Launch & Landing Operations in the Presence of a Lunar Outpost

Lunar Soil Erosion Physics and Impact Damage

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Must Protect Spacecraft from Itself

- Landing visibility
- Contamination of mechanisms
- Jamming or spoofing sensors
- Erosion of coated surfaces
- Pitting of optics
Must Protect Surrounding Hardware

• Damage
• Erosion of coatings
• Contamination with dust
• Jamming mechanisms
• Excessive blast hardening required
Damage to Surveyor III by Apollo 12 LM

- Apollo 12 LM landed 160 to 180 meters from deactivated Surveyor 3 spacecraft
- Effects:
  - Scoured and pitted the exposed surfaces [1,2]
  - Fractured paint surface into a “mud cracking” pattern [2]
  - Injected grit into the inspection hole of the camera [1,2]
  - Glass or plastic would also sustain surface damage in these conditions

Sources:
Characteristics of Lunar Exhaust Plume

Viscous Erosion

- Plume expanding in vacuum
- Standoff Shockwave
- Horizontal Ground Jet
- Toroidal region of maximum traction, maximum viscous erosion
Viscous Erosion
Lunar Boundary Layer

Estimated Dust Ejection Speed and Angle from Ballistics Simulations

Particle trajectory angles relative to ground for various particle sizes and CFD cases.

Particle speeds exiting the CFD model boundary.

Dust ejection angle implied by footpad shadow elongation
Particle Size Distribution of Lunar Soil

\[
\ln[P(D)] = \begin{cases} 
13.5 \cos(D\pi/383.756), & \text{if } D < 70 \text{ microns} \\
13.4637 \exp(-(D - 35)337/1.65), & \text{if } D \geq 70 \text{ microns}
\end{cases}
\]
Equilibration to Apollo Conditions

Calculated velocities for Apollo LM spray

Measured velocities in sandblasting chamber

\[ V = K_D v^3 D^3 \sigma^{3/2} H_V^{-3/2} \]
Equilibration to Apollo Conditions

\[ V = K_D v^3 D^3 \sigma^{3/2} H_V^{-3/2} \]

\[ V^{(\text{Total})} = \int_{D_{\min}}^{D_{\max}} N \cdot P(D) \cdot K_D v(D)^3 D^3 \sigma^{3/2} H_V^{-3/2} \, dD \]

\[ = N K_D \sigma^{3/2} H_V^{-3/2} \int_{D_{\min}}^{D_{\max}} v(D)^3 P(D) D^3 \, dD \]

\[ = N K_D \sigma^{3/2} H_V^{-3/2} \left\langle v^3 \right\rangle \]

\[ V^{(\text{Total})}_{\text{Apollo LM}} = N_{\text{Apollo LM}} K_D \sigma^{3/2} H_V^{-3/2} \left\langle v^3_{\text{Apollo LM}} \right\rangle \]

\[ V^{(\text{Total})}_{\text{Experiment}} = N_{\text{Experiment}} K_D \sigma^{3/2} H_V^{-3/2} \left\langle v^3_{\text{Experiment}} \right\rangle \]
Equilibration to Apollo Conditions

\[ \text{Insist: } V_{\text{Total}}^{(\text{Apollo LM})} = V_{\text{Total}}^{(\text{Experiment})} \]

\[ N_{\text{Experiment}} = \frac{\left< v^3_{\text{Apollo LM}} \right>}{\left< v^3_{\text{Experiment}} \right>} \cdot N_{\text{Apollo LM}} \]

\[ = 568 \cdot N_{\text{Apollo LM}} \]

All material parameters cancel out!

This is the benefit of doing the experiment.

Determines how many particles to shoot at a target to create the same damage as would have occurred from 1 Apollo landing.

Requires too much lunar simulant! Our experiments used only 1/10 this amount and therefore caused only 1/10 the damage of a single Apollo landing.
Trajectories of Lunar Plume Ejecta

- Spray reaches orbital altitudes and encompasses the entire Moon
  - Flux in orbit very low but preliminary modeling indicates significant chance of some impacts if spacecraft flies through the spray
  - Net velocity may be >4000 mps (hypervelocity regime)

Example 1:
  900 mps, 45° ejection angle

Example 21:
  1900 mps, 3° ejection angle
Low Velocity Impact Test Chamber

- Exhaust filter
- Media input
- Air Pressure Regulator
- Light
- Target Holder
- Velocity Sensor
JSC-1A versus common sandblasting media
Target: 4” sq. Plate Glass
JSC-1A as sandblasting media
Target: 4” sq. Plate Glass
JSC-1A and Carbon Fiber
Kevlar Fiber from JSC-1A
Kevlar-Carbon Fiber against JSC-1A

Before

After
Glass against JSC-1A
Questions?