cratering in microsphere targets (Figure 6*a*) closely match the effects for compacted pumice. The falloff at very high values of the pressure parameter can be correlated directly with collapse of the crater rim, i.e., reduction in rim height and change in crater aspect ratio. Also as expected from Figure 3*a*, the role of an atmosphere on impacts into no. 24 sand is minimal. Additions of small amounts of the atmosphere-sensitive target materials (pumice and microspheres), however, dramatically reduce cratering efficiency. The addition of either material does not significantly affect the internal angle of friction or any other bulk properties (e.g., porosity). Hence Figure 6 reveals that the basic pressure dependence on standard and simple targets (Figures 5*a* and 5*b*) extends to highly sensitive particulates (Figure 6*a*) and mixtures (Figure 6*b*).

Figures 5 and 6 reveal that target materials with very different cohesions exhibit essentially the same dependence on atmospheric pressure. Moreover, the reduction in cratering efficiency observed for pumice is close to the reduction for microspheres. Different exponents should be expected if the data reflect transitional effects between gravity, strength, and pressure. The similar empirical value of the exponent ($\beta \cong$ 0.23), however, is considerably less than the value of $\beta' \cong$ 0.6, which might be expected for pressure-dominated scaling. Because impacts in sand are observed to undergo collapse as atmospheric pressure increases, the complete pumice data set is reviewed in more detail before reconciling the observed ambiguities.

Figure 7*a* includes data for all atmospheric conditions for pumice. Although cratering efficiency decreases with increasing atmospheric pressure, the scatter is considered excessive. For a given atmospheric composition (and temperature), atmospheric pressure and density are obviously related. Consequently Figure 7*b* isolates results for monoatomic gases having very different densities (helium and argon) for pumice targets and provides comparison with trends shown in Figure 5 for a given projectile size. Statistically significant differences in the exponent β are found for impacts in helium and argon (pumice targets). These differences could have three possible causes: error in estimating projectile deceleration; energy losses due to ionization around the projectile; and the effect of atmospheric density (drag) on the ejecta. As noted above, high-speed imaging confirmed the derived impact velocities; nevertheless, Figure 7*b* illustrates the expected offset due to a 15% error in the estimated velocity in order to underscore its minimal effect.

Although the ionization potential for helium (24.5 V) is significantly greater than the potential for argon (15.7 V), its effect on significantly reducing cratering efficiency by absorbing energy at impact is questionable. Above ground nuclear explosions exhibit significant energy losses due to radiation and ionization of surrounding gas before coupling with the ground, thereby significantly reducing cratering efficiency. Impacts, however, mechanically transfer energy to the target with irreversible heat/losses occurring after (not before) coupling with the target. Energy partitioned to ionization of compressed gas between the projectile and target immediately after impact should be a small fraction of the energy transferred to the projectile and target. Even if it is assumed that one half of the initial kinetic energy is equally partitioned between irreversible heating of the target, projectile, and ionization, then the reduction in cratering efficiency would be less than 10%, hence of secondary importance.

Aerodynamic drag is the most likely cause for the observed differences in Figure 7*b*. First, the effect of an atmosphere on cratering efficiency should be less for impacts into sand than into pumice for a given $P/\delta_t v^2$ owing to the differences in ejecta size (see Figure 3). Second, efficiency should be reduced in argon relative to helium at a given $P/\delta_t v^2$ due to the difference in atmospheric density. Third, at low atmospheric densities cratering efficiency in helium and argon should merge. Fourth, Plate 1 graphically demonstrated that the ejecta curtain for impacts in a low-density environment (helium and air with $\rho/\rho_o < 0.1$) does not change significantly with atmospheric pressure, in contrast with impacts in argon. And fifth, introduction of a small component of fine-grained material is observed to dramatically affect cratering efficiency and curtain evolution while not affecting the internal angle of friction. Consequently, the following discussion considers a strategy for quantitatively assessing the effect of aerodynamic drag.

Aerodynamic Drag

Aerodynamic deceleration of ejecta could affect cratering efficiency in two ways. First, dynamic pressures acting on individual ejecta also affect the entire ensemble of debris comprising the curtain. Viscous drag affecting particulate systems can be illustrated by avalanches, pyroclastic flows, and release of particulates from airborne firefighters. If the cratering flow field acts as an incompressible flow, then aerodynamic forces acting on the ejecta curtain should be transmitted hydrostatically throughout the system. In this sense, aerodynamic drag forces resemble the role of gravitational forces limiting ballistic ejection from the cavity. An alternative perspective views drag as a first step to entrainment, thereby leading to turbulence, and energy loss. In this case, entrainment could be induced not only by drag acting on individual ejecta but also by instabilities in the boundary layer between the ambient atmosphere and upward flow of material comprising the outward moving ejecta curtain. Second, atmospheric gases in interparticle pore spaces introduce viscous drag within the ejecta flow and curtain. Either perspective involves assessing the relative effect of drag *d* and gravity *g* acting on an ejecta particle, which can be described by a dimensionless parameter [*Schultz and Gault*, 1979]:

$$d/g \sim C_D \rho v_e^2 / \delta_e g a \qquad (11)$$

where C_D is the drag coefficient (dependent on Reynolds number at scales considered); ρ, the ambient atmospheric density; v_e, velocity of an ejecta fragment with density, δ_e, and diameter, a. Alternatively, interactions between ejecta and atmosphere could be described by a set of separate dimensionless parameters including the Reynolds number (in