RECOIL FROM CRATER EJECTA IN HYPERVELOCITY IMPACT OF HYDROUS AND POROUS TARGETS .

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Introduction: The momentum change of an asteroid in response to impact cratering has two components: 1) the direct transfer of momentum by the impacting projectile, and, 2) the recoil of the asteroid in response to the crater ejecta, which is directed in the half-plane away from the surface of the asteroid. The total momentum gain of the target is characterized by the momentum multiplication factor, β, given by:

$$\beta = (m_p v_p + p_e)/m_p v_p \ = M_t V_t \ / \ m_p v_p$$

where m_p is the mass of the projectile, v_p is the speed of the projectile, p_e is the magnitude of the momentum of the crater ejecta opposite the recoil direction, M_t is the mass of the target, and v_t is the change in the speed of the target due to the impact.

Kinetic impactor deflection of an object on a collision course with Earth was described in a 2007 NASA Report to Congress as “the most mature approach and could be used in some deflection/mitigation scenarios, especially for NEOs [Near Earth Objects] that consist of a single small, solid body” [1]. However, a detailed knowledge of β for the target NEO is particularly critical to the success of a deflection by kinetic impactor [2]. To constrain β, we have begun a series of hypervelocity cratering experiments on meteorites and analogs at the NASA Ames Vertical Gun Range (AVGR).

Thus far we have reported β values for 13 *dry* ordinary and carbonaceous chondrite meteorite samples, including 7 samples of the Northwest Africa (NWA) 869 L3-6 ordinary chondrite, 5 samples of the Northwest Africa 4502 CV3 carbonaceous chondrite, and 1 sample of the highly-porous Saratov L4 ordinary chondrite [3]. All 7 of the cratering impacts into NWA 869 targets produced β values in the narrow range from 1.82 to 3.81, with a mean of 2.71 ± 0.6. Four of the 5 cratering impacts into NWA 4502 targets produced β values in the narrow range from 2.88 to 3.97, with a mean β of 3.37 ± 0.5. The fifth NWA 4502 gave a remarkably different value of β (11.72), well outside the range of the other four shots, suggesting the impactor in this shot struck a different material than the other four NWA 4502 impacts [3].

Since the NWA 4502 targets contained obvious weathering veins comparable in size to the 1/16th inch projectiles, we suggested that this anomalous β value resulted from cratering into hydrous weathering material [3], since β for a strengthless water target is reported to be 152, much larger than β for even non-porous rocks [2]. If so, hydrous meteorites, and their parent hydrous asteroids, as well as comets might have remarkably different cratering recoil behavior than dry asteroids. Since hydrous, carbonaceous asteroids are common in the outer half of the main belt and are found among NEOs, a characterization of the recoil of hydrous asteroids is important to understand the dispersal of hydrous asteroid families and the deflection of potentially hazardous, hydrous NEOs.

Samples and Procedure: To test the proposition that the vaporization of water in hydrous targets causes “jetting” that significantly enhances the recoil in hypervelocity cratering we have conducted three cratering impacts into hydrous clay mineral targets of terrestrial serpentiue. Serpentine was chosen because of its easy availability and because the the bulk of the crystalline material in the hydrous CI carbonaceous chondrite Orgueil consists of serpentine and montmorillonite [4]. We prepared three serpentine targets ranging in mass from 62 to 105 grams (Table 1) and determined the bulk and grain densities, allowing calculation of the porosity of each target. Two of the serpentine targets had moderate porosities, in the 17.0 to 18.8% range, comparable to the mean porosity of 22.2 ± 0.7% reported for hydrous CM chondrites, but significantly lower than the 34.9% porosity reported for CI meteorites [5]. As a comparison, we also measured β for three more Saratov L4 ordinary chondrite targets, having comparable porosity to two of the serpentine targets. We measure both the porosity (Table 1) and the compressive strength (in progress) of our cratering targets because sensitivity testing shows that of the numerous parameters that can be included in modeling the recoil due to crater eject the predicted outcome is most sensitive to target strength and porosity [2].

To quantitatively determine the momentum transfer in a hypervelocity cratering event we suspended each serpentine target in front of a large rectangular grid in the vacuum chamber at the NASA Ames Vertical Gun Range. Each target was cratered by a 1/16” Al-projec-

Table 1: Properties of Serpentine Targets

Mass (g)	Bulk Vol. (cm^3)	Grain Vol. (cm^3)	Porosity (%)
61.96	27.52 ± 0.15	22.86 ± 0.09	17.0 ± 0.6
104.72	46.58 ± 0.21	37.83 ± 0.06	18.8 ± 0.4
75.24	30.18 ± 0.08	29.21 ± 0.06	3.2 ± 0.3

Table 2: Conditions and Outcomes of Serpentine and Saratov Hypervelocity Cratering Impacts

Target			Projectile			β		
Type	Initial Mass (g)	Final Mass (g)	Type	Mass (g)	Speed (km/s)	Side	Top	Avg.
Serpentine	104.74	102.2	1/16" Al	0.0054	4.21	4.68	5.18	4.93
Serpentine	75.27	73.87	1/16" Al	0.0068	4.35	3.94	3.36	3.65
Serpentine*	64.89	35.45	1/16" Al	0.0058	4.38	4.30$^{\#}$	4.51$^{\#}$	4.40
Saratov	113.0	100.0	1/16" Al	0.0059	5.21	1.52	1.46	1.49
Saratov	75.34	51.73	1/16" Al	0.0059	4.94	2.78	2.90	2.84
Saratov	67.92	53.5	1/16" Al	0.0059	4.18	2.10	1.94	2.02
Saratov	59.94	36.8	1/16" Al	0.0058	4.02	1.64	2.29	1.97

*** Sample soaked in water for 2 days adding ~3 g of water. $^{\#}$Combining the recoil speeds for two fragments.**

tile, fired at 5 km/sec at the center-of-mass of the target. Two high-speed cameras, one parallel to the floor (Side) and one looking down (Top) on the target, photographed each impact. The recoil speed was determined from each high-speed video sequence, measuring the target recoil motion relative to the grid, giving the β values in Table 2.

To minimize the effect on the target of gas emitted by the gun, a mylar disk was located downstream from the sabot stripper, and a paper disk was placed over the exit port of the gun chamber. Both disks were easily penetrated by the hypervelocity Al projectile, but tend to diffuse the gas emitted by the gun. To validate this, we conducted a "blank" shot in which the gun was fired, with the normal powder load for a 5 km/s shot with a 1/16" Al projectile at a 135 g meteorite target, but no projectile was loaded. Analysis of the high-speed video showed no detectable recoil of the target.

Despite the significant difference in their porosities (p), the 104.7 g serpentine target (p = 18.8%) and the 75.2 g serpentine target (p = 3.2%) gave relatively consistent β values of 4.93 and 3.65, with a mean β = 4.29 ± 0.82. We measured the porosities of two of the Saratov samples prior to the cratering, and found p = 16.1% for the 67.9 g target and p = 15.2% for the 59.9 g target, comparable to the porosities of two of the serpentine samples. The β values clustered for the four Saratov samples and gave a mean β = 2.08 ± 0.56.

The masses of the crater ejecta are very low for both serpentine targets, only 1.5 to 2.5 g. To produce a mean β = 4.29 either the speed of the solid ejecta must have been quite high (average ejecta speed ~ 50 m/s for the 104.7 g target) or there must have been a significant enhancement of β due to vaporization of water.

A third serpentine sample was immersed in water for two days before the cratering shot to add liquid water to the target. The mass inceased from 61.96 g to 64.89 g, indicating that the sample absorbed almost 3 g of water. However, we could not determine how much of this water was lost during the more than half-hour interval while the AVGR chamber was pumped to ~0.5 torr before the shot. This target disrupted with the first noticeable separation occurring 0.18 ms after impact. Soaking may have weakened the serpentuine, resulting in the disruption rather than cratering. The two largest fragments have masses of 35.45 g and 25.87 g. We measured the recoil speed of each fragment and determined β using the total momentum transferred to these two largest fragments.

Conclusions: The Saratov samples, with ~15.5% porosity have a mean β = 2.08 ± 0.56, indicating that even moderately porous targets experience a significant enhancement in the recoil momentum due to the ejecta from hypervelocity cratering. The β value for the high porosity (p = 18.8%) serpentine target (β = 4.93) is more than twice the β value for the Saratov targets, which have comparable porosities, suggesting that the hydration of the serpentine target substantially enhances the momentum transfer by hypervelocity impact cratering. These measurements on porous and hydrous targets provide important data to validate hydrocode modeling of the recoil in cratering impacts.

Further experiments on hydrous CM meteorites and either CI meteorites or CI meteorite analogs are required to determine the β values appropriate for hydrous NEOs and main-belt asteroids. The effect of vapor jetting is likely to be even more significant for hypervelocity impact cratering of comets.

References: [1] NASA Report to Congress, Near-Earth Object Survey and Deflection: Analysis of Alternatives (2007) 27 pages. [2] K. A. Holsapple and K. R. Housen (2012) *Icarus*, 221, 875-887. [3] G. J. Flynn et al. (2017) *Proc. Engineering,* 204, 146-153 [4] M. N. Bass (1971) *Geochim. Cosmochim. Acta,* 35, 139-147. [5] R. J. Macke (2010) *Ph D. dissertation*, University of Central Florida, Orlando, FL. 332 pp.