Wind-tunnel Measurements of the Coefficient of Restitution and Kinetic Energy of Quartz Sand for Mars and Earth Impacting on a Basalt Rock with Numerical Simulation

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The methods by which rocks physically weather over time on the surfaces of planets with atmospheres can provide important information on the geologic history of a region. One of the most significant mechanisms by which rock physical weathering occurs is through aeolian abrasion. This process produces ventifacts, i.e., rocks that have been abraded by windborne particles. Ventifact morphology is dependent upon rock properties and the history of abrasion. Ventifacts can provide important clues on rock and atmospheric properties over time. Up until recently, Earth was the only planet on which ventifacts had been definitively identified. That changed in 1997 with the finding of abundant ventifacts at the Pathfinder landing site on Mars. The presence of ventifacts at the Pathfinder landing site are important for several reasons. First, they indicate that rock abrasion is a significant geologic process on Mars. Second, they point to a defined range of abrading particle and rock properties such that ventifacts can form. Third, the orientation of ventifact features implies formation under a climatic regime different than that of today. However, insight into these implications is hindered by our lack of understanding of i) the rate of ventifact formation; and, ii) the link between morphology and geologic and atmospheric properties, especially on Mars. Investigation of these questions was the central goal of this research effort. This paper presents a series of abrasion experiments coupled with theoretical models that address ventifact formation on Mars and Earth. Rock analog materials have been abraded under terrestrial and Martian conditions to determine the effects of target and atmospheric properties on ventifact morphology. The relation between the target properties and experimental conditions and the resulting morphological forms produced allow formulation of models of ventifact formation applied to planetary rocks. These models can now be coupled to theoretical treatments of abrasion energy due to saltation. These results of these models will, in turn, provide estimates for the rates of ventifact formation and the link between morphology and geologic and aeolian factors for rocks on Earth and Mars. The results of this research: i) increase our understanding of the factors involved in terrestrial and Martian rock abrasion and ventifact formation; ii) result in a better theoretical treatment of the relation between saltation properties and abrasion; and, iii) provide information on the ancient weathering regime and climate on Mars.

I. Introduction

THIS study is part of research being conducted by Jet Propulsion Laboratory and NASA in exploration of the Martian planet surface conditions. Specifically this is part of an ongoing need to understand the physics of rock morphology under different atmospheric conditions. Experiments of impacting saltating sand particles on a mass surrogate surface sample in a wind tunnel were conducted and data were captured using a high speed video camera.

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Knowing how sand saltates and collides is critical to understanding abrasion process of surface rocks and other elements on the planet Mars. The velocity and kinetic energy of individual grains vary as a function of wind speed, grain size, atmospheric density, gravity and rock orientation.

Experiments conducted under Earth and Mars atmospheric pressures using the appropriate wind speeds were performed at the Martian Surface Wind Tunnel (MARSWIT) facility located at the NASA Ames Research Center, Moffet Field, California. Analyses of the trajectories and individual positions of sand grains were recorded and used to obtain: a) the coefficient of restitution of sand grains; and b) kinetic energy loss to the rock. These parameters were determined: particle speed, momentum and kinetic energy as functions of the various experimental test conditions that were used in the MARSWIT facility.

Lasers scan of the rock sample surfaces were performed using a profilometer at UC Davis. Scans were preformed before and after each of the wind-tunnel experiments. An area of about one quarter of the total sample surface area of the rock was scanned to evaluate the effect of abrasion on the rock. The same area was scanned after the rock has been subjected to particle saltating sand of known conditions in the wind-tunnel program, thus making it possible to determine the erosion/abrasion caused solely by the impacting saltating sand.

II. Testing Facility: MARSWIT

Mars Surface Wind Tunnel (MARSWIT) at NASA's Ames Research Center in Moffett Field, CA has, over the years, been used to conduct experiments simulating the lower atmospheric pressure on Mars. Sand is fed through a hopper (1.3 m from the air intake and flow straighteners) with a flux rate of 0.007 kg s^{-1} for quartz grains that have a mean diameter of 400 μm. A High Speed Video (HSV) running at 500 frames per second was used to film all the experiments for a duration of approximately 30 s per angle and per speed tested.

For such extreme pressure conditions, the low-pressure chamber was designed pentagon-shaped with reinforced concrete walls ranging three to six feet in thickness. Along the walls inside the chamber are ports of various types of instrumentation and plumbing pass-throughs that extend into an adjacent laboratory control room where tests can be monitored. To accommodate for the rockets, the chamber also was built 30-m high with a 164-m^2 floor-space totaling to 4058 m^3 in volume. Using a five-stage steam-ejection system, the entire tower can be evacuated to a minimum 3.8-mb pressure in approximately 45 minutes. Figure 1 presents an aerial photograph indicating the location of the low-pressure chamber in Building N-242 and the close proximity of the steam-plant facility identified as Building N-234.

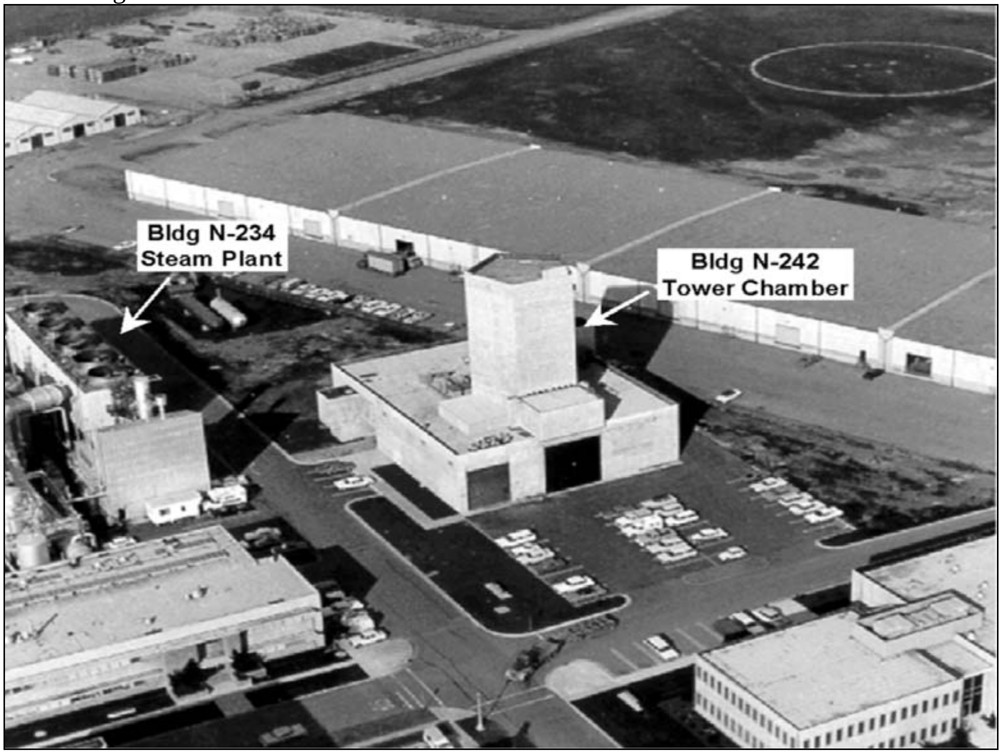

Figure 1. Aerial photo of NASA Ames Research Center low-pressure tower facility in Building N-242.

A sustainable atmosphere is generally limited to about 10-mb pressure. CO_2 also could be supplied for experiments by first evacuating the existing chamber air to the lowest pressure obtainable. Once the chamber volume is filled and pressurized with the desired gas, it must be evacuated to the desired low-pressure condition.

MARSWIT is a 14-m long, open-circuit, suction-type atmospheric boundary-layer wind tunnel with a 1.1-m^2 by 2.4-m length test section. Flow in the wind tunnel is first drawn into the inlet contraction section and then through 10-cm grid flow-straighteners. In order to develop turbulent boundary layer flow, a 5-m long "fetch" of slightly increasing cross-sectional size with downstream distance is attached upstream from the test section. The frame of the tunnel was constructed out of steel I-beams and wood, while the inlet contraction and the diffuser downwind of the test-section was made from fiberglass. For easy viewing, the "fetch" and test section side and upper walls were installed with 2.4-cm-thick, clear Plexiglas. Figure 2 presents a schematic diagram of the MARSWIT facility.

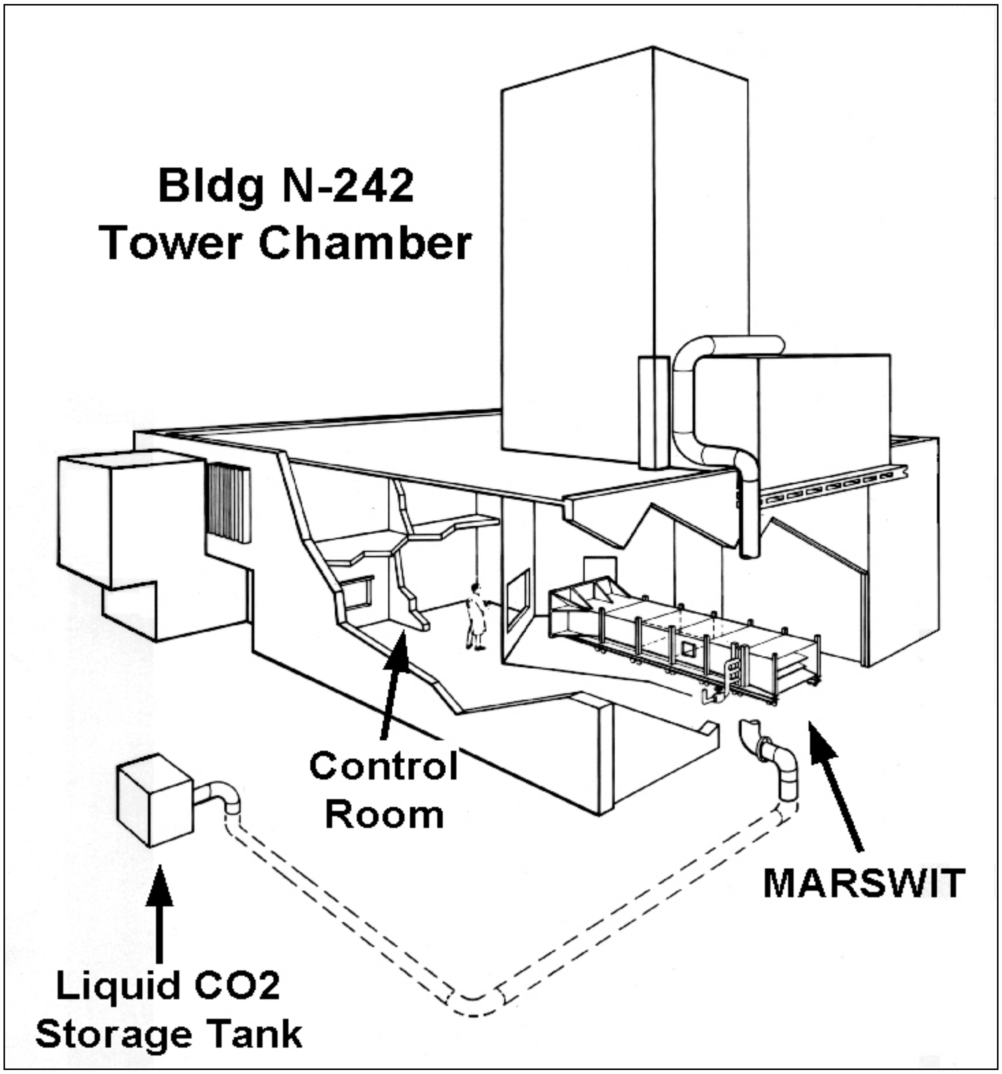

Figure 2. Internal schematic of Bldg N-242 tower chamber with MARSWIT facility.

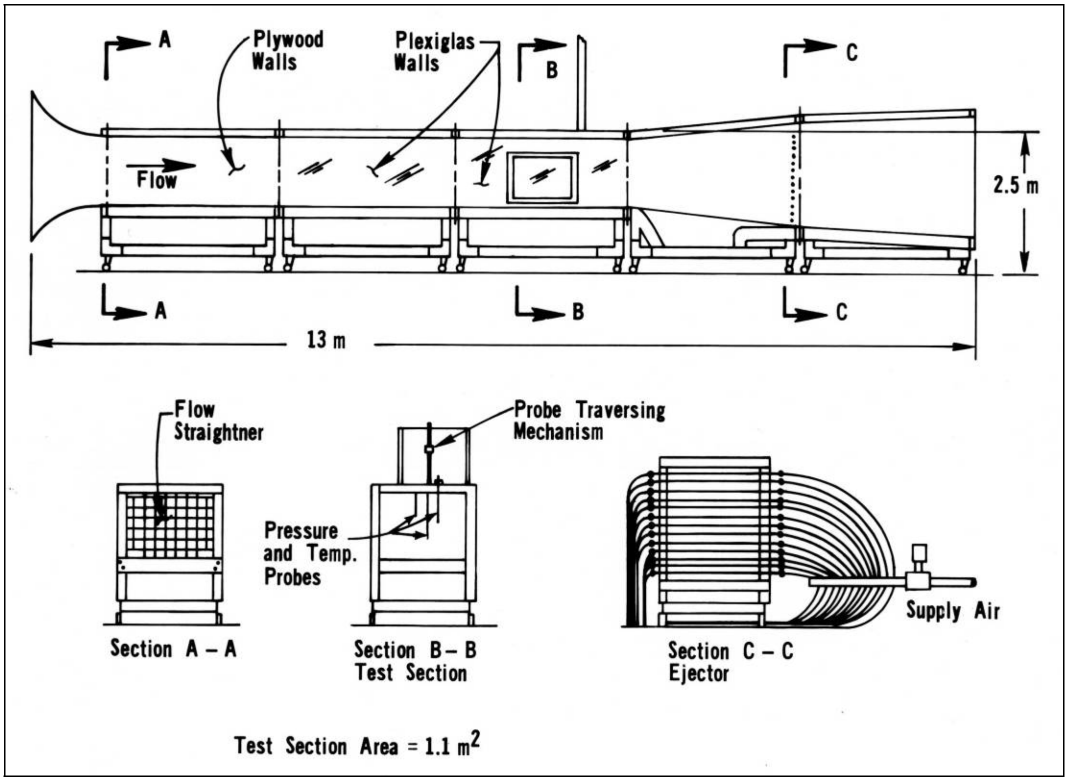

Figure 3. Schematic of Low-pressure Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center, Moffett Field, California.

For experiments conducted under Earth conditions, the wind tunnel is operated with a 6-blade fan system, which is capable of velocities of up to 12 m/s. At low pressure, winds are driven by a network-ejector system placed at the diffuser section. This ejector system consists of 72 equally spaced 1.6-mm nozzles. It releases high-pressure air or CO_2 into the diffuser section to induce a high-velocity, low-pressure region, thus, developing a form of suction through the tunnel. Using the network-ejector system at low pressure, MARSWIT is capable of attaining wind tunnel speeds of up to 180 m/s at 5-mb pressure.

Low-pressure tests are remotely monitored from the Planetary Aeolian Laboratory control room, located outside and adjacent to the chamber. Here, experimental data is acquired with a Microsoft Windows based National Instruments LabVIEW data-acquisition system. The system hardware consists of a National Instruments Model AT-MIO-16E-1 12-bit, 16-channel analog to digital (A/D) board. Its channel capabilities also are further expanded by a National Instruments Signal Conditioning Extension for Instrumentation (SCXI) chassis, which contains two multiplexer modules. The first module provides 32 thermocouple channels, while the second offers 16 double-ended or 32 single-ended voltage channels. The LabVIEW software allows the laboratory user freedom to custom design data acquisition programs known as virtual instruments (VIs), which can be as simple as acquiring highly-sampled analog voltage readings from instruments from one of more channels. Using the "block-averaging" technique, a VI also can be rendered to perform near-simultaneous acquisition, viewing, and analysis of experimental variables. In MARSWIT, parameters such as boundary-layer thermal profiles, wind profiles, atmospheric density, pressure, particle impact count, kinetic energy of particles, concentration of fine particles, and wind velocity are commonly monitored and acquired simultaneously.

III. Background and Previous Results

Ventifact Characteristics on Earth and Mars. Ventifacts are rocks that have been sculpted by windborne particles. The link between their morphology and formation mechanism has been well documented in both field and laboratory studies [*Blake*, 1855; *Kuenen*, 1928; *Schoewe*, 1932; *Sharp*, 1949, 1964, 1980; *Whitney and Dietrich*, 1973; *Dietrich*, 1977a,b; *Whitney*, 1978; *Laity*, 1994, 1995]. Terrestrial ventifacts are located in areas where high velocity, generally unidirectional winds occur or prevailed in the past and a large supply of projectiles capable of eroding rocks is present. They comonly form in areas lacking vegetation or other obstacles that can act as wind shields. All of these requirements restrict ventifact formation to arid regimes. Although ventifact formation by windblown snow has been documented [*Dietrich*, 1977b; *Whitney*, 1978; *Whitney and Splettstoesser*, 1982; *Schlyter*, 1994] and abrasion by dust or silt [*Whitney and Dietrich*, 1973; *Whitney*, 1979; *Schlyter*, 1994] and even air molecules has been advocated [*Whitney*, 1979], sand-sized grains moved by saltation is far more efficient than these abrasive agents in eroding rock surfaces [*Greeley and Iversen*, 1985]. Ventifacts form from all types of rocks, but are favored on heterogeneous rocks, which become preferentially pitted due to etching of soft components. The morphology and orientation of ventifacts and their component features are a function of the direction of the wind that carried the abrading particles [*Maxson*, 1940; *Laity*, 1987, 1994]. As such, ventifacts serve as modern and paleo wind indicators and offer insight into ancient climatic regimes. Three broad categories of ventifacts are recognized in natural terrestrial settings [*Greeley and Iversen*, 1985]: (1) Rocks with wind cut faces or facets, (2) rocks with polished or etched surfaces, and (3) rocks marked by indentations.

Prior to the Pathfinder mission, evidence for ventifacts on Mars was limited to a few faceted rocks, flutes, and circular to elongated pits of uncertain origin seen in Viking lander images [*Binder et al.*, 1977; *Mutch et al.*, 1977; *Viking Lander Team*, 1978; *McCauley et al.*, 1979]. Given the fact that other forms of aeolian modification are abundant on the Martian surface and that saltating particles are predicted to travel faster and have more horizontal trajectories than those on Earth [e.g., *White*, 1979], it was perhaps not surprising that abundant ventifacts were eventually found at the Pathfinder landing site [*Bridges et al.*, 1999a; *Greeley et al.*, 1999]. Rocks with pits, flutes, grooves, and possible rills were documented. The orientations of ventifact features are generally indicative of southeast to northwest winds [*Bridges et al.*, 1999a,b] and differ from the trend of wind tails at the landing site, the direction of local wind streaks, and predictions of the Global Circulation Model, all of which indicate northeast to southwest winds [*Smith et al.*, 1997; *Greeley et al.*, 1999]. Since this finding, further evidence for a paleo wind direction from the southeast in the Pathfinder region has been found in the form of craters eroded on their northwest rims and in the orientation of intracrater dunes [*Greeley et al.*, 2000]. The disparity between these data sets strongly suggests that local circulation patterns have changed or crustal rotation has occurred since the abrasion of most of the ventifacted rocks.

Previous Ventifact and Abrasion Studies. The earliest scientifically reported study of ventifacts was that of *Blake* [1855] of wind sculpted features in the Coachella Valley, CA. *Sharp* [1964, 1980] recorded the erosion rate and morphological changes of natural and analog materials over a period of 17 years. *Laity* [1994, 1995], in an ongoing series of investigations, has done a systematic study of the shape, size, position, and types of rocks undergoing abrasion in the Little Cowhole Mountains of the Mojave Desert, CA. Prior to the Pathfinder mission, the only field study of ventifacts in relation to Mars was an investigation of pitted and fluted rocks in Egypt [*McCauley et al.*, 1979].

Laboratory studies of abrasion reported in the literature are dominated by industrial studies, with only a limited number of geologic investigations. Early studies involved the abrasion of rock fragments to determine the effects of wind direction and rock shape on morphology [*Kuenen*, 1928; *Schoewe*, 1932]. Later wind-blast experiments, both in open air and in wind tunnels, were able to produce erosion on the windward, lee, and even the underside of samples [*Whitney and Dietrich*, 1973; *Whitney*, 1978, 1979]. *McCauley et al.* [1979] arranged ventifacts in various orientations relative to the windstream within a wind tunnel. These studies were generally qualitative and lacked quantitative estimates of the rates of erosion and ventifact morphological variation.

More recently, quantitative studies of rock abrasion in the laboratory have been made. In a study of sand abrasion, *Suzuki and Takahashi* [1981] derived a relation among the kinetic energy of the impacting particles, the compressive rock strength, and abrasion rate. Estimates of erosion rates on Mars were made by impacting ~100 µm particles of quartz, basalt, and ash on to basalt and hydrocal (a type of cement) [*Greeley et al.*, 1982, 1985]. These studies were fairly successful in abrading rocks and estimating the rate that this abrasion occurred. Similarly, studies of ventifacts have addressed the processes by which ventifacts may form. There is yet to be, however, a quantitative study linking the physical parameters of abrasion and saltation theory to the formation of ventifacts.

IV. Experiments

A basaltic rock was set at about 5 m downwind from the hopper and the bottom of the rock was set at an elevation of 10 cm from the surface of the tunnel. The tunnel was run at 11 m/s and 5.5 m/s for Earth atmosphere and at 58 m/s and 30 m/s for Martian atmosphere for six angles orientation of the rock (0^{o}, 15^{o}, 30^{o}, 45^{o}, 60^{o}, 90^{o}) with respect to the horizontal. For each set of experiments, 25 trajectories were tracked down, except for 90^{o} at 11m/s where 50 trajectories were traced down leading to a total of 175 for earth atmosphere at 11m/s and 150 trajectories for the rest of the settings.

Figure 4. Basaltic rock at 60^{o} with tunnel speed at 11 m/s at terrestrial pressure.

Quartz sand was processed through a feeder hopper (1.3 m from the air intake and flow straighter) located at the inside top of the MARSWIT, with a flux rate of 0.007 kg s^{-1} for the quartz sand grains having a mean diameter of 400 μm. A High Speed Video (HSV) running at 500 frames per second was used to film all the experiments for the duration of approximately 30 s per angle and per speed.

The basalt samples were prepared in an identical method, which consisted of cutting a larger sample into several smaller rock blocks from the original basalt slab. An unsaltated sample rock was used for determining the surface roughness from a laser that scanned the basalt sample using a profilometer (located at UC Davis), that has the capacity to measure the surface roughness to +/- 1μm resolution. The rock that was subjected to the saltating sand in the wind tunnel, with an orientation of 90 ° to account for normal forces and 15 ° to account for shear forces, will be scanned again to determine the changes in surface roughness of the sample.

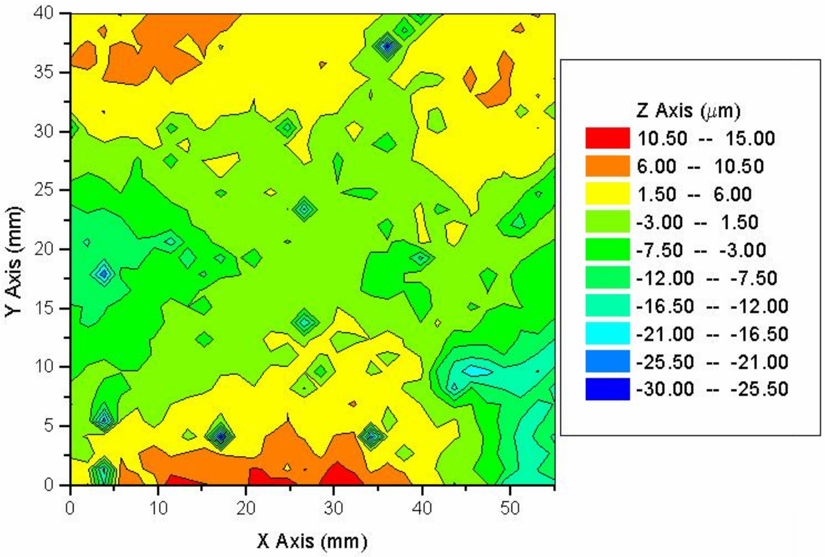

Figure 5. Surface profile of basaltic rock before testing. The Z axis refers to the change in surface height where zero μm is considered a smooth surface.

The video film data of the experiments were converted to still images using Final Cut Pro. To trace the movement of sand particles, a 1 cm x 1 cm grid was placed at the center of the rock before each test. The assumption is that movement of sand is solely two-dimensional, horizontally and vertically, with no movement in the third direction. Using the grid orientation system, this allows for conversion factor from pixels in the digital image to more common units. Using this method, trajectories of impacting grains were tracked manually on a labor-intensive frame-by-frame basis.

Once the trajectories were recorded, positions of the sand grains as a function of time were used to determine the velocity before and after impact. The velocity v of a grain was determined from the change in displacement in the horizontal (Δx) and vertical (Δy) direction over the corresponding change of time (Δt): $v=[(\Delta x/\Delta t)^2 + (\Delta x/\Delta t)^2]^{1/2}$. An embedded chronometer recorded the relative time of each frame with respect to the previous one, which Δt.

V. Discussion of Results

Saltation Theory. A theoretical treatment for abrasion rate is only part of what is needed to model the process of ventifact formation. Because ventifacts are abraded by saltating sand and in order to better model the flux and energy of particles participating in abrasion, it is necessary to link saltation theory to abrasion theory. In regard to abrasion and the formation of ventifacts, the three parameters of greatest interest are particle kinetic energy, trajectory angle, and flux. The kinetic energy determines the amount of energy per grain that is imparted to the rock upon collision. The trajectory angle determines the way in which this energy is transferred to the rock surface (e.g., brittle deformation, ductile deformation, particle disintegration, etc.) and the position on the rock at which collisions occur. The flux determines the total kinetic energy and, when combined with trajectory angle, the potential for abrasion on a given part of a rock.

The energy attained by a particle is determined by its mass and velocity. The velocity can be estimated from the equations of motions for saltating particles combined with a relationship between free stream velocity/friction speed to free stream height/roughness height. Combined with the particle mass, determined for a given size (D_p) and density (ρ_p), the kinetic energy of the particle ($mV_p^2/2$) can be determined. Recently, a new computer code that models the trajectory, velocities, and energies of saltating particles sizes using these equations. Using a new lifting function and surface properties estimated for the Pathfinder landing site the relationship between position along the saltation path to dimensionless energy were computed. It is found that the greatest kinetic energy occurs when the particle is near its maximum height along the saltation path. The height as a function of distance, and, in turn, the trajectory angle, can also be estimated. From these models, combined with wind tunnel testing, it is found that Martian saltating grains travel faster, higher, and farther than on Earth [*White et al.*, 1976; *White*, 1979; *Greeley and Iversen*, 1985].

Ideally, it would be desirable to know a given height and angle to the surface (e.g., a rock facet at a height above the ground oriented at an angle) and measure the flux, total kinetic energy, K.E., (K.E. of individual particles times the flux), and trajectory angle. This would provide estimates of the energy participating in aeolian abrasion.

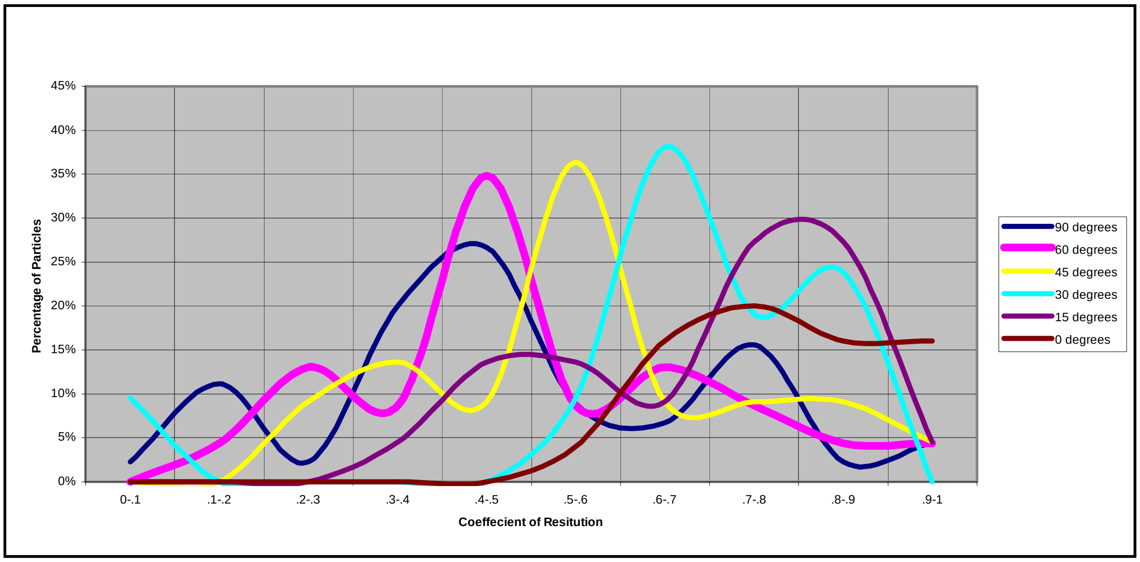

Figure 6. Coefficient of Restitution for Various Angles at a Wind Speed of 11m/s.

With the assumption that the grains have the same density and the same diameter, the kinetic energy per unit mass lost due to impact is equal to the change of kinetic energy before and after impact or: $KE=.5(v_{in}^2 - v_{out}^2)$. While the loss in the 90^o orientation is more or less evenly distributed with only 49% of the particles losing 20 J/kg or less, that number rises steadily and reaches 88% for the 0^o orientation. This is expected, as frontal impact should have energy loss distributed evenly, while horizontal impact should be a low energy loss.

Knowing the velocity before and after impact, the coefficient of restitution (e) was calculated for each experiment e.g.: e= (v after impact)/(v before impact). The coefficient of restitution e has a strong dependence on the orientation of the rock. As the rock is rotated from 0^o to 90^o, its value decreased as shown in Figure 6.

Assuming that the grains have the same diameter and the same density, the kinetic energy per unit mass lost due to impact is equal to the change of kinetic energy of the dust particle before and after impact or: $KE=.5(v_{in}^2 - v_{out}^2)$. Because kinetic energy lost to the rock is dependent on velocity of the imparting grains, it is expected to equal to zero when the collision is perfectly elastic and at maximum when collision is inelastic. This is in agreement with the data shown on Figure 7, where kinetic energy per unit mass decreases as the coefficient of restitution approaches unity.

Since it has been shown that "e" increases as the angle of orientation decreases the expectation here is that kinetic energy loss will be smallest at 0^o and much larger at 90^o. Figure 8 shows that at a 90^o orientation, kinetic energy is "more or less" evenly distributed with only 49% of the particles losing 20 J/kg or less. That number rises steadily and reaches 88% for the 0^o orientation suggesting that abrasion is more important in frontal impact situations.

Numerical Solutions. White et al. (1976) solved the equations of motion for a saltating particle and simulated its trajectory for terrestrial and Martian atmospheres. Further analyses by White et al. (1977) showed that saltating particles generate more lift due to Magnus affects which agreed very well with filmed experiments of saltating particles. Based on this work, similar analysis is underway to predict particle trajectory numerically and compare it to experimental results. The numerical solution uses the location and speed of the particle in the x and y direction as input. An example is of a saltating particle at 11 m/s with a flat rock (zero degree angle) where numerical solution is in good agreement with the measued trajectory. The results of the simulation are encouraging considering that they were done for particle diameter of 500 µm while the particle used in the experiments have a diameter of 400 µm.

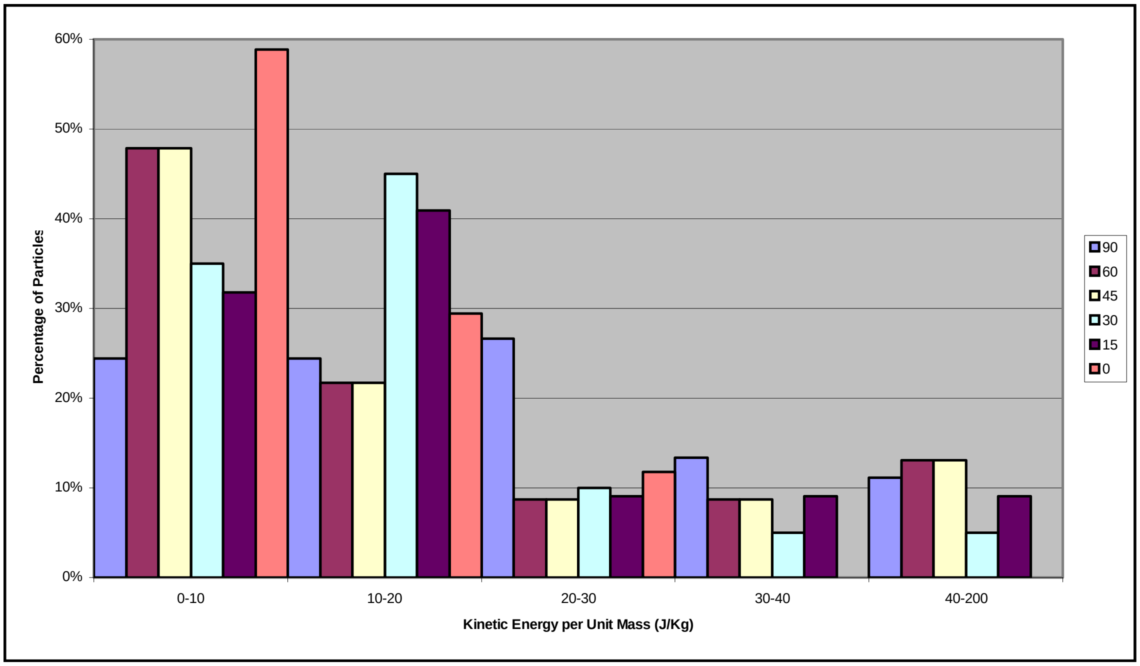

Figure 7. Distribution of Kinetic Energy Lost by a Grain Impacting a Rock with Various Orientation for Wind Speed of 11m/s.

Since kinetic energy is dependent of velocity, one expects it to be at maximum when the coefficient of restitution "e" is near zero and the smallest when "e" approaches unity. This is indeed true for both terrestrial experiments and is still to be determined for Martian condition experiments.

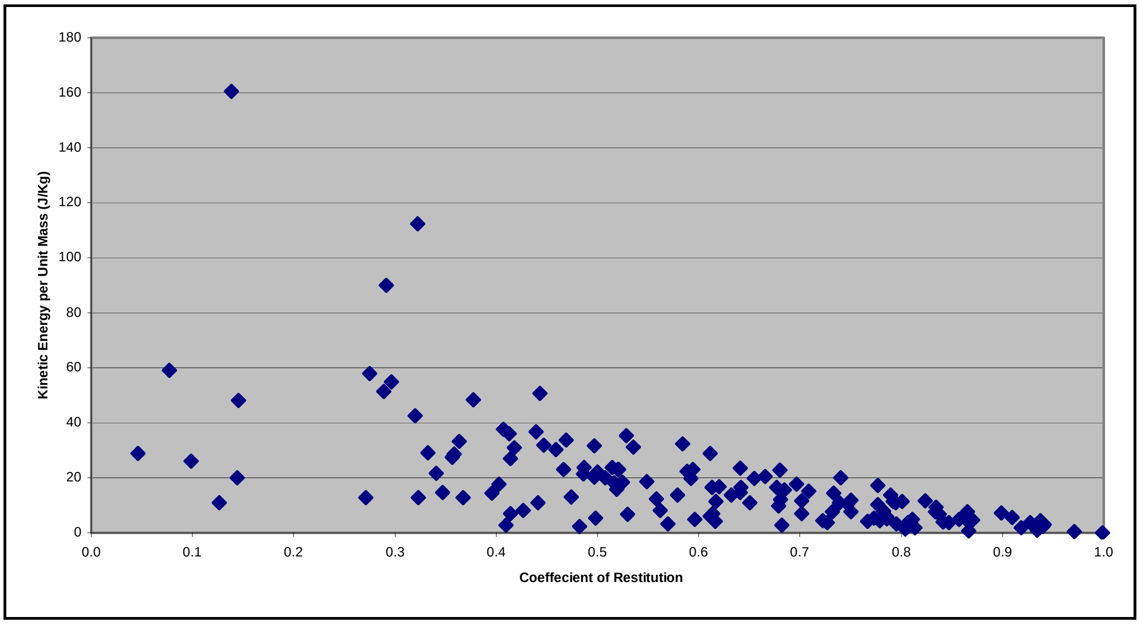

Figure 8. Kinetics Energy per Unit Mass versus Coefficient of Restitution Subject to a Wind Speed of 11m/s.

Future Work. Further analysis of terrestrial and Martian data is currently being conducted. Specifically, studying the impact angle that each grain creates as it impacts the target and correlates that with kinetic energy and coefficient of restitution._ These results will allow for comparison between the two atmospheres. The surface of the abraded rocks will be scanned allowing for comparison of before and after effects of saltation on the sample rock.

VI. Concluding Remarks

Saltating particles impacting on a basalt rock were documented for Martian and terrestrial atmospheres using HSV. These experiments involved changing the orientation of the rock target (90 °, 60 °, 45 °, 30 °, 15 °, and 0°) as well as the wind speed of tunnel (5.5 and 11m/s for Earth; and, 30 and 58 m/s for Mars). The videos were converted into still images that made it feasible to plot the position of a traveling dust particle.

From position of the grains: velocities, coefficient of restitution, and kinetic energy lost to the rock have been documented. Current results suggest that: i) coefficients of restitution decrease as the angle of the rock becomes more and more perpendicular to the flow, resulting in ii) a kinetic energy transfer loss, also decreasing as the coefficients of restitution approach unity; and, iii) energy loss transfer increases as target angle increases; and, iv) favorable comparison between computational modeling to predict particle trajectory and experimental results.

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