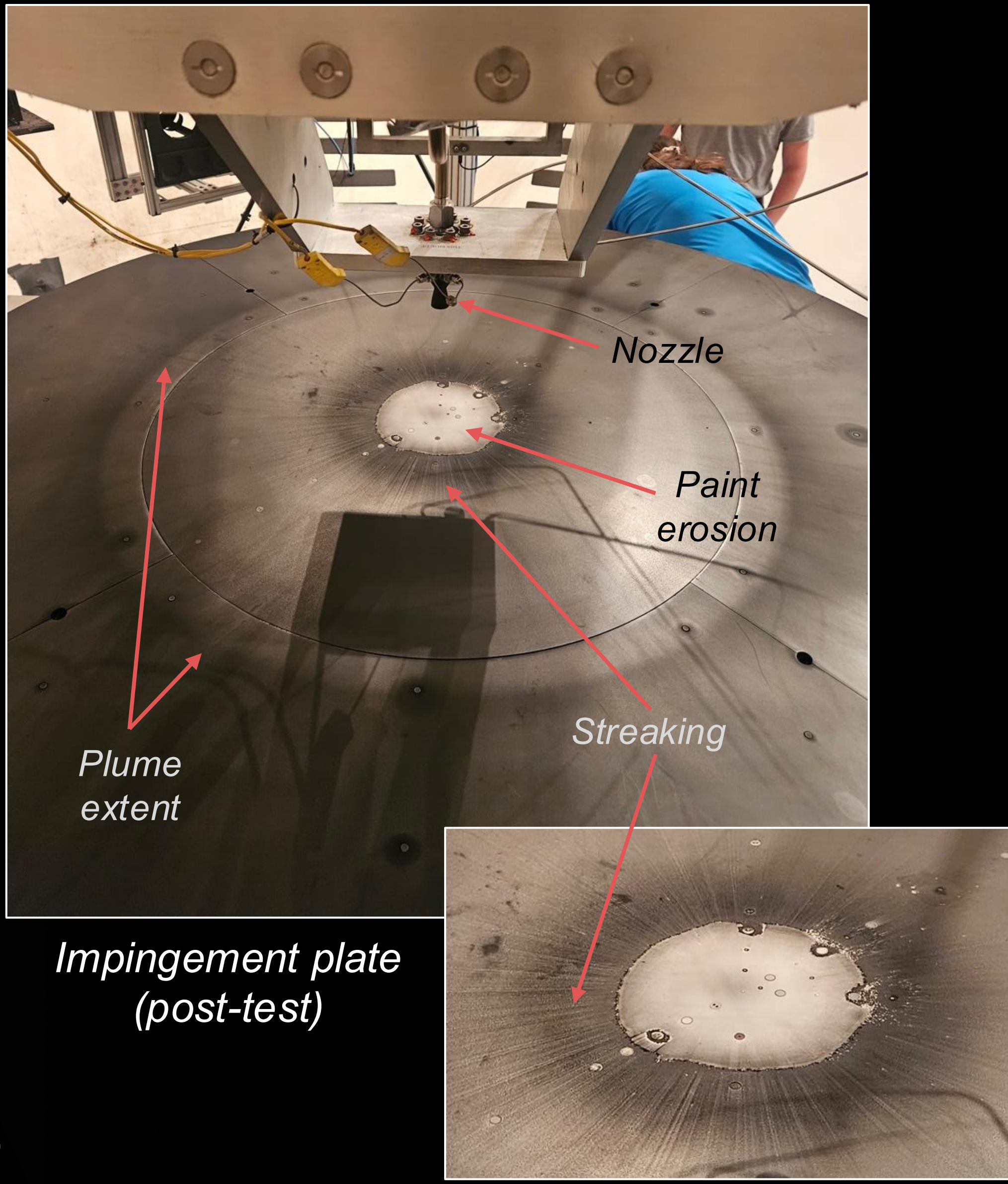
- Flat plate instrumented for pressure, shear, and temperature
- 80 total test runs completed with the impingement plate, 78 runs under vacuum
- Paint and sensor damage incurred due to initial heating issues and inherent soot particle formation from ethane pyrolysis



*High-pressure test run at lowest nozzle height*

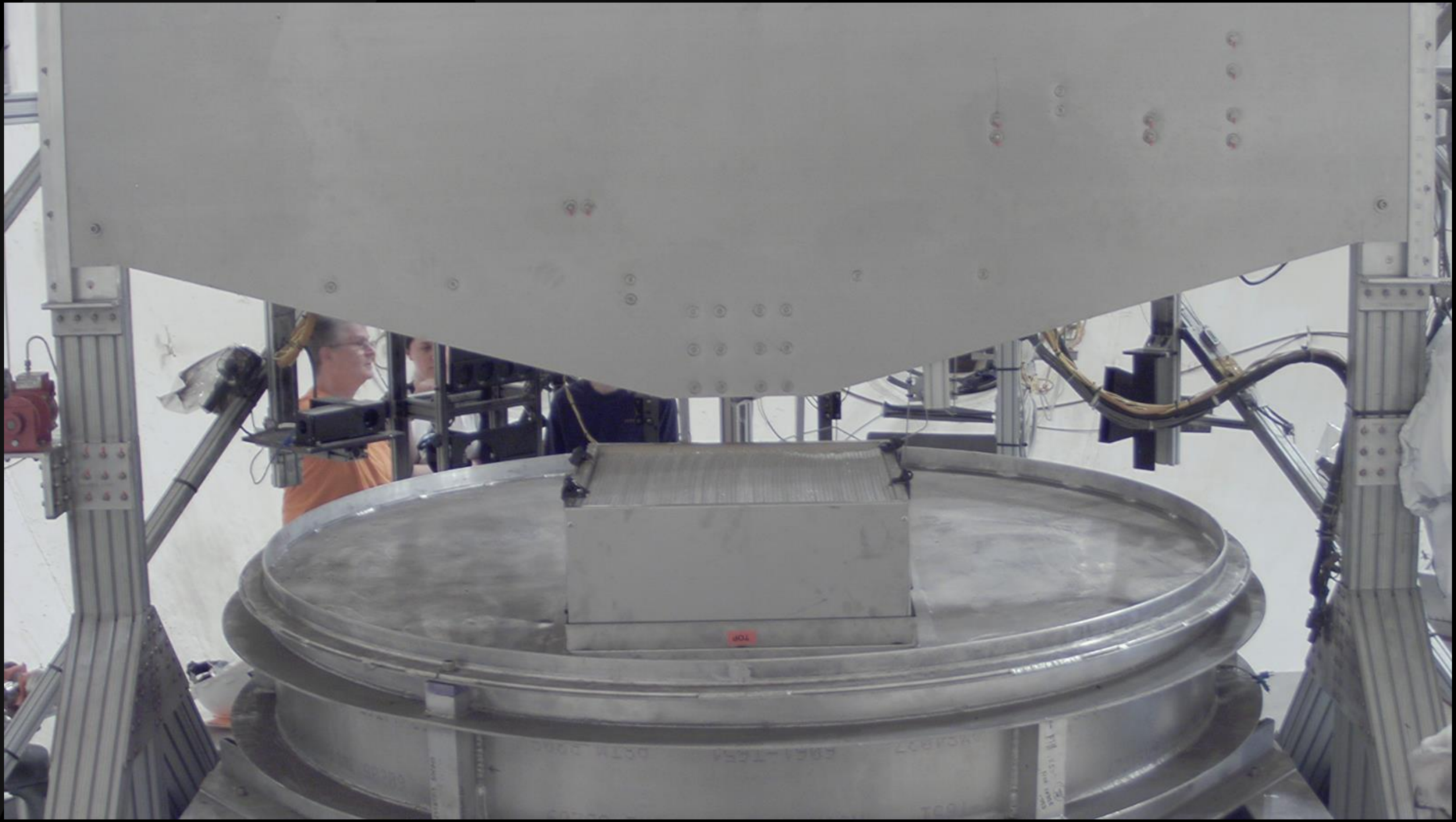



*Plume visualization (credit: N. Rodrigues and T. Schwartz)*




*Impingement plate (post-test)*

# First Results with Regolith



# Summary and Forward Work

- PSI testing continues through end of 2026
  - Full set of conditions with the ethane plume simulant, including compacted regolith
  - Full set of conditions with the hybrid rocket motor

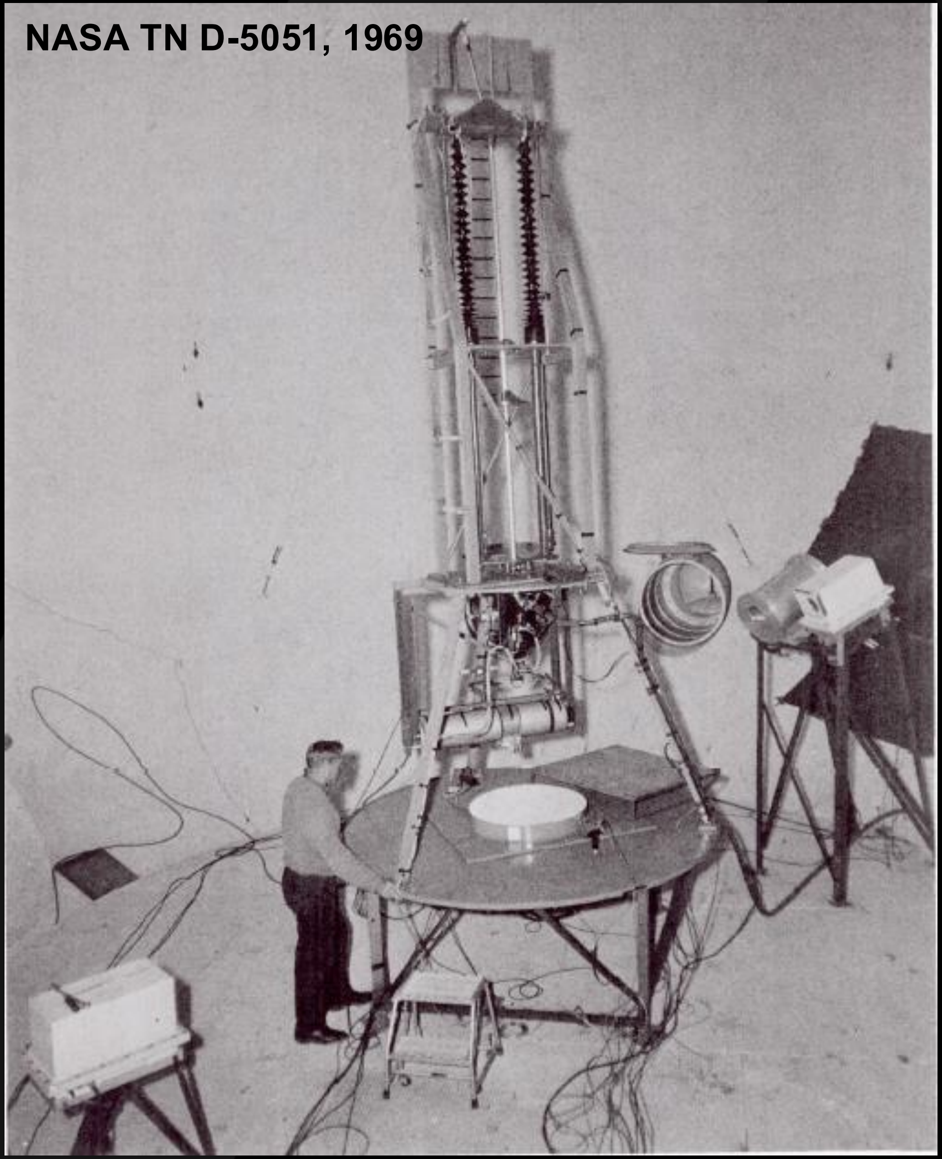
- Post-processing of data and direct infusion into data-driven modeling to predict erosion and ejecta for large lunar landers and nearby surface assets and infrastructure

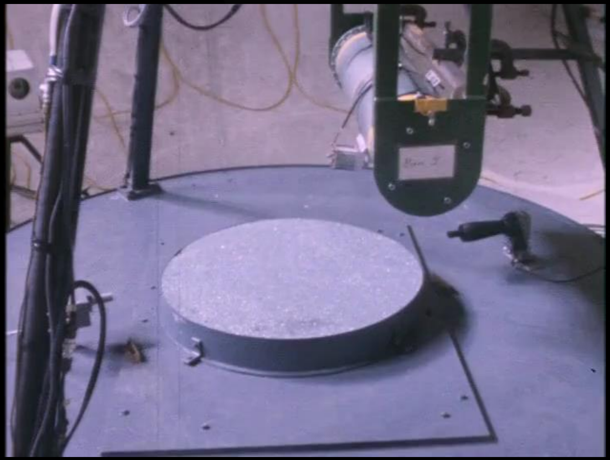
- Potential expanded scope:
  - Multiple plume impingement
  - Radar degradation in near-surface landing environments
  - Acoustics effects and lander base/leg environments
  - New candidates for flight instrumentation and payloads
  - Testing for destinations other than the moon

# Questions?

# Historical Lunar PSI Testing

NASA TN D-5051, 1969





*Land and Scholl (1969)*

FIX REFERENCE

# Ground Testing – HLS PSI Test Campaign

## Facility: NASA LaRC 60-ft Vacuum Sphere

- Legacy facility for Apollo and Viking PSI testing
- 0.75 Torr initial ambient pressure
- Large volume reduces transients to ambient conditions
- “Dirty” facility – permits regolith use

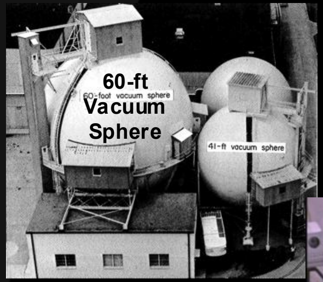
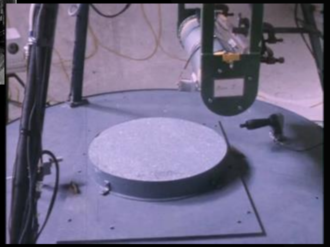


Image credit: NASA


Land and Scholl (1969)

## Plume Gas Simulants: Heated Ethane and Hybrid Rocket Motor

- Heated ethane: proven scaled test capability for hot-fire engine plumes
- Small GOX/ABS hybrid rocket motor with water in the exhaust; true hot-fire testing
- Two separate run matrices with scaled conditions relevant for understanding PSI from large lunar landers

Hybrid Motor

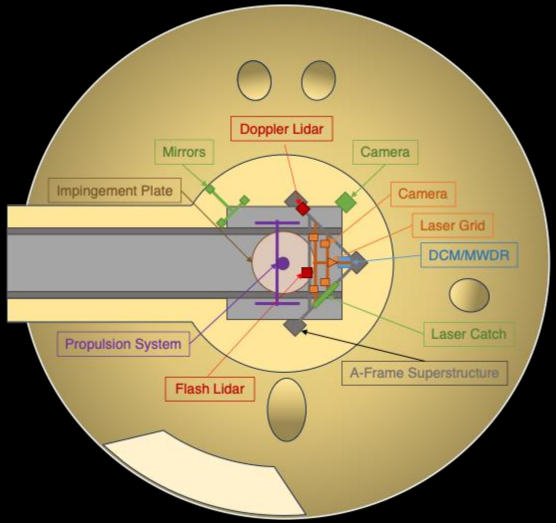

Ethane System


## Regolith Simulant

- BP-1 Lunar regolith simulant
- Geotechnical properties considerations:
  - Particle size distribution
  - Particle morphology/shape
  - Bulk/relative density
  - Cohesion/angle of internal friction
  - Permeability
- Previous experience in PSI testing and existing geotechnical characterization


## Data Products

- 3D erosion geometry as a function of time, including onset (start) and final profiles and erosion rates
- Ejecta energy measurements at discrete locations
- Plume flow visualization
- Pressure and shear on an impingement plate



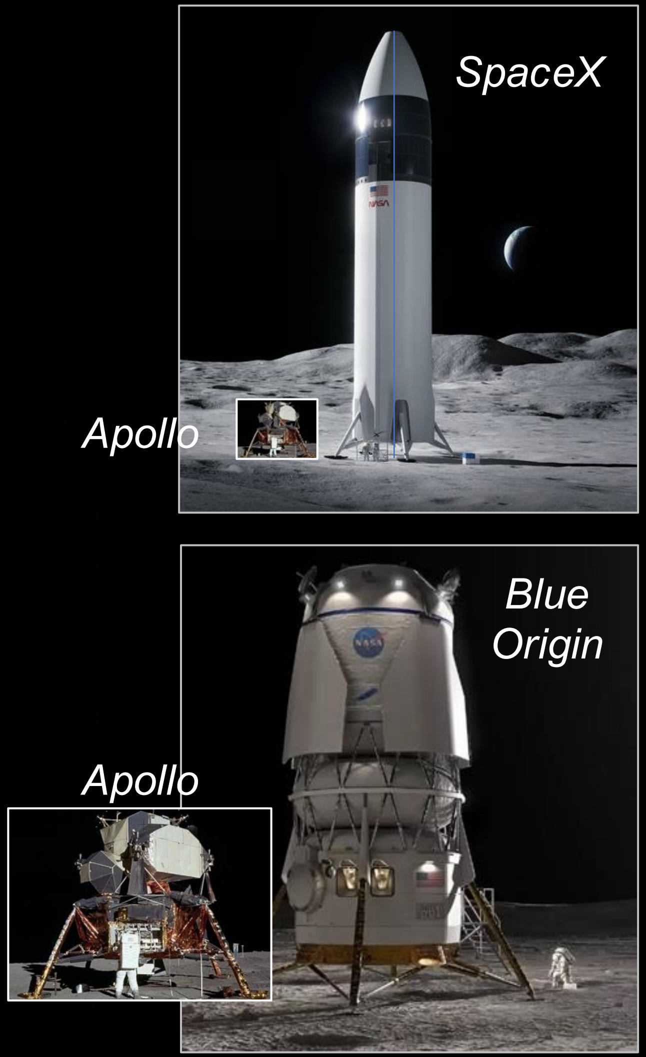
# Moving Beyond Apollo

- NASA's Human Landing System (HLS) will take astronauts to the lunar surface using commercial vehicles from SpaceX and Blue Origin as part of the Artemis program

- Each vehicle is considerably larger and uses a different concept of operations than that from Apollo

***Apollo flight experience cannot be extrapolated to upcoming large Human Landing Systems (HLS) for PSI***

***→ new data and modeling required***




*HLS Lander Concepts*