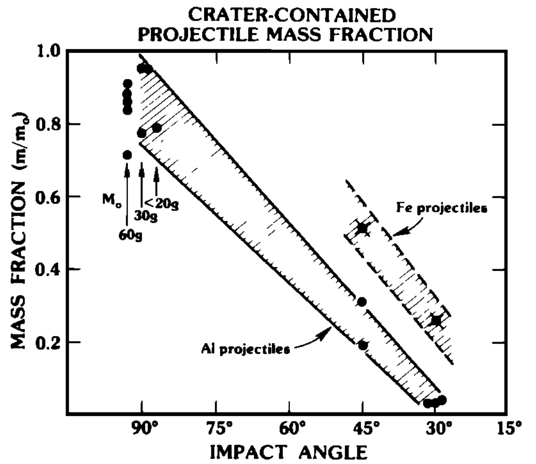

Fig. 22. The fraction of projectile material m relative to total launched projectile mass m_0 contained inside the crater for different impact angles, impacting mass, and impactor density. The clustered impactors represent 0.16-cm-diameter aluminum or iron shot launched with an air gun at velocities of about 100 m/s into no. 40 sand. Vertical impacts (90°) retain between 75 and 95% of the impacting mass within the crater, whereas oblique impacts lose progressively increasing amounts. At 30°, nearly all the aluminum and 75% of the steel impactors are found outside the crater.

proposed secondary craters such as the Struve L [see *Schultz*, 1976, p. 248; *Wilhelms*, 1976] and large crater chains [*Schultz and Mendenhall*, 1979] exhibit many of the same features produced in the laboratory. Struve L, in particular, exhibits a downrange fan of debris, large raised rim, and floor profile typical of oblique clustered impacts.

This and section 6.1 have provided a physical and observational basis for considering clustered impacts to be important for secondary cratering. Section 6.3 considers the implication of such an analogy for estimating the degree of mixing between ejecta from the primary crater and material excavated by the secondary impact.

6.3. *Secondary Cratering Efficiencies and Mixing Ratios*

The results of laboratory experiments involving single-body impacts into sand have become the foundation for interpreting the degree of local versus foreign components on the lunar surface and for estimating the sizes of ejecta fragments from the sizes of secondary craters. This section considers the implications of both viewing secondary cratering as an ensemble of impacting debris and considering the effects of impacting targets with finite strength.

Table 2 shows values of displaced mass ratios for different ballistic ranges and ejecta masses. These ratios are calculated on the basis of expressions for single impactors used by *Oberbeck et al.* [1975] and extrapolations of empirical data used in the present paper. If the calculated displaced-mass ratios are reduced by a factor of 5 owing to clustered impactors, then the amount of primary material preserved in an ejecta deposit or secondary crater increases significantly.

A factor of 5 reduction in cratering efficiency is, however, a very conservative estimate. As discussed in section 6.2, impacts into sand targets are performed in order to minimize strength effects, thereby permitting analogies with large, high-velocity events where strong shock waves pulverize the target prior to excavation. Since secondary impacts represent low-velocity, low shock pressure events, the relative strength of the target becomes important. Compacted pumice targets illustrate this trend. Single impactors into compacted pumice displace 2.5 times less mass than the same impactors into sand; however, they displace about 30 times more mass than the same impactors into solid basalt. Thus secondary impacts on the moon may excavate very different amounts of local material depending on the target. Basalt surfaces and loosely compacted dark mantle deposits illustrate two possible extremes.

Oberbeck et al. [1975] indicate that their experimental results were not directly used to estimate cratering efficiencies for large secondary craters. Rather, the displaced-mass ratios shown in Table 2 were based on shallow-buried nuclear explosion craters in alluvium. Nevertheless, the derived diameter-energy scaling relation in the paper by *Oberbeck et al.* [1975 equation (A2)] is essentially the same as that derived for impact events in sand quoted by *Gault* [1974]. Table 2 also reveals that the displaced-mass ratios predicted from the present experiments reasonably match the results estimated from the nuclear explosion data by *Oberbeck et al.* [1975] for impact velocities greater than 0.5 km/s. If this widely used scaling relation is considered valid, then the experimental results reported herein should be equally valid.

To place this discussion in better perspective, we first consider the emplacement of ejecta at $0.4R$ from the rim of a 150-km-diameter crater on the moon. If we assume that this crater has undergone plastic deformation and slumping resulting in 40% enlargement, then we can estimate the ballistic range (~ 52 km) and velocity at impact (~294 m/s) for a 45° ejection angle. Expressions for displaced-mass ratios from *Oberbeck et al.* [1975] predict that a solid block 500 m across (density of 3.0 g/cm^3, ejection angle of 45°) would displace about twice as much local material as impacting primary ejecta. Direct extrapolation of laboratory experiments of solid body impacts into sand predicts a displaced-mass ratio of 3.0, whereas extrapolation of impacts into pumice predicts a ratio of 0.56. Because clustered impacts provide a more realistic analogy for secondary cratering, the displaced mass ratio must be reduced by a factor between 5 and 10. If the target is more competent than sand or pumice, then further reduction is

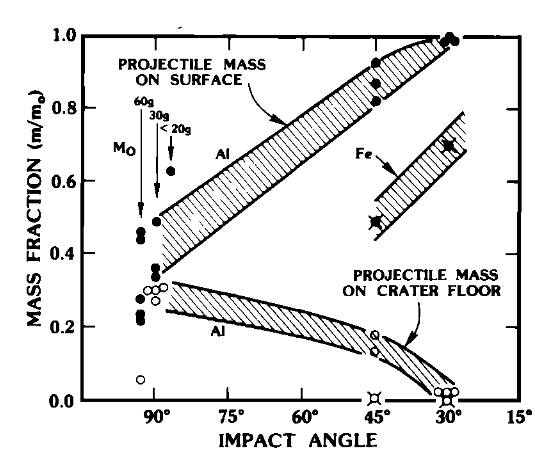

Fig. 23. The fraction of projectile material m relative to the total launched mass m_0 contained on the surface for different impact angles and impactor density. Vertical impacts retain only 20–45% on the surface (solid circles) with about one half of this on the crater floor (open circles). Oblique impacts below 30° ricochet most of the projectiles out of the crater and are deposited on top of the surface.