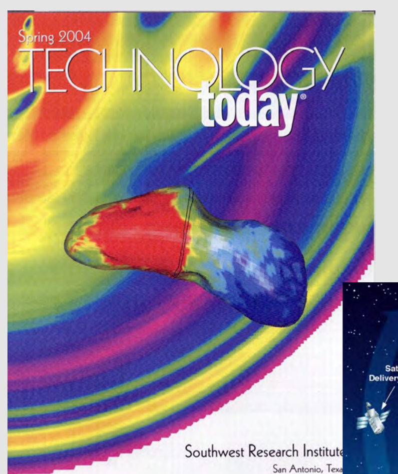
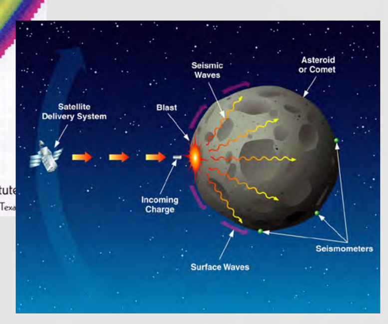
Momentum Enhancement as a Function of Impactor Scale Size: Momentum Transfer Mechanisms or How impactor size (big spacecraft vs. small laboratory projectile) enters in and why it is so important

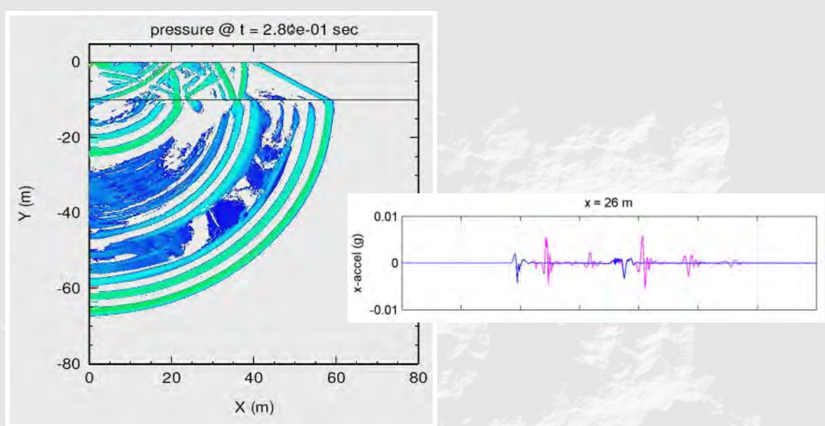
James D. Walker and Sidney Chocron • Southwest Research Institute, San Antonio, Texas 78238

From 1990s, SwRI Explored Seismology on Asteroids

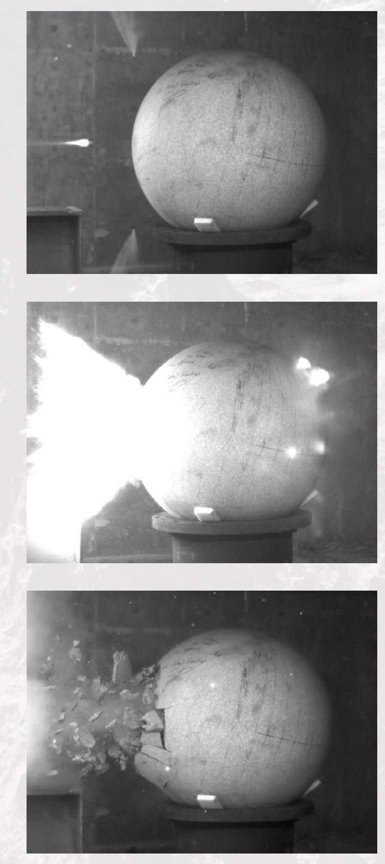


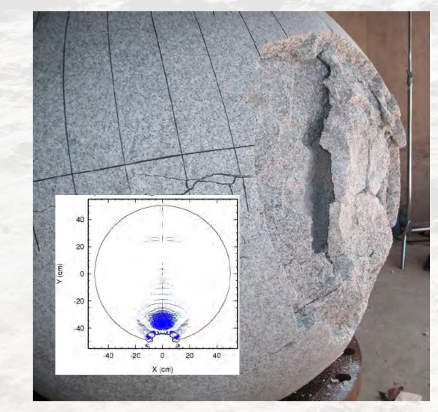


Since the mid 1990s, SwRI explored performing seismology on asteroids. We began examining momentum enhancement in the context of quantifying the seismic pulse provided by an impactor, first presenting results at the 2002 Hypervelocity Impact Symposium in Noordwijk, The Netherlands (HVIS, published in IJIE,2003). We first presented the importance of the impactor size effect on the momentum enhancement at the 2010 HVIS in Freiberg, Germany (published IJIE, 2011).



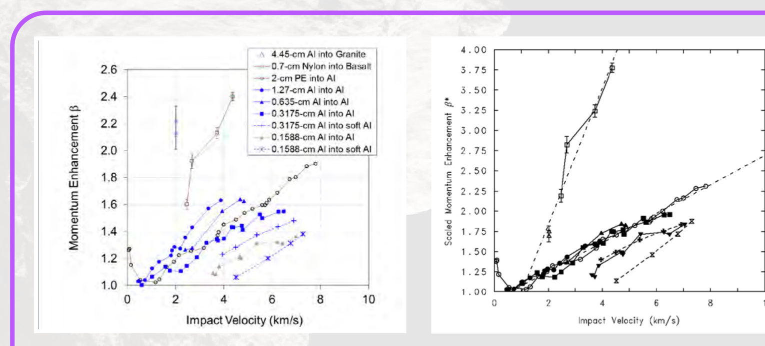
Experiment of a 4.45-cm Aluminum Sphere into 1-meter Sphere Granite at 2.01 km/s at SwRI Confirmed Role of Size





- Analysis of data in comparison with other data shows that the momentum enhancement ß is very dependent on impactor size, to a power between 0.4 and 0.5. This analysis was presented at the 2012 HVIS in Baltimore, MD (published IJIE, 2013). (Work was awarded HVIS Best Paper)

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

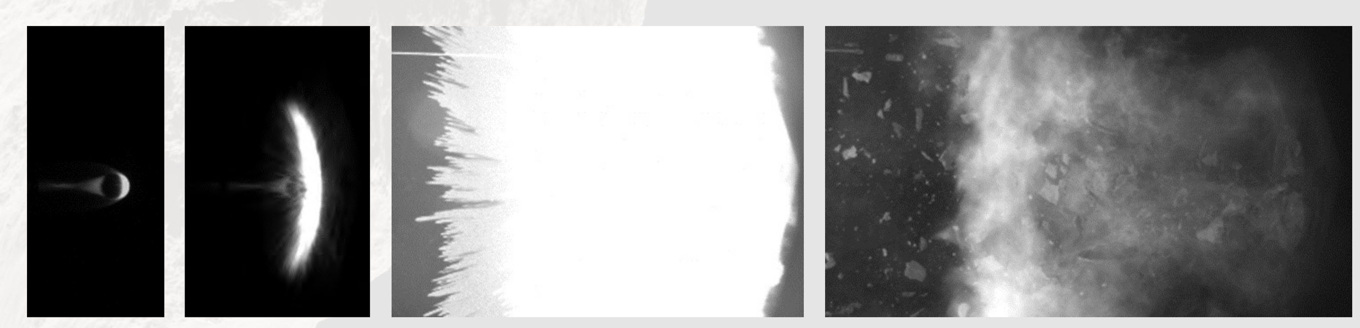


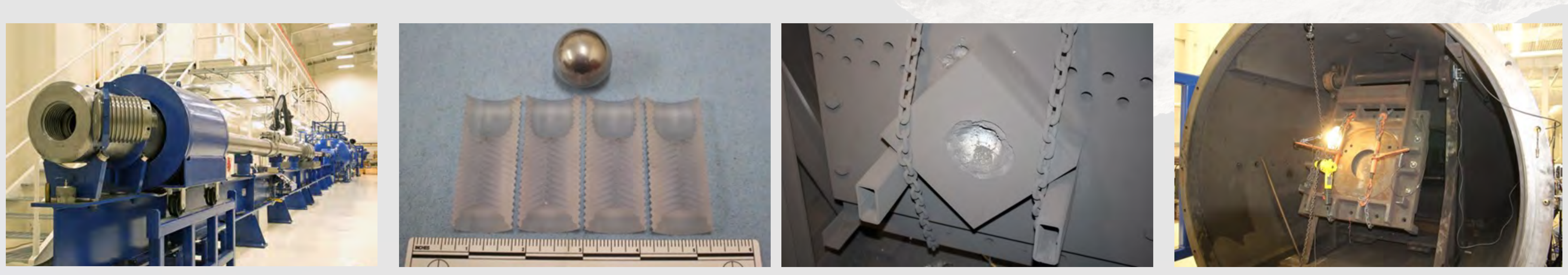
$$\beta^* - 1 = (\rho / \rho_{def})^{0.5} (D / D_{ref})^{0.4} (\beta - 1)$$

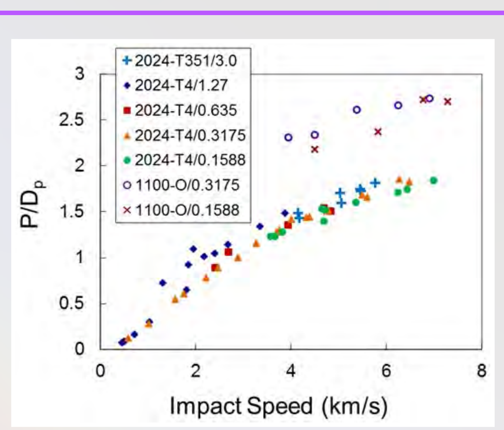
Size scale effects (as well as impact speed effect) on momentum enhancement: upper left data points are impacts into rock at different scales, lower right data points are impact into aluminum at different scales.

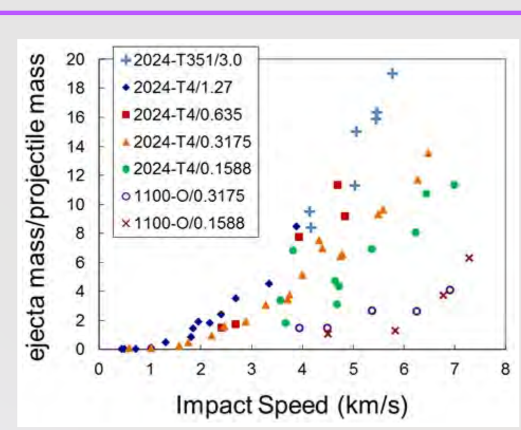
Further Confirmation of Size Scale Effect: Going up in Size and Speed

- There is a wonderful set of data due to Denardo and Nysmith using the NASA Ames gun looking at aluminum spheres striking Al 2024-T4 targets (see refs).
- It ranges a size scale of 8; the largest projectile they were able to shoot was 1.27 cm in diameter.
- In September/October 2018, we performed impact tests with our two-stage light gas gun using internal IR&D funds. These tests were to determine if the size scale effect observed by Denardo and Nysmith on projectiles with diameters ranging from 0.159 cm to 1.27 cm continued up to 3.0 cm and high speeds of up to 5.77 km/s.
- This went up another 2.36 times in scale.
- We collected 7 data points, 4.15 to 5.77 km/s, shooting 3.0 cm aluminum spheres into 2024-T351 targets..
- The size scale effect does persist, as was amply demonstrated in the experiments.

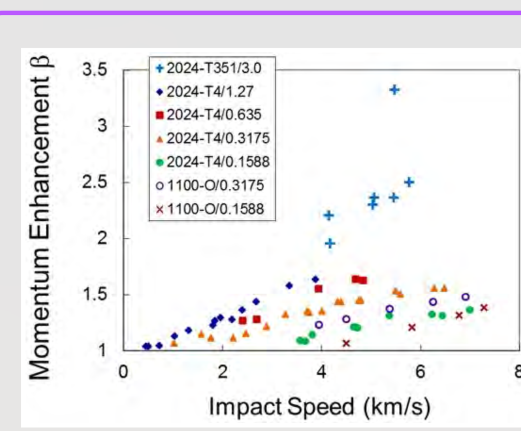


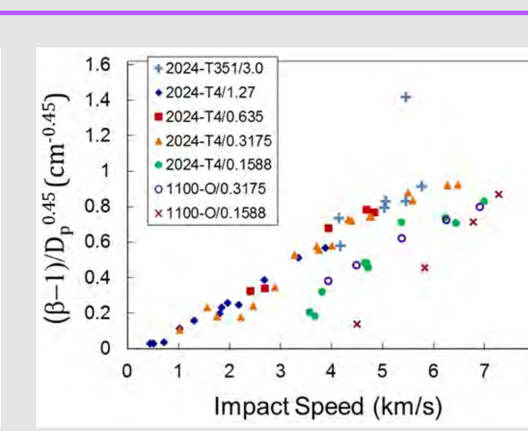






- Our new data points are blue plus signs.
- Depth of penetration shows no size-scale effect (it is just a function of velocity), but ejecta mass clearly shows a size-scale effect (it is not just a function of velocity).

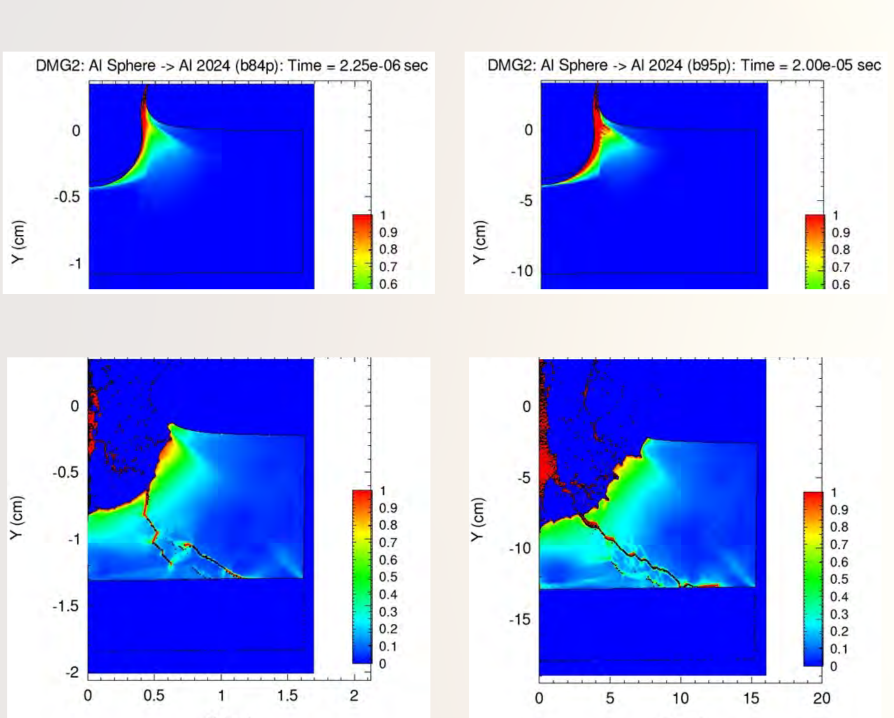




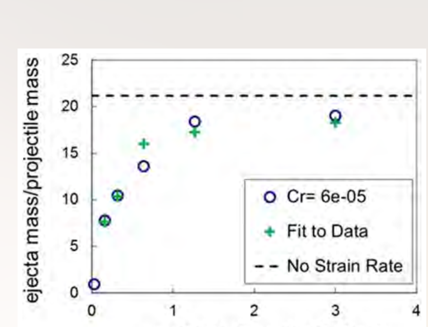
- At 5.77 km/s we have a large β = 2.5
- The large value of β > 3 shows further enhancement due to a separation of the target from the pendulum, as might be observed if a spacecraft struck a boulder sitting on a rock surface.

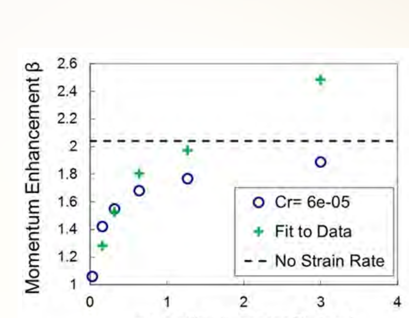
Computational Analysis

- Extensive Computations were performed using newly developed sophisticated flow and failure constitutive models within CTH.
- Experiments were presented at the 2019 HVIS in Destin, Florida and computational results were published in IJIE 2020.
- We match the ejecta mass size scale behavior, but the computations were not able to match the size scale behavior of momentum enhancement.



CTH computations showing differences in damage and crater at different projectile diameters (scales): Left: 0.3175 cm, Right 3.0 cm



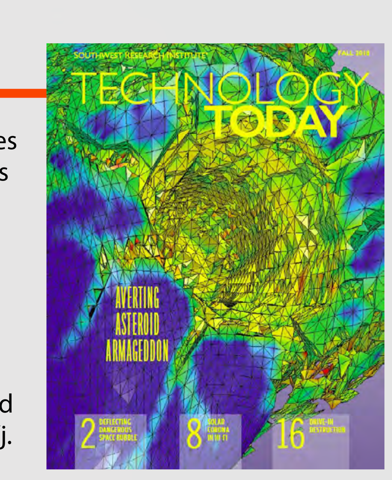


- Experimental results for 5.77 km/s impacts for a range of project sizes, performed at NASA Ames and SwRI (green crosses). CTH computations with a sophisticated failure model (blue circles) with 60 cells across the radius of the projectile. Details in the references (2020).

The Implications

- For these results at 5.77 km/s, when we go from a 1.27 cm diameter impactor to a 3 cm diameter impactor (an increase of 2.36),
  - The ejecta mass increases from 17.23 projectile masses to 18.29 projectile masses, an increase factor of 1.06 or 6% percent.
  - The excess momentum transfer (β – 1) goes from 0.97 to 1.49, an increase factor of 1.54 or 54% percent. $(3/1.27)^{0.5} = 1.54$
  - The increase in momentum enhancement is NOT due to more ejecta.
- A spacecraft will have a size of at least 1 meter, which is an increase of 33 times. It is clear that the size effect on momentum enhancement is the central question. The power 0.5 says the momentum enhancement would be 5.7 times greater.
- Since we hope to extrapolate this momentum enhancement behavior, it is important to understand its physical origins. Since the mass saturates but the momentum enhancement does not, it is clear the momentum enhancement increase due to size is not strictly due to an increase in ejecta mass. (Obviously, an increase in ejecta mass does increase momentum enhancement, but there is another mechanism at work here beyond the mass saturation.)
- It is clear that current popular impact analysis tools with current constitutive models are not adequate in predicting momentum enhancement – even those with internal length scale (which is an absolute minimum for replicating the observed experimental work for mass scaling).
- It is likely that the computational tools are not adequately addressing the post-failed behavior of the material – within CTH it is handled as a strengthless fluid, but the high speed photographs clearly show solid fragments that are weakly interacting, and presumably there are multiple impacts of these fragments with the crater walls as part of the ejecta process.
- Until these results with aluminum (which is much simpler than rock) can be replicated there is limited utility in performing momentum enhancement computations with existing tools and models for spacecraft scale impacts, because the necessary physics is not present in the modeling.

References



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