Launch & Landing Operations in the Presence of a Lunar Outpost

Lunar Soil Erosion Physics and Impact Damage

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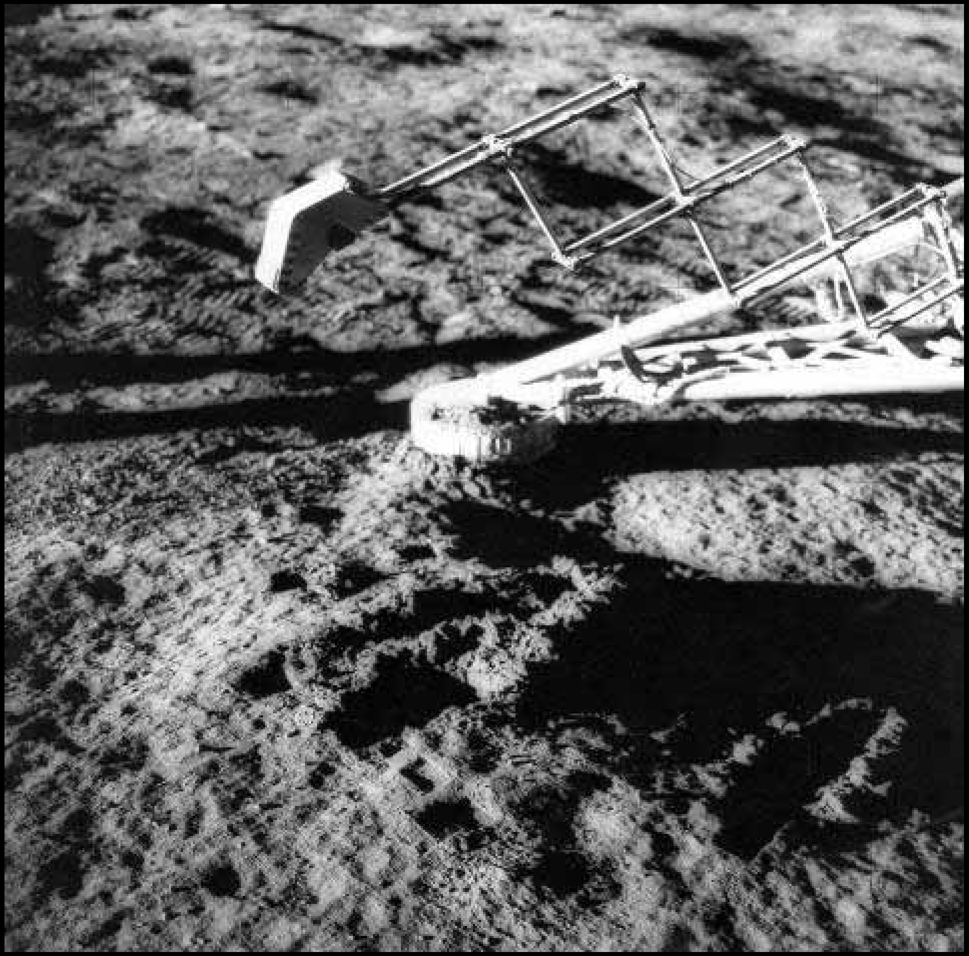
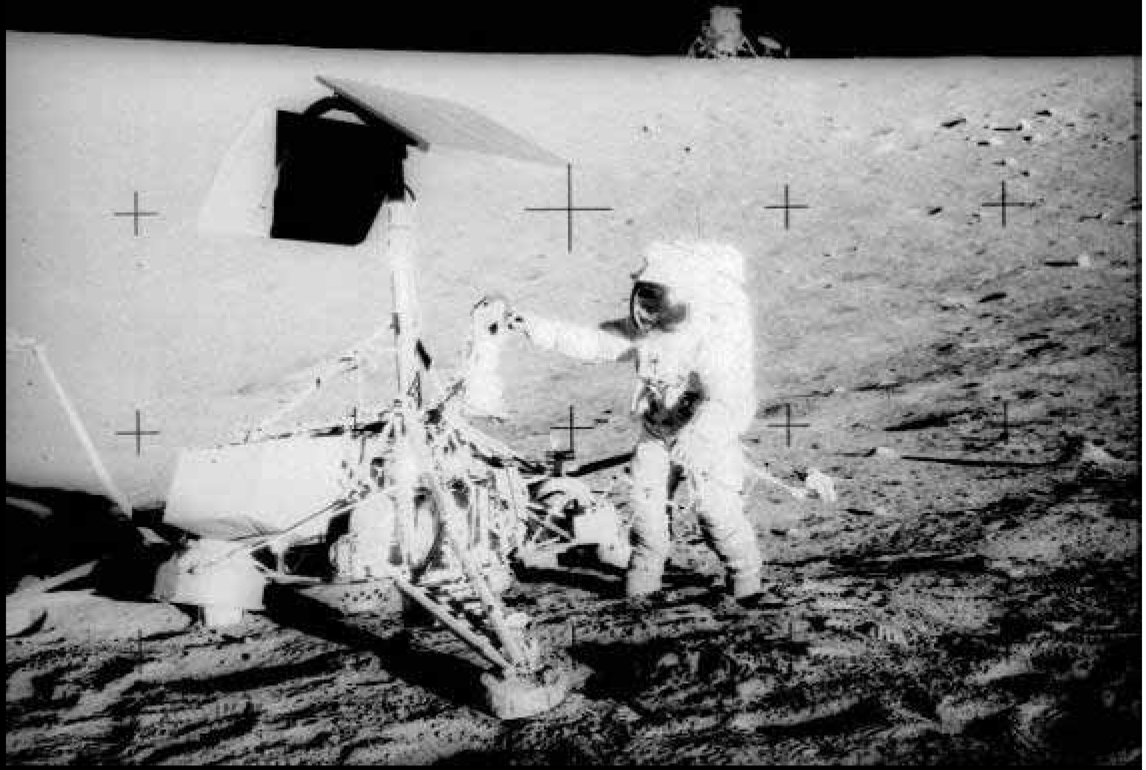
Must Protect Spacecraft from Itself

- 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:[1] Cour-Palais, B.G., *et al.,* “Results of examination of the returned Surveyor 3 samples for particulate impacts,” in *Analysis of Surveyor 3 material and photographs returned by Apollo 12*, (NASA SP-284, 1972), p. 161.

[2] Hughes Aircraft Technical Journal (in lunar material repository, JSC), reviewed by P. Metzger 04/23/07

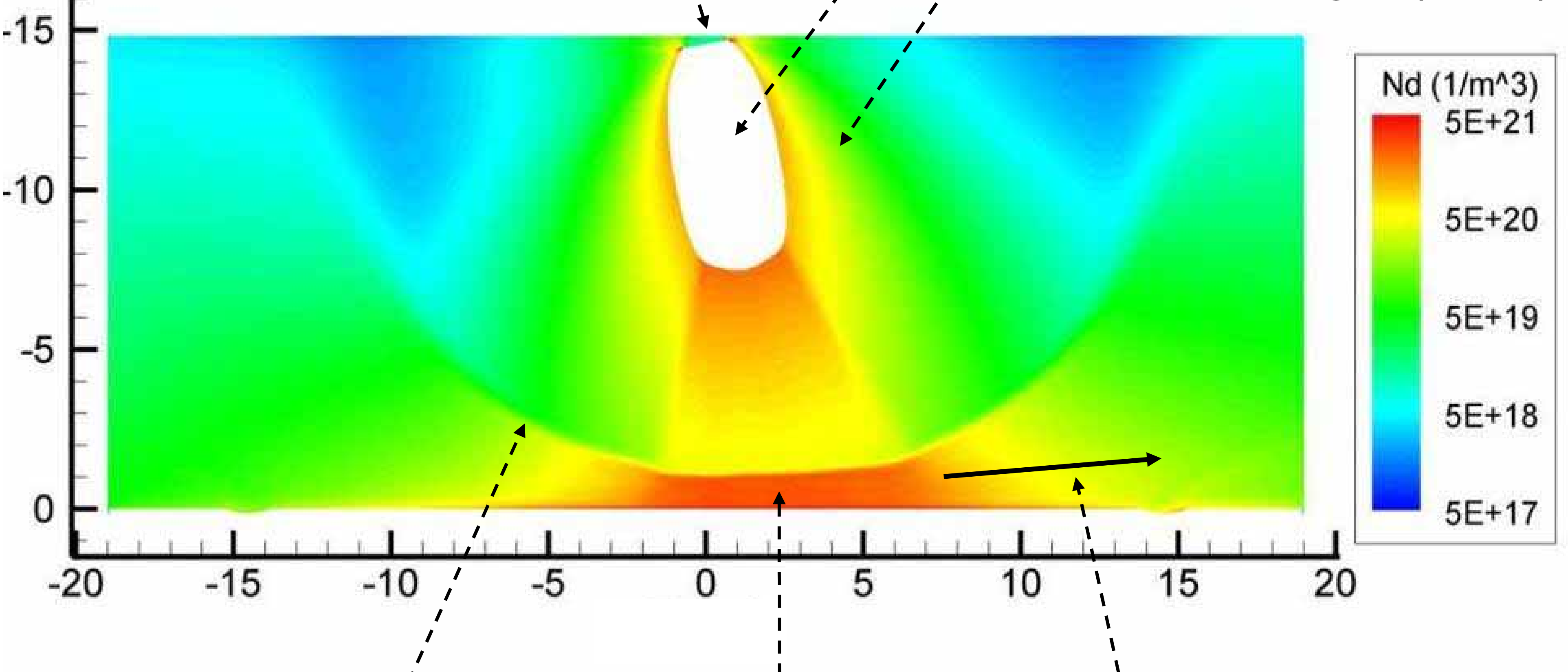
[3] Katzan, Cynthia M. and Jonathan L. Edwards, *Lunar Dust Transport and Potential Interactions with Power System Components*, NASA Contractor Report 4404, (Sverdrup Technologies, Nov. 1999), p. 17, and references therein.

Characteristics of Lunar Exhaust Plume

Nozzle

Continuum flow region (CFD)

Non-continuum flow region (DSMC)



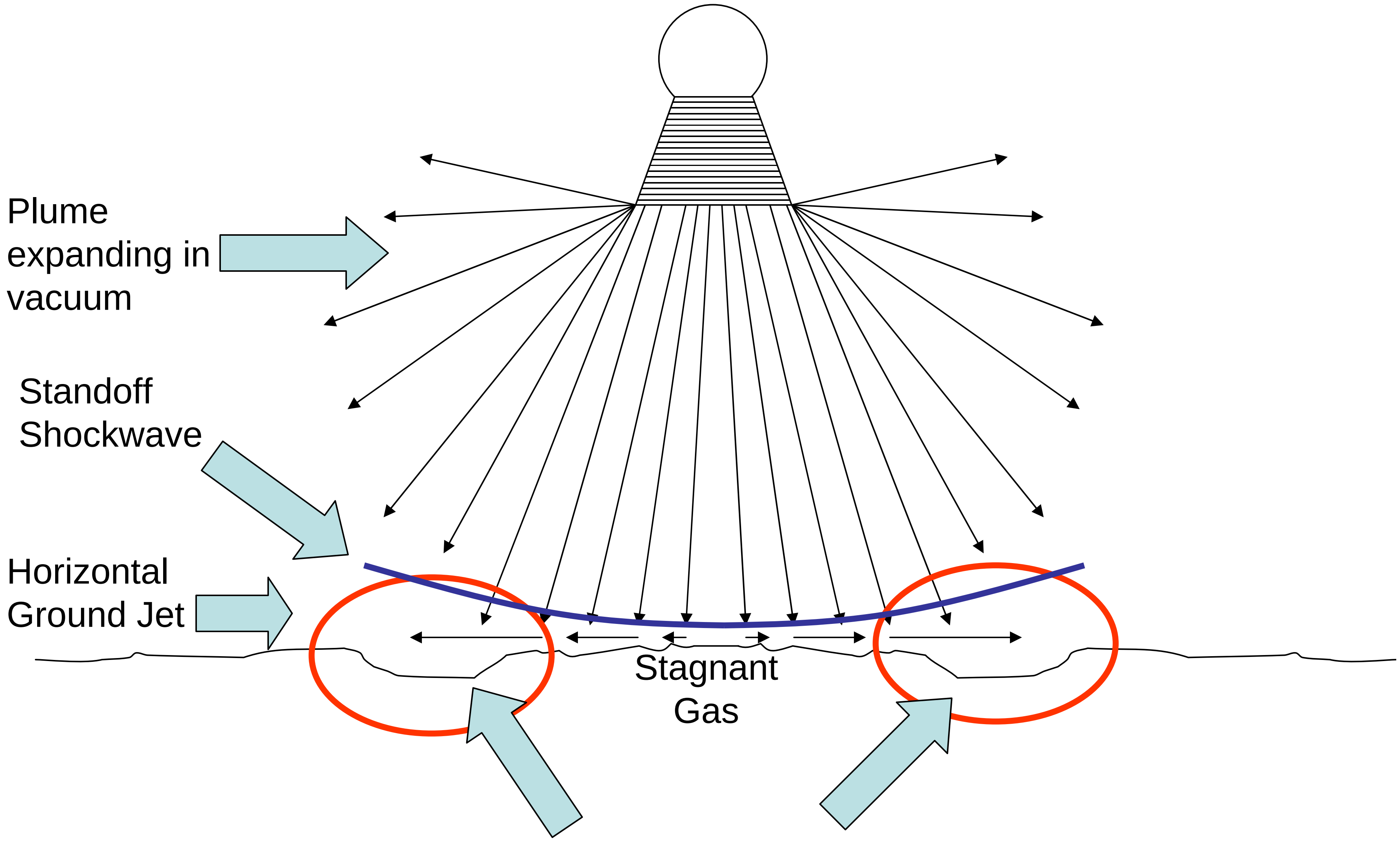
Standoff Shock

Stagnation region

Supersonic, horizontal jet

CFD and DSMC simulations by Forrest Lumpkin (NASA/JSC) and Jeremiah Marichalar (Jacobs/JSC), “Plume Impingement to the Lunar Surface: A Challenging Problem for DSMC,” in *Direct Simulation Monte Carlo Theory, Methods & Applications*, Santa Fe, NM (2007).

Viscous Erosion



Plume expanding in vacuum

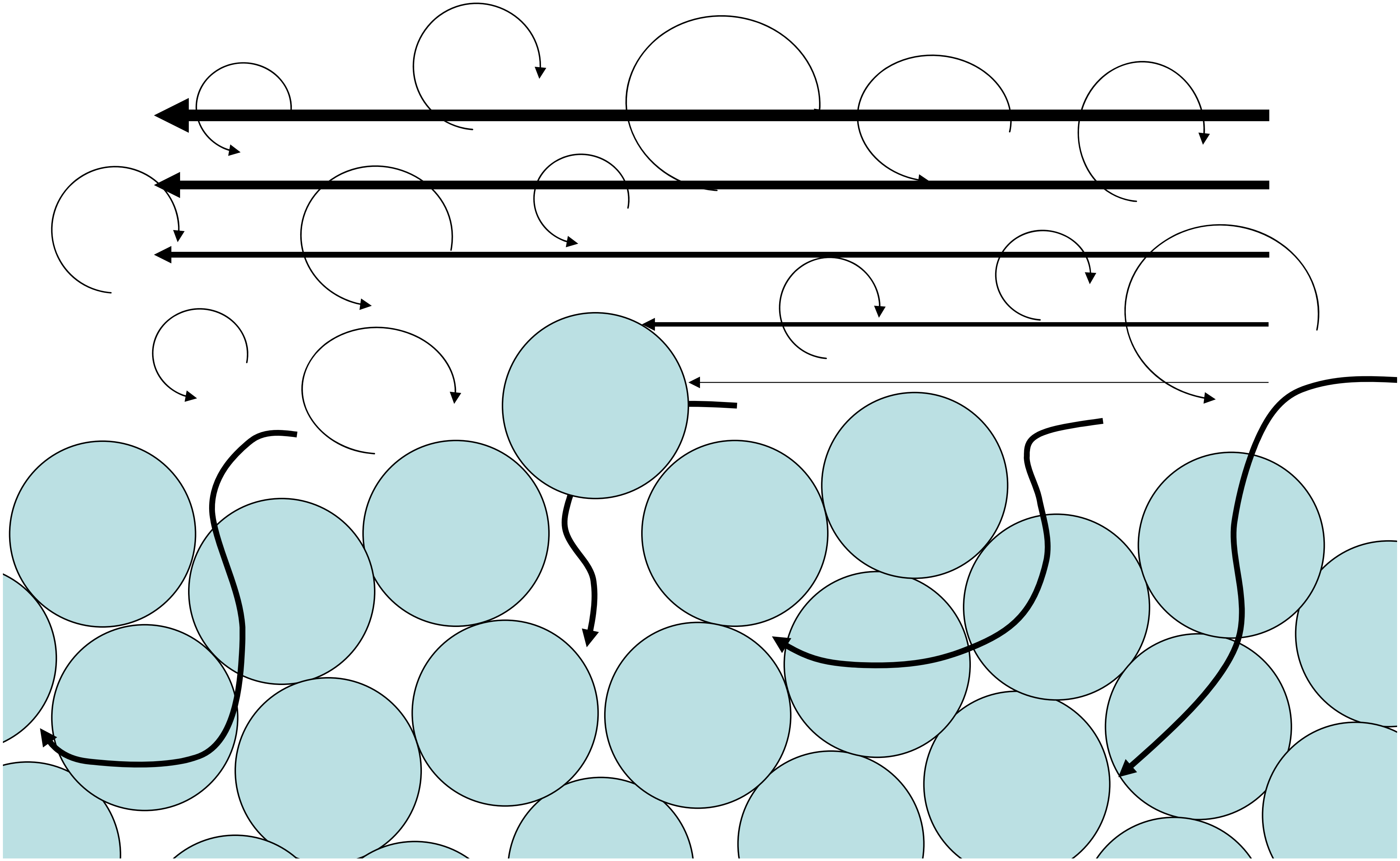
Standoff Shockwave

Horizontal Ground Jet

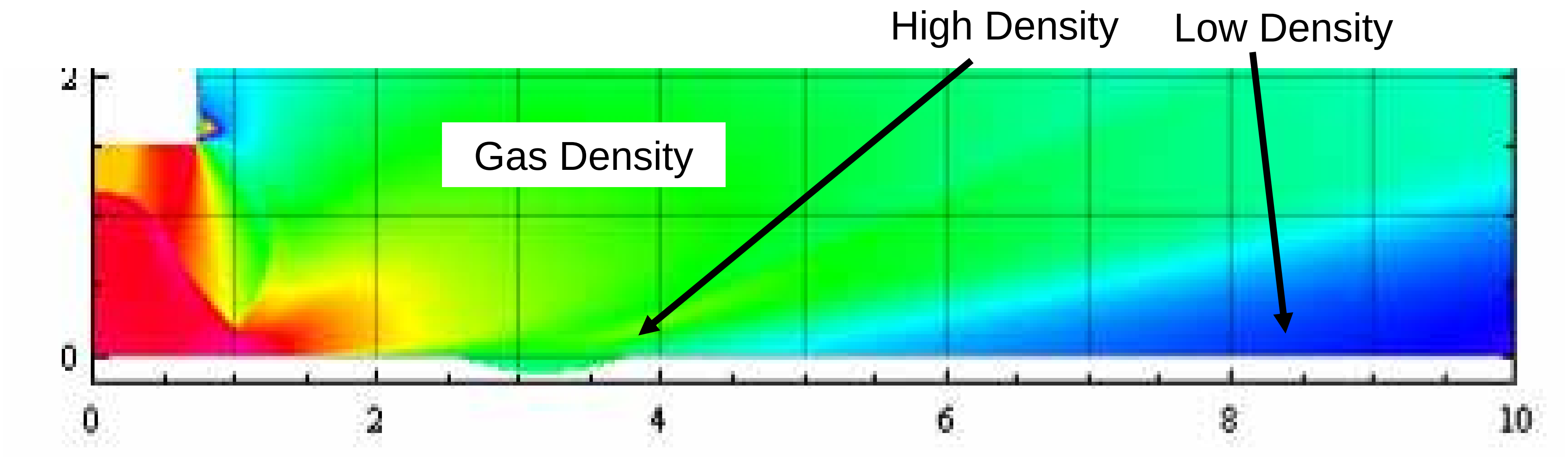
Stagnant Gas

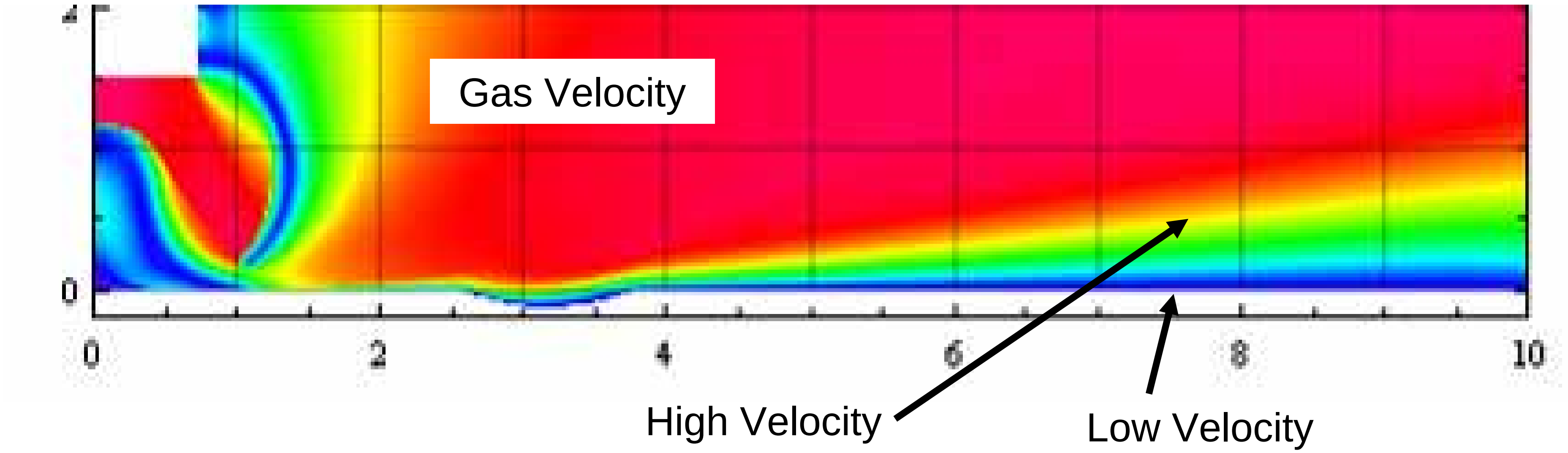
Toroidal region of maximum traction, maximum viscous erosion

Viscous Erosion



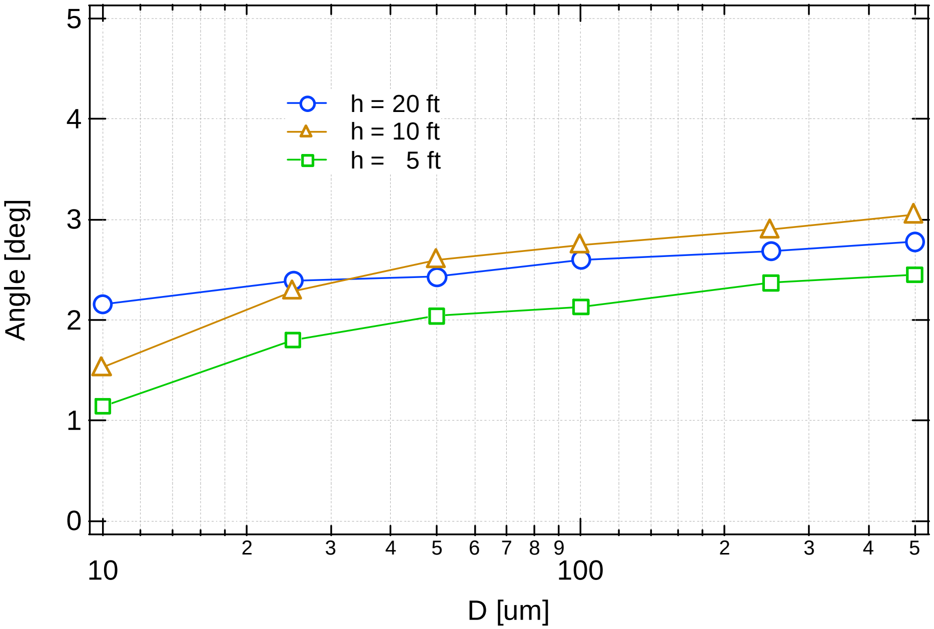
Lunar Boundary Layer



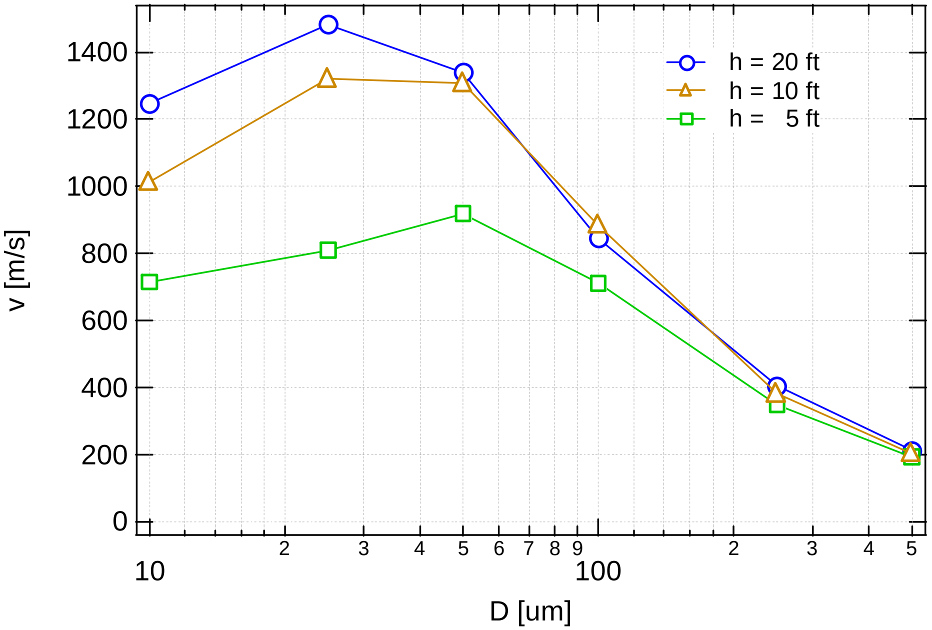


Source: John E. Lane, Philip T. Metzger, Christopher D. Immer, and Xiaoyi Li, “Lagrangian Trajectory Modeling of Lunar Dust Particles,” Earth & Space 2008, Long Beach, CA, Mar. 3, 2008

Estimated Dust Ejection Speed and Angle from Ballistics Simulations

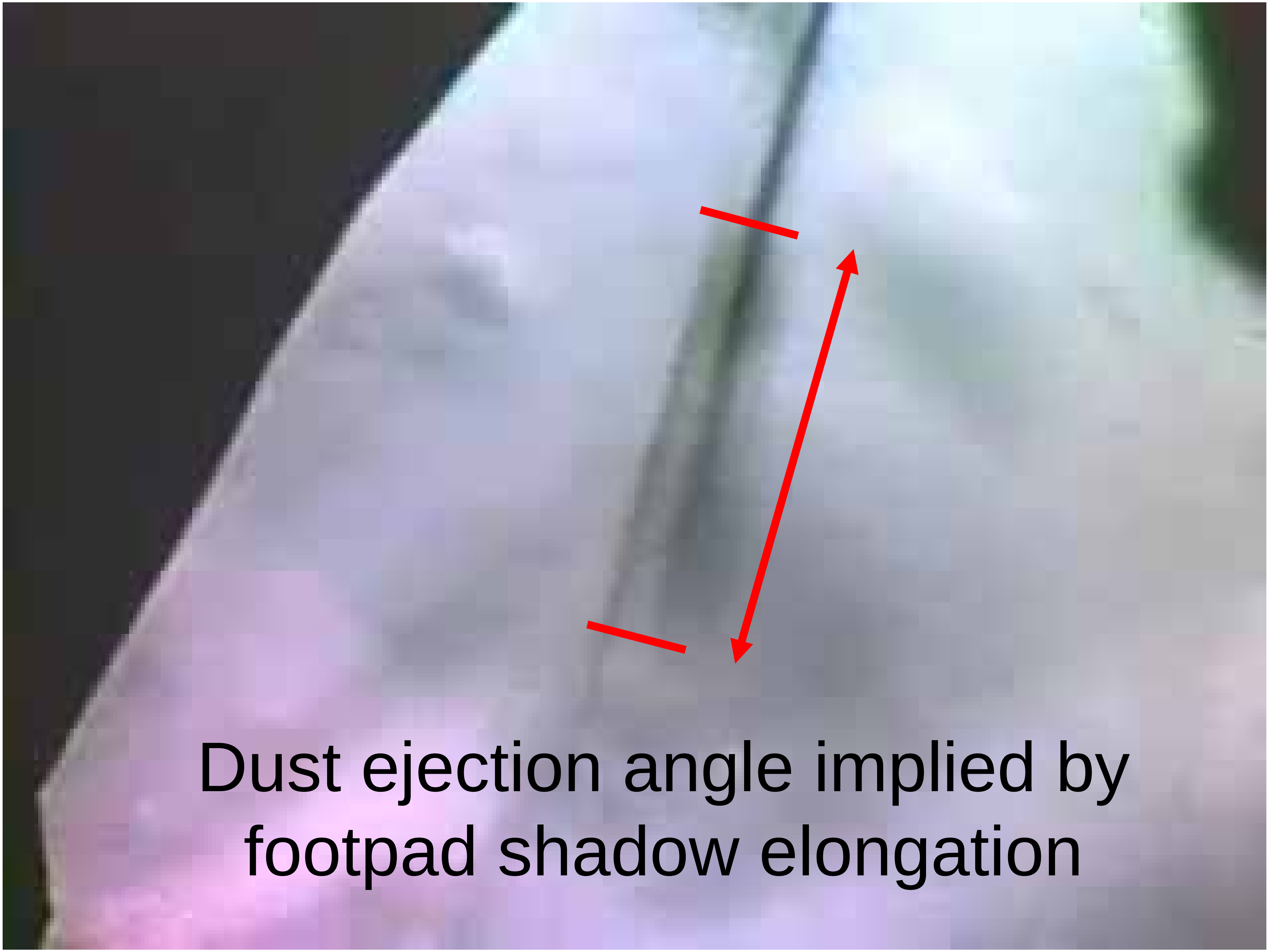


Particle trajectory angles relative to ground for various particle sizes and CFD cases.



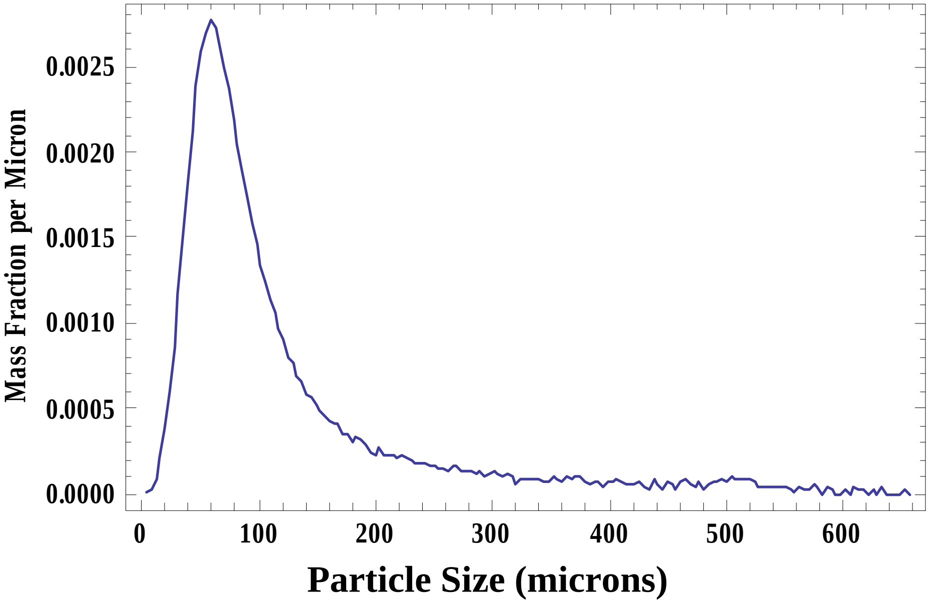
Particle speeds exiting the CFD model boundary.

Source: John E. Lane, Philip T. Metzger, Christopher D. Immer, and Xiaoyi Li, “Lagrangian Trajectory Modeling of Lunar Dust Particles,” Earth & Space 2008, Long Beach, CA, Mar. 3, 2008

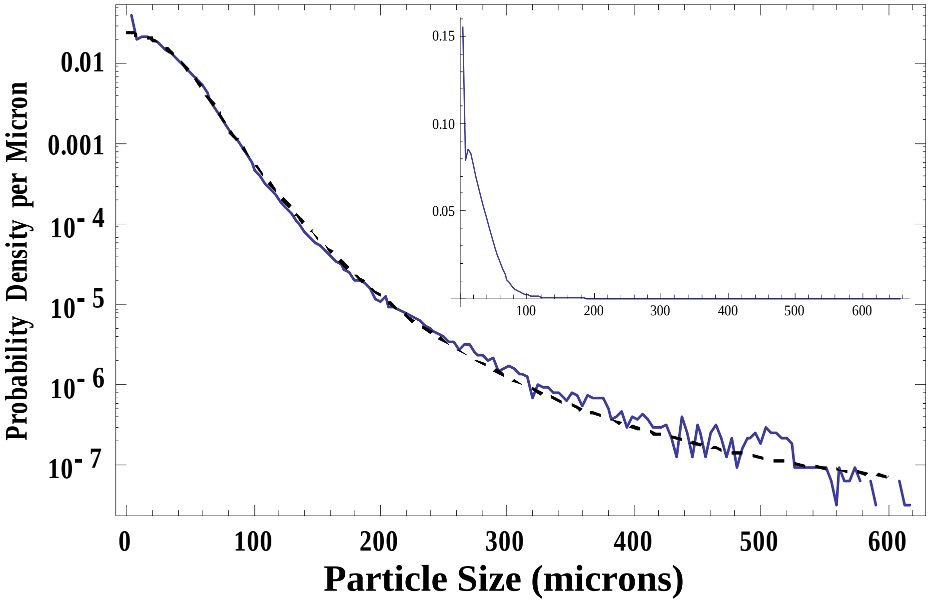


Dust ejection angle implied by footpad shadow elongation

Particle Size Distribution of Lunar Soil



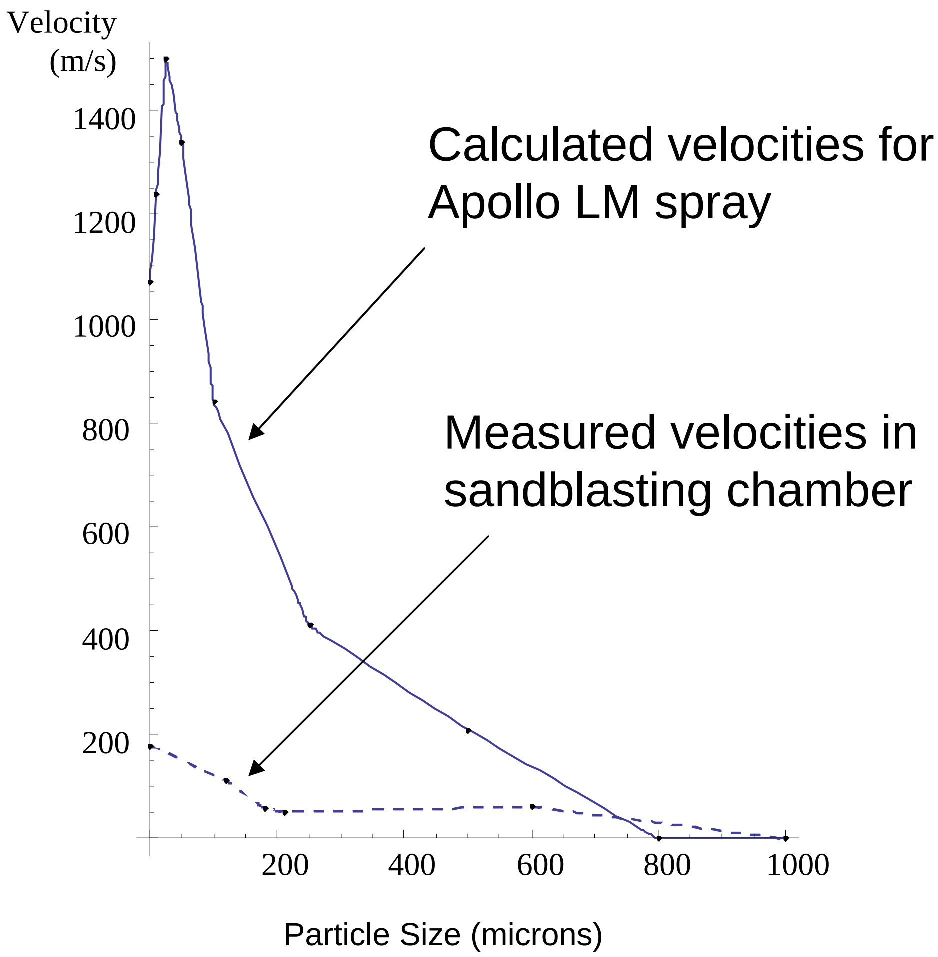
JSC-1A Particle Size Distribution by Mass



JSC-1A Particle Number Count (semillog)

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

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

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

$$V^{(\mathrm{Total})} = \int_{D_{\min}}^{D_{\max}} N \cdot P(D) \cdot K_D v(D)^3 D^3 \sigma^{3/2} H_V{}^{-3/2}\, \mathrm{d}D$$

$$= N\, K_D\, \sigma^{3/2} H_V{}^{-3/2} \int_{D_{\min}}^{D_{\max}} v(D)^3 P(D) D^3\, \mathrm{d}D$$

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

$$V_{\mathrm{Apollo\,LM}}^{(\mathrm{Total})} = N_{\mathrm{Apollo\,LM}} K_D \sigma^{3/2} H_V{}^{-3/2} \left\langle v_{\mathrm{Apollo\,LM}}^3 \right\rangle$$

$$V_{\mathrm{Experiment}}^{(\mathrm{Total})} = N_{\mathrm{Experiment}} K_D \sigma^{3/2} H_V{}^{-3/2} \left\langle v_{\mathrm{Experiment}}^3 \right\rangle$$

Equilibration to Apollo Conditions

$$\text{Insist}: \quad V_{\text{Apollo LM}}^{(\text{Total})} = V_{\text{Experiment}}^{(\text{Total})}$$

All material parameters cancel out!

$$N_{\text{Experiment}} = \frac{\left\langle v_{\text{Apollo LM}}^{3} \right\rangle}{\left\langle v_{\text{Experiment}}^{3} \right\rangle} \cdot N_{\text{Apollo LM}}$$

This is the benefit of doing the experiment.

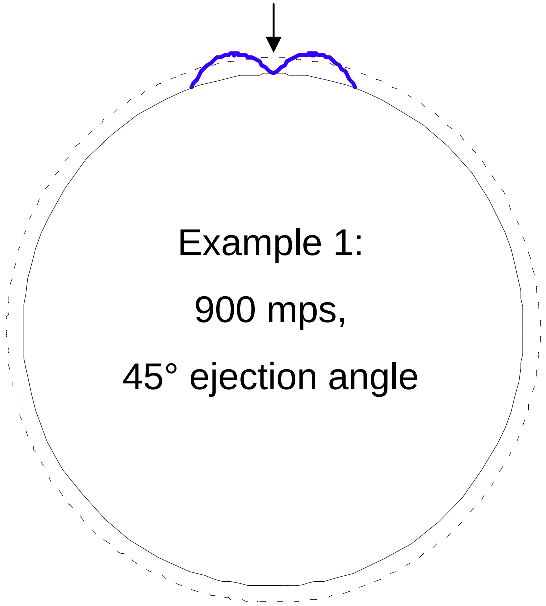
$$= 568 \cdot N_{\text{Apollo LM}}$$

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

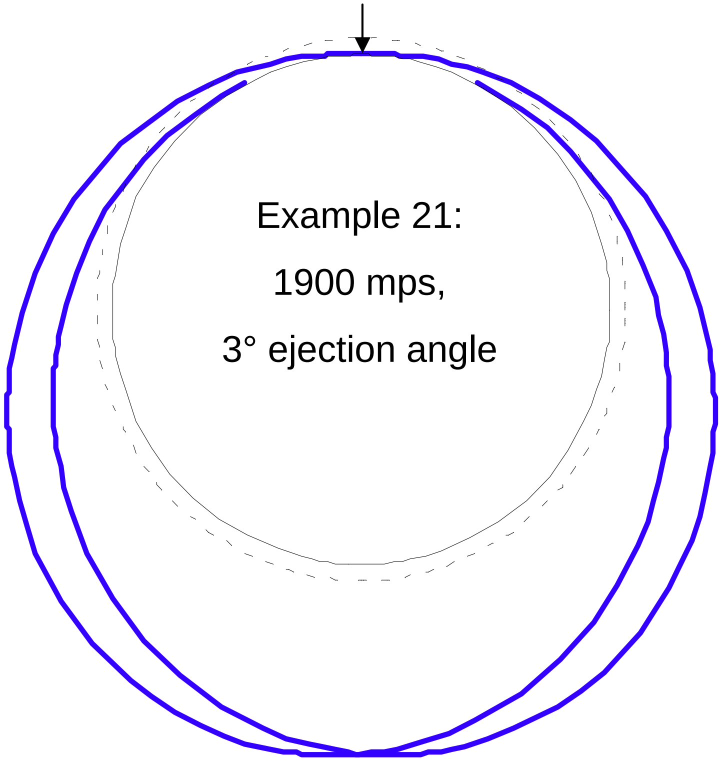
- Spray reaches orbital altitudes and encompasses the entire Moon
  - Flux in orbit very low but preliminary modeling indicates significant chance of some impacts if spacecraft flies through the spray
  - Net velocity may be >4000 mps (hypervelocity regime)



Example 1:

900 mps,

45° ejection angle



Example 21:

1900 mps,

3° ejection angle

Low Velocity Impact Test Chamber

Light

Exhaust filter

Media input

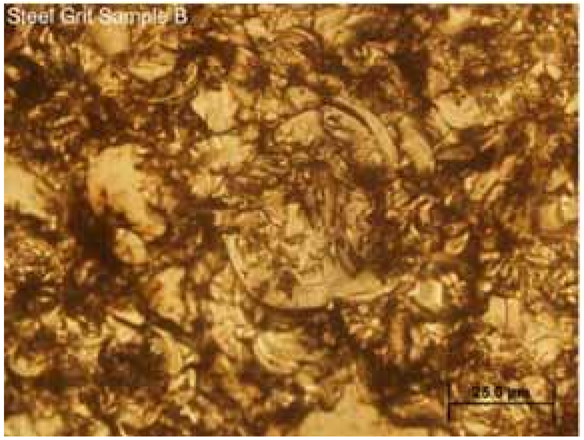
Air Pressure Regulator

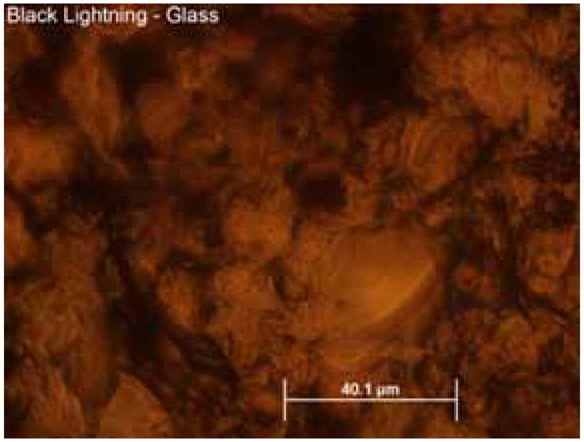
Target Holder

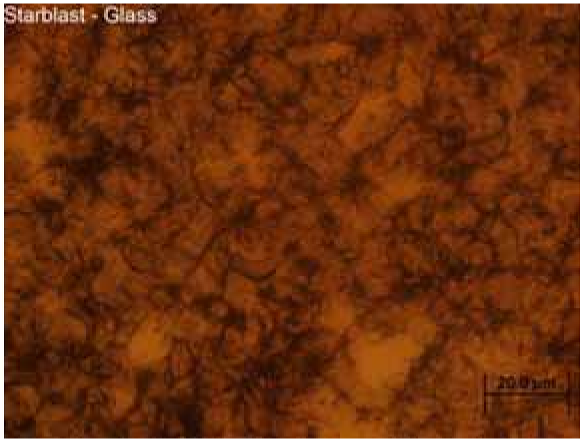
Velocity Sensor

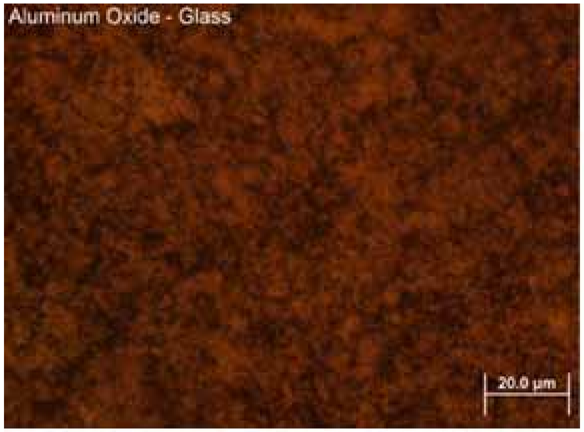
JSC-1A versus common sandblasting media

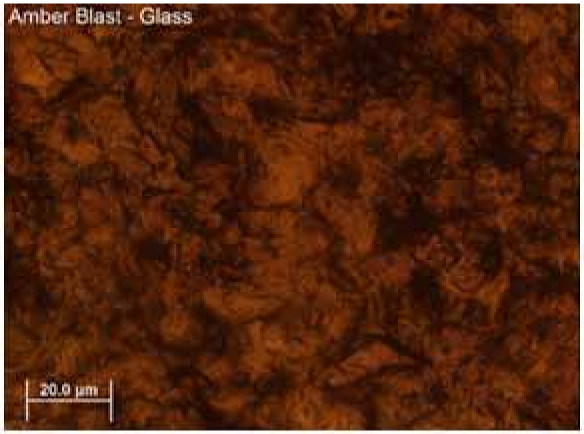
Target: 4” sq. Plate Glass





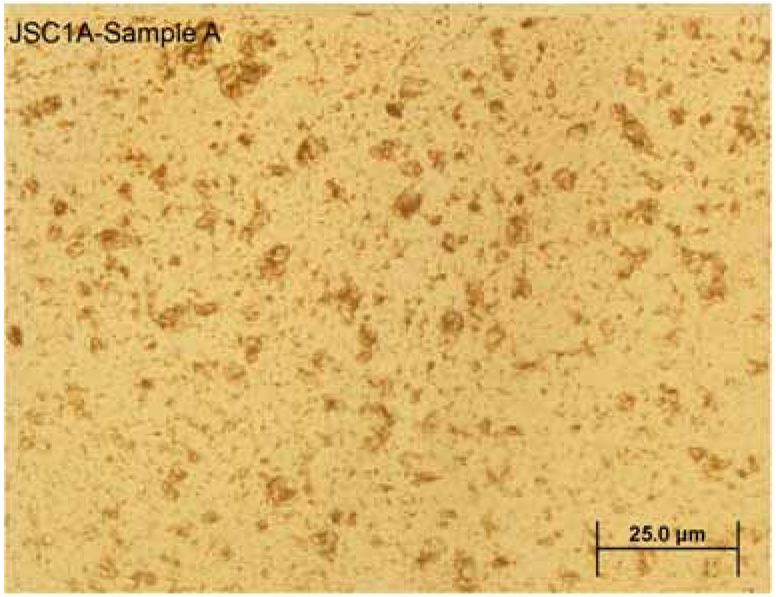


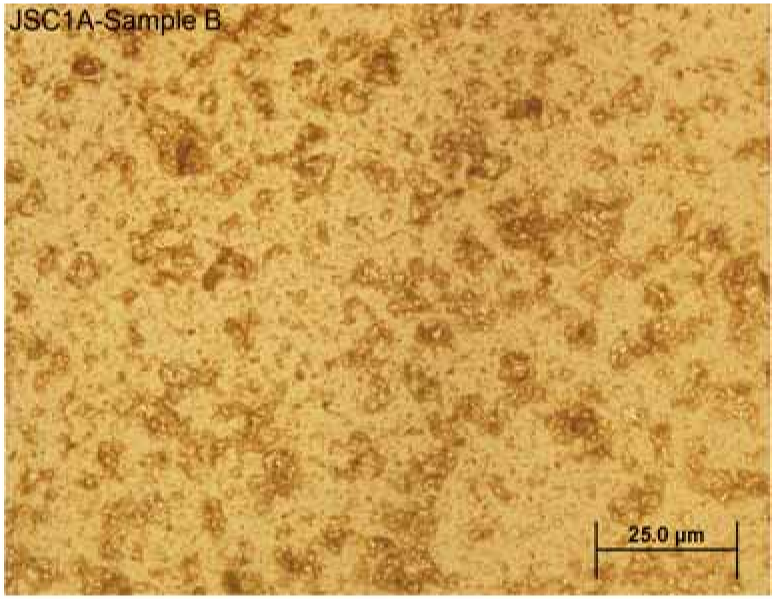


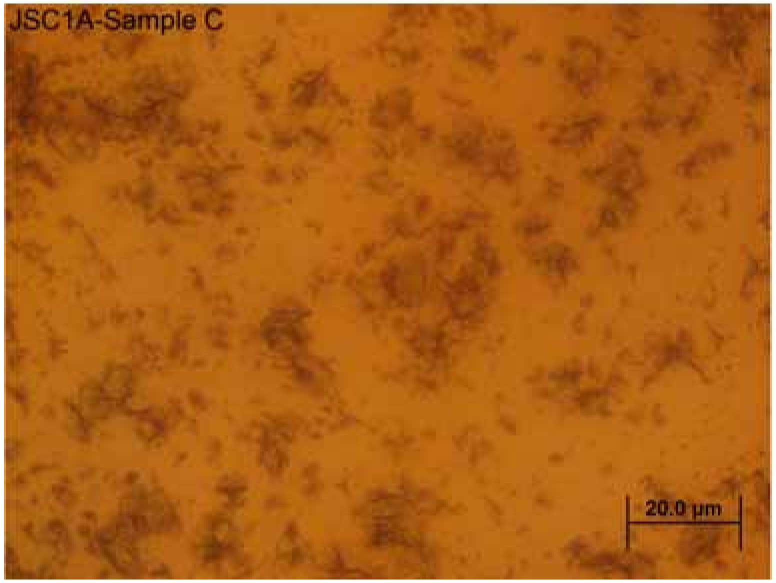


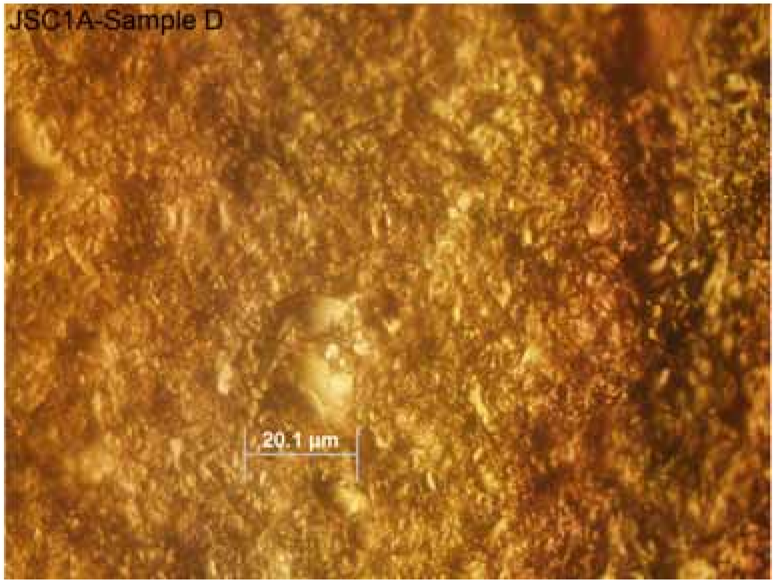
JSC-1A as sandblasting media

Target: 4” sq. Plate Glass

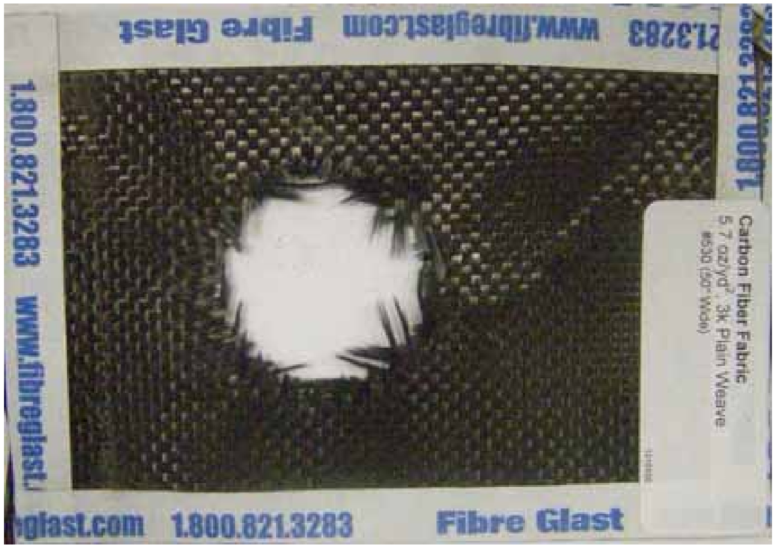


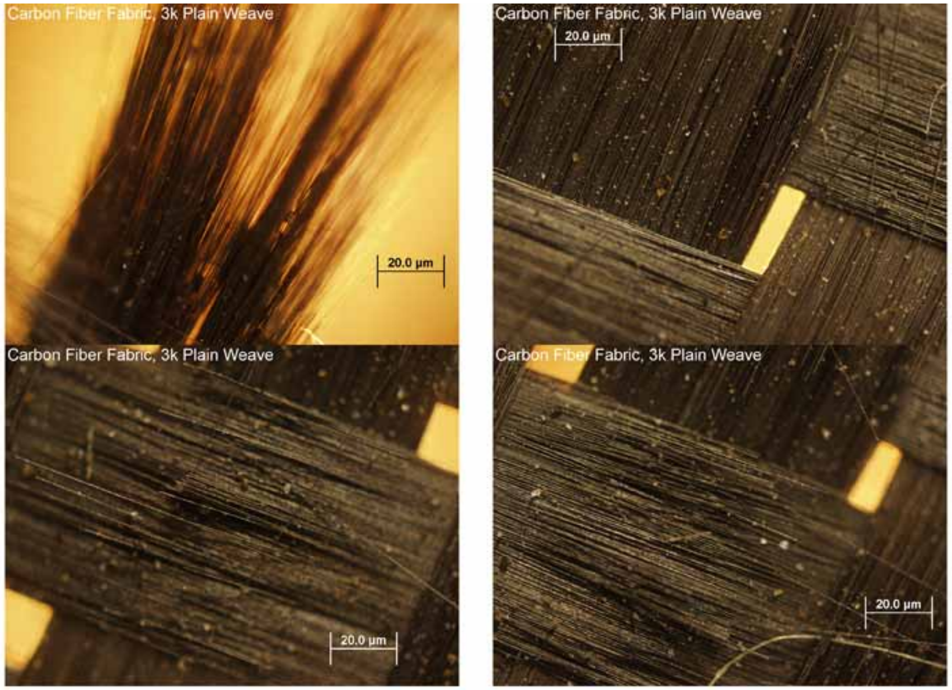




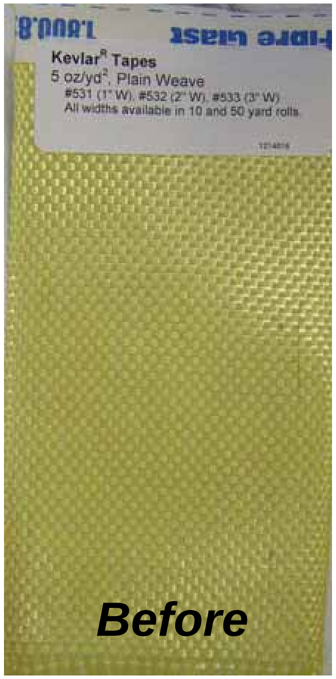


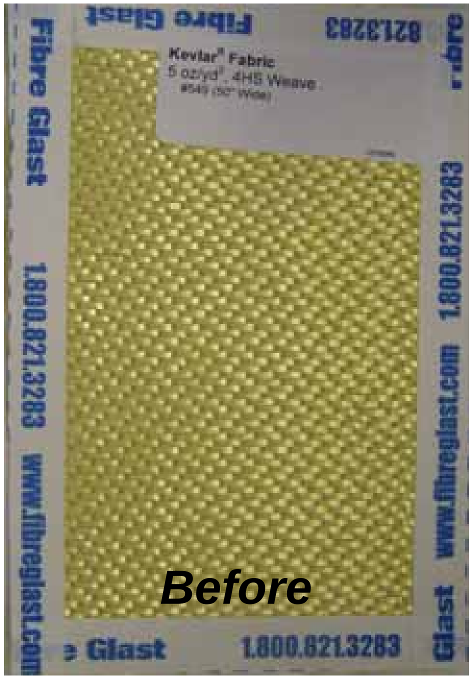
JSC-1A and Carbon Fiber

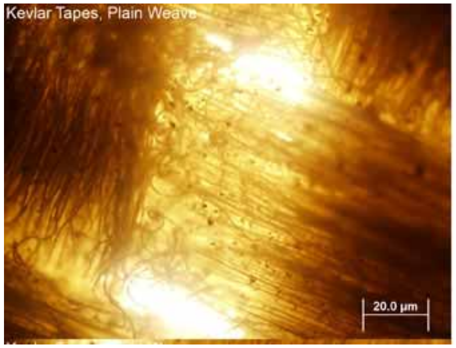


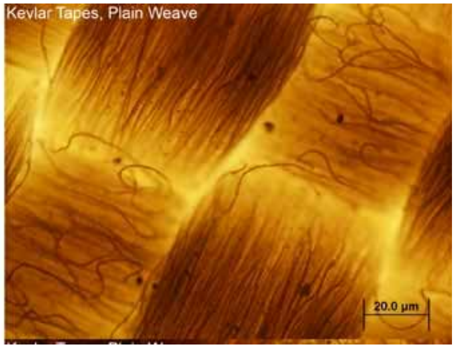


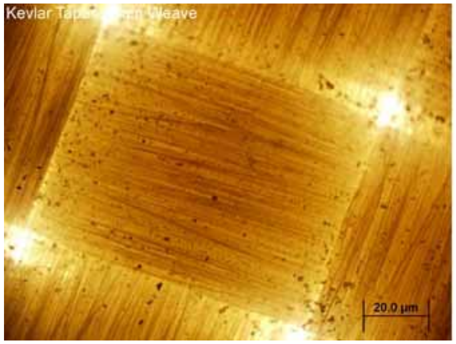
Kevlar Fiber from JSC-1A

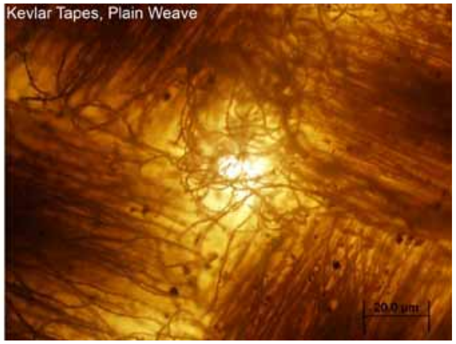








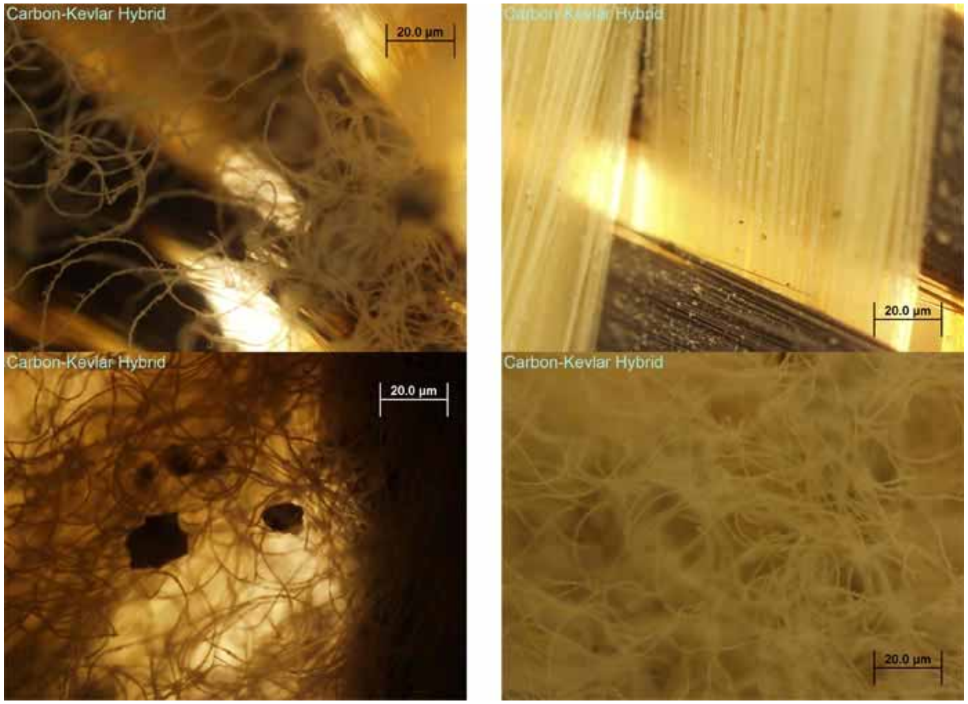




Kevlar-Carbon Fiber against JSC-1A

Before

After



Glass against JSC-1A

Questions?