

THE EFFECT OF PROJECTILE DENSITY AND DISRUPTION ON THE CRATER EXCAVATION FLOW-FIELD. J. L. B. Anderson and P. H. Schultz, Geological Sciences, Brown University, Providence, RI 02912-1846 (Jennifer_Anderson@Brown.edu).

Introduction: The ejection parameters of material excavated by a growing crater directly relate to the subsurface excavation flow-field [1-5]. The ejection angles and speeds define the end of subsurface material streamlines at the target surface. Differences in the subsurface flow-fields can be inferred by comparing observed ejection parameters of various impacts obtained using three-dimensional particle image velocimetry (3D PIV) [4, 6].

The work presented here investigates the observed ejection speeds and angles of material ejected during vertical (90° impact angle) experimental impacts for a range of different projectile types. The subsurface flow-fields produced during vertical impacts are simple when compared with that of oblique impacts [3, 4, 5], affected primarily by the depth of the energy and momentum deposition of the projectile. This depth is highly controlled by the projectile/target density ratio and the disruption of the projectile (brittle vs. ductile deformation). Previous studies [7, 8] indicated that cratering efficiency and the crater diameter/depth ratio were affected by projectile disruption, velocity, and the projectile/target density ratio. The effect of these projectile properties on the excavation flow-field are examined by comparing different projectile materials.

Method: In this study, ejection parameters from vertical (90°) impacts are measured using three-dimensional particle image velocimetry (3D PIV) at the NASA Ames Vertical Gun Range (AVGR) [9]. 3D PIV measures the three-dimensional velocities and positions of ejecta particles in a horizontal cross-section of the growing ejecta curtain located slightly above the target surface [4, 6]. The three-dimensional location and velocity of the particles fully define their entire ballistic trajectories in a vacuum. The intersection of these ballistic trajectories with the target surface yields ejection parameters such as ejection speed, angle, and position from the flow-field center (in the case of vertical impacts, this is also the location of the impact point and final crater center [5]).

All of the experiments in this study were performed under vacuum conditions (7×10^{-4} atm) and at a vertical incidence angle (90° to the target surface). The target material remained the same for each projectile type and consisted of a dry, medium-grained (0.5 mm) particulate sand. Four suites of experiments were performed with different projectile types

and impact velocities in order to compare the effects of projectile density and disruption. Three different projectile densities were examined: 2.17 g/cc (Pyrex), 2.80 g/cc (aluminum), and 8.97 g/cc (copper). At low velocities near 1.0 km/s, both aluminum and copper projectiles deform ductilely, while Pyrex deforms brittlely and is completely disrupted upon impact [7, 8]. Similarly, at high velocities near 5.5 km/s, aluminum deforms brittlely and disrupts catastrophically. The experimental parameters for each of these suites of experiments is given in Table 1.

Type	Projectile		Impact Velocity
	Diameter	Density	
Aluminum	3.13 mm	2.80 g/cc	5.5 km/s
Aluminum	6.35 mm	2.80 g/cc	1.0 km/s
Copper	3.13 mm	8.97 g/cc	1.0 km/s
Pyrex	6.35 mm	2.17 g/cc	1.0 km/s

Table 1. Experimental parameters for the four suites of impacts in this study. All impacts were performed at 90°. Target sand bulk density is 1.62 g/cc.

Results: Data obtained via 3D PIV for these experiments are presented in Figures 1 and 2 for ejection-speed scaling and ejection-angle scaling, respectively.

Low-velocity copper and aluminum data are similar in both Figures 1 and 2, thereby implying that the excavation flow-fields produced by these two types of projectiles at low velocities are very similar. The ejection angles at early stages in crater growth are slightly higher for the copper projectiles (Figure 2); hence the depth to the flow-field center may be slightly deeper than in the aluminum impacts [5]. This agrees with expectations for the copper projectiles, since higher density projectiles penetrate deeper into the target material and transport their momentum farther below the target surface [10].

Both the low-velocity Pyrex and the hypervelocity aluminum data exhibit trends in ejection-speed decay that are consistently offset to higher values when compared to the low-velocity aluminum and copper data (Figure 1). Ejection angles for Pyrex initially are also lower than the low-velocity aluminum and copper impacts and remain nearly constant throughout crater growth (Figure 2). The ejection-angle decay during the hypervelocity aluminum impacts follows the general trend observed for the low-velocity aluminum and copper, but is offset to initially lower ejection angles.

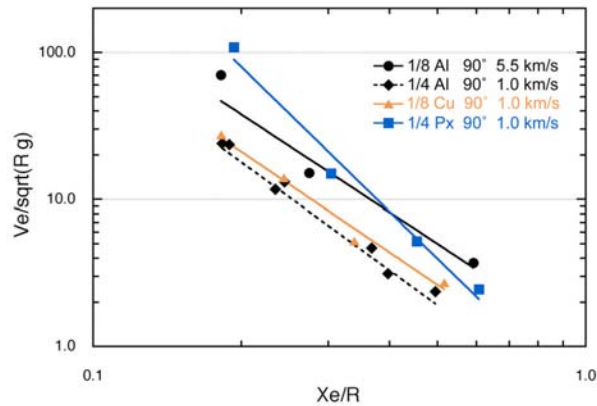


Figure 1. Ejection speed as a function of ejection position scaled by the average final crater radius for 90° impacts of different projectile types.

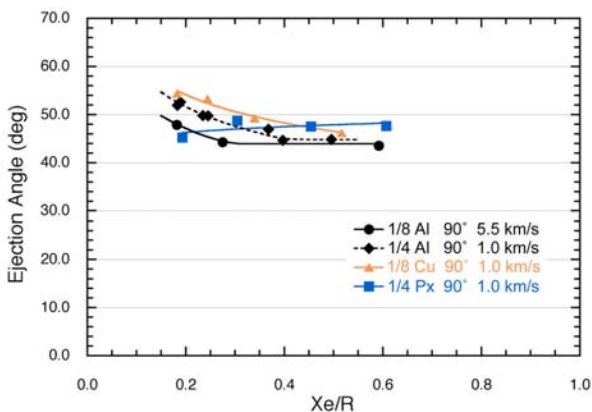


Figure 2. Ejection angles as a function of ejection position scaled by the average final crater radius for the same four series of experiments as shown in Figure 1.

Discussion: At impact velocities of 1 km/s, Pyrex projectiles shatter on impact in contrast with aluminum and copper projectiles. This occurs at the moment of contact and results in energy and momentum coupling near the surface. These lower ejection angles at early times reflect this shallow flow-field center. The shallow coupling of Pyrex also reduces the effect of the projectile's downward-directed momentum. As a result, more energy is deposited in the near-surface pressure/rarefaction wave allowing for more efficient excavation and higher ejection speeds.

The low-velocity aluminum and copper impacts initially exhibit higher ejection angles, thereby implying a deeper penetration depth than the Pyrex impacts (Figure 2). More energy is used to compress the target material below the impact point during the low-velocity aluminum and copper impacts; consequently, less energy is available for crater excavation resulting in lower ejection speeds (Figure 1).

Hypervelocity aluminum projectiles are denser than Pyrex, and penetrate deeper into the target before disrupting completely, as expressed by initial ejection angles between the Pyrex and low-velocity aluminum and copper impacts (Figure 2). Hypervelocity aluminum projectiles still disrupt closer to the target surface than either the low-velocity aluminum or copper projectiles, which again leaves more energy for crater excavation as evidenced by the higher trend in ejection speed (Figure 1).

Implications: The energy of the projectile overwhelms the effect of its momentum on the excavation flow-field at high velocities and shallow penetration depths (as in the hypervelocity aluminum and low-velocity Pyrex experiments here) because of the reduced capability of the projectile to create a deep penetration cavity. The effect of projectile momentum is more apparent during low-velocity, deep penetration impacts (the low-velocity aluminum and copper experiments here) when more time is needed for the projectile to transfer its momentum to the target. As a result, ejection angles can be used as a measure of penetration depth of the projectile or as a method to estimate the projectile to target density ratio. High ejection angles imply a deeper penetration depth or, conversely, a higher projectile to target density ratio. If the target material is highly porous, or has an otherwise low bulk density, ejection angles during a vertical impact will start out much higher than 45° and then decrease throughout the initial stages of crater growth.

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