LUNAR SOIL EROSION PHYSICS FOR LANDING ROCKETS ON THE MOON. Ryan N. Clegg[1], Philip T. Metzger[1], Stephen Huff[1], and Luke B. Roberson[1], [1]NASA Kennedy Space Center, Mail Code KT-D-3, Kennedy Space Center, Florida, 32899, USA, Philip.T.Metzger@nasa.gov or Luke.B.Roberson@nasa.gov.

Introduction. To develop a lunar outpost, we must understand the blowing of soil during launch and landing of the new Altair Lander. For example, the Apollo 12 Lunar Module landed approximately 165 meters from the deactivated Surveyor III spacecraft, scouring its surfaces and creating numerous tiny pits. Based on simulations and video analysis from the Apollo missions, blowing lunar soil particles have velocities up to 2000 m/s at low ejection angles relative to the horizon, reach an apogee higher than the orbiting Command and Service Module, and travel nearly the circumference of the Moon [1-3]. The low ejection angle and high velocity are concerns for the lunar outpost.

Figure 1: Carbon Fiber (A), Kevlar (B), Hybrid (C), and Vectra (front) (D) textiles after exposure to lunar simulant spray.

Experimental. As a first step in investigating this concern, we have performed a series of low-velocity impact experiments in a modified sandblasting hood using lunar soil simulant impacted upon various materials that are commonly used in spaceflight hardware. The impacted materials include glass, gold foil blankets, multi-layer insulation (MLI) for cryogenic tanks, and several textiles that are under consideration for building a blast barrier around the lunar landing pad.

Velocity Calibration: The velocities of individual soil particles of different diameters were calibrated with a high-speed video camera that recorded their trajectories through the chamber. Their velocities were in the range of 30-85 m/s, depending on the particle size and the experiment settings. This is much slower than will occur in a lunar landing. However, even in the lunar case the impacts are not hyper velocity and so the resulting damage can be compared through the Sheldon-Kanhere equation [4],

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

which predicts the volume V of a pit caused by a single impacting particle of diameter D and velocity v, when the particle has a material density σ and the target material has a Vicker's hardness value H_V. (K_D is related to the angle of impact upon the target.) We integrated this equation across the particle size and the velocity distributions as determined by [1] for lunar soil in actual landings and for lunar stimulant (JSC-1A) in our experiment. Taking the ratio of these (or similar) integrals, the material parameters cancel out, and we determine what quantity of lunar simulant will produce the same total volume (or surface area) of pitting in the target to simulate a specified number of lunar landings.

Lunar Simulation: We applied this methodology to simulate the same area and volume of pitting damage as experienced by Surveyor III. We exposed five different sheets of glass to the equivalent of between one and five lunar landings at 200 m distance. After one landing equivalent of spray, the glass was severely eroded and unusable. Thermal control gold foil blankets exposed to this spray lost all of their gold coating. Candidate lunar fence impact barrier materials [5] were blasted with 1 landing equivalent JSC-1A. Kevlar (Figure 1B) experienced surface erosion. Woven carbon fiber samples (1A) and hybrid Kevlar-carbon fiber (1C) failed. Vectra fabric (1D), used in the Mars rover balloons, showed no significant impact damage when impacted on the front, finished portion of the fabric; however, the back, unfinished part of the fabric showed erosion similar to Kevlar.

Further Work: On-going work aims to verify the predictions of the Sheldon-Kanhere equation and quantify the damage that lunar outpost hardware will experience. We also plan to functionally test thermal control blankets for loss of reflectivity and solar cells for loss of received power. Future work must also include impacts at realistic lunar velocities at an appropriate NASA facility.

References. [1] Lane, John E., et al, "Lagrangian trajectory modeling of lunar dust particles," Earth and Space 2008 (Long Beach, California), Mar. 3-5, 2008. [2] Immer, Christopher D., et al, "Apollo Video Photo-grammetry Estimation of Plume Impingement Effects," Earth and Space 2008 (Long Beach, California), Mar. 3-5, 2008. [3] Metzger, Philip T., et al., "Modification of Roberts' theory for rocket exhaust plumes eroding lunar soil," Earth and Space 2008 (Long Beach, California), Mar. 3-5, 2008. [4] Sheldon and Kanhere (1972), "An Investigation of Impingement Erosion Using Single Particles," *Wear* **21**, 195-209. [5] Smith, David J. et. al., "Rapidly Deployable Blast Barriers for Lunar Surface Operations," in press.