# METER-SCALE TARGET IMPACT EXPERIMENTS: MEASURING MOMENTUM ENHANCEMENT FACTOR SIZE SCALE EFFECTS.

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**Introduction:** Among the more technically practical methods of deflecting a potentially hazardous object (PHO) is kinetic impact, whereby the momentum change imparted to the object by the cratering impact of a targeted spacecraft or other projectile affects the required minor orbital change to avert impending disaster. The ratio of the momentum change of the target to the impact momentum is commonly denoted as $\beta$, the *momentum enhancement factor* (e.g. [1]). Knowledge of what values of $\beta$ to expect for impacts into near-Earth asteroids (NEAs) in the range of size and composition representative of objects in the known population of PHOs is thus crucial in designing and planning for mitigation strategies focused on the kinetic impact method.

Our team has made some important progress in extending laboratory impact experiments, often conducted with decimeter-scale targets, to meter size scales and measuring $\beta$ in the process [2]. In February 2010 we impacted 4.45-cm-diameter aluminum spheres into two 1-meter-diameter granite spheres at 2 km/s, yielding measurements of $\beta$ for the two tests of 2.13 ± 0.10 and 2.21 ± 0.10, respectively. Compared with data from other momentum transfer impact experiments at much smaller scale these initial tests imply an impactor scale and an impactor density effect for hypervelocity strikes into competent rock. The implied impactor size scale effect is surprisingly large (to a 0.4 power) and extrapolation indicates that a 1-m aluminum sphere striking a consolidated rock surface at 10 km/s could have $\beta$ exceeding 40 (though the scale size saturation may be just larger than the tests we performed, which would reduce this value).

Our present large-scale experimental work, designed to optimize data taking for measuring momentum transfer and focused on a range of materials including more porous silicate materials, is intended to greatly extend our understanding of how $\beta$ scales for asteroid-sized objects.

**Experiment Approach:** Our impact experiments utilize the SwRI 50mm powder gun, which can fire up to 260-gram mass projectiles at speeds of ~2 km/s, supplemented by smaller-scale experiments using the NASA Ames Vertical Gun Range (AVGR) as necessary to cover required parameter space (e.g., faster impact speeds, off-normal-incidence impacts, temperature-controlled impacts into metals, etc.). Targets are mounted to allow recoil (either via a conventional ballistic pendulum for smaller targets or on a horizontal rail/track/sled assembly for larger targets) and all impact experiments are documented by high-speed video allowing the required analysis to quantify impact outcome and target recoil.

**Ongoing Experiments:** To date we have completed over two dozen small-scale shots at the AVGR and several large-scale shots with the SwRI 50mm powder gun. AVGR experiments include 13 shots into 4- and 6-inch right cylinders composed of a plaster-sand mix that is a good porous silicate asteroid analog, two shots into 6-inch pumice cubes, and 14 shots into 4-inch right cylinders of an iron-nickel alloy approximating the composition of iron meteorites. $\beta$ values of ~1-2 and ~1 were obtained for the plaster-sand mix and the pumice, respectively. Analysis of the data for the iron-nickel shots, performed at temperatures of about 297 K and 149 K, thus spanning the ductile to-brittle fracture transition, are underway [3]. SwRI 50mm powder gun shots were conducted with large pieces of pumice impacted with 2.54-cm and 4.45 cm aluminum projectiles at impact speeds of ~2.0 km/s.

In preparation for the 50mm powder gun shots several pallets of pumice rock samples of various sizes and shapes were purchased from Keller Materials in San Antonio, Texas. Several smaller rocks were cut with a water-jet to create numerous 6-inch cubes of the material, but the larger irregularly-shaped rocks were shot ‘as-is’.

Two series of experiments were conducted. The initial test series was conducted to determine what type of response could be expected when hitting these rocks with a 1-inch diameter aluminum sphere. For these tests, two rocks that were not shaped particularly well for actual data tests were chosen. The rock for each test was chained-down onto the 50mm gun beam and held relatively rigidly. Two high-speed video cameras were fielded for these tests; one positioned perpendicular to the shotline of the projectile to measure its velocity and the second positioned for an oblique view of the impact. For the two test shots a 1-inch diameter aluminum 2017-T4, Grade 200 sphere was fired from the 50mm gun, at speeds of 6680 and 6721 feet per second. The results showed that without confinement the edges of the rock around the impact point would likely break off, thus making momentum calculations difficult. This information along with the size of the impact crater helped guide the development of the test plan for the ballistic pendulum test series to follow.

Because large chunks of the rock broke-off the main rock body during the preliminary ballistic tests, the rocks for the second test series were wrapped in chicken wire to prevent large chunks of the rock from falling off during the event. For most shots the wire was wrapped entirely around the rock and then cut in the area of the impact to allow impact-related spallation and ejecta to occur without obstruction. In some cases, only the side and back portion of the rock was wrapped (this depended on the size and shape of the rock). After each rock was wrapped with chicken wire, two 3/16-inch chains, one near the front and one near the back, were secured to the rock. The actual placement of each chain was often dictated by the shape of the rock.

For testing, the rocks were then suspended on the gun shotline using four 3/16-inch steel cables to form a ballistic pendulum (Fig. 1). Because the rocks were so irregular in shape, the length of each of the four cables was not always the same even though every attempt was made to make them so. The cable positions were adjusted to provide an ‘easy’ and ‘linear, front-to-back’ swing of the rock when pushed-on by hand. A summary of the shot conditions in this second test series is provided in Table 1. In this table, the rock weight prior to adding any material is provided as the “Rock” value. The “Package Weight” is the weight of the rock, the chicken wire, and the chain.

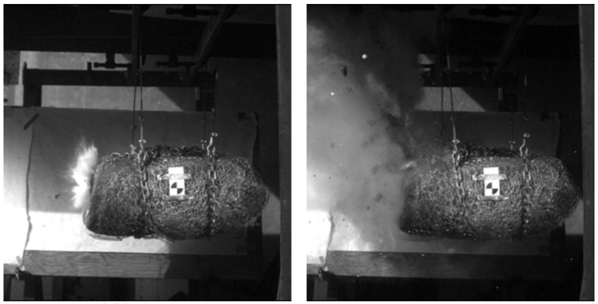
**Table 1. Shot Conditions for Test Series 2**

| Test No./Rock No. | Rock/Package Weight (lbs) | Impact Speed (ft/s) | Impactor Mass (gm) |
|---|---|---|---|
| 1/1 | 371/416 | 6990 | 23.70 |
| 2/1 | 371/416 | 6930 | 23.85 |
| 4/2 | 202/233 | 6969 | 23.85 |
| 5/3 | 302/333 | 6807 | 24.00 |
| 6/4 | 155/186 | 6906 | 23.95 |

Similar to the initial test series, a ‘velocity’ high-speed video camera and an ‘oblique view’ camera were fielded for these tests. A third camera, perpendicular to the right-side edge of the rock, was fielded to provide a means of measuring the movement of the rock. To aid in the measurement, a fiducial marker was taped to the side of the rock. The distance between the center of the fiducial marker and the vertical pivot axis of the rock, as well as the measured movement of the target (both the total movement and the vertical component of the measured total movement), were measured for each shot. Figure 2 shows frame grabs from the high-speed video from Test 6.

Analysis of the high-speed video data is underway. These tests provide data for understanding $\beta$ (for non-consolidatd materials) in the context of our previous large-scale shots into solid granite and the size scaling of the momentum enhancement.

Figure 1. Ballistic pendulum suspension setup for pumice rock shots.



At 2.75 microseconds
(impact was at 2.1 microseconds)

At 68 microseconds

Figure 2. Stills from high-speed video of Test No. 6 showing pumice rock recoil motion. Note the fiducial marker for measuring rock motion.

**References:** [1] Holsapple K. A. and Housen K. R. (2012) *Icarus*, *221*, 875–887. [2] Walker J. D. et al. (2013) *International Journal of Impact Engineering*, 56, 12–18. [3] Durda D. D. et al. (2017) *LPS XLVIII (this meeting).*