characteristic length ΔL must be multiplied by $(\gamma + 1)/(\gamma - 1)$ in order to accommodate different gases with different ratios of specific heat γ. Consequently, the scaled radius of the disturbed air zone for any gas becomes

$$(r_e/r_p) = [(\rho v^2/P)(\gamma + 1)/(\gamma - 1)]^{1/3} \quad (22)$$

If r_e now replaces r_p in the π_2 scaling parameter, then wake-coupled scaling predicts that cratering efficiency relative to vacuum conditions should be reduced by about 40% (for $\gamma = 1.28$) and will decrease with increasing impact velocity.

Alternatively, it can be assumed that the energy contained in the colliding wake reflects (to first order) the energy lost by aerodynamic deceleration of the projectile. The effective volume of this colliding wake is simply $(\Delta E/P)$. If scaled to the projectile mass, $(r_e/r_p)^3$ becomes $\delta_p \,\Delta Q/P$ where ΔQ is the change in the specific energy of the impactor. This approach, however, implicitly assumes that the entire column of atmosphere traversed by the projectile can be incorporated into r_e/r_p. Such an assumption is a gross oversimplification; nevertheless, the approach should provide an alternative test for the process.

The derived expression for (r_e/r_p) and the effect of the coupled wake on cratering efficiency can again be tested by isolating the wake from the projectile as it collides with a sand target, rather than simply scouring a thin sand layer (Figure 15*a*). A tube through the target allowed passage of the projectile without interference. Cratering efficiency for the wake impact can now be expressed as

$$(M/m_p) \sim (m_\omega/m_p)(\pi_{2\omega})^{-\alpha} \quad (23a)$$

$$(M/m_p) \sim (\rho_\omega/\delta_p)(r/r_p)^{3-\alpha}(\pi_{2_p})^{-\alpha} \quad (23b)$$

where the subscripts ω and p refer to the wake and projectile, respectively. Equation (23) can be rearranged and combined with equation (22) to give

$$(k\pi_2{}^{\alpha}\pi_v)(\delta_p/\rho_\omega) \sim (r_e/r_p)^{3-\alpha} \quad (24a)$$

$$(k\pi_2{}^{\alpha}\pi_v)(\delta_p/\rho_\omega) \sim [(\rho v^2/p)(\gamma + 1)/(\gamma - 1)]^{1-\alpha/3} \quad (24b)$$

for a given projectile size. Figure 15*b* illustrates the results of these preliminary experiments for wake impacts into no. 140-200 sand. Although future experiments will explore a broader range of variables, Figure 15 confirms the basic premise. Moreover, the observed target mass displaced by the impacting wake approaches a measurable fraction (~8%) of the mass displaced by the projectile, even though the wake immediately behind the projectile (within $5r_p$) was isolated from the collision.

The results from the projectile-less impacts suggest that the systematic departures in cratering efficiency for different atmospheric compositions (Figures 7b, 11, and 14) also might be interpreted as relative differences in effective radius of the impactor due to the accompanying disturbed air mass. A larger effective radius should result in lower cratering efficiency. For a given impact velocity, an atmosphere of carbon dioxide should result in a larger disturbed air mass than atmospheres composed of nitrogen or argon. Hence cratering efficiencies in a CO_2 atmosphere should be less than in argon or nitrogen as observed (Figure 11). At very high impact velocities, ionization can change the ratio of specific heats, thereby causing additional departures even for a given atmospheric composition.

The effect of wake-coupled scaling on impacts into pumice is now included in Figure 16, where it is assumed that $C_D \sim \sqrt{1/Re}$ over a limited range in larger Reynolds numbers (values from about 4 to 18) and includes a correction for enhancement by the decoupled wake (Figure 14*b*). Figure 16*a* illustrates the results where (r_e/r_p) is given by equation (22) with the values of γ corresponding to ambient conditions for each gas. It is also assumed here that the characteristic length scale ΔL in equation (22) is essentially the same once the appropriate γ has been introduced. If r_e should replace r_p in the π^2 parameter, then the pressure/drag/wake-corrected cratering efficiency should depend on $(r_e/r_p)^{-\alpha}$. Figure 16*a* reveals that such a dependence may be emerging. High-frame photography reveals, however, that considerable ionization occurs at high impact velocities, provided that there is sufficient ambient density. Consequently, Figure 16*b* uses ambient values of γ for all gases with impact velocities less than 3 km/s and/or relative densities less than 0.7 (with respect to air at 1 bar) but assigns high-temperature values of $\gamma(1.1)$ for impact velocities exceeding 4 km/s and relative densities greater than 0.9. This first-order correction reveals a dependence on r_e/r_p not only between different gases but for a specific gas (argon) as well.

Thus projectile-atmosphere interactions create a wake-blast that further modify cratering efficiencies in particulate targets. Wake-blast effects should be most apparent in targets with very low internal angles of friction such as dry, fine-grained sand and low-density microspheres (Figures 7*b*, 10, and 11*c*). The effect of large back pressures created in the cavity by the wake is similar to observed effects of vapor release in volatile-rich particulate targets [*Schultz and Gault*, 1986]. Further experiments are needed to detail such aspects and to explore implications for nonporous targets. Nevertheless, the present results raise caution when deriving impact crater-scaling relations for loose particulates under high atmospheric pressures and densities.

Summary and Concluding Remarks

The effect of an atmosphere on impact cratering efficiency in the laboratory can be separated into three independent processes. Each process can be described by dimensionless ratios of controlling variables or can be viewed as modifications to variables in existing dimensionless parameters described by *Holsapple and Schmidt* [1982]. The effect of atmospheric pressure is revealed by using low density gases at high atmospheric pressures, thereby reducing the effects of competing processes, and its effect can be described by a dimensionless pressure term $P/\delta Q$, suggested by *Holsapple* [1980]. The effect of aerodynamic drag depends on the ratio of deceleration by drag to deceleration by gravity. The derived power law dependence is consistent with replacing the gravity variable with the drag variable in the π_2 term.