TABLE 4. $k\pi_2^{\alpha}\pi_v = 1$

	k	α	Standard Deviation
Pumice	8.741	0.518	±0.037
No. 140-200 sand	2.778	0.488	±0.035
No. 24 sand	3.25	0.510	±0.027
Low-density microspheres	2.42	0.480	±0.026
Ottawa Flint	4.27	0.506	NA

Calculated for impact velocities greater than 1.5 km/s for projectile sizes 0.159-0.635 cm in diameter. NA, not available.

nevertheless expressed in the overall reduction in cratering efficiency for pumice relative to sand under vacuum conditions.

Impact craters are observed in both laboratory and in computational experiments to first achieve a maximum depth and then to expand laterally [e.g., *Orphal et al.*, 1980; *Schultz et al.*, 1981]. Consequently, crater shape changes continuously. If crater growth is arrested by some process (including atmospheric effects), the final crater shape should change. This phenomenon is in fact observed but is the focus of a different contribution [see *Schultz*, 1990, 1991]. Of interest here is an important consequence for crater profiles too steep for the internal angle of friction, thereby resulting in crater collapse. Craters in sand and microspheres are particularly affected by this process. Ironically, the low cohesion of dry sand that favors its use under vacuum conditions becomes problematic under atmospheric conditions due to rim collapse. Conversely, the internal cohesion of compacted pumice, which can cause ambiguities in interpretation under vacuum conditions, nevertheless preserves the transient crater limited by atmospheric effects.

The principal question in this study is whether atmospheric effects, cohesion, or gravity (or some combination) controls cratering efficiency. For very strong rock targets at laboratory scales, the ballisitic excavation ("coast") phase may never fully develop, and very high atmospheric pressures are required before the atmosphere can play a role. For very weak targets (dry particulates), the ballistic "coast" phase dominates late stage growth to 40 projectile diameters until finally limited by diminishing ejection velocities or the comparable role of strength. This description also should apply to shock-pulverized solid targets at large scales [e.g., *Orphal et al.*, 1980; *Schultz et al.*, 1981; *Holsapple and Schmidt*, 1987]. For such targets, sufficient atmospheric pressure will first affect the gravity-dominated ballistic excavation phase. As the atmosphere reduces the ballistic field below a critical value, cohesion again plays a role and preserves the final limit. In this case, cohesion plays a subsidiary role. These considerations implicitly assume that the presence of an atmosphere not only adds to the lithostatic overpressure in the target but also could restrict advance of the ejecta plume, thereby limiting growth. If this perspective is correct, then cratering efficiencies for targets exhibiting contrasting cohesion should exhibit the same atmospheric response for sufficiently high pressures.

The effect of atmospheric pressure can be given in terms of vacuum conditions by combining equations (1) and (2):

$$(M/m)/(M/m)_o = k\pi_2^{\alpha}\pi_v = f_o(P) \qquad (4)$$

where π_V is defined as (M/m) for cratering efficiency in the presence of an atmosphere and $k = 1/k'$ from equation (2). Previous studies generally combine the three factors f_o, f_e, and f_a into a single dimensionless pressure parameter, π_p. Here a distinction is made in order to emphasize different processes and to acknowledge explicitly the distinction between the impact and explosion cratering process. For reference, Figures 2 and 3 show the effect of atmospheric pressure alone (i.e., not scaled to other variables) on cratering efficiency for different target types. Because the range in impact velocity is much less than the range in atmospheric pressure for both the sand (Figure 2*a*) and mixed (Figure 2*d*) targets, the observations essentially indicate the dependence between the observed cratering efficiency and atmospheric pressure, with π_2^{α} providing a minor correction (see Table 5). Figure 3*a* allows more direct comparison of the effects of pressure on cratering efficiency in various targets (excepting mixed sand, Figure 2*d*) for given impactor conditions (i.e., given π_2). Atmospheric pressure can have a significant effect on cratering efficiency for fine-grained targets but disappears for coarse-grained targets (no. 24 sand). Additionally, Figure 3*a* reveals that fine-grained targets with high or low internal angles of friction (compacted pumice and low-density microspheres, respectively) exhibit the same degree of reduction. At high atmospheric pressures, craters in targets with low cohesion are observed to undergo collapse or other modification related to the blast from the trailing wake (data in parentheses). Figure 3*b* dramatizes the contrast between a crater formed under vacuum and atmospheric conditions in a target of microspheres. A target composed of dry no. 24 sand with much larger constituent grains exhibits virtually no change.

Three alternative scaling relations have previously been applied in the literature to gravity-controlled crater growth. Perhaps the most familiar is drawn from the analogy with explosion cratering where the static ambient pressure adds to the lithostatic overburden [*Herr*, 1971]:

$$f_o(P) = \left(\frac{P_o + \delta_t gh}{\delta_t gh}\right)^{\beta} \qquad (5a)$$

$$f_o(P) = (P_o/\delta_t gh)^{\beta} \quad \text{for } P_o >> \delta_t gh \qquad (5b)$$

$$f_o(P) = 1 \quad \text{for } P_o << \delta_t gh \qquad (5c)$$

where P_o is the static ambient pressure, g is the gravitational acceleration, δ_t is the target density, and h is a depth characterizing the net lithostatic overburden. In the laboratory, the ambient static pressure greatly exceeds the