Momentum Enhancement of Rubble-Pile Simulants at 5 km/s

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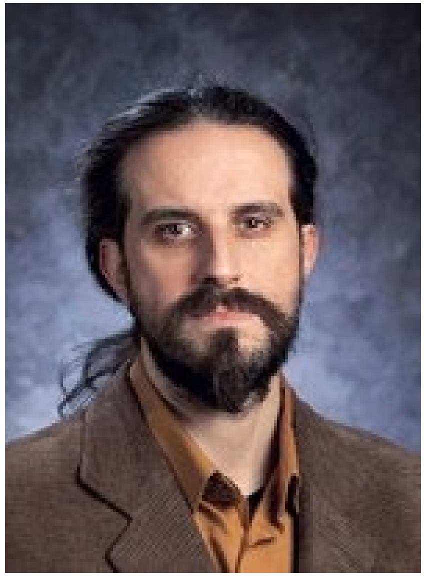


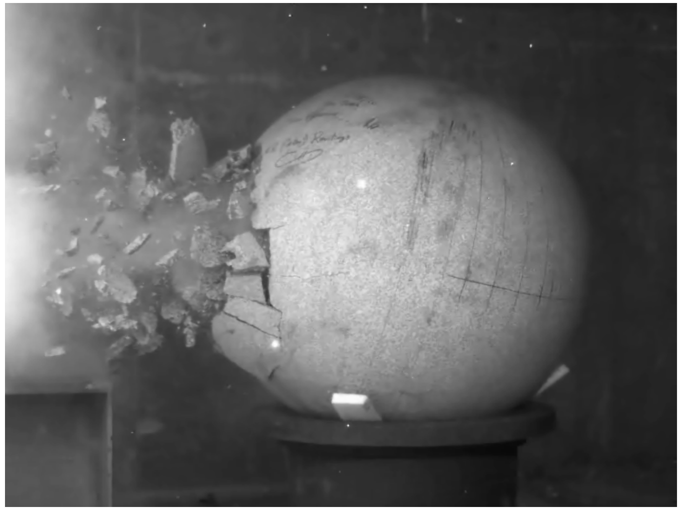
- Left to right: James Walker, Don Grosch, Sidney Chocron, Dan Durda, Simone Marchi.

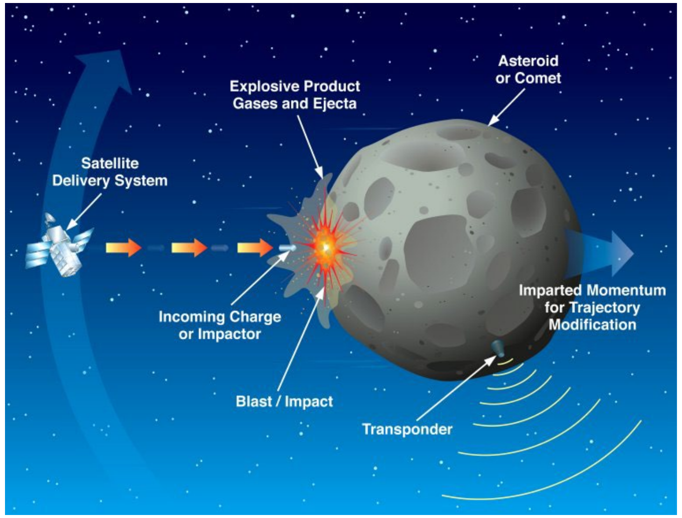
Southwest Research Institute
Independent Non-profit Applied R&D Center
2,800 Staff on 1,500 acres in San Antonio, Texas

Topics

- Size and impactor density scaling
- Impact test of rubble pile simulant before DART impact at 5.44 km/s
- Study of rubble-pile rock size distribution effect on momentum enhancement

Momentum Enhancement





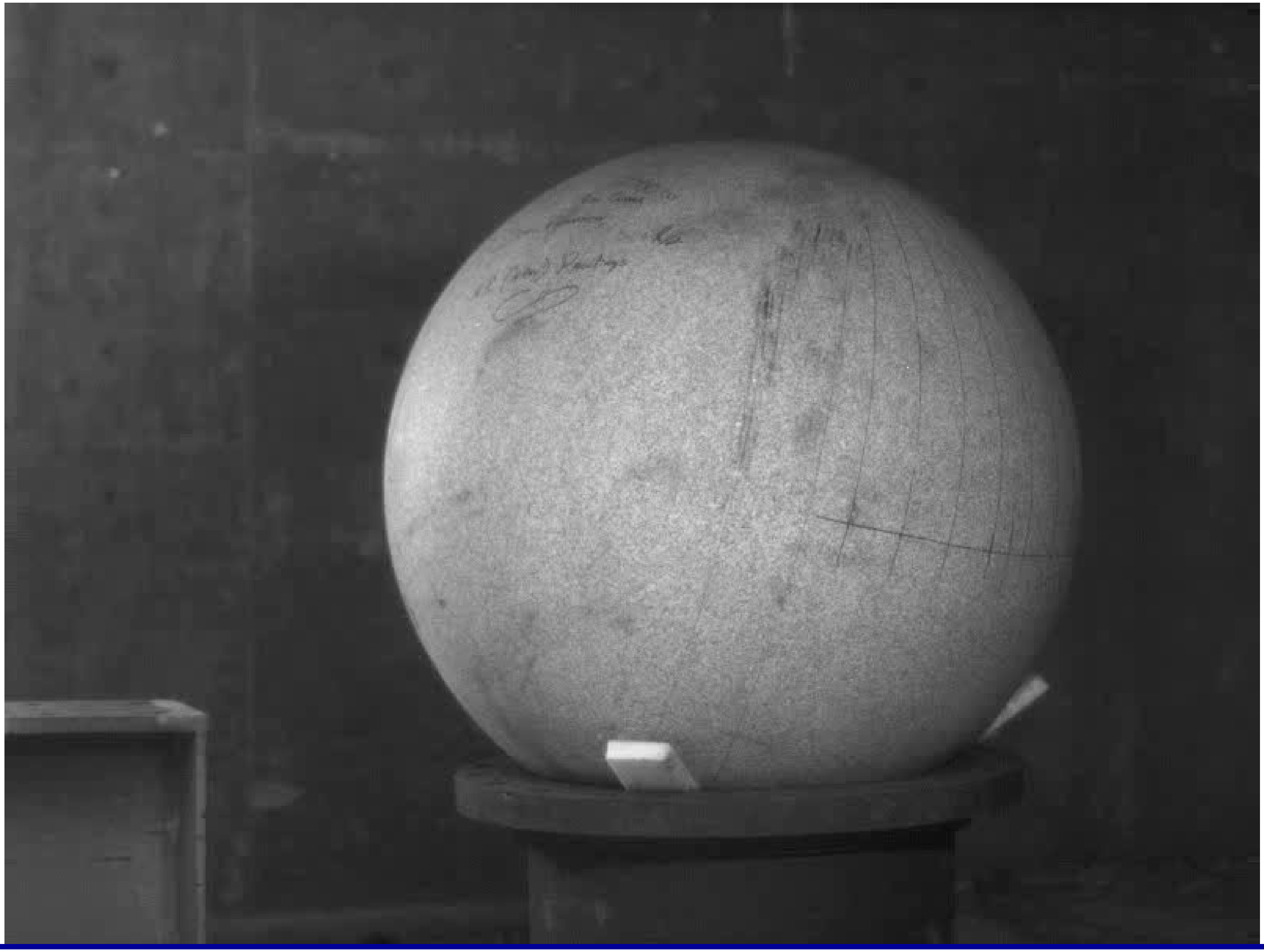
- When an object is struck at high velocities, crater material is ejected in the opposite direction, thus leading to more momentum transferred to the struck object than just that of the impactor.
- The application of interest is deflecting an asteroid or comet nucleus on a collision course with Earth.
- The momentum enhancement will be characterized by β

$$\beta(v, \rho_p, D_p) = \frac{\Delta momentum}{m_p v}$$

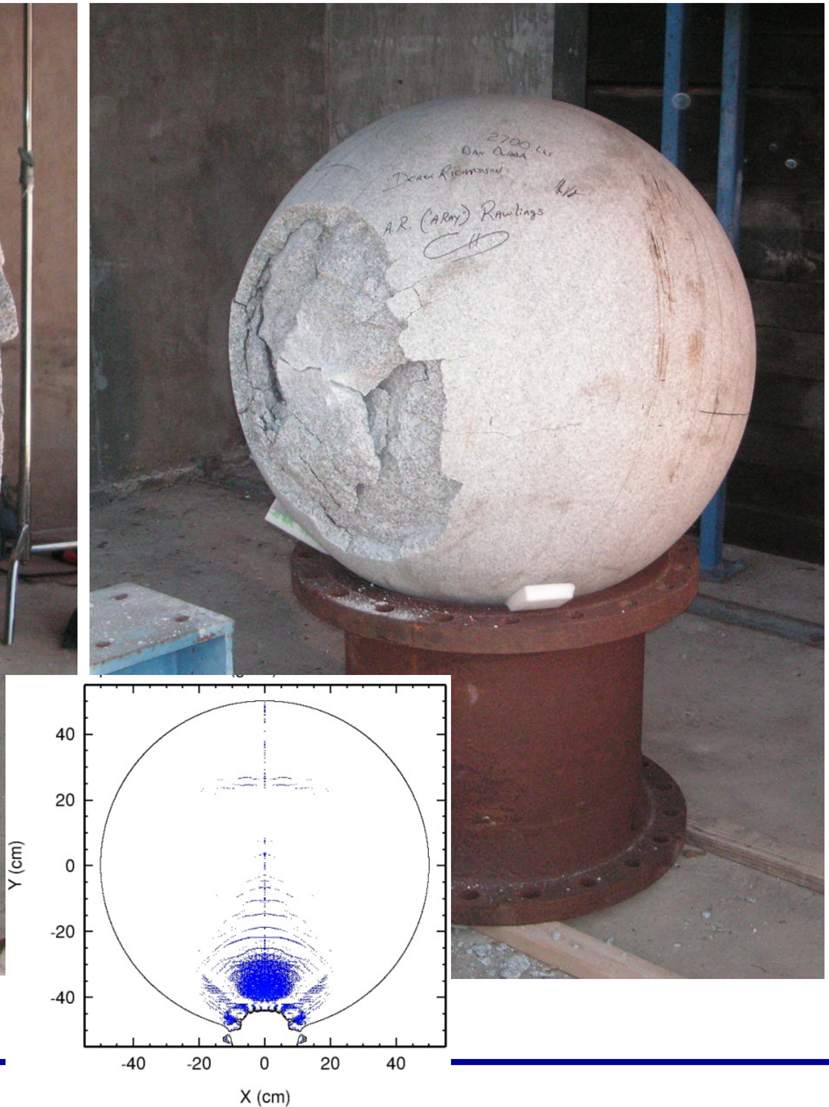
Large Scale Impact of 4.45-cm Aluminum Sphere into 1-meter Sphere Granite at 2 km/s (2010)

- Aluminum sphere held in lexan sabot.
- Massed 124.4 grams.
  - For high speed gun launches, this is big.
- Launched with SwRI’s 50-mm powder gun.
- 1 meter diameter granite sphere massed 1225 kg.

Momentum Enhancement Experiment
2.01 km/s (4,500 mph), β=2.13±0.10



Test 1: 2.01 km/s, β=2.13±0.10
(A repeat Test 2 at 2.01 km/s had β=2.22±0.10)

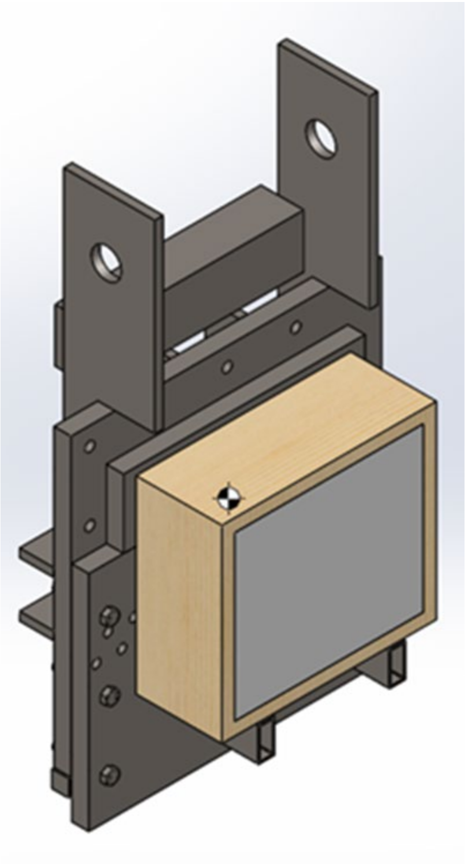


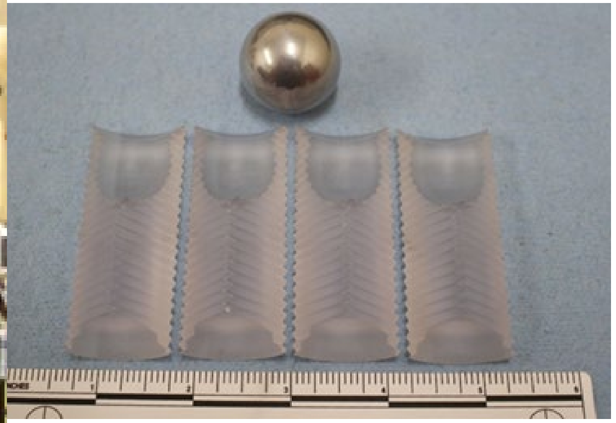
Going Faster – up to 6 km/s
SwRI's Large Two-stage Light Gas Gun

- First stage uses gun powder to drive a piston at up to 1 km/s that compresses hydrogen gas (the "light gas").
- Second stage uses hot, compressed hydrogen to drive the projectile at up to over 6 km/s.
- Flight is into evacuated chambers (5 to 50 torr).

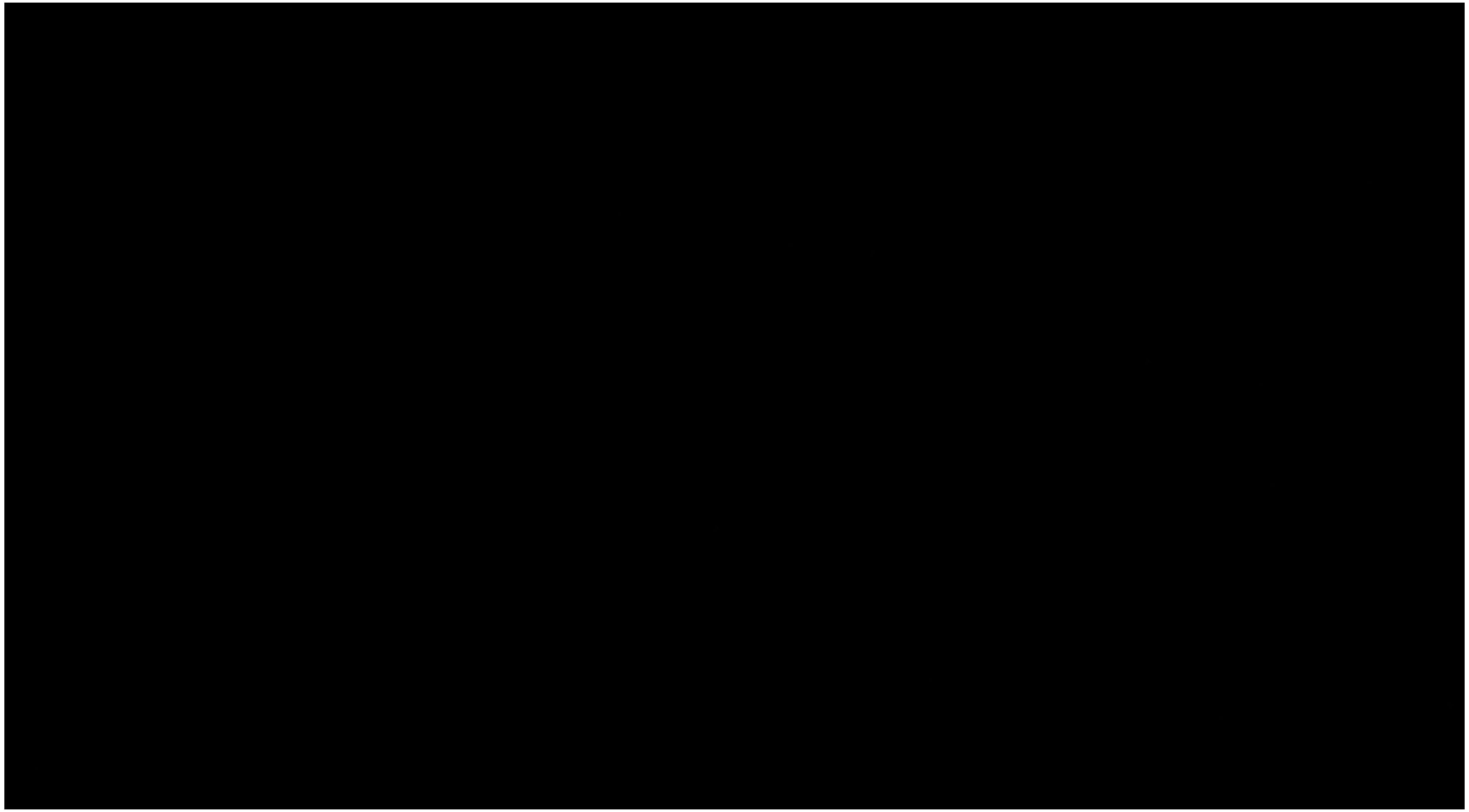
Bldg 292 Light Gas Gun Laboratory

Impact Experiments at SwRI; 3.0 cm Al Projectile and Sabot, Pendulum in Evacuated Target Tank

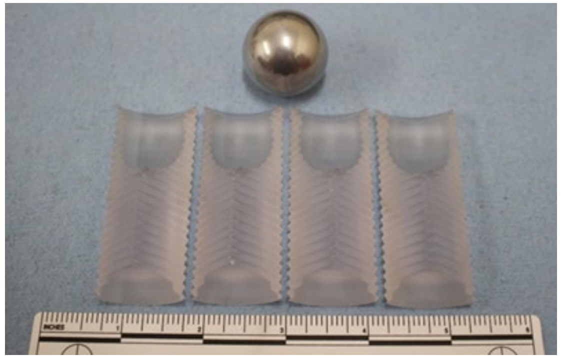


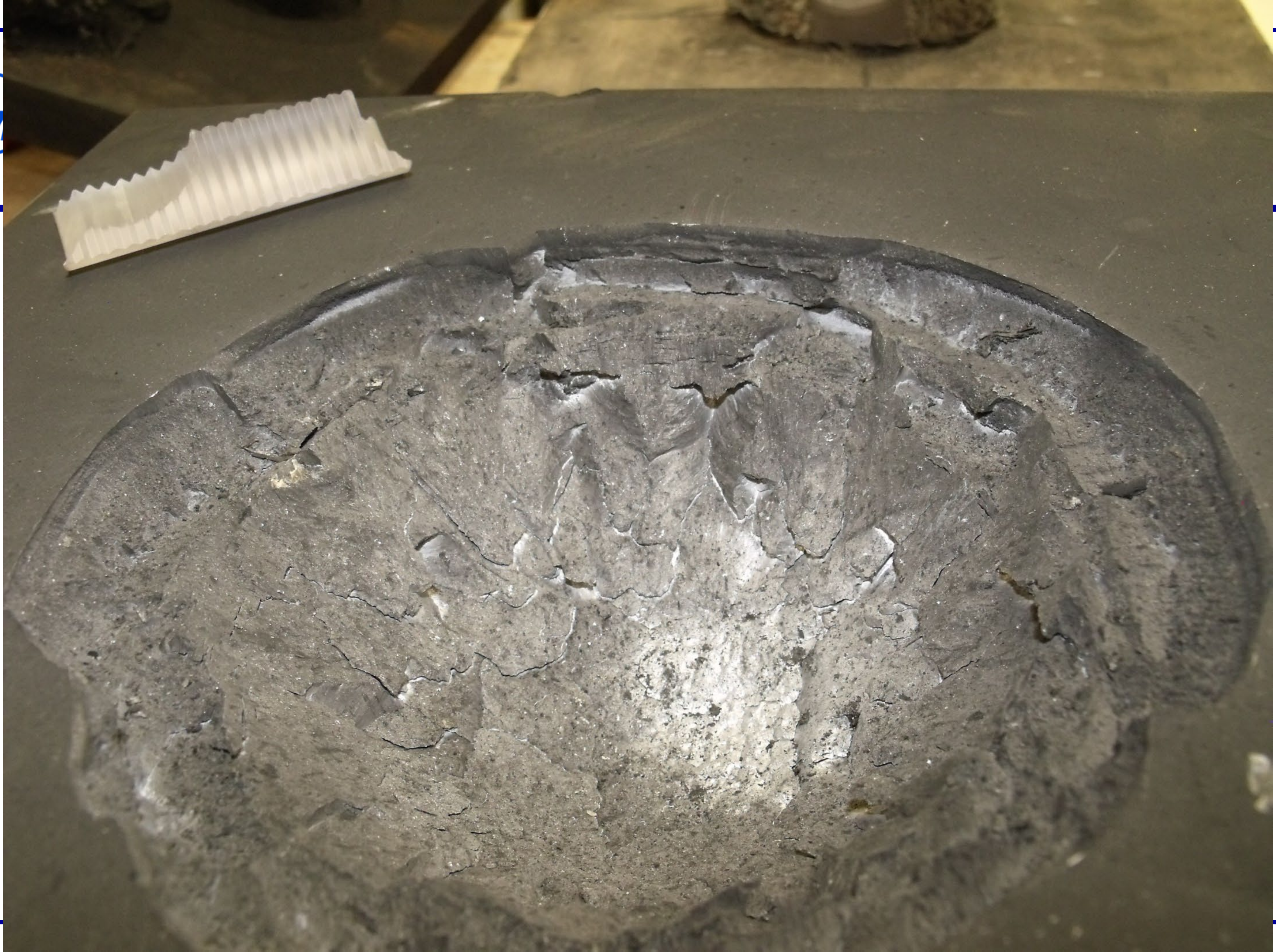


3.0 cm Sphere at 5.77 km/s, $\beta = 2.50$

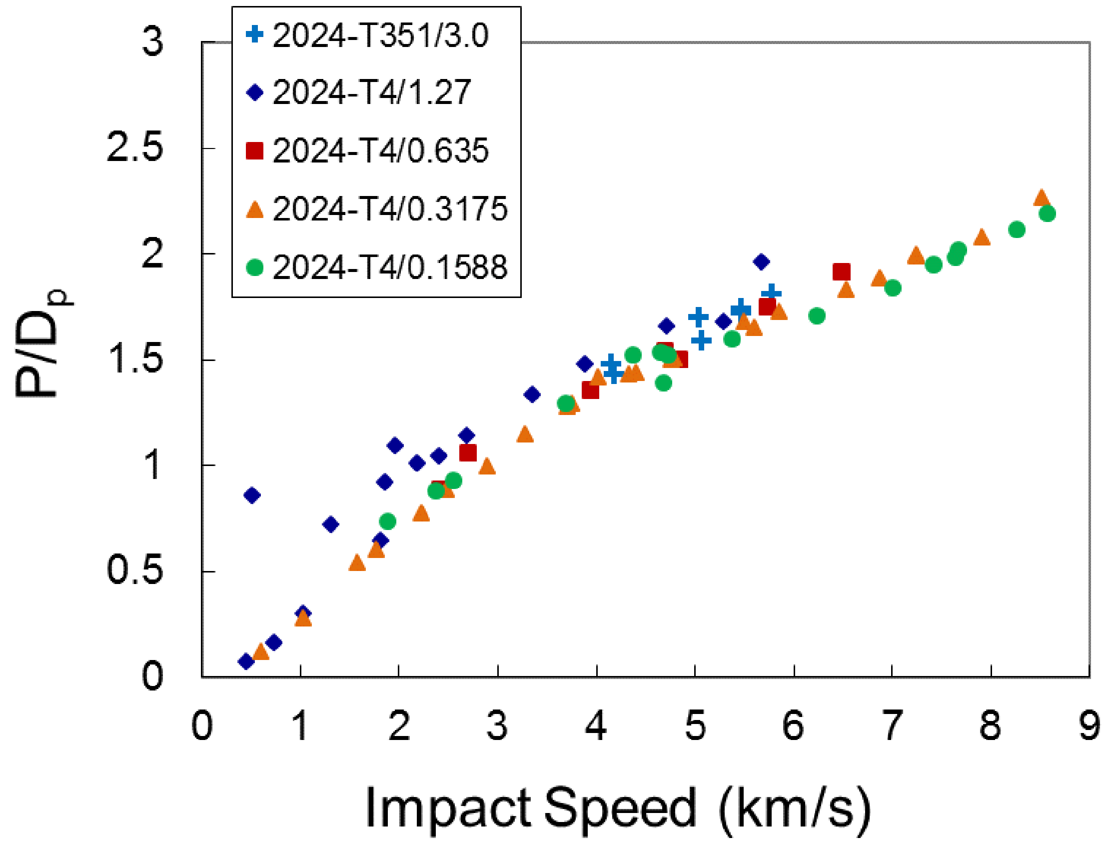


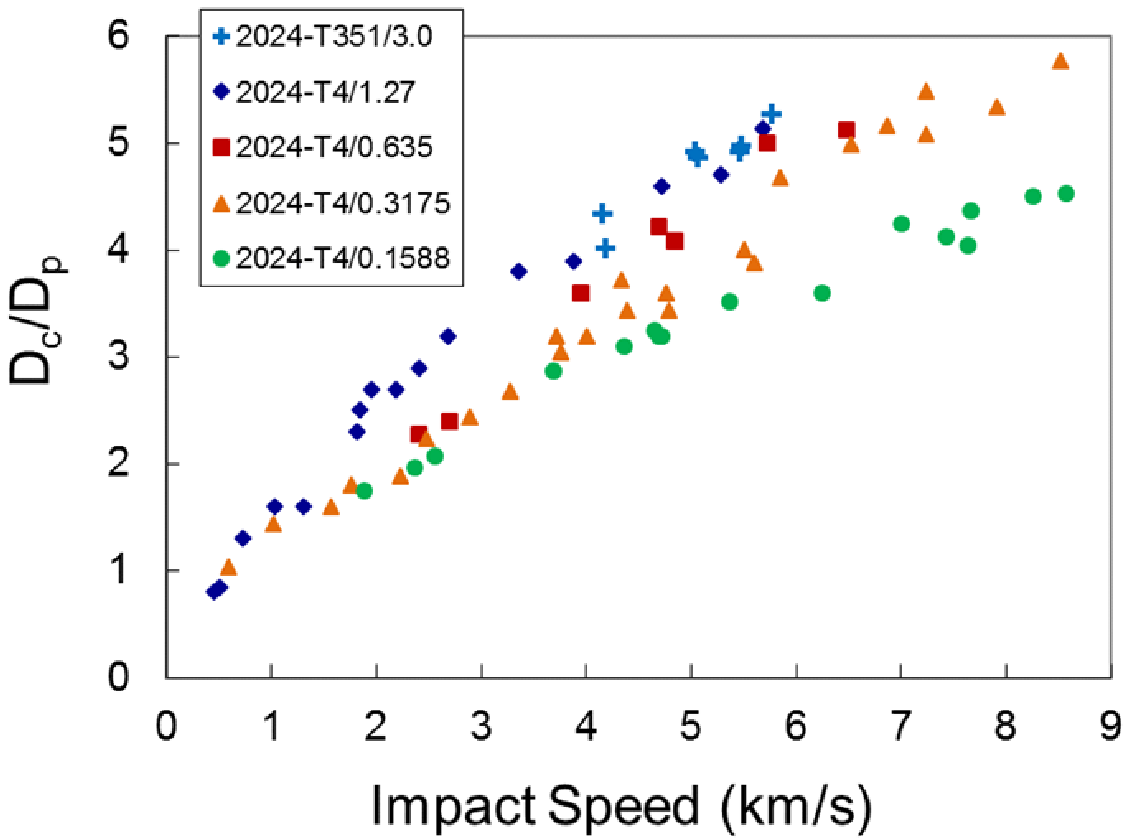
3.0 cm Al Projectile and Sabot, Target Attached to Ballistic Pendulum in Evacuated Target Tank



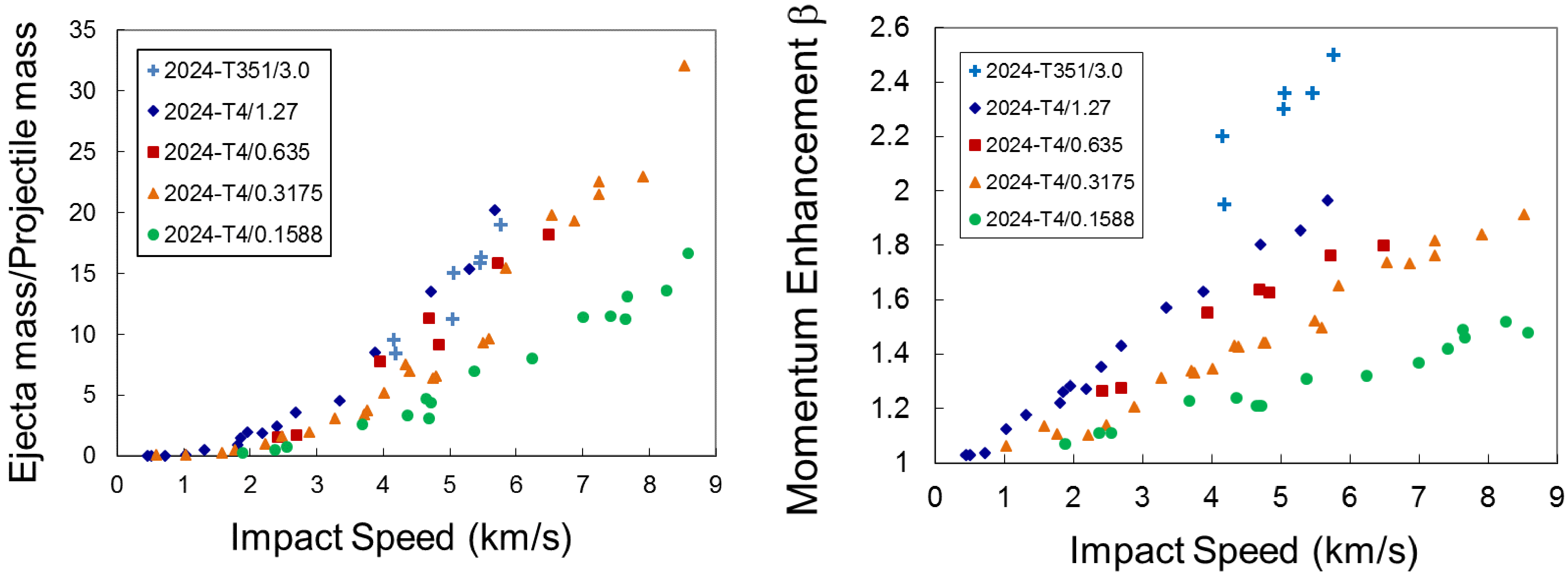


Al 2024-T351/4 Data
Crater Depth and Crater Diameter normalized by Projectile Diameter

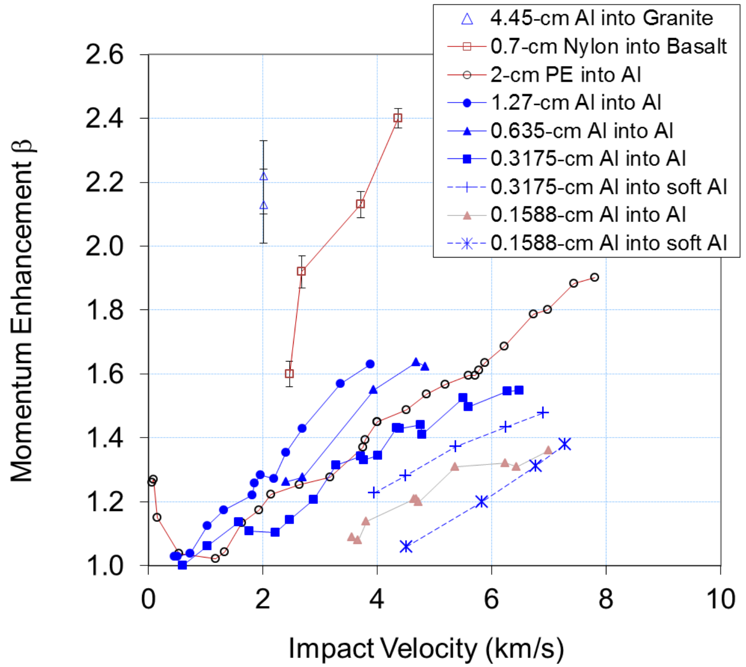


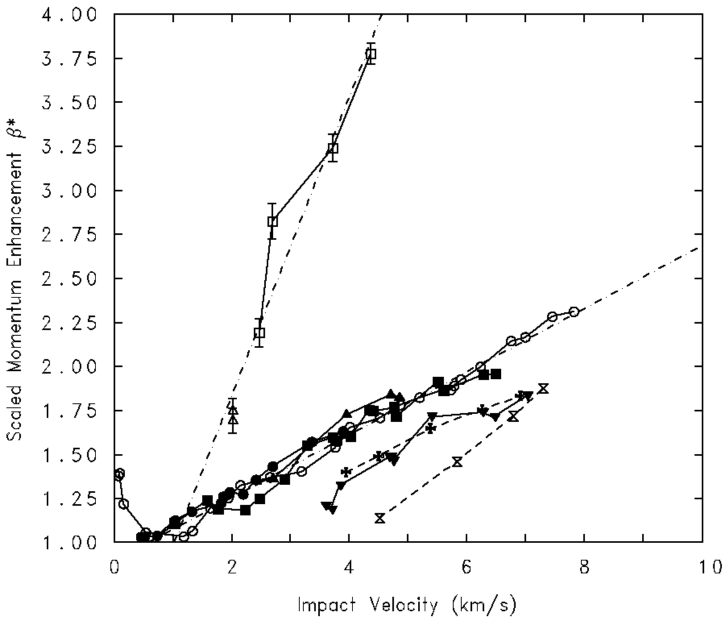


Al 2024-T351/4 Data
Normalized Ejecta Mass and Momentum Enhancement
Nonlinear Size Scaling



Size and Impactor Density Scaling

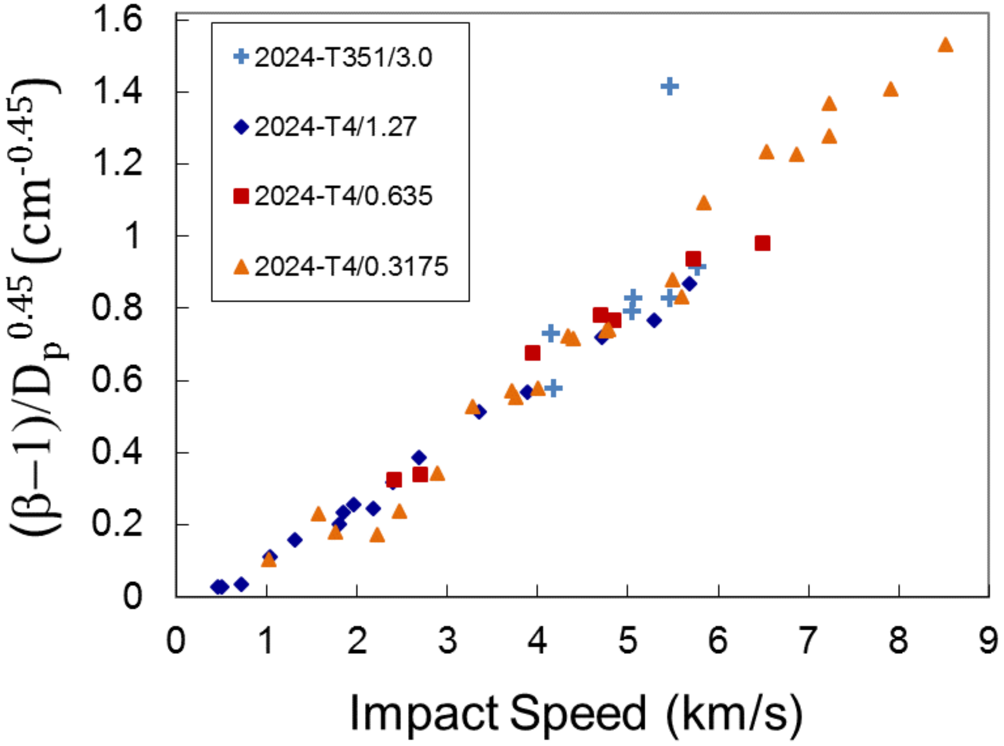




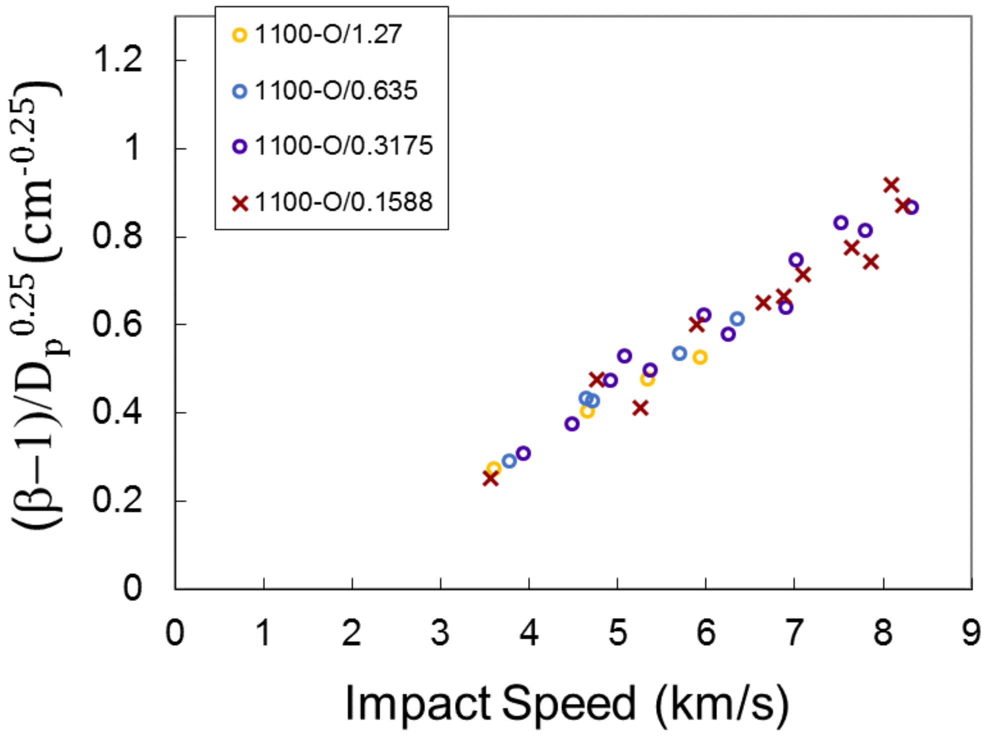
- These charts show the size and impactor density scaling for granite, basalt, and aluminum targets and polyethylene, nylon, and aluminum targets. The second chart shows that the following equation can collapse the data in the first chart, thus quantifying the size and impactor density scaling,

$$\beta - 1 = \left(\frac{\min(\rho_i, \rho_t)}{\min(\rho_0, \rho_t)}\right)^a \left(\frac{D_i}{D_0}\right)^b (\beta_0 - 1).$$

Momentum Enhancement Size Dependence in Aluminum

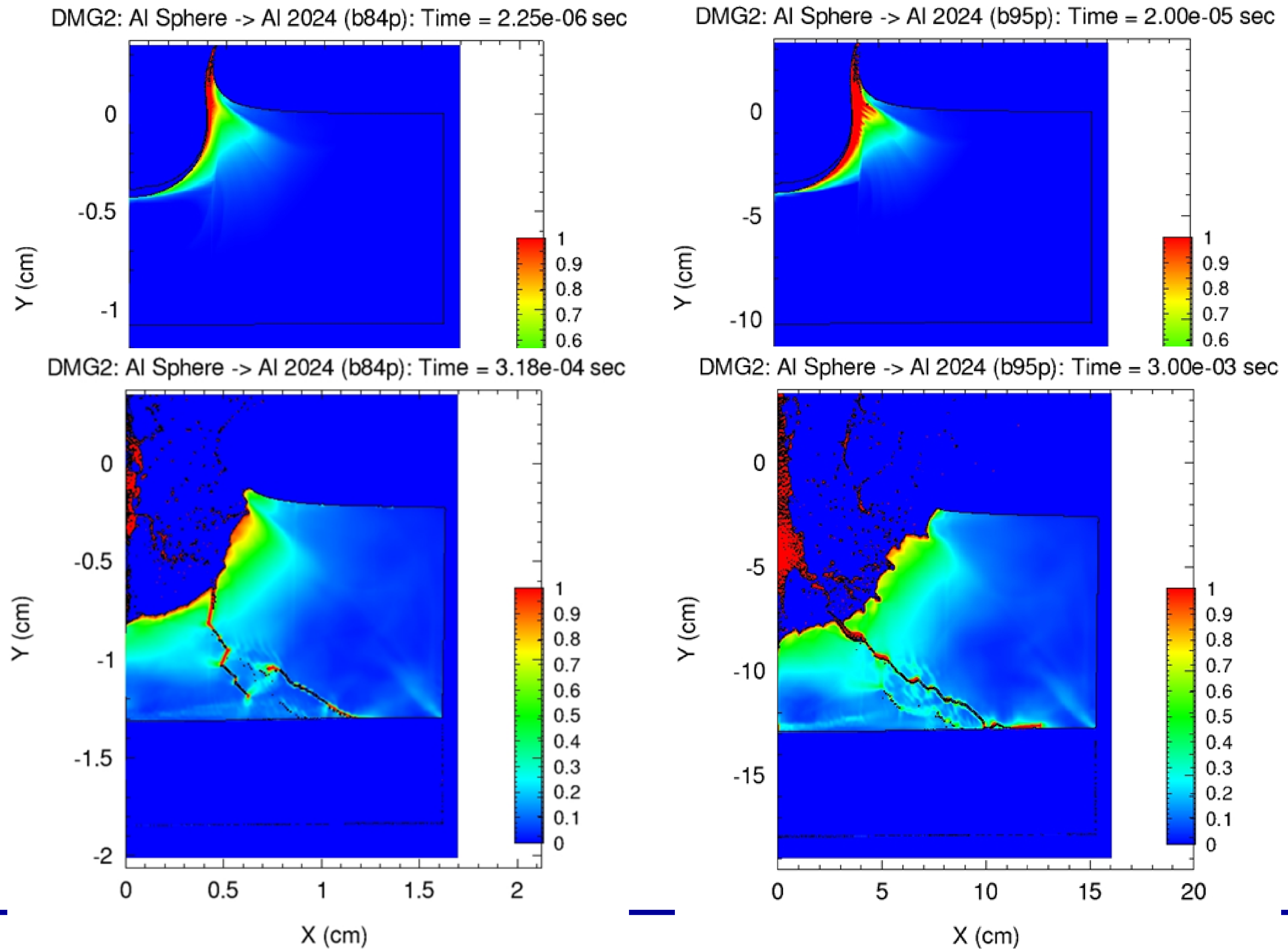


Al 2024-T351/4; Power 0.45 on Dp

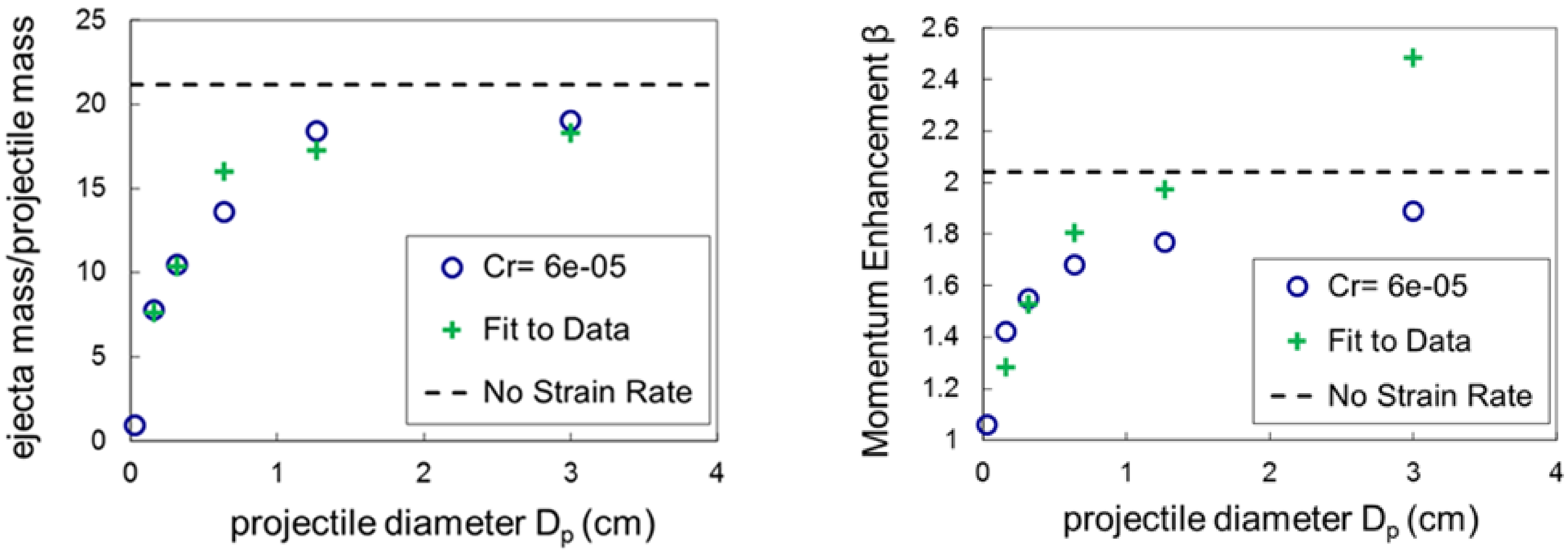


Al 1100-O; Power 0.25 on Dp

Damage at Different Scales
Left: 0.3175 cm,   Right 3.0 cm



Computational Results at 5.77 km/s (60 Cells Across Projectile Radius)



- The value in the damage model that matched data is $C_r = 0.6\times10^{-4}\ \mathrm{s}^{2/3}$.
- Using $Y = 500$ MPa, and with a density of $\rho = 2.785$ g/cm^3 the critical length is $2y_c = 0.0093$ cm = 93 μm.
- Excellent agreement with the ejecta mass from ensembles, including the size-scale transition from little damage to a saturated damage.
- Not matching momentum enhancement.

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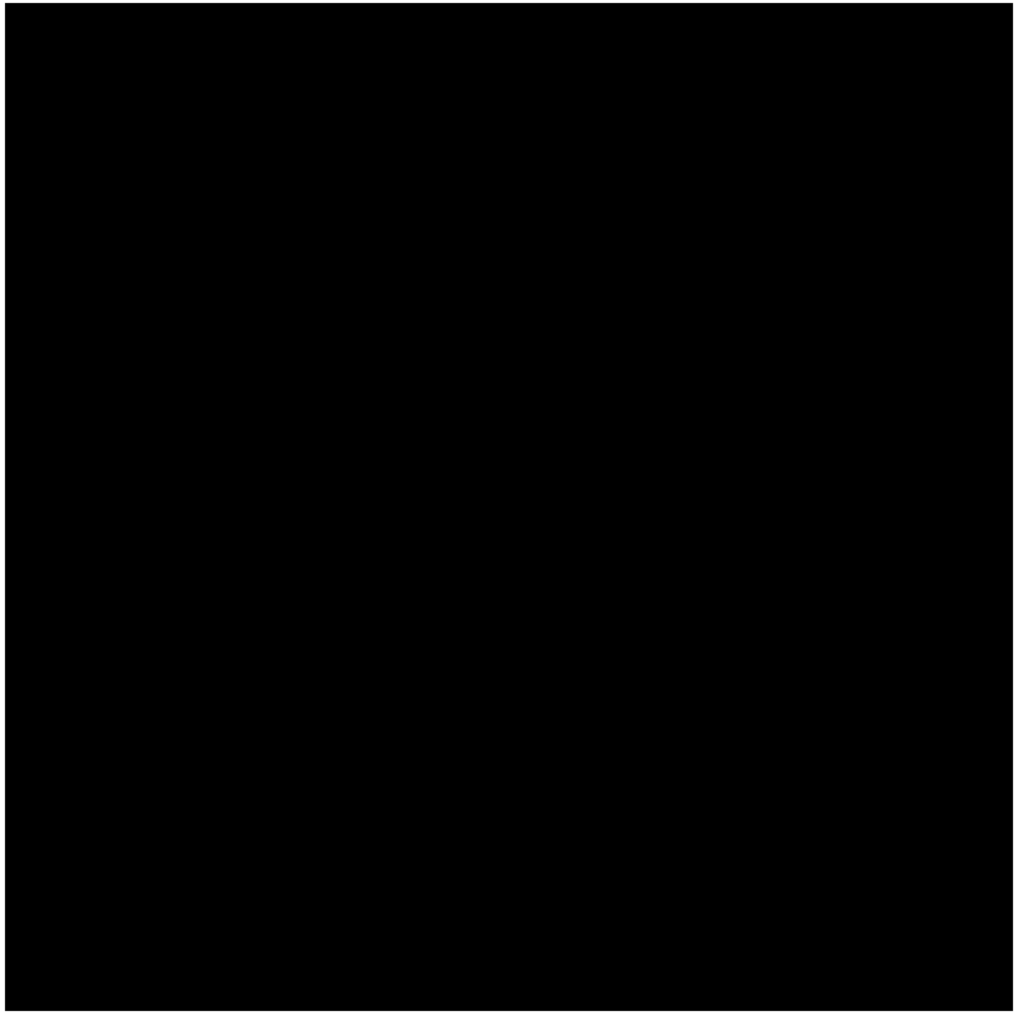
Stones/Concrete Target

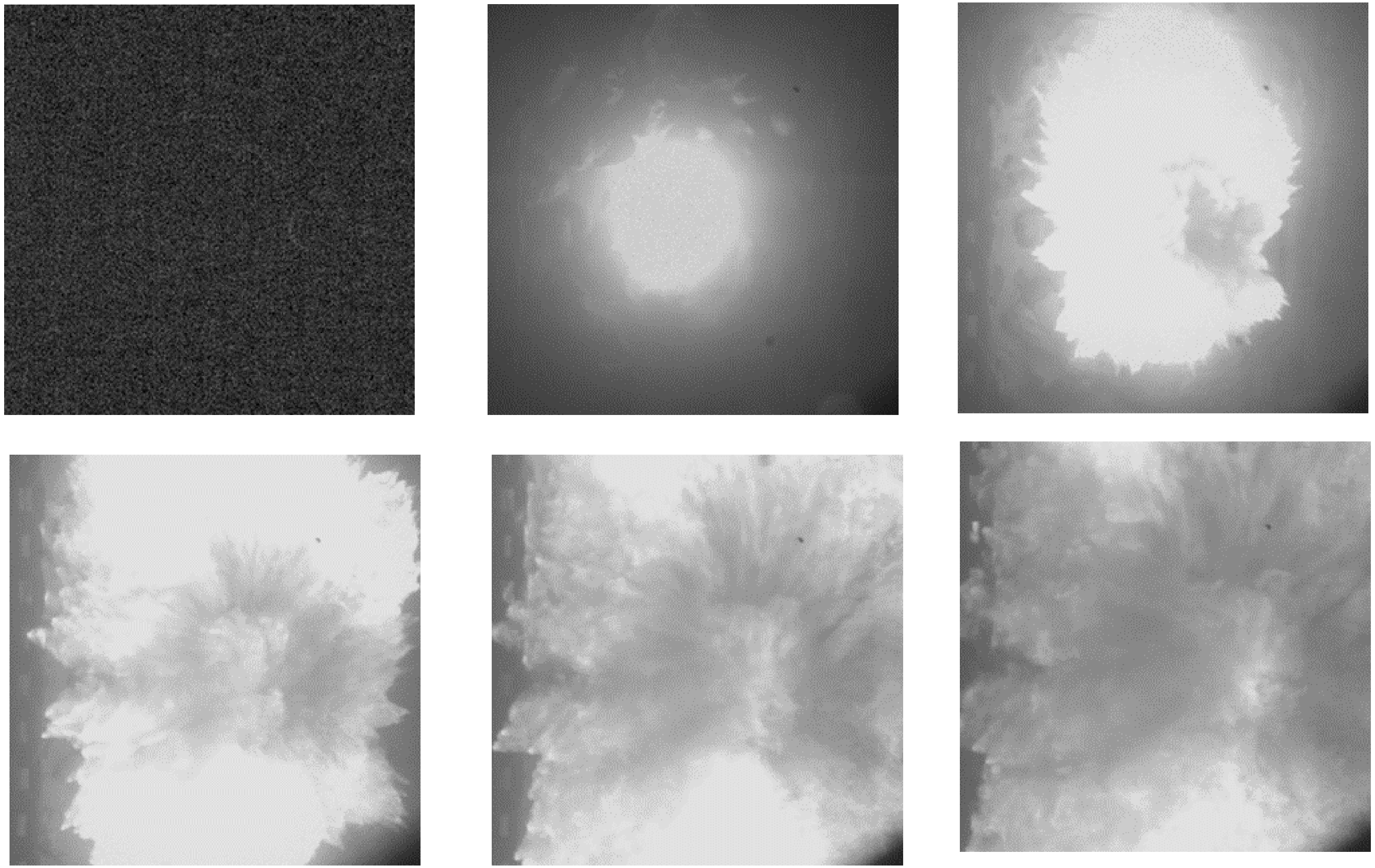
- Dimensions:
  - 15 in x 15in x 4 in with the wood. Note wood from the back was removed. Backed by aluminum for impact test.
  - 40.7 lbs of stones.
  - Density of stones + air = 1.9 g/cm^3.
  - 20.0 lbs of cement plus water after drying for one hour.
  - Frame: 9.3 lbs.
  - Total weight: 70 lbs.
  - Density of stones + cement = 2.92 g/cm^3.

Target in Pendulum with Mirror for Imaging (LGG-251)

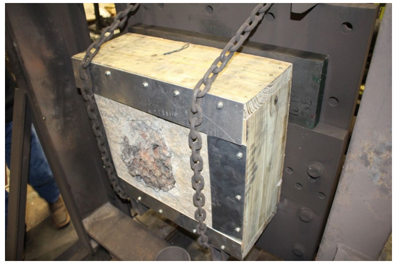
Stones/Concrete Target (LGG-251), 5.44 km/s



Stones/Concrete Target (LGG-251), 5.44 km/s 0.29 microsecond exposure, 12.65 microseconds frame to frame



Momentum Enhancement from Impacts into a Variety of Target Materials

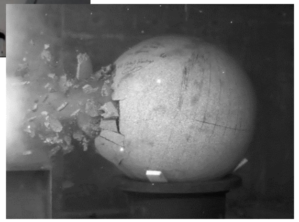


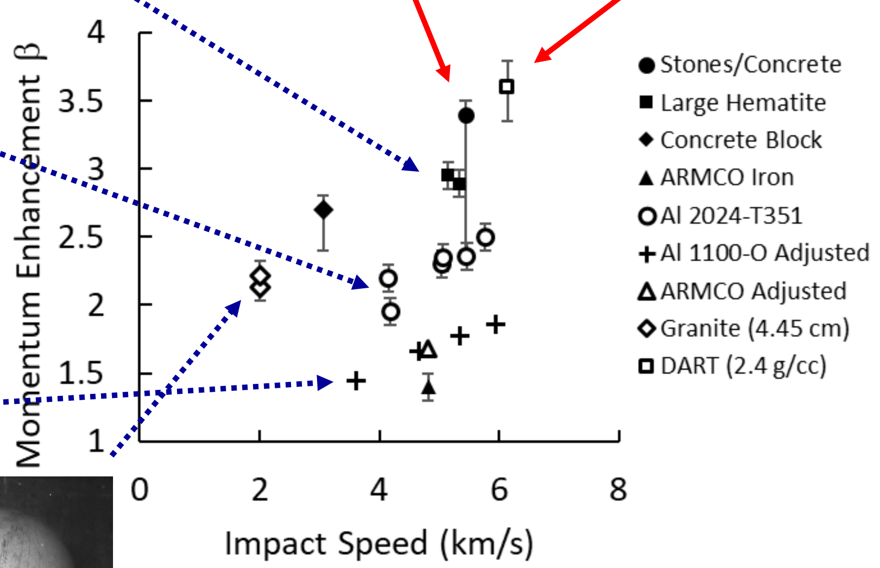
DART
Double Asteroid Redirection Test

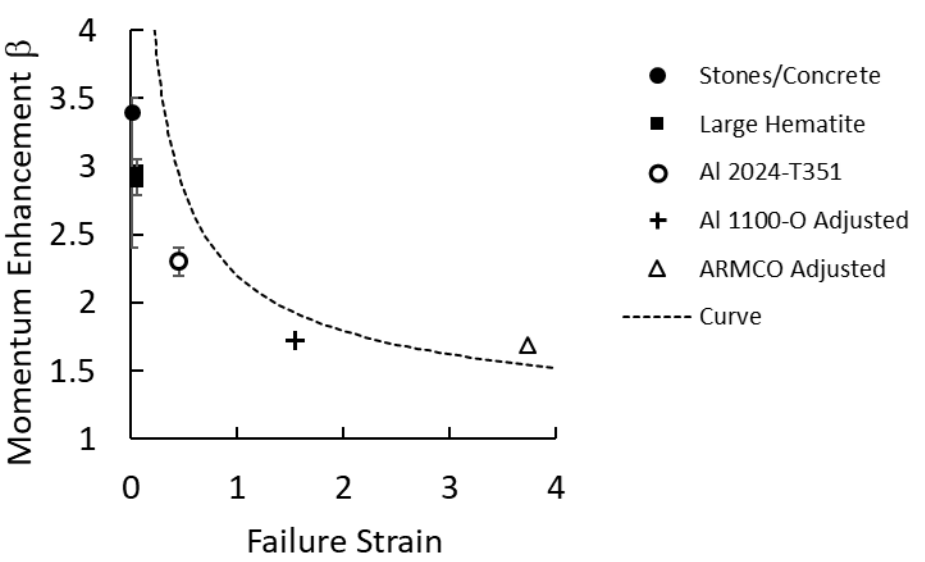
- Impactors are 3-cm aluminum spheres except for the two 2 km/s granite impacts and the DART impact.

β = 3.4

β = 3.6







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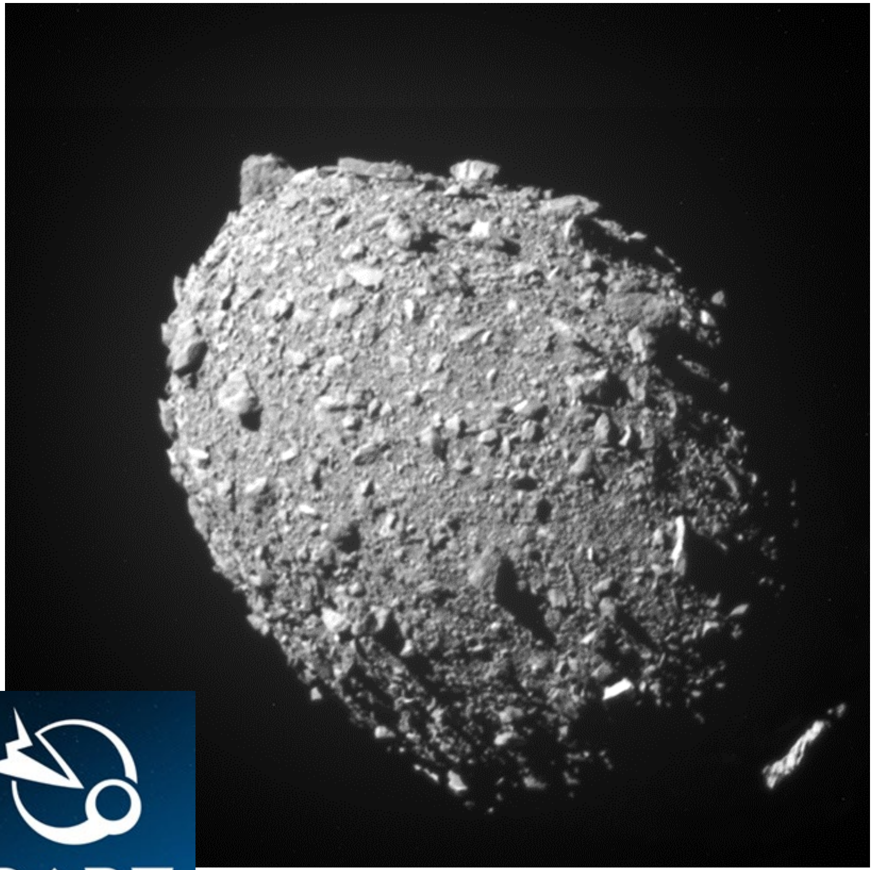
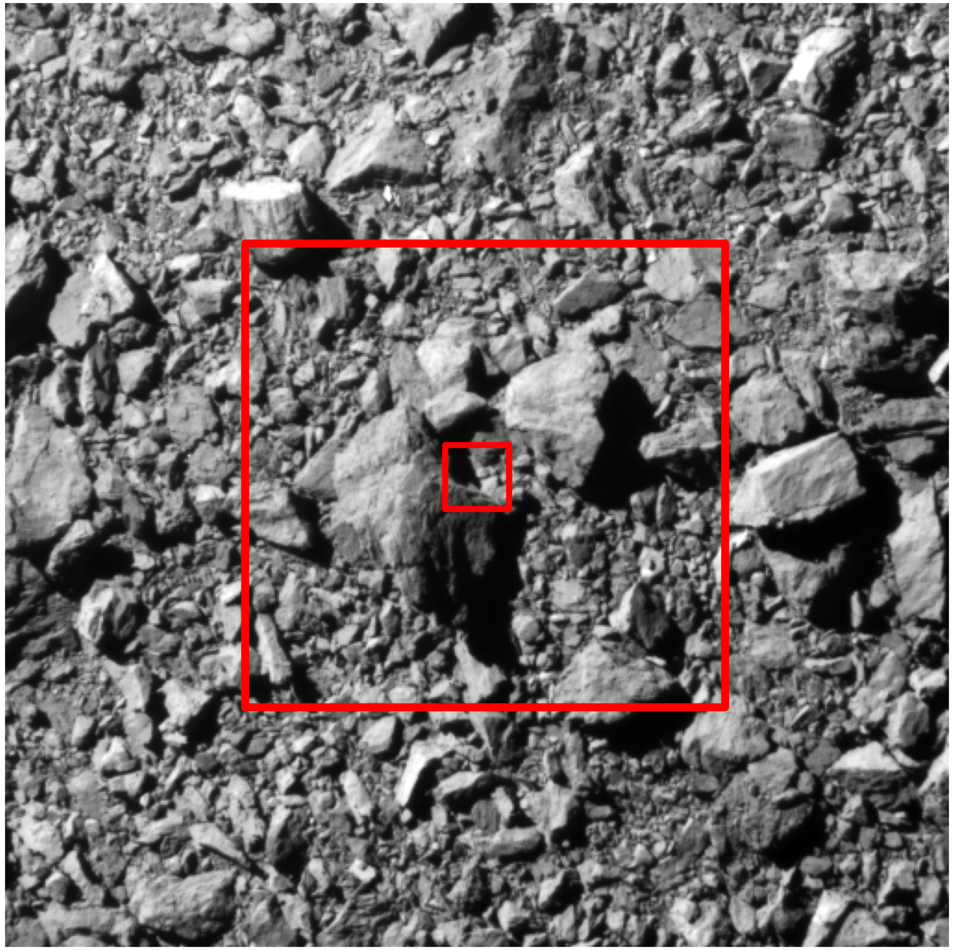
Crushed Basalt Targets with Different Size Distributions of Rock (Experiments performed December 2022)

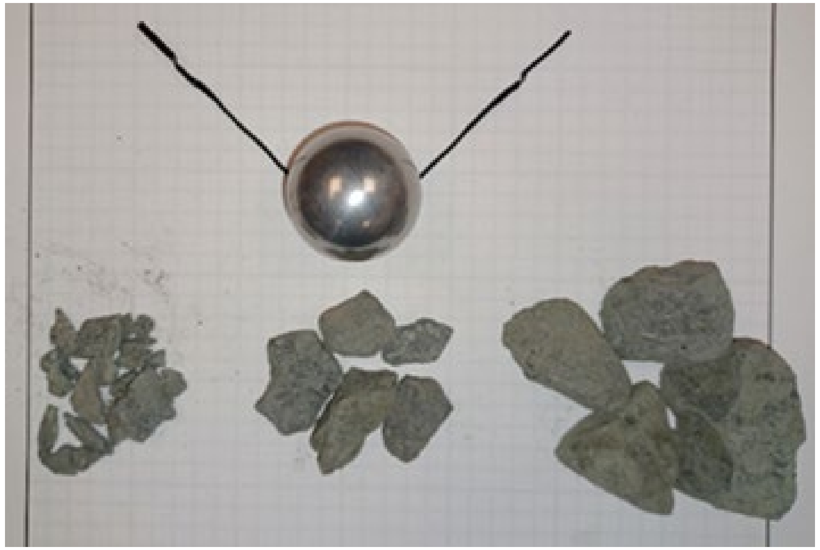


- Photographs of Dimorphos show the surface morphology.
- Examination of the photographs allowed us to propose simulants for the asteroid to perform additional impact experiments to study momentum enhancement due to hypervelocity impact on the simulated surfaces.
- We decided to build targets of basalt since
  - 1) Basalt is viewed by many as an appropriate analog to the asteroid material and
  - 2) Within the DART community, nearly all computations are being performed with basalt as a surrogate for the Dimorphos surface material.
- The use of crushed-basalt-based targets will allow the results to be directly comparable to computations performed by DART Impact Modeling Working Group.

Last Two Images of Dimorphos from DART
31 meters across (100 ft), 12 km out, 2 seconds before impact
16 meter across image (51 ft), 6 km out, 1 second before impact



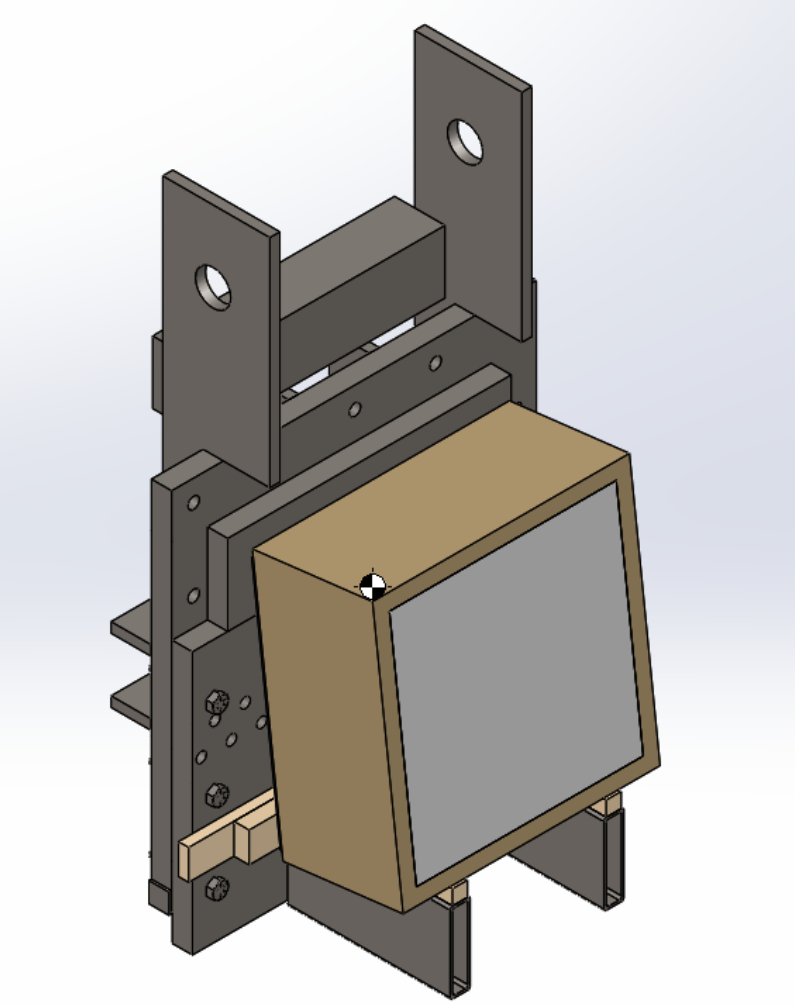
Crushed Basalt Rock Size Distribution



3-cm-diameter aluminum impactor and the three sizes of crushed basalt used in the study

- Five experiments were performed in December 2022 with targets made of crushed basalt of a variety of sizes.
- The specific targets were over 200 kg and were 60 x 60 x 30 cm.
- The targets were held in a vertical pendulum, and so it was necessary to hold the basalt with a binder.
- We used grout mixed with sand, trying to make it relatively weak.
  - Typically the target weight was 2/3rd rock, 1/3rd binder.
  - For "S" targets it was all the small basalt
  - For the "S, M" target it was roughly half small, half medium crushed basalt
  - For the "S, M, L" targets it was roughly 1/3rd of each constituent size.
- Shots were between 5.25 and 5.50 km/s.

Small Basalt Rock Target Hanging in Pendulum with CAD model (LGG-403, Small, 5.25 km/s)

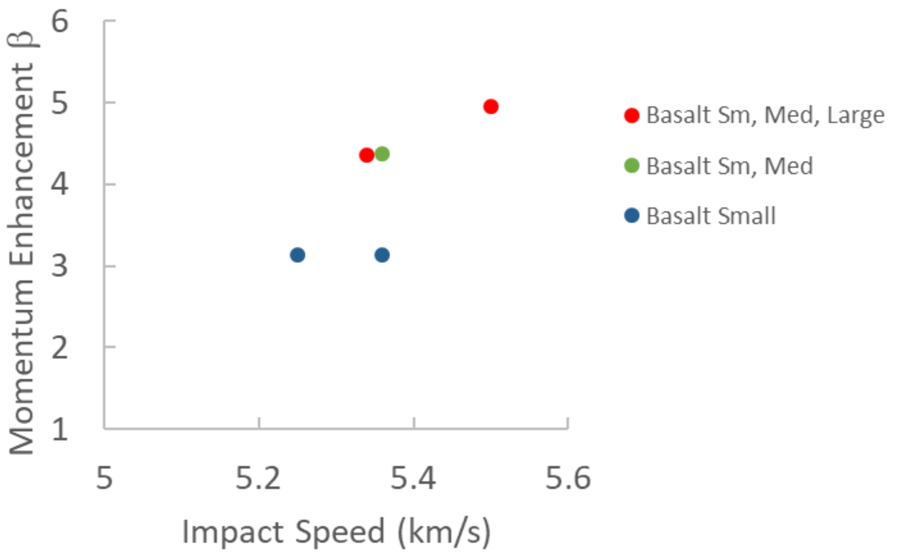


Result of 3-cm-Aluminum Sphere Impact into Small Basalt Target (LGG-403, Small, 5.25 km/s)

Small, Medium, Large Distribution Basalt Rock Target Before and After Impact (LGG-407 Small, Medium, Large, 5.50 km/s)

Post-test LGG-407
Small, Medium, Large, 5.50 km/s

Preliminary Results showing Momentum Enhancement β on Rock Size Distribution



		km/s	beta
LGG-403	S	5.25	3.14
LGG-406	S	5.36	3.14
LGG-404	S,M	5.36	4.37
LGG-405	S.M,L	5.34	4.36
LGG_407	S,M,L	5.50	4.96

- Preliminary results from December 2022 experiments (internal review, error bars, and significant figures still in process).
- Experiments clearly show the size distribution of the basalt rocks affects the momentum enhancement:
  - Small rock targets have β ~ 3.1.
  - Large rock targets have β ~ 4.4 to 5.
- These results show that Dimorphos rock distribution can have a large effect on the momentum enhancement β.
- Current work: We made material test specimens at the time of making the targets and we are currently determining the tensile and compressive strength of these target compositions.
- These results provide a baseline case for computational comparison.

End of Charts

Some References

- Crushed basalt work still in progress and will be submitted to a journal. Will be presented at LPSC, the Planetary Defense Conference in Vienna (April 2023), and ACM in Flagstaff (June 2023).
- Impact into rock assembly was published right before the DART impact in PSJ:
  - “Momentum Enhancement from a 3 cm Diameter Aluminum Sphere Striking a Small Boulder Assembly at 5.4 km s^{-1},” J. D. Walker, S. Chocron, D. J. Grosch, S. Marchi, A. M. Alexander, *Planetary Science Journal* **3** 215, 2022. https://doi.org/10.3847/PSJ/ac854f.
- Additional rock and iron impacts in graph were presented at the Hypervelocity Impact Symposium (HVIS 2022) and have been submitted to IJIE for the HVIS special issue:
  - “Momentum Enhancement from 3-cm-diameter Sphere Impacts at over 5 km/s into Iron and Rock,” J. D. Walker, S. Chocron, D. J. Grosch, S. Marchi, and A. Alexander, Hypervelocity Impact Symposium, Alexandria, VA, Sept. 19 – 22, 2022, submitted to International Journal of Impact Engineering.
- Aluminum data in graph was presented at the HVIS 2019 and appeared in the IJIE special issue for that conference:
  - “Size Scaling of Hypervelocity-impact Ejecta Mass and Momentum Enhancement: Experiments and a Nonlocal-shear-band-motivated Strain-rate-dependent Failure Model,” J. D. Walker, S. Chocron, D. J. Grosch, Int. J. Impact Engng 135 (2020) 103388:1-14 DOI: 10.1016/j.ijimpeng.2019.103388.