the evolution of the ejecta curtain. High frame rate photographs (400 frames per second, fps) of each impact were computerized with a digitizing video camera. Subtracting images taken over a 5-ms time interval removed elements of the scene that have not changed, thereby revealing relative movement of the ejecta. Subtracted image sets at time steps increasing by a factor of 2 were then combined in order to compress the entire evolution of crater growth and ejecta curtain advance into a single frame as shown in Plate 1.

As the atmospheric pressure of air increases for impacts into pumice, the ejecta curtain develops an increasingly convex-outward profile (Plate 1, top). This characteristic evolution is observed for impact velocities from 0.03 to over 6 km/s. Impacts into no. 140-200 sand produce a similar evolution (Plate 1, middle), but the ejecta curtain in sand at one atmosphere has a profile similar to an impact into pumice at a lower atmospheric pressure. This difference is believed to reflect the effect of aerodynamic drag, which is less for the impacts into coarser size sand. The razor edge crispness of the images in Plate 1 (middle) for sand reflects the very narrow size range in sand grains, in contrast to pumice. As a further test for effects due to aerodynamic drag, Plate 1 (bottom) reveals the same sequence for impacts into pumice but with a helium atmosphere, thereby preserving any effects related to atmospheric pressure while drastically reducing the effects of aerodynamic drag. As clearly shown, the ejecta curtain remains relatively undistorted, even at very late times. Plate 1, therefore, indicates that aerodynamic drag might play an important role in the late time ballistic trajectories collectively represented in the ejecta curtain. Very low Reynolds numbers (Re < 1) for individual ballistic ejecta, however, result in a drag coefficient proportional to (1/Re). For a given projectile size and impact velocity, this Reynolds number dependence results in drag controlled only by viscosity of the atmosphere and target grain size, as will be shown below. Consequently, the possible effect of drag should not disappear, even at low atmospheric densities: effects of both target grain size and atmospheric composition should be present and should be separable from the effects of ambient pressure.

The following discussion first considers the effect of atmospheric pressure. Correction for this effect permits exploring the possible role of aerodynamic drag by varying atmospheric density and ejecta size. These separable processes and dependences can be understood in the context of scaling relations and material properties. Remaining systematic second-order differences are then examined in terms of the projectile bow shock.

Atmospheric Pressure

The effect of an atmosphere on cratering efficiency by an impact can be expressed in the following general terms:

$$(M/m) \sim f_0(P)\, f_e(P)\, f_a(P)\, (M/m)_0 \qquad (1)$$

Where (M/m) and $(M/m)_0$ represent the cratering efficiency for different environments (pressure, gas composition) and vacuum conditions, respectively; and the subscripts of the dimensionless functional relations with pressure P incorporate the effects of static atmospheric/lithostatic overburden f_o, dynamic pressure acting on the moving curtain of ejecta f_e, and dynamic atmospheric effects introduced by the disturbed air mass accompanying the projectile f_a. Gravity-controlled cratering efficiency for impacts under vacuum conditions can be given by the scaling relations proposed by *Holsapple and Schmidt* [1982]:

$$(M/m)_0 \equiv \pi_{v_0} = k' \pi_2^{-\alpha} \qquad (2)$$

where π_2 is a dimensionless parameter that for an impact is given by the following:

$$\pi_2 = 3.22\, gr/v^2 \qquad (3)$$

where g is the gravitational acceleration, r is the projectile radius, and v is the impact velocity. The exponent α in equation (2) depends on target properties and the particular cratering regime as discussed by *Holsapple and Schmidt* [1982]. *Holsapple and Schmidt* [1987] also include a projectile/target density term with an exponent dependent on target porosity, i.e., the coupling at impact. This functional form for cratering efficiency is an assumption that applies over a wide ange of values of π_2 [*Holsapple and Schmidt*, 1982]. Other studies, however, reveal that changes in energy partitioning change the exponent α in equation (2) [*Gault and Wedekind*, 1977; *Schultz and Gault*, 1985; *Schultz*, 1988*b*]. Consequently, the present study restricted experiments to impact velocities exceeding 1.5 km/s in order to minimize scatter due to such changes in the scaling exponent.

Table 4 shows the values and dispersion for k' and α derived for different particulate targets under vacuum conditions used in this study. It is assumed that all of these dry particulate targets result in gravity-controlled excavation (equations (2) and (3)) even though the internal angles of friction range from 20°(microspheres) to 80°(compacted pumice). This assumption is clearly reasonable for sands and microspheres but can be questioned for compacted pumice. The static internal angle of friction (cohesion) is reflected in the angle of repose of a face cut into paticulates. The effective strength limiting impact crater growth, however, must reflect dynamic (rather than static) properties of material responding to and flowing within the rarefaction wave behind the shock. As the dynamic material flow field reduces below a critical value, cohesion will finally limit further growth. If this critical value occurs just before the stage when gravity prevents further excavation, then the distinction between gravity- and strength-limited growth becomes problematic. Craters formed in compacted pumice under vacuum conditions exhibit nearly identical final crater profiles as those in sand and microspheres even though the internal angles of friction are very different. Consequently, the late stage material flow field can be considered very similar. Further, the use of different projectile sizes and velocities (each over a factor of 10) establish a value of α consistent with gravity-dominated growth of a dry particulate medium. The role of cohesion is