the effect of the impinging wake blast even at much greater distances from the projectile ($8.5r_p$ from trajectory axis) at low and high Mach numbers. Consequently, energy and momentum contained in the disturbed air trailing the projectile should be more than capable of excavating a crater in particulate targets analogous to transient jets [*Land and Clarke*, 1965].

There are two ways to incorporate quantitatively the possible effects of impactor-atmosphere interactions on cratering efficiency. The first approach establishes a set of dimensionless independent variables required for similarity between different impactor and atmospheric conditions and then derives the scaling relations empirically. The second approach incorporates a model of the process that modifies the basic scaling relations already discussed; again, this is the approach followed here. The effect of the colliding wake gases on cratering should depend on the degree of coupling between the impactor and gas at the time of impact. If decoupled from the impactor, the wake gas should modify the environmental scaling parameter (drag or pressure terms). Decoupled scaling will occur if the time of interaction between the air disturbance and the target is long compared with impactor penetration thereby creating a back pressure within the early time transient cavity. Low Mach numbers with a high-density atmosphere should favor decoupled scaling. If the impacting wake transfers its energy fast enough, it can be viewed as coupled to the projectile. The colliding air mass changes the energy density of the impact, a situation likely for high Mach numbers and high-density atmospheres.

For decoupled scaling effects, backpressures created by the trailing wake involves replacing static ambient pressure P_o in equation (6c) with the dynamic wake pressure P_ω created in the cavity. Wake pressure should depend on projectile velocity and ambient atmospheric density. Supersonic projectiles ($1 < M < 5$) produce a subsonic wake "wind" trailing at a velocity v_ω, thereby creating a dynamic pressure $1/2\rho v^2_\omega$. The wake column behind a hypersonic projectile ($M > 5$), however, collides at supersonic velocities. At large distances from the projectile, as in Figure 12*b*, the gas can be treated as incompressible and $P_\omega = P\gamma M^2$, but close to (or behind) the projectile the colliding wake column resembles a hypersonic gas jet, a process examined by *Land and Clarke* [1965]. The balance of mass and momentum flux for such a hypersonic compressible gas gives the following expression necessary for similitude:

$$P_\omega = 1/2 P_o\gamma(\gamma - 1)M^2 \qquad (19)$$

where γ is the ratio of specific heats and M is the Mach number. The transition from wake "wind" to wake "blast" can be inferred from projectile-less impact experiments isolating the colliding wake 8.5 projectile radii from the trajectory axis (Figure 12*b*). Figure 13*a* reveals that the radius of scoured sand scaled to the projectile radius gradually increases at low Mach numbers (<6) but increases abruptly at high Mach numbers ($M > 14$). This abrupt increase could reflect the transition from subsonic (ρv_ω^2) to supersonic (equation (19)) as indicated in Figure 13*b*.

Consequently, the experimental data for impacts into sand and pumice should show an augmentation in cratering efficiency as back pressures created by the colliding wake filling the transient cavity offset ambient atmospheric pressure effects. In dimensionless form, the effect of the impacting wake decoupled from the projectile can be expressed by the following:

$$P_\omega/\delta_t Q \sim \rho v_\omega^2/\delta_t v_i^2 \sim \rho/\delta_t \quad (M < 6) \qquad (20a)$$

$$P_\omega/\delta_t Q \sim [P_o\gamma(\gamma - 1)]/\delta_t c^2 \quad (M > 10) \qquad (20b)$$

Atmosphere-dependent departures noted in Figure 11 now emerge as trends in Figure 14. At low Mach numbers (Figure 14*a*), both pumice and sand exhibit enhancement in cratering efficiency corrected for ambient pressure and drag effects exceeding some critical threshold. At higher Mach numbers (Figure 14*b*), equation (20*b*) was found to apply, as the impinging wake near the projectile requires treatment as a compressible gas. It should be noted that departures from the assumed values of the drag coefficient over a very broad range of Reynolds numbers result in a slight downward shift of data in Figure 14*b* relative to Figure 14*a*. Figure 14*c* considers high Mach numbers at high atmospheric densities with more restricted ranges in the Reynolds number, thereby resulting in nearly the same drag coefficient. The augmentation in cratering efficiency indicated in Figures 15*a* and 15*b* is confirmed at Re ≈ 6, but there appears to be a decrease at higher values of the wake blast parameter (Re ≈ 10). This could reflect a systematic change in γ due to ionization or could indicate a change from the decoupled to coupled scaling process.

If the atmospheric disturbance is now considered coupled to the impactor, then the resulting change in energy density can be viewed as increasing the effective radius of the projectile. This perspective is based on previous experiments involving the impacts of extremely low-density projectiles [*Schultz and Gault*, 1983, 1984]. For impactor densities ranging from 10^{-4} g/cm^3 (extended clusters) to 10 g/cm^3 (lead), cratering efficiency for impacts into sand was found to be independent of impactor density provided that the actual impactor radius is used in the π_2 term. For application here, the solid impactor radius is replaced by the effective radius (r_e) of the disturbed air. This radius can be derived by equating the work expended in slowing the projectile to the work expended on the air mass as it decompresses from the air cap in front to r_e behind the projectile. The second law of thermodynamics also requires inclusion of any heat absorbed by the system, e.g., by ionization, but this is neglected for discussion here. The effective volume of the disturbed air scaled to the projectile volume r_p^3 becomes

$$(r_e/r_p)^3 = (\rho v^2/P)(\Delta L/r_p) \qquad (21)$$

where ΔL is a characteristic length overwhich deceleration occurs. Conservation of mass from the Rankine-Hugoniot equations reveals that the atmospheric column intercepted and compressed in front of the projectile requires that the