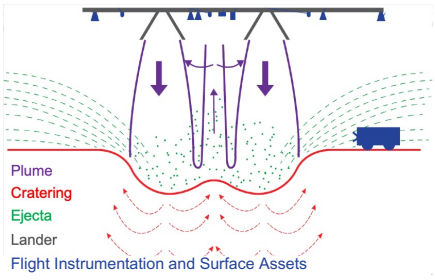
Moving Beyond Apollo: Vacuum Ground Testing to Reduce Plume-Surface Interaction Risks to Lunar Landers

Ashley M. Korzun[1], Wesley A. Chambers[2]
[1]NASA Langley Research Center, Hampton, VA, USA
[2]NASA Marshall Space Flight Center, Huntsville, AL, USA

Introduction

*Rocket **Plume-Surface Interaction (PSI)** is a complex, multi-phase discipline that describes the lander environment due to the impingement of hot rocket exhaust on regolith of planetary bodies*



Risks Posed by PSI

- All propulsive landers experience PSI
- Visual and sensor obscuration, vehicle stability and tilt, localized augmentation of heating, pressure, and abrasion damage, debris/ejecta

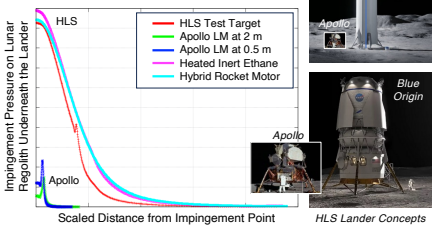

Visual Obscuration During Apollo 16 Landing (Metzger, 2010)


11-deg Tilt on Apollo 15 Lander (NASA)

Apollo flight experience cannot be extrapolated to HLS for PSI → new data and modeling required

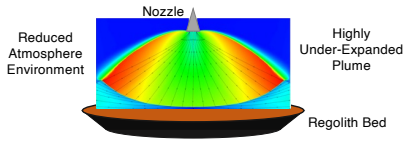
Moving Beyond Apollo

- 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

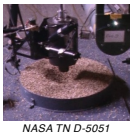


HLS Lander Concepts

PSI Test Concept



- Objective: To reduce risk to the HLS lander(s) 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 an Apollo condition
- Parameters:
  - Nozzle height above regolith
  - Plume total pressure
  - Plume mass flow rate
- Target 30 runs per propulsion type:
  - Inert Ethane: June – Sept 2024
  - Hybrid Motor: Jan – Apr 2025

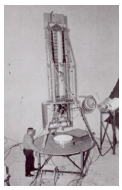

NASA TN D-5051

Vacuum Test Facility

- 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: 0.75 Torr (100 Pa)

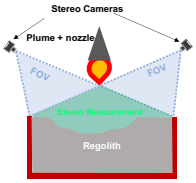

60-ft Vacuum Sphere (NASA LaRC)


60-ft Vacuum Sphere PSI Testing for Apollo (NASA TN D-5051)

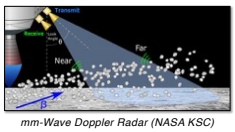
Instrumentation & Diagnostics

Primary

- Capture of 3D time-evolving erosion, onset and final
- Ejecta energy measurements at discrete locations
- Direct measurement of facility and propulsion conditions



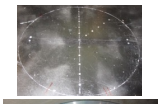
SCALPSS (NASA LaRC)

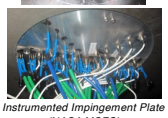


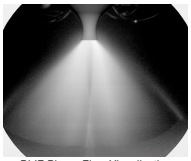
mm-Wave Doppler Radar (NASA KSC)

Secondary

- Direct quantitative verification of plume impingement conditions (pressure, shear)
- Plume flow visualization and characterization




Instrumented Impingement Plate (NASA MSFC)


PLIF Plume Flow Visualization (NASA LaRC)

Data Use for Risk Reduction

Qualitative Comparison
Are we outside Apollo-informed experience?

↓

Rapid Modeling
Erosion-rate based, test-derived rapid methods

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One-Way / Loosely Coupled Models
CFD inputs to physics-based/engineering models

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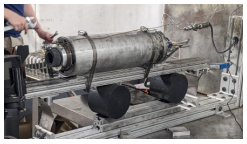
Two-Way Coupled Models
Data products used to validate high-fidelity models

Propulsion Elements

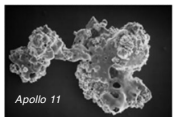
- Highly under-expanded exhaust plume used to match peak and radially scaled distributions for surface impingement pressure and shear
- Firing durations: 4-6 seconds per test run
- PSI testing will use two separate propulsion elements:
  - Inert, heated ethane plume (Purdue Univ.)
  - GOX/ABS hybrid rocket motor (Utah State Univ.)
  - Thrust < 50 lb_f

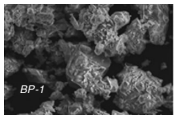

98 mm GOX/ABS Hybrid Motor (Utah State)


Portable Ethane Cart (NASA SSC / Purdue)

Lunar Regolith Simulant

- BP-1 crushed basalt lunar regolith simulant having similar geotechnical properties to HLS landing sites
- Handling, preparation, and hardware design require drying, venting, PPE, and specialized procedures for use






Cohesiveness of BP-1 (NASA KSC)


Vented Prototype Regolith Bin Design (NASA KSC)

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Acknowledgments

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Summary

- PSI poses risks to *all* propulsive landers, as well as nearby surface assets and infrastructure
- PSI testing will reduce risk to HLS lunar landers operating outside of environments and experience from Apollo
- Targeted PSI testing of this type was last conducted using vacuum facilities for the Apollo and Viking programs
- These test data will not be applicable for Mars, but the ability to conduct relevant testing and eventual validation of generalized erosion models will extend to PSI for Mars