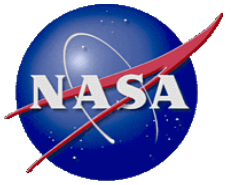
National Aeronautics and Space Administration



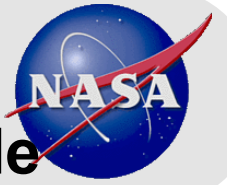
DEVELOPMENT OF ANALYSIS TECHNIQUES FOR NON-SPHERICAL HYPERVELOCITY IMPACTS

Joshua E. Miller[1,2], Eric L. Christiansen[3] and James L. Hyde[2]

[1] University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79986
[2] Jacobs, NASA Johnson Space Center, 2224 Bay Area Blvd., Houston, TX 77058
[3] NASA Johnson Space Center, 2101 NASA Road One, Houston, TX 77058

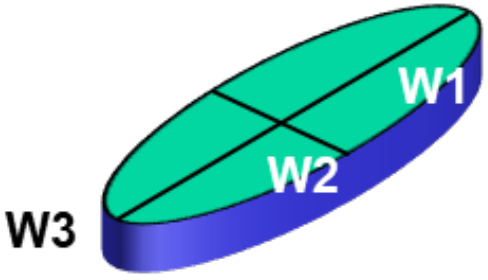
Interagency Space Debris Coordination Committee (IADC)
2023 IADC in Darmstadt, Germany
12-15 June 2023

Significant progress in addressing non-spherical projectiles in spacecraft assessments has been made



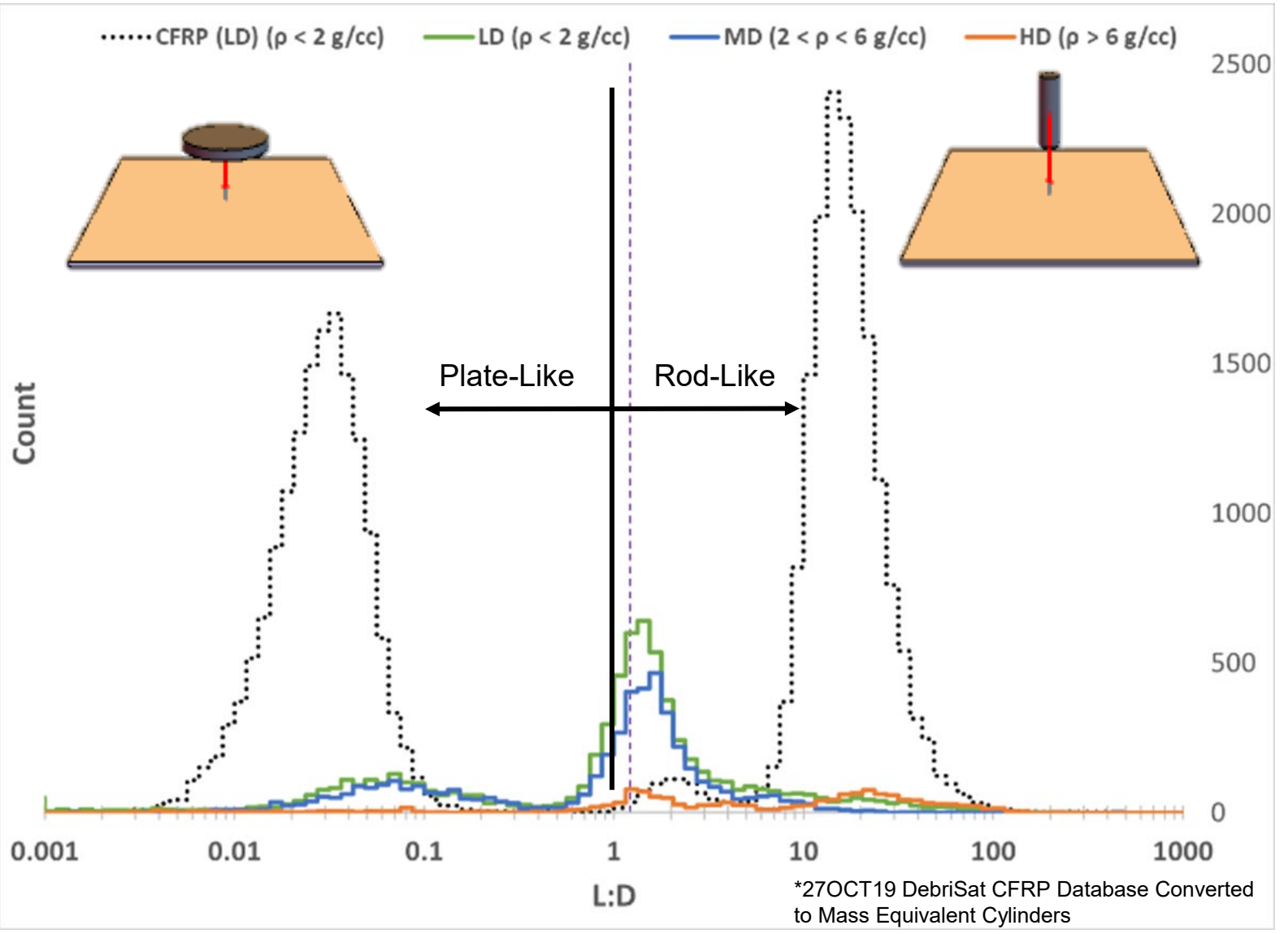
- To address non-spherical projectiles, a departure from sphericity parameter and principal axis orientation are needed to determine the performance of a shield in addition to existing recognized ballistic parameters
- To this end, a general sheet metal and Whipple shields have been used to quantify this dependence for non-spherical adaptation
- Implicit to understanding shield performance is defining the orientation of the non-spherical projectile at impact
- A set of hypervelocity impacts have been conducted to validate simulation models for numerical extrapolation
- These simulations are used to extend impact conditions and precision beyond what is capable in the lab

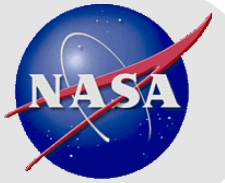
Arbitrary shape widths along principal axes and volume are solved for L:D

Representative Shape Definition	Virtual RCC Characteristics	$1 \le \frac{W_1}{W_2} < 2$ $\frac{W_1}{W_3} > 2$	$1 \le \frac{W_1}{W_2} < 2$ $1 \le \frac{W_1}{W_3} < 2$	$\frac{W_1}{W_2} \ge 2$
	L	$\frac{4\,V}{\pi\,W_1\,W_2}$	W_2	W_1
	D	$(W_1\,W_2)^{1/2}$	$\left(\frac{4\,V}{\pi\,W_2}\right)^{1/2}$	$\left(\frac{4\,V}{\pi\,W_1}\right)^{1/2}$
	L:D	$\frac{4\,V}{\pi\,(W_1\,W_2)^{3/2}}$	$\left(\frac{\pi\,W_2^3}{4\,V}\right)^{1/2}$	$\left(\frac{\pi\,W_1^3}{4\,V}\right)^{1/2}$

Converting the DebriSat CFRP to Mass Equivalent Cylinders Shows Plate and Rod Populations







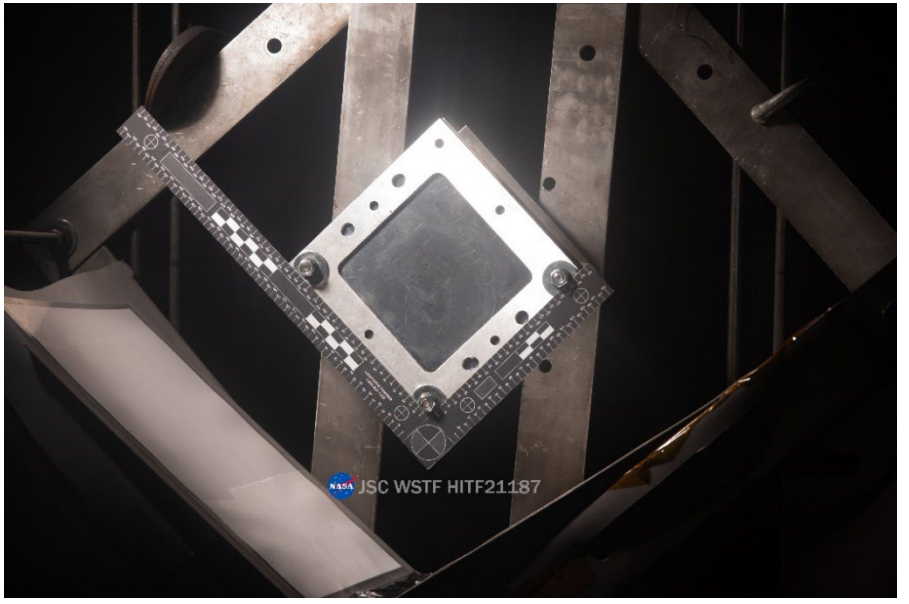
MONOLITHIC METALS

The 0.17cal updated with orthogonal, high-speed cameras to record impacts with small projectiles

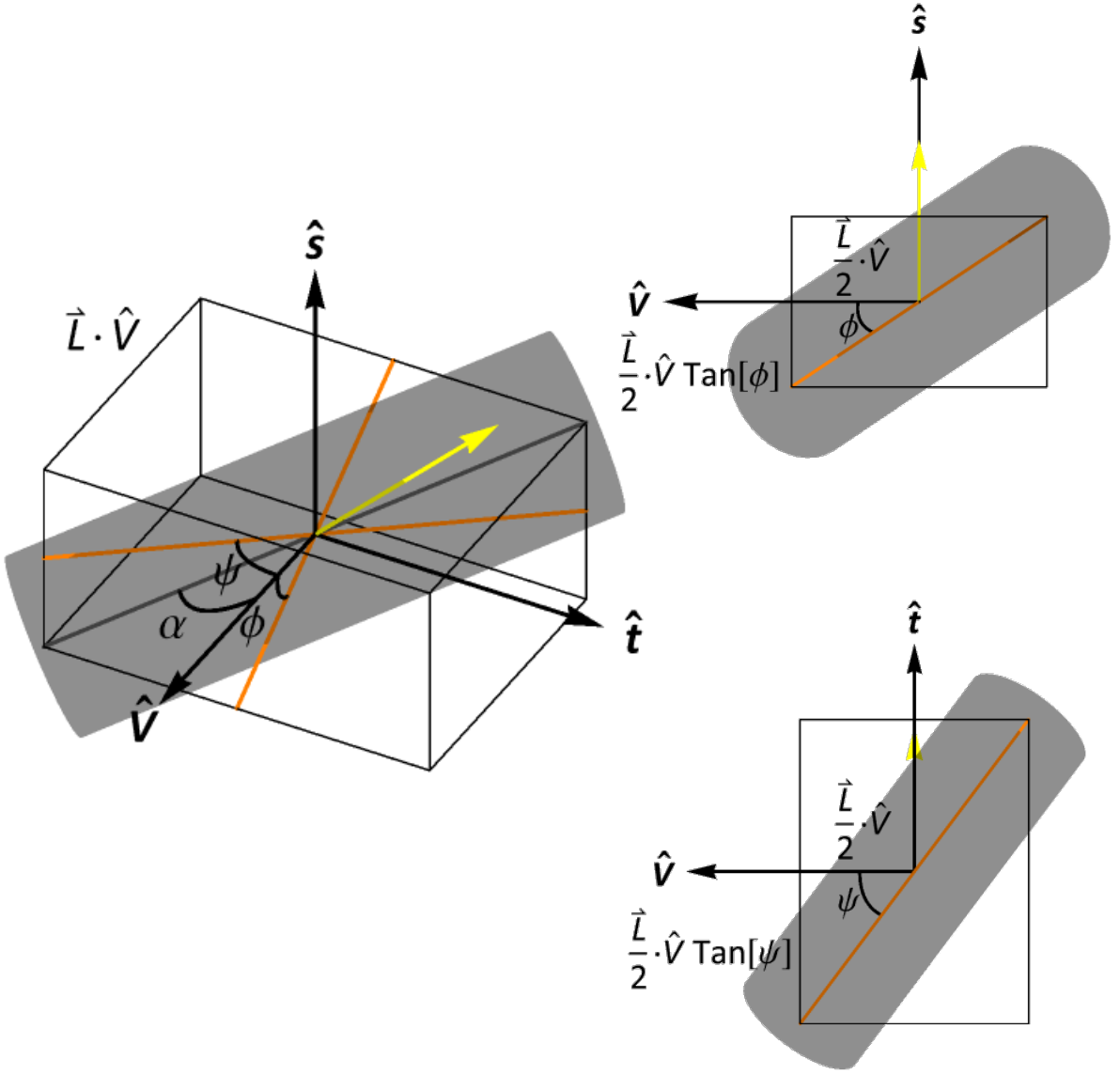
0.17cal target tank with attached light sources and orthogonal high-speed cameras that record at 5 million frames per second



Whipple shield target in a specialized mount that backlights the projectile for the high-speed cameras



The pair of orthogonal cameras can be solved to determine the projectile orientation angles



- **Dot product between the central axis and velocity vector yields the attack angle**

$$\vec{L}\cdot\hat{V} = L\,Cos[\alpha]$$

- **From geometry the shadows are related to central axis**

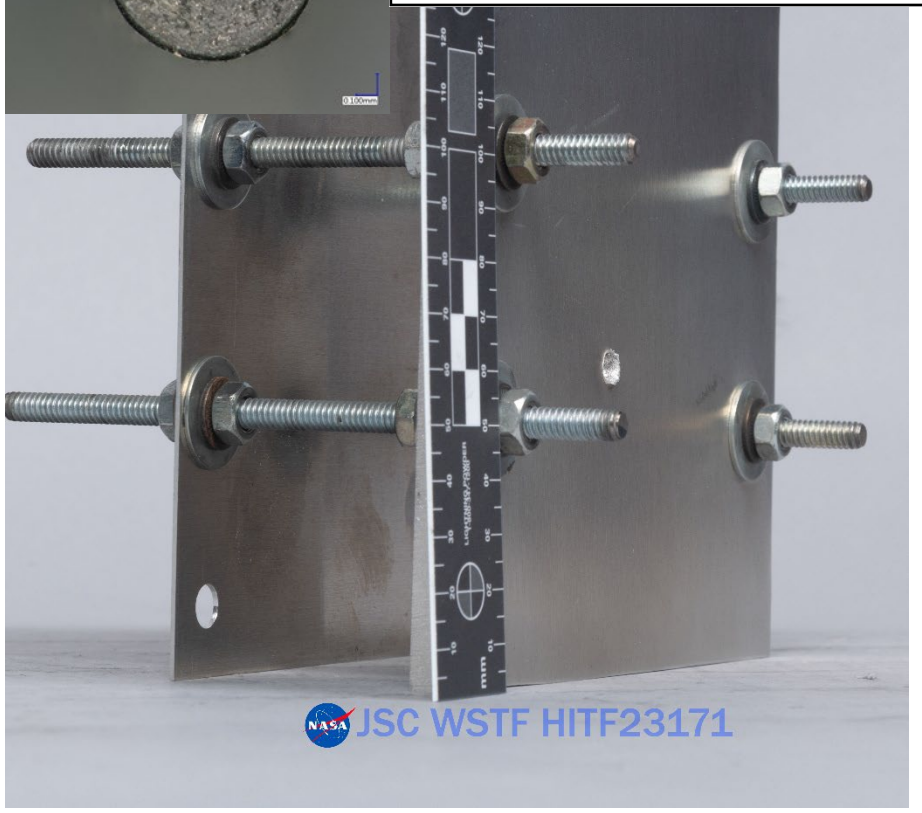
$$L^2 = \left(\vec{L}\cdot\hat{V}\right)^2 + \left(\vec{L}\cdot\hat{V}\,Tan[\phi]\right)^2 + \left(\vec{L}\cdot\hat{V}\,Tan[\psi]\right)^2$$

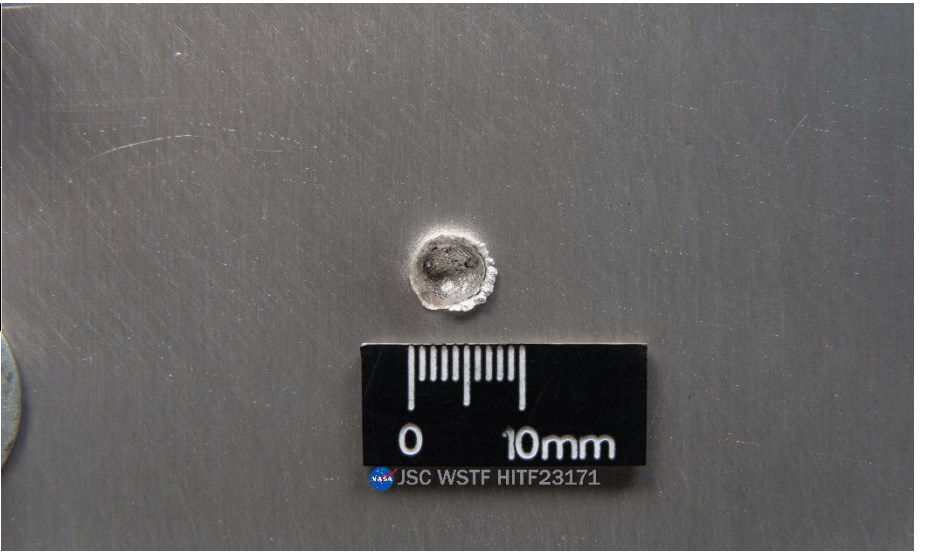
- **Combining the dot product and geometry and solving for attack angle**

$$\alpha = ArcCos\left[\sqrt{\frac{1}{1+Tan[\phi]^2+Tan[\psi]^2}}\right]$$

9.5 mm Al6061 – CFRP 3.00L x 1.01D mm @ 7.01 km/s & 38.0° Pitch

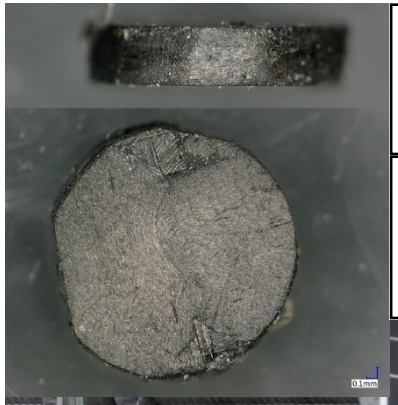


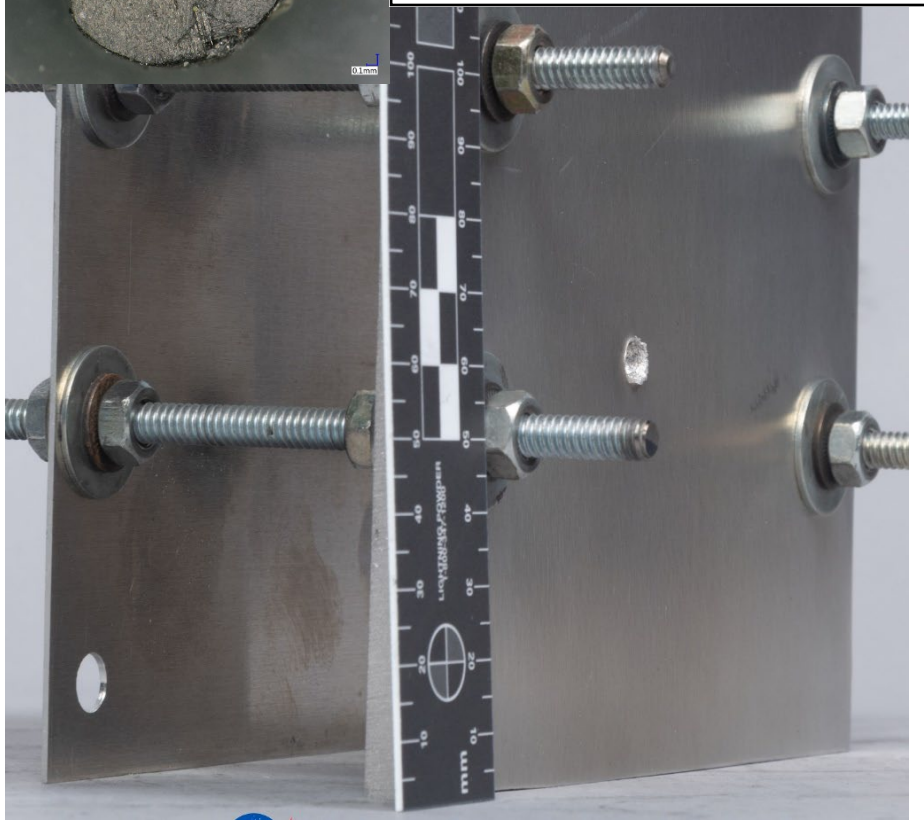


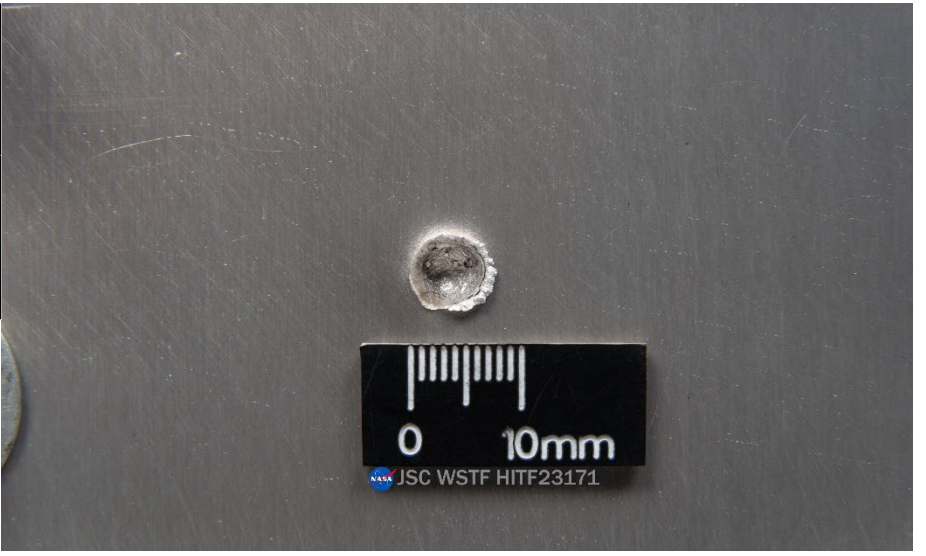




9.5 mm Al6061 – CFRP 0.60L x 2.40D mm @ 7.00 km/s & 4.5° Pitch

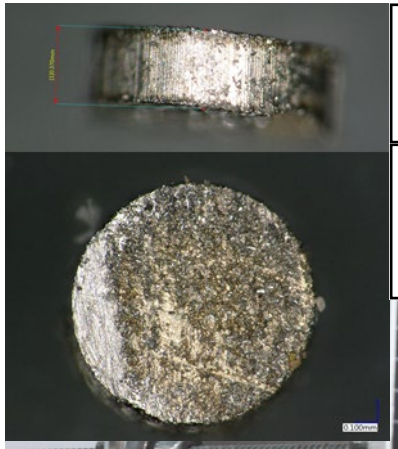




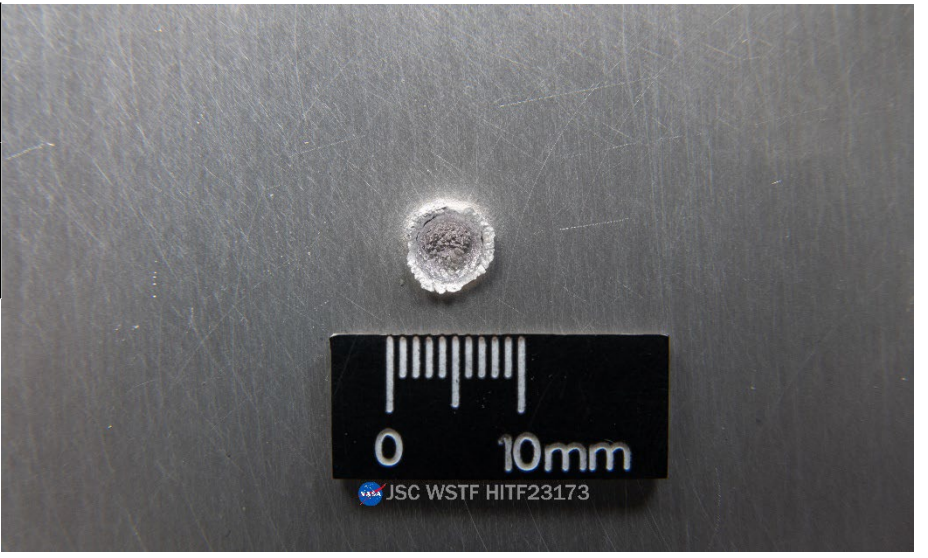


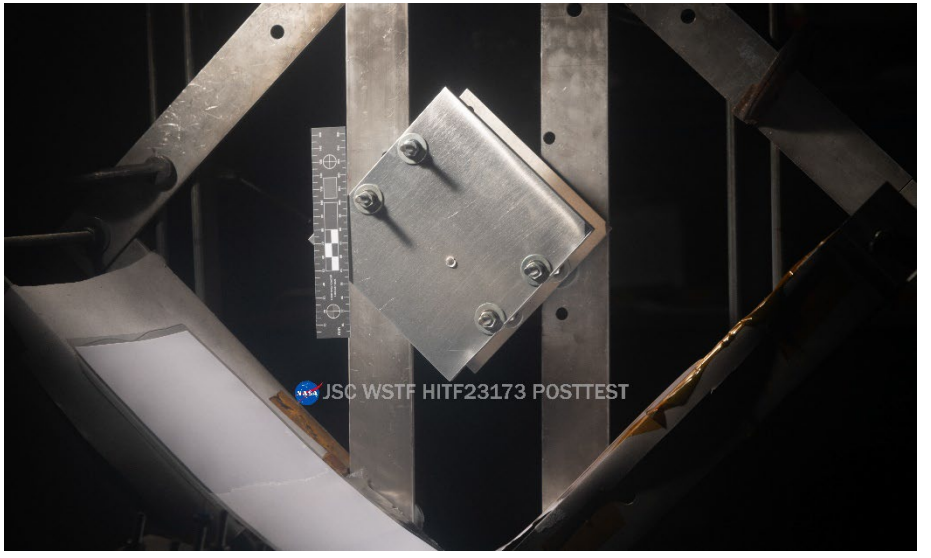


9.5 mm Al6061 – SS304L 0.37L x 1.14D mm @ 7.19 km/s & 8.3° Pitch

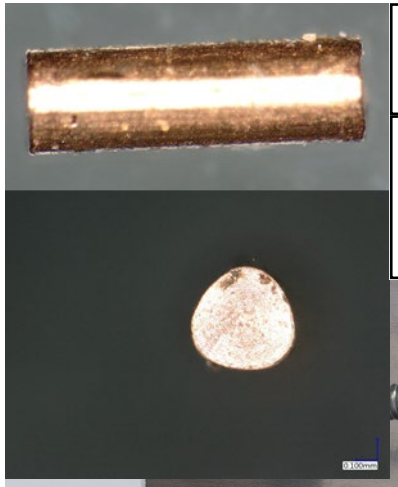


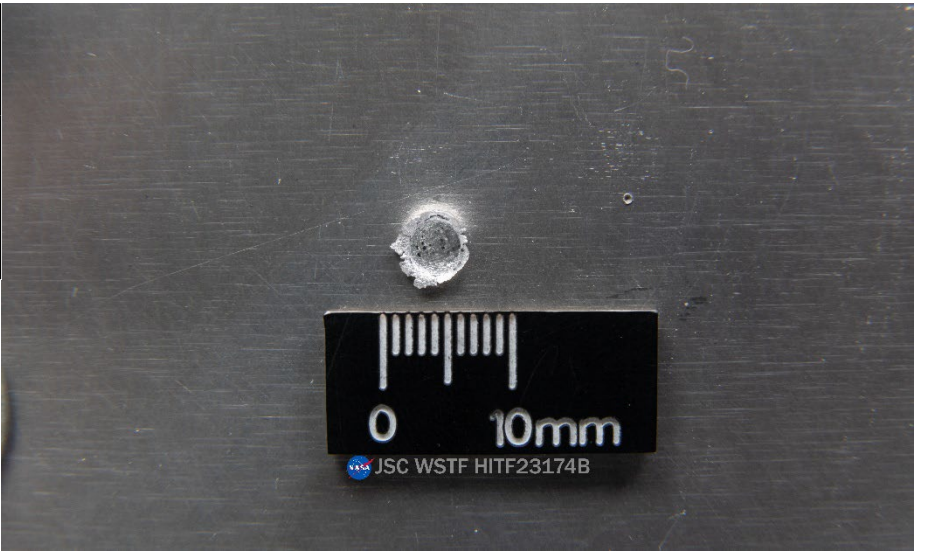






9.5 mm Al6061 – Cu 1.59L x 0.51D mm @ 6.01 km/s & 67.0° Pitch

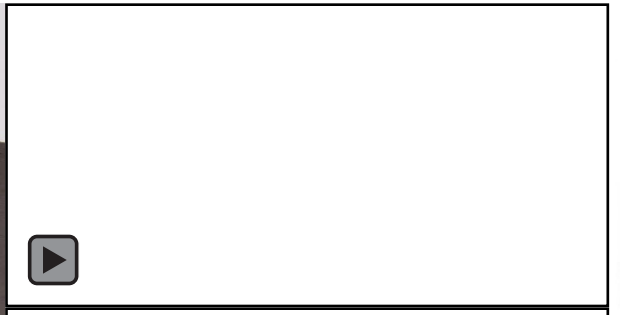




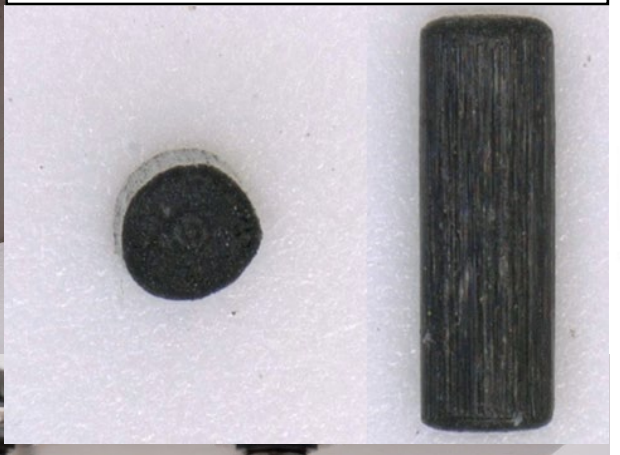


3.2 mm Ti6Al4V – CFRP 1.06D x 3.07L mm @ 7.00 km/s & 48.9° Pitch Produced 1.62 mm Crater

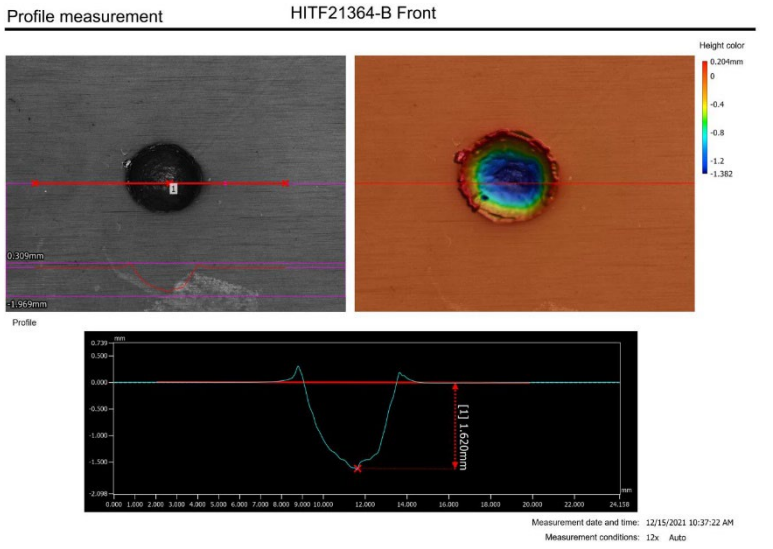


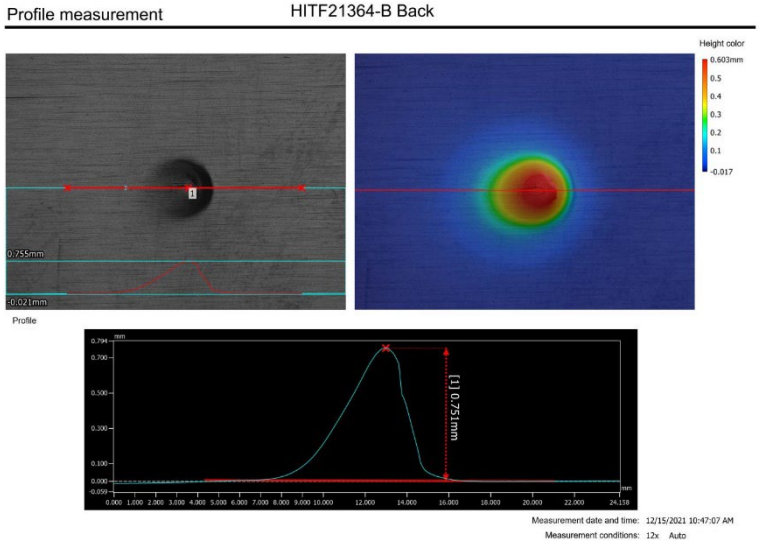




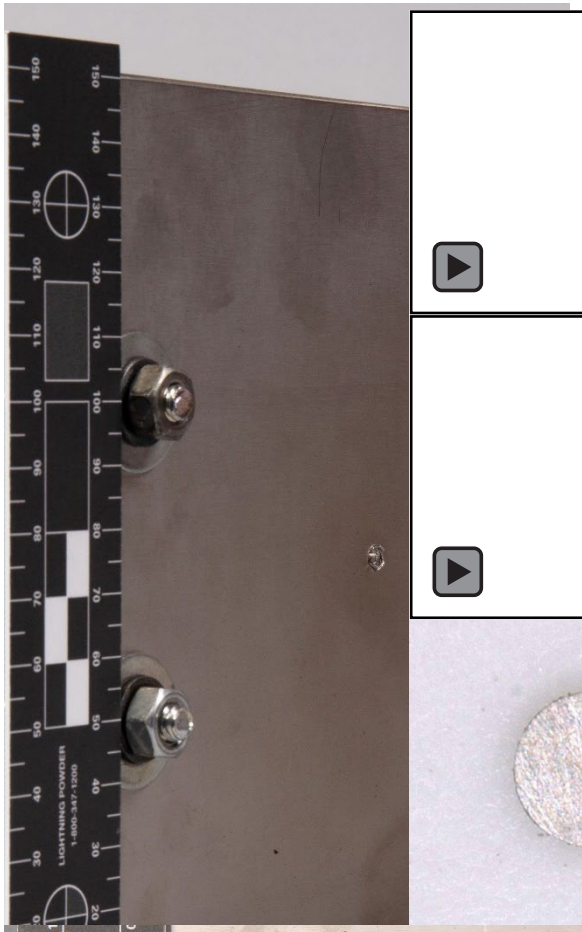


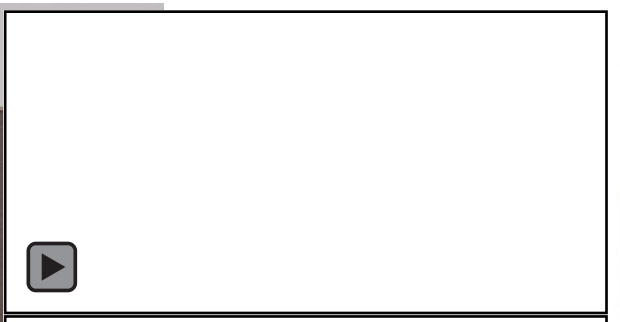






3.2 mm Ti6Al4V – SS304L 1.14D x 0.40L mm @ 7.10 km/s & 7.1° Pitch Produced ~3.2 mm Crater

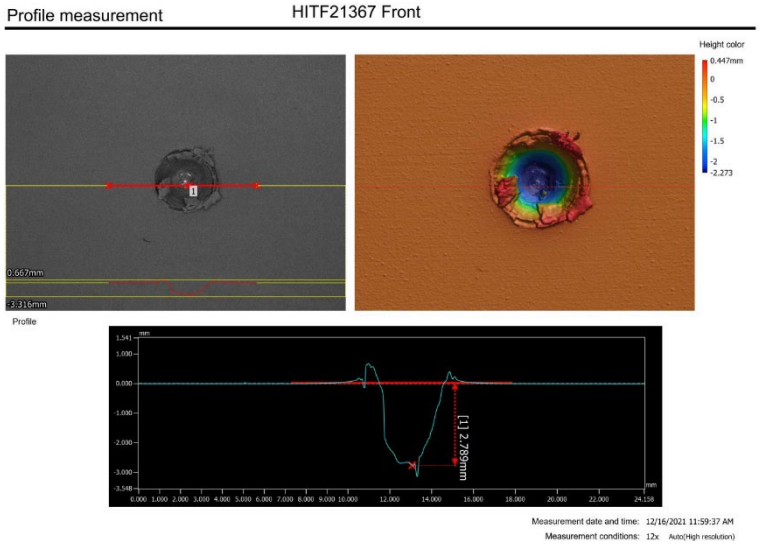


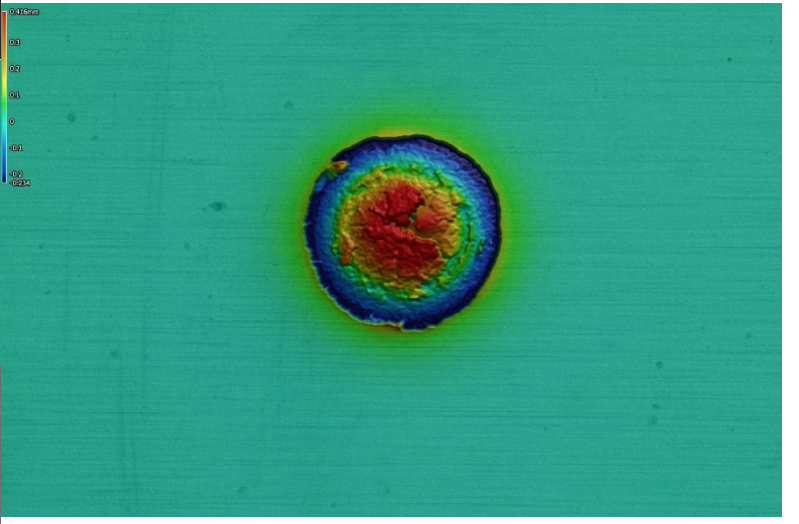




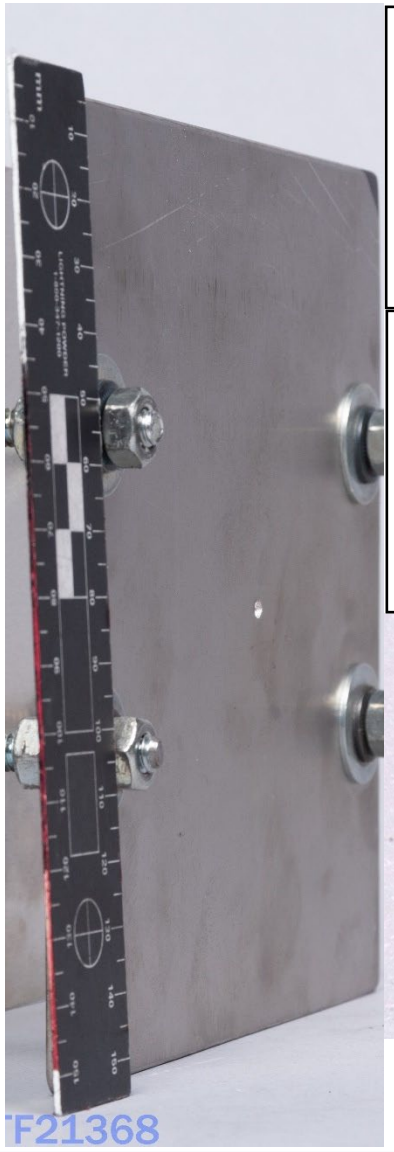




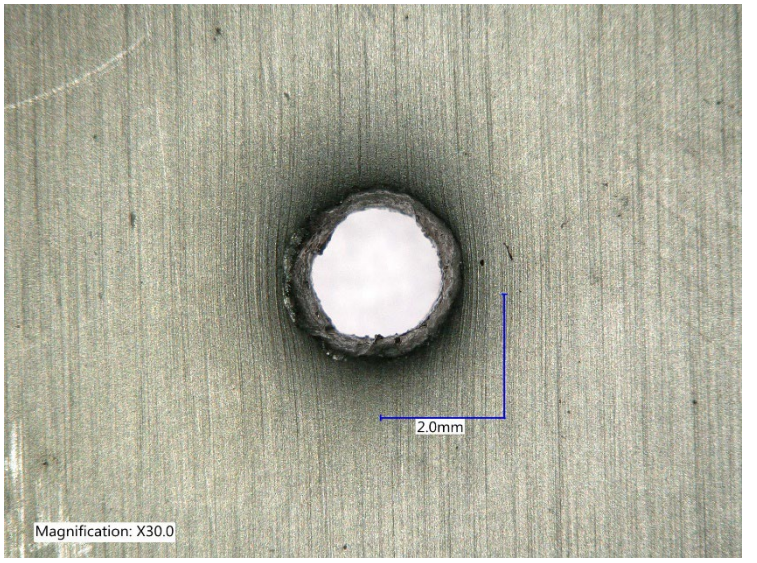


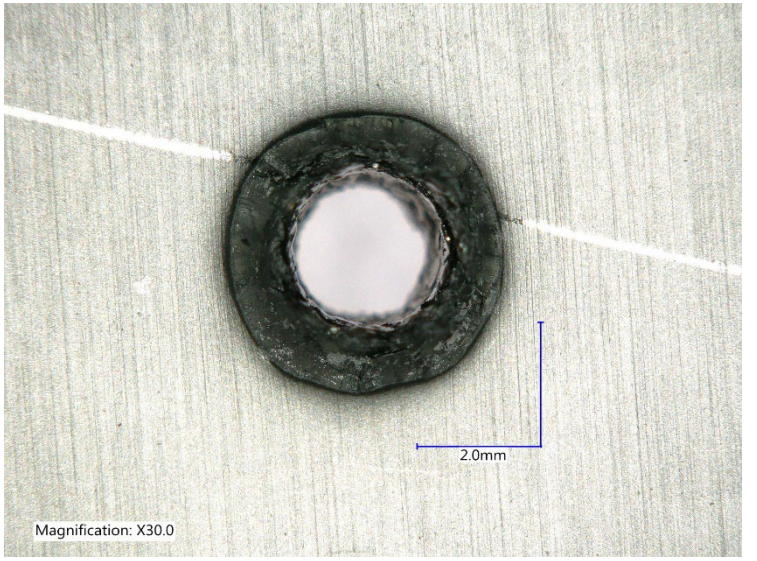


3.2 mm Ti6Al4V – Cu 0.5D x 1.5L mm @ 5.98 km/s & 15.2° Pitch Produced ~4.5D mm Hole

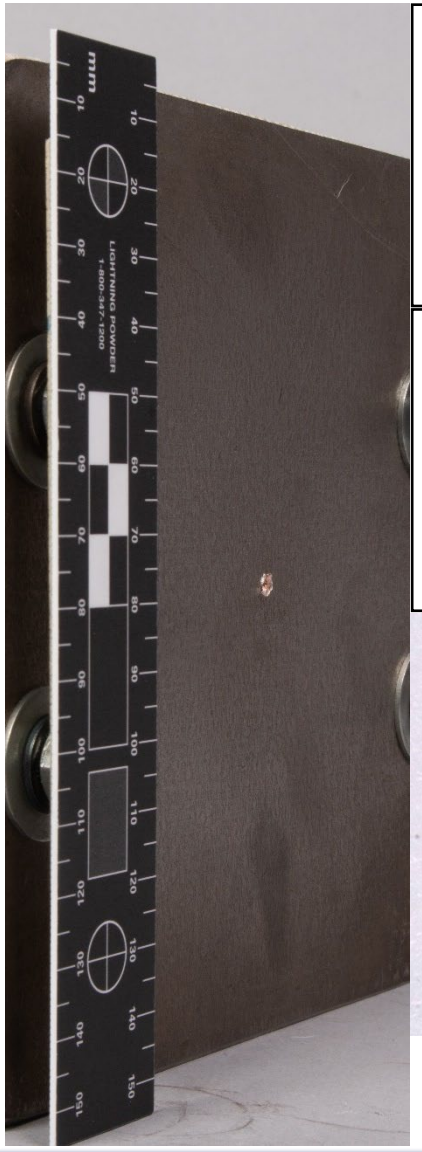


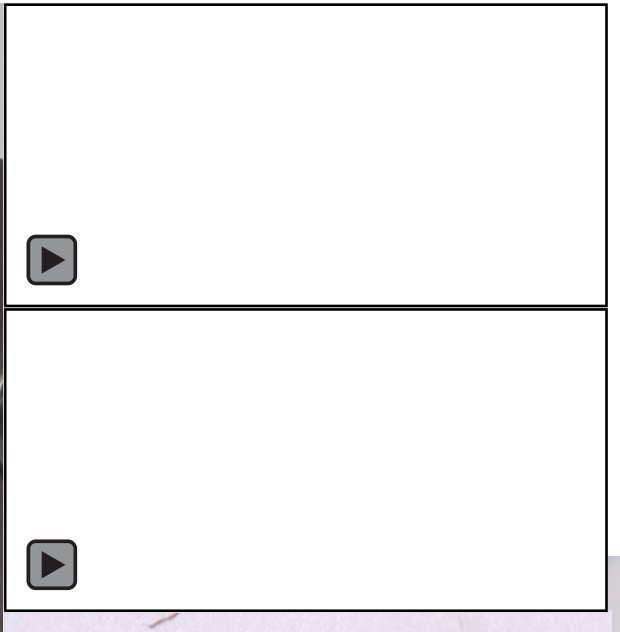


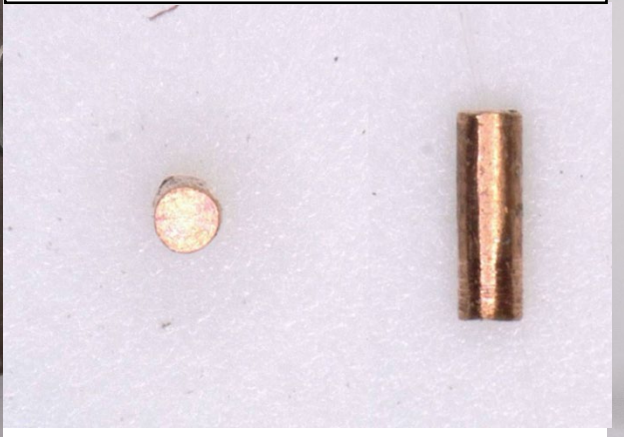


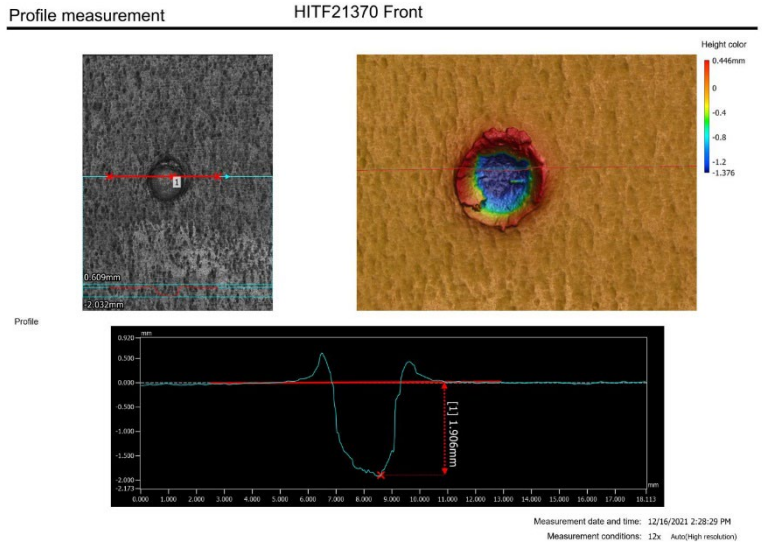


4.8mm SS 15-5PH H1150–Cu 0.49Dx1.51L mm @ 5.99 km/s & 42.6° Pitch Produced 1.91 mm Crater



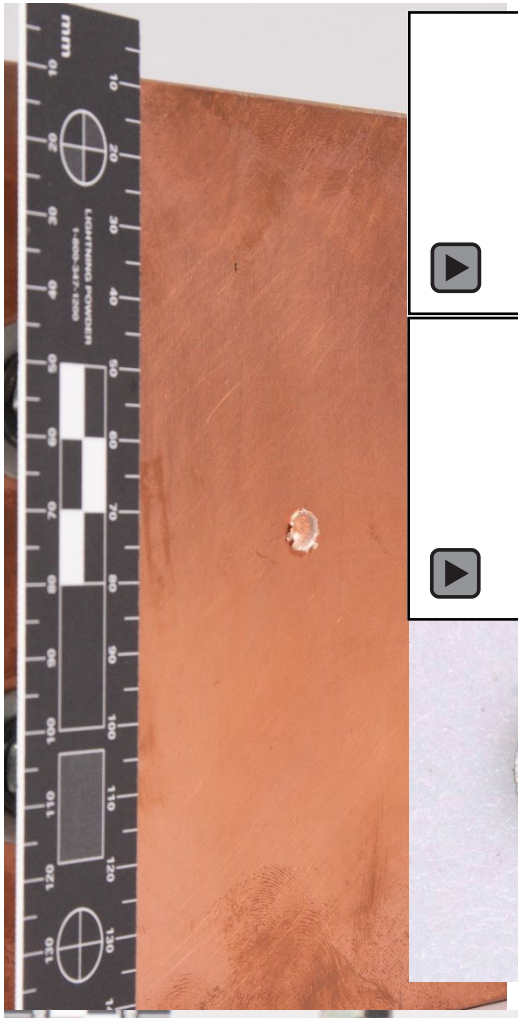


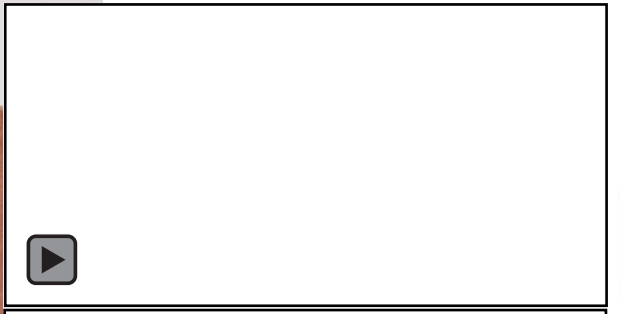


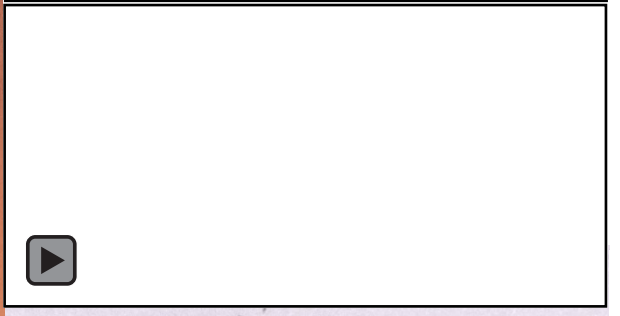




6.4 mm Cu – SS304L 1.15D x 0.40L mm @ 6.93 km/s & 2.0° Pitch Produced 2.28 mm Crater

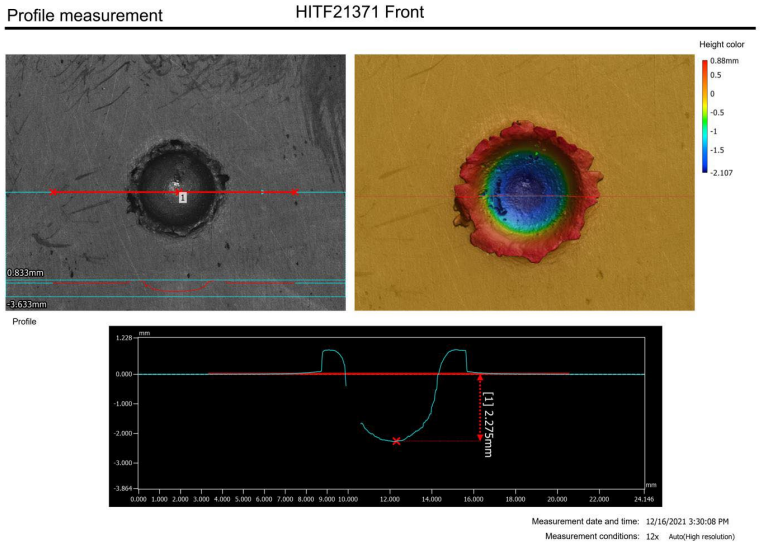


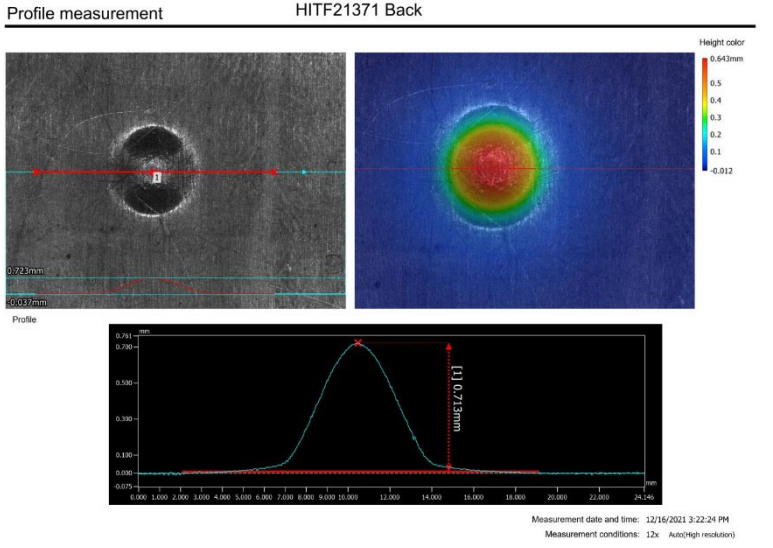




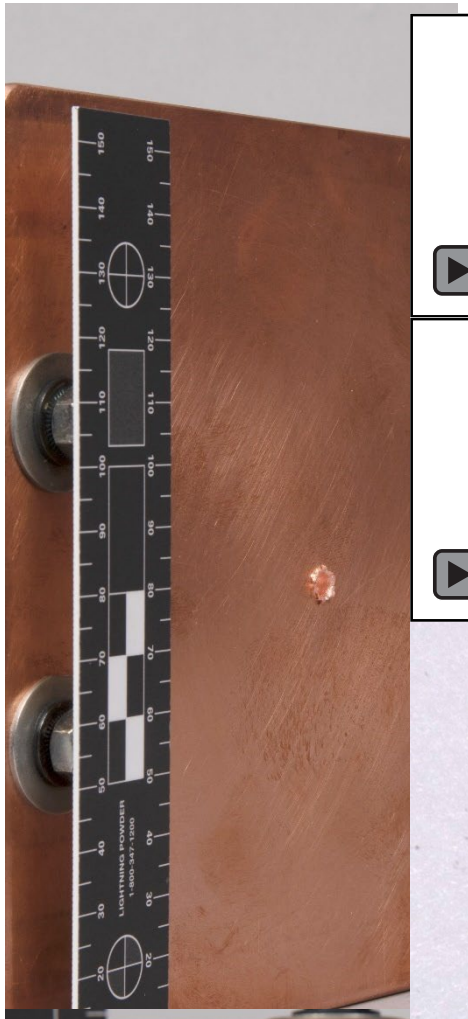






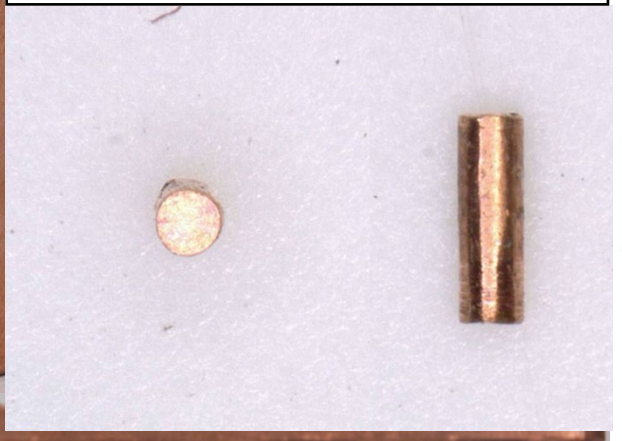


6.4 mm Cu – Cu 0.50D x 1.55L mm @ 6.07 km/s & 5.2° Pitch Produced 1.97 mm Crater

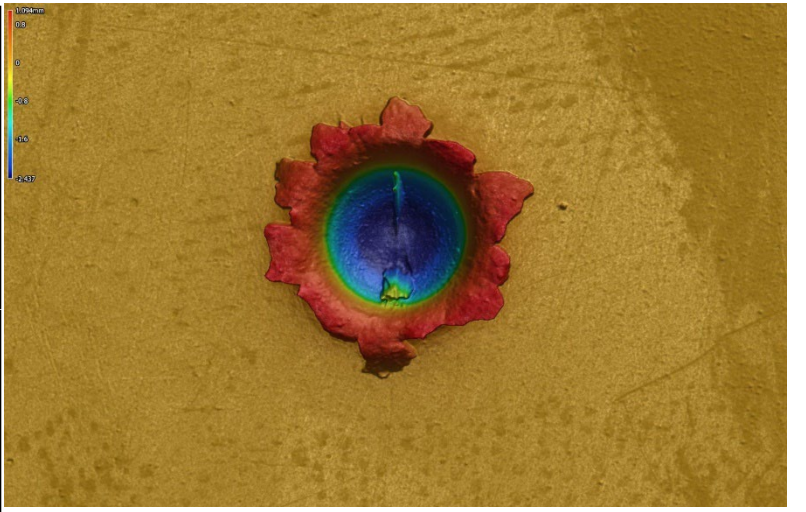


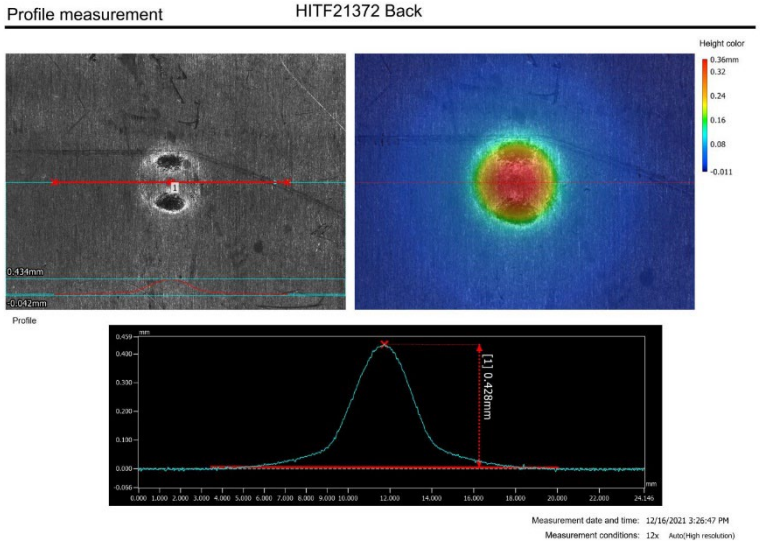


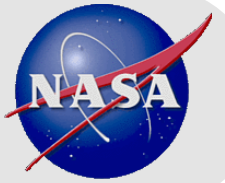








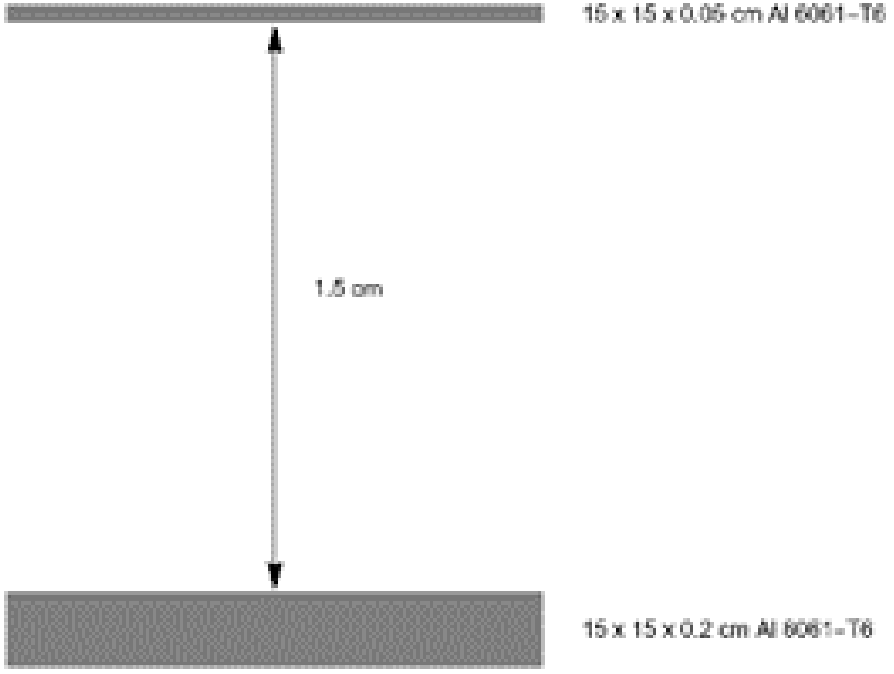




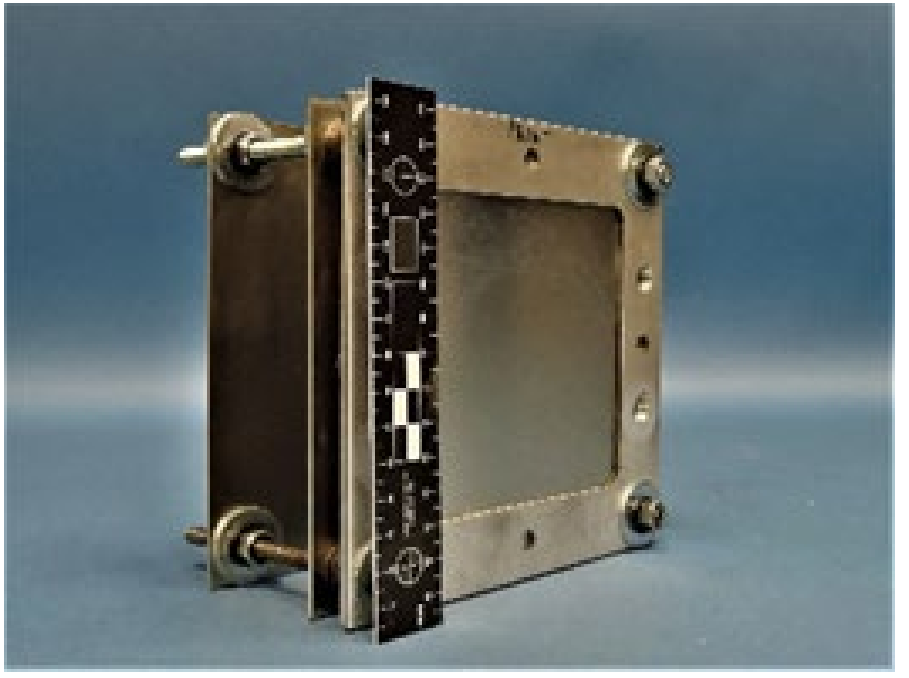
WHIPPLE SHIELDS

A basic Whipple shield has been used to develop generalized dependence on shield parameters

Schematic of the Whipple shield under for this study

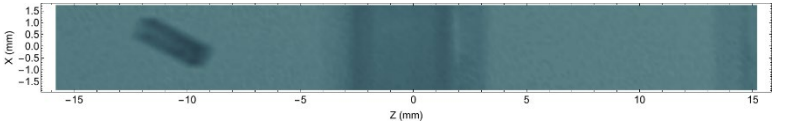


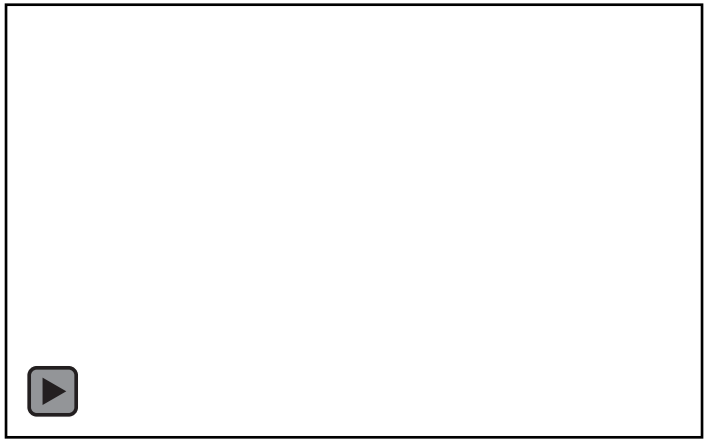
Representative test article used to validate models

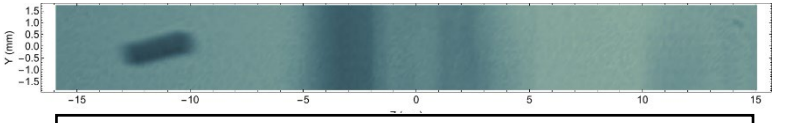


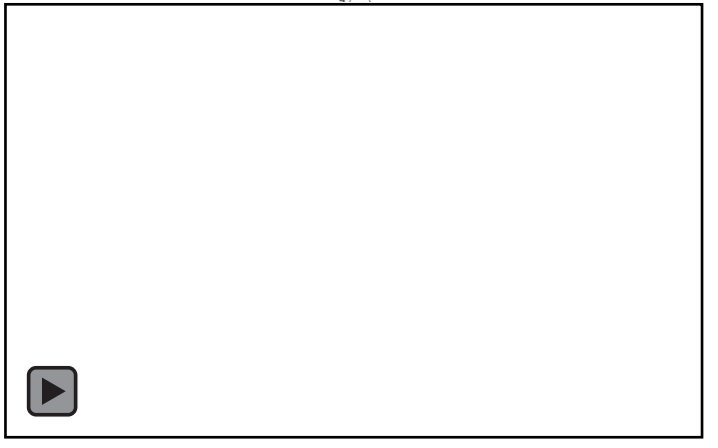
Representative example of a L:D = 3:1 impact on the shield

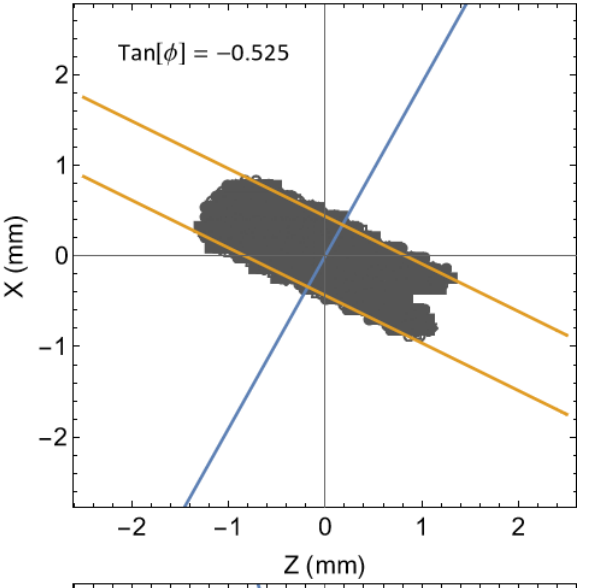


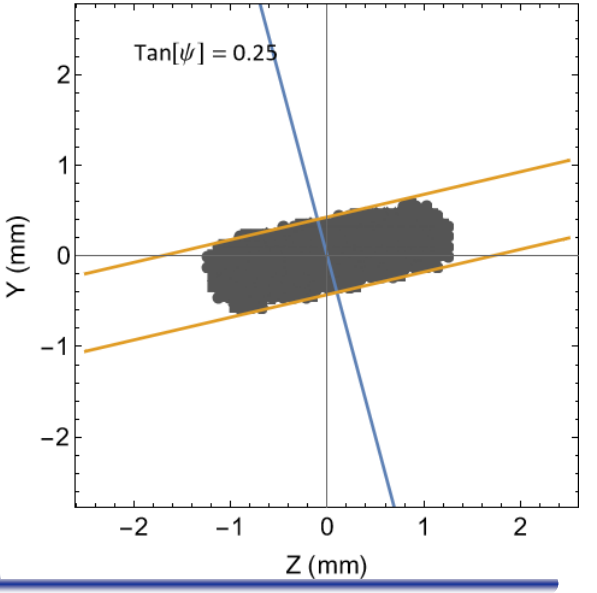










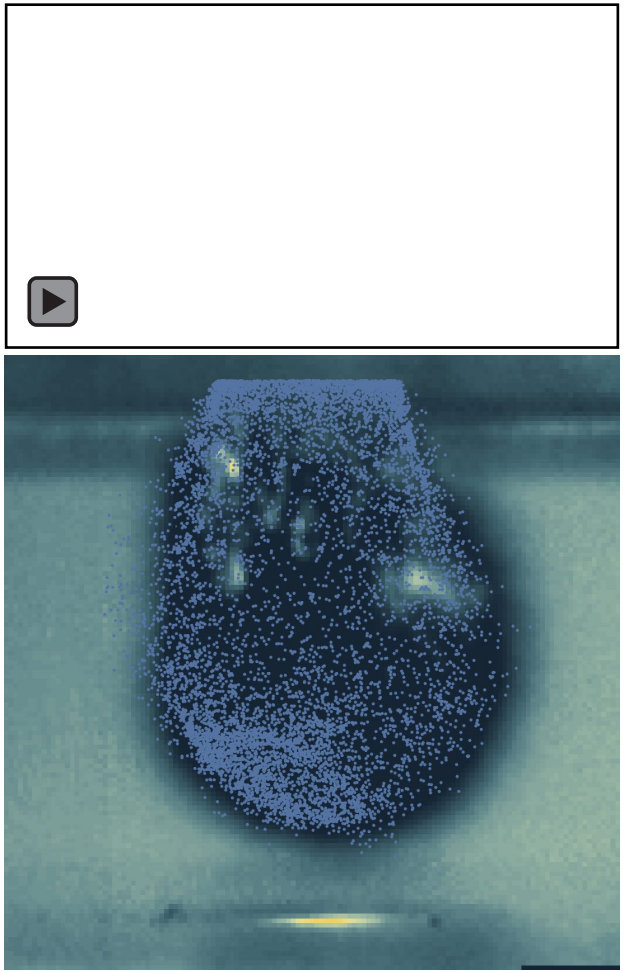


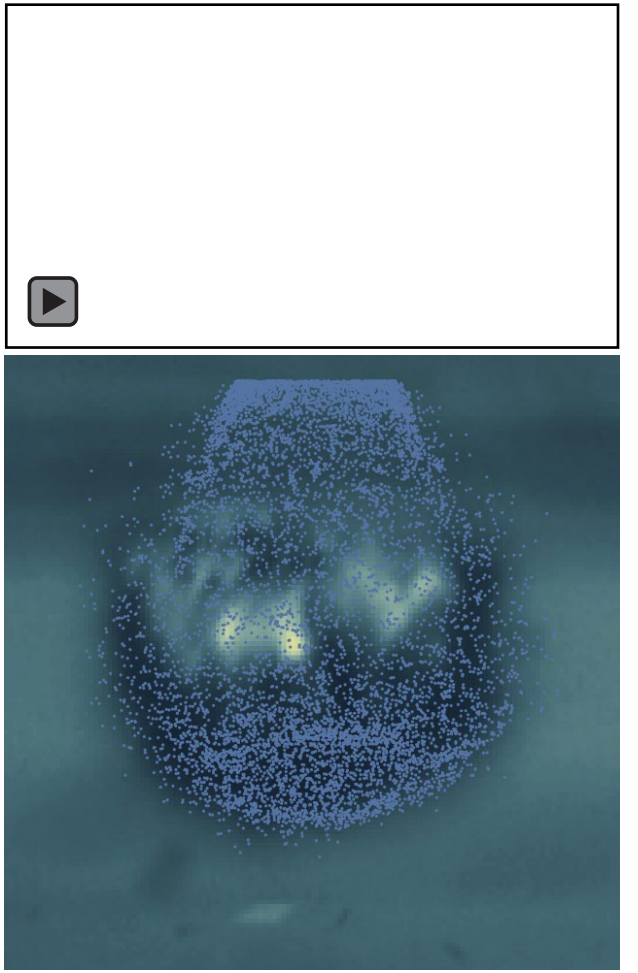
$$\alpha = Cos^{-1}\left[\sqrt{\frac{1}{1+0.525^2+0.25^2}}\right] = 30.2°$$

L:D=3:1 CFRP simulations from Impetus γSPH and comparison to observed debris cloud

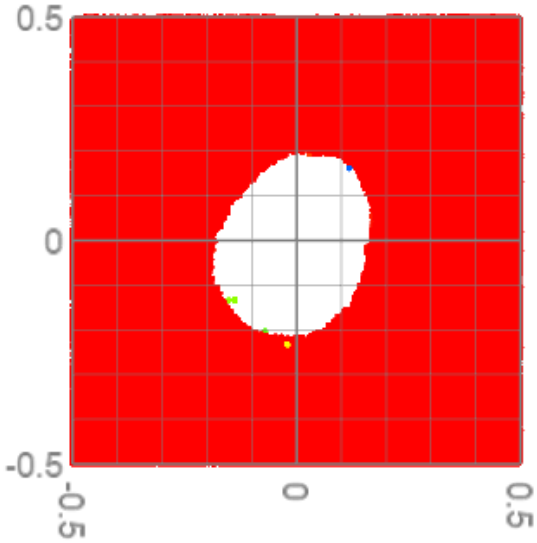
CFRP
- Mie-Gruneisen EOS
- Johnson-Cook Deviatoric
- Cockroft-Latham Damage Accumulation

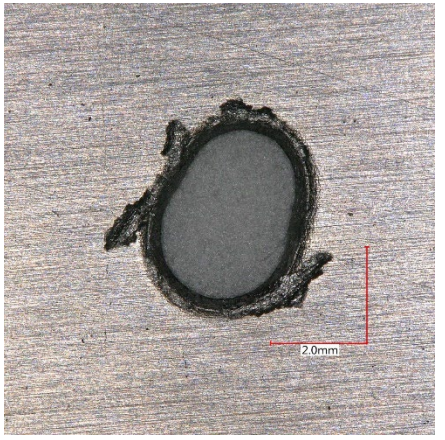
Al6061
- Mie-Gruneisen EOS
- Johnson-Cook Deviatoric
- Cockroft-Latham Damage Accumulation





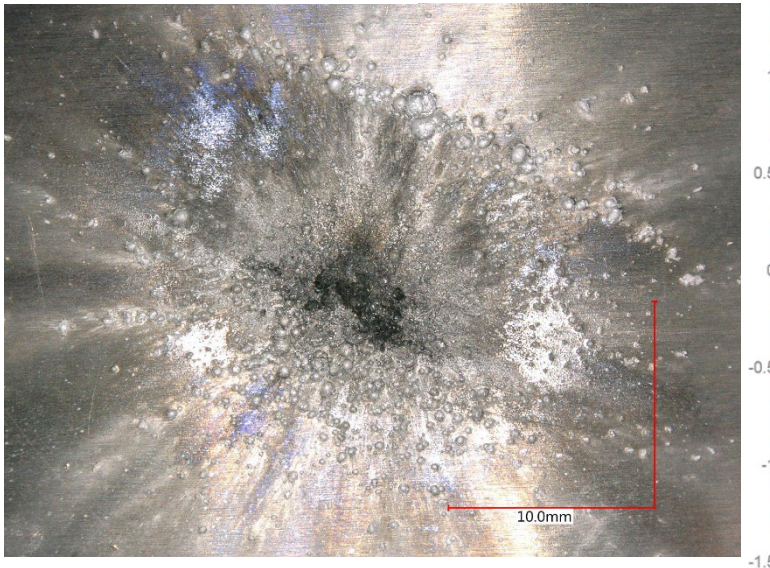
Whipple shield wall damage for the front and rear wall against the L:D = 3:1 projectile

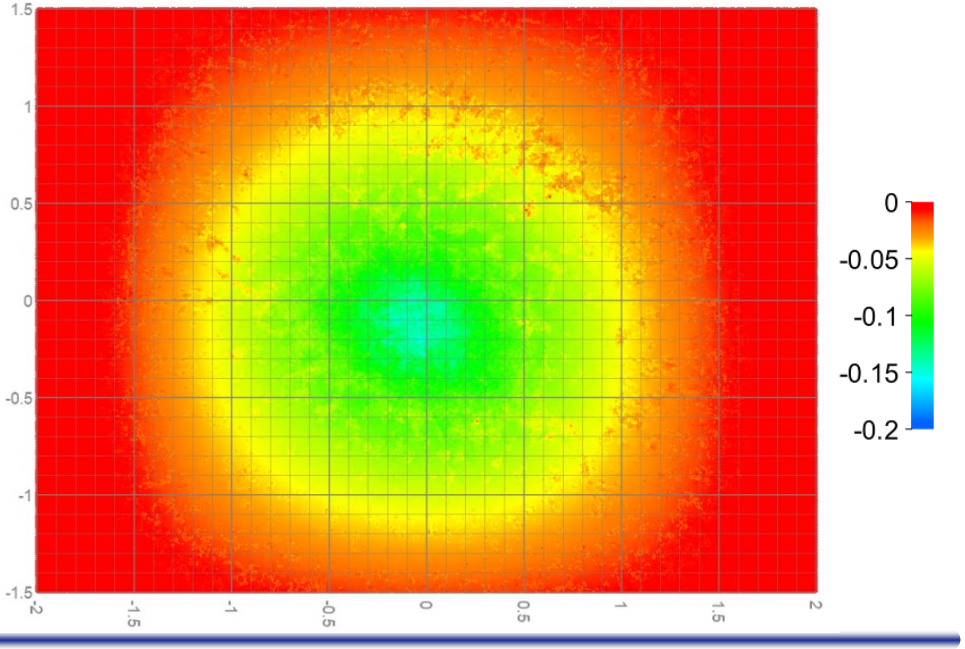




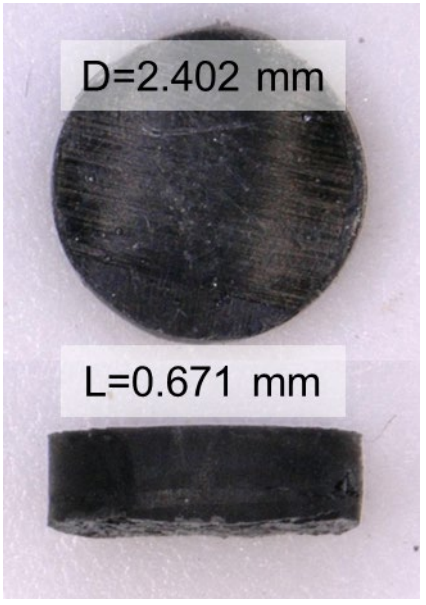
Measured crater depth- 0.72 mm

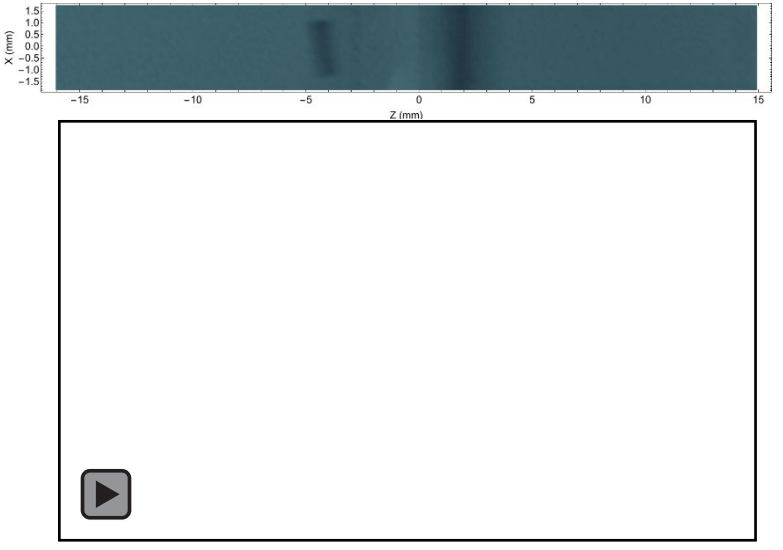
Simulated crater depth- 0.96 mm

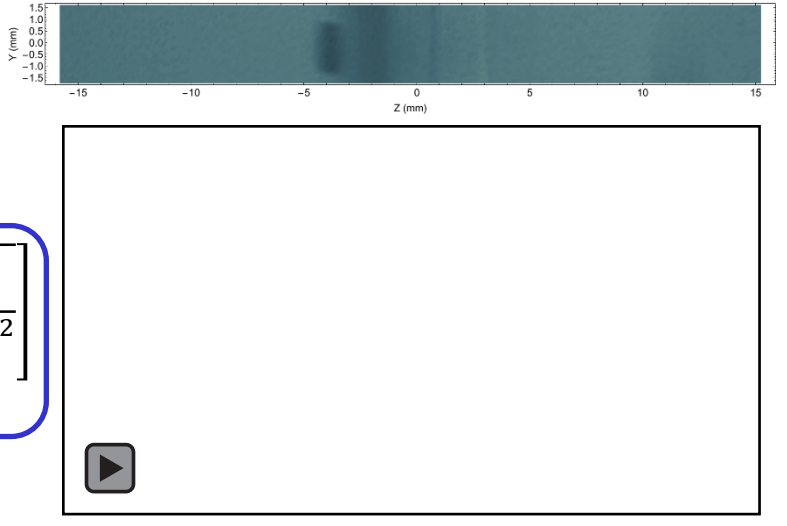


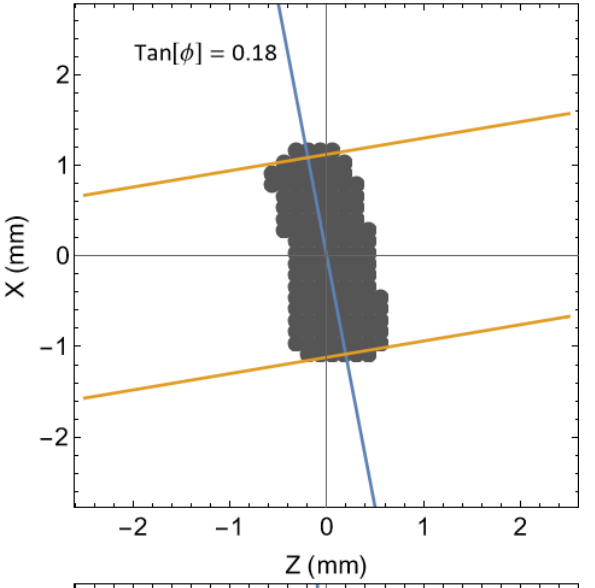


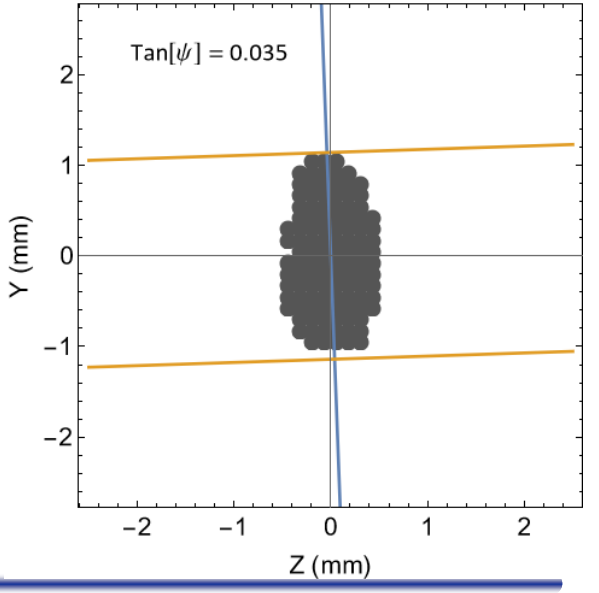
Representative example of a L:D = 1:3 impact on the shield









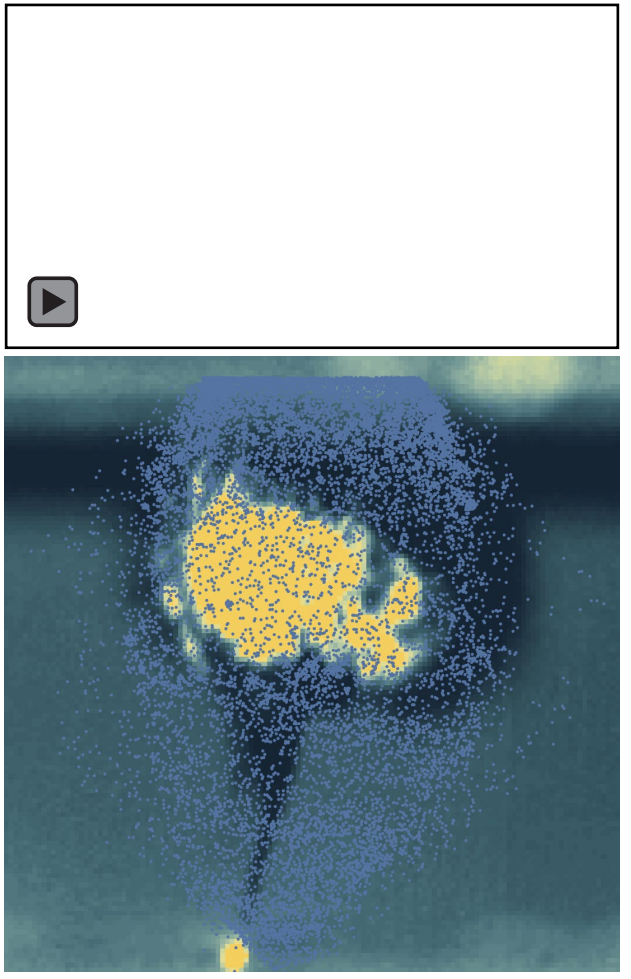


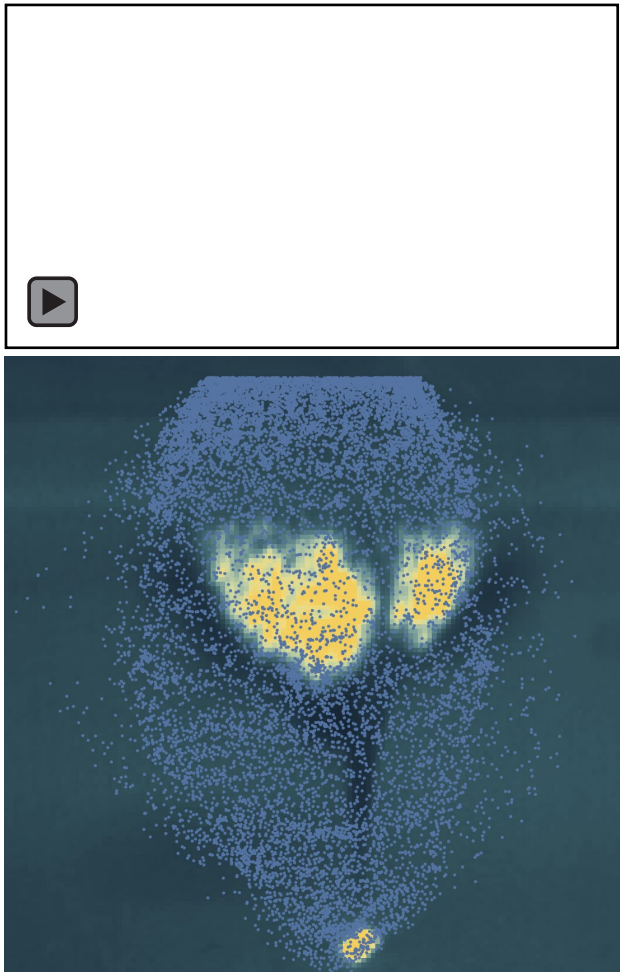
$$\alpha = Cos^{-1}\left[\sqrt{\frac{1}{1+0.18^2+0.035^2}}\right] = 10.3°$$

L:D=1:3 CFRP simulations from Impetus γSPH and comparison to observed debris cloud

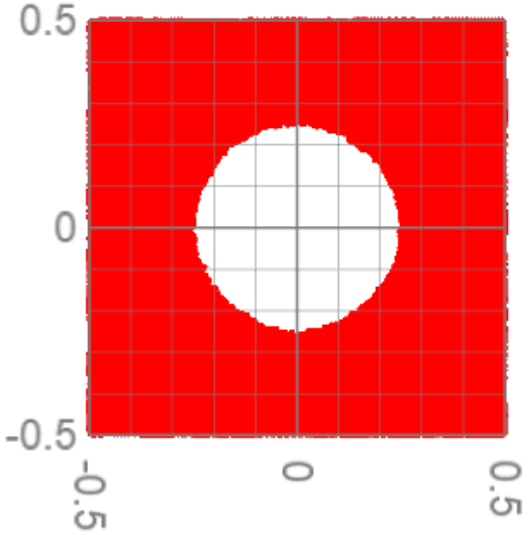
CFRP
- Mie-Gruneisen EOS
- Johnson-Cook Deviatoric
- Cockroft-Latham Damage Accumulation

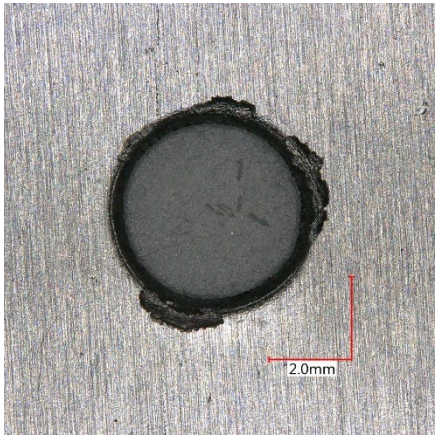
Al6061
- Mie-Gruneisen EOS
- Johnson-Cook Deviatoric
- Cockroft-Latham Damage Accumulation





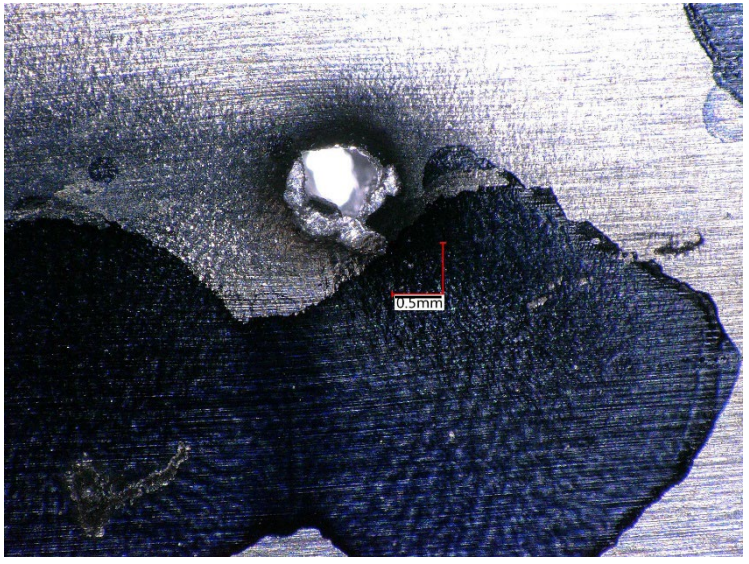
Whipple shield wall damage for the front and rear wall against the L:D = 1:3 projectile

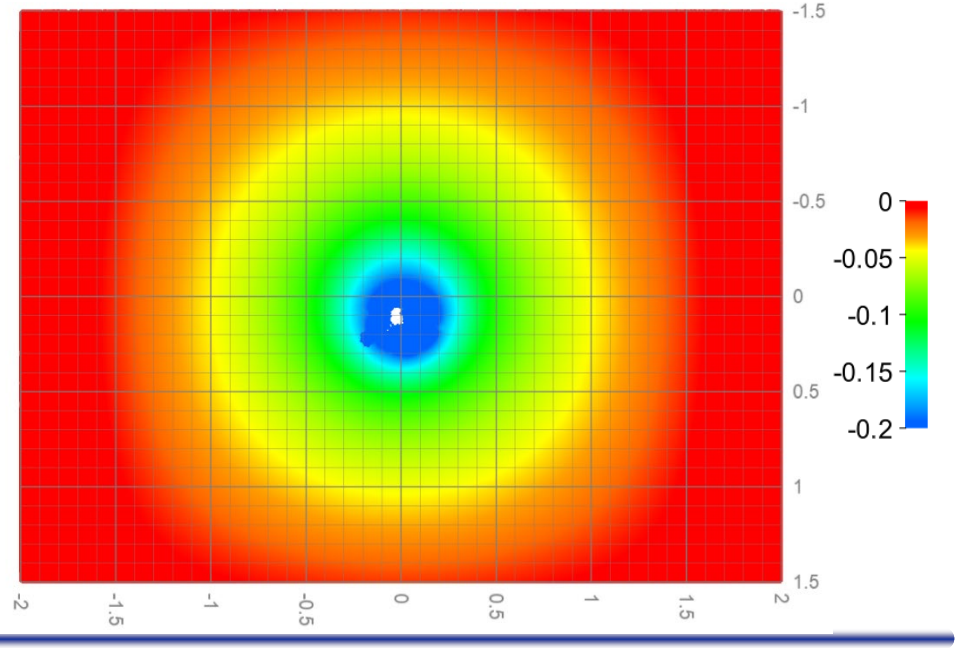




Measured hole diameter- 0.70 mm

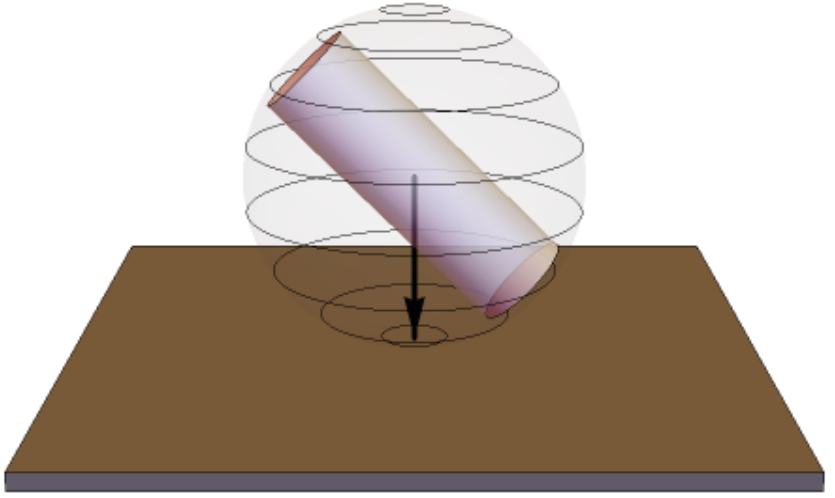
Simulated hole diameter- 0.95 mm



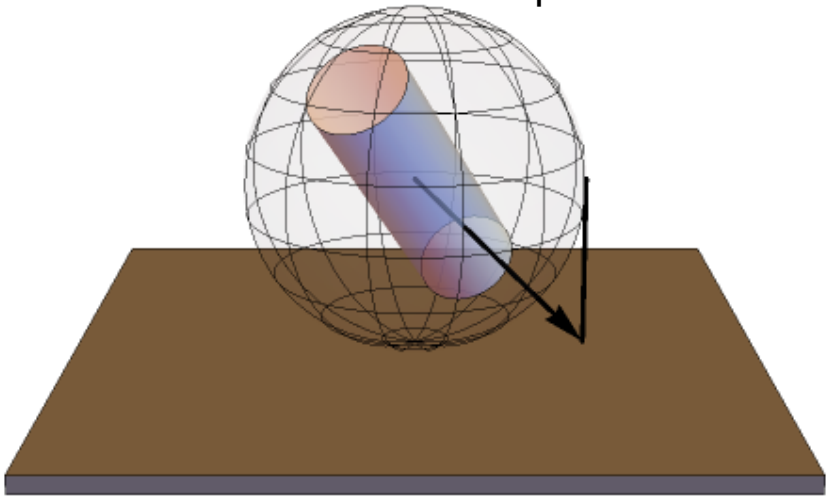


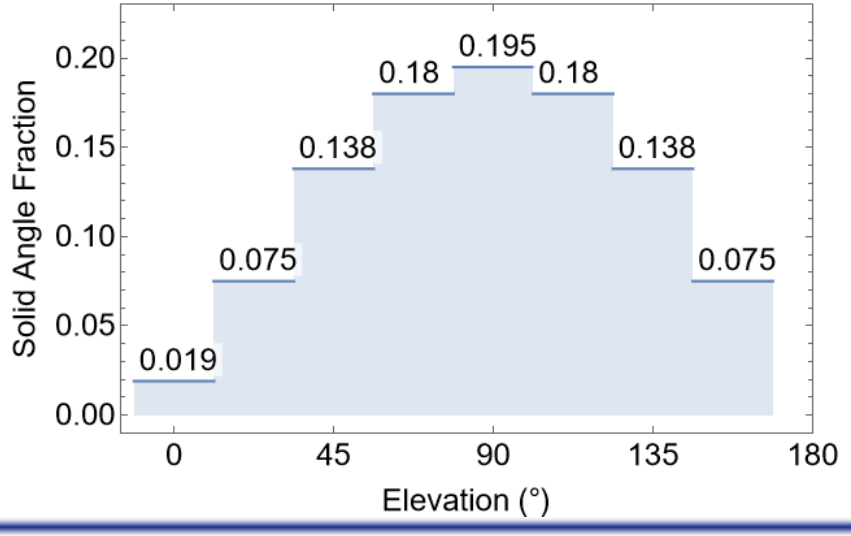
Non-spherical projectiles have an orientation dependent probability

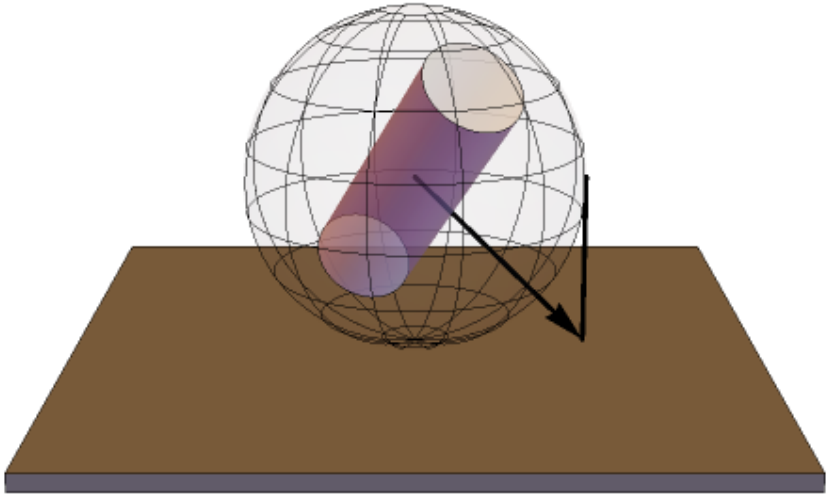
0° to Normal Impact



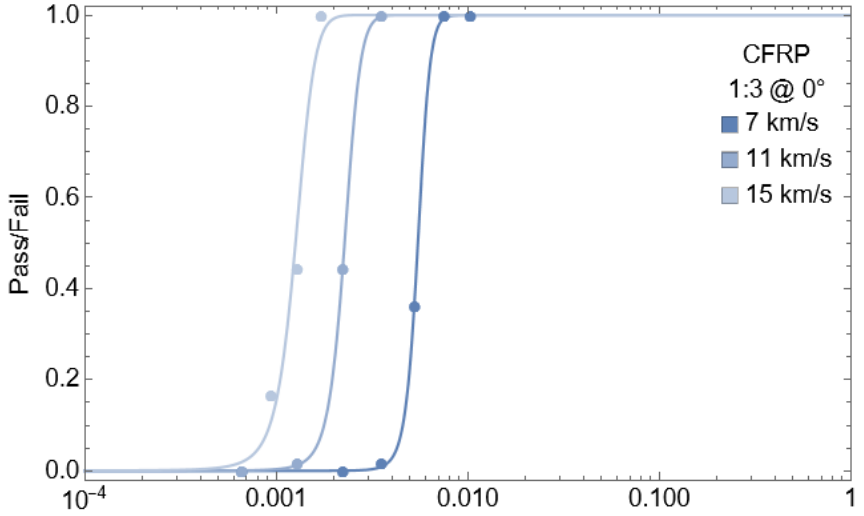
45° to Normal Impact

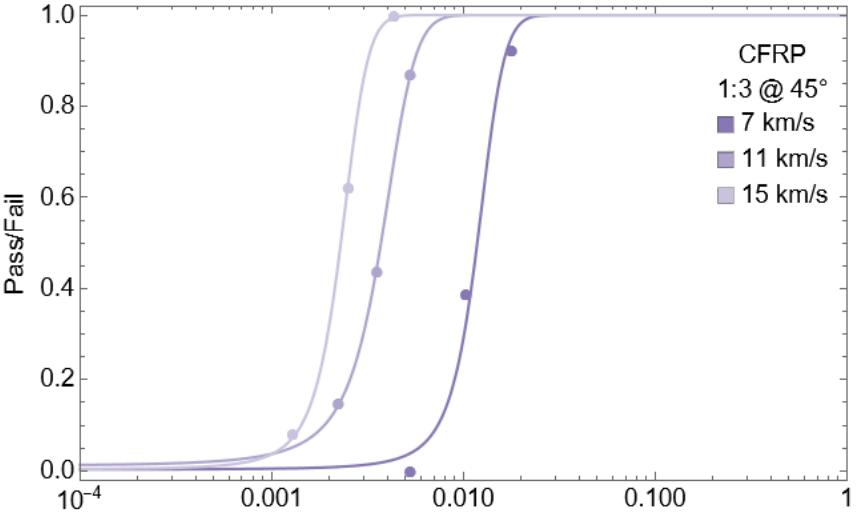


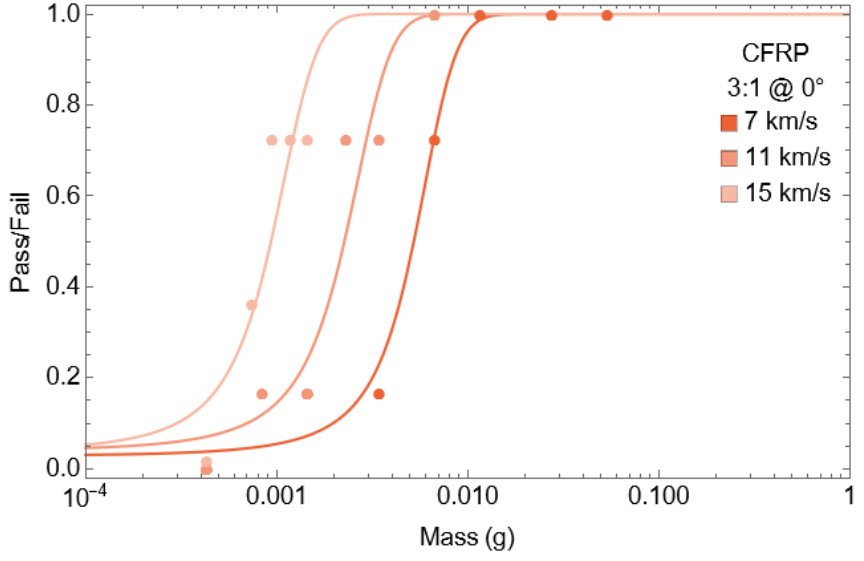


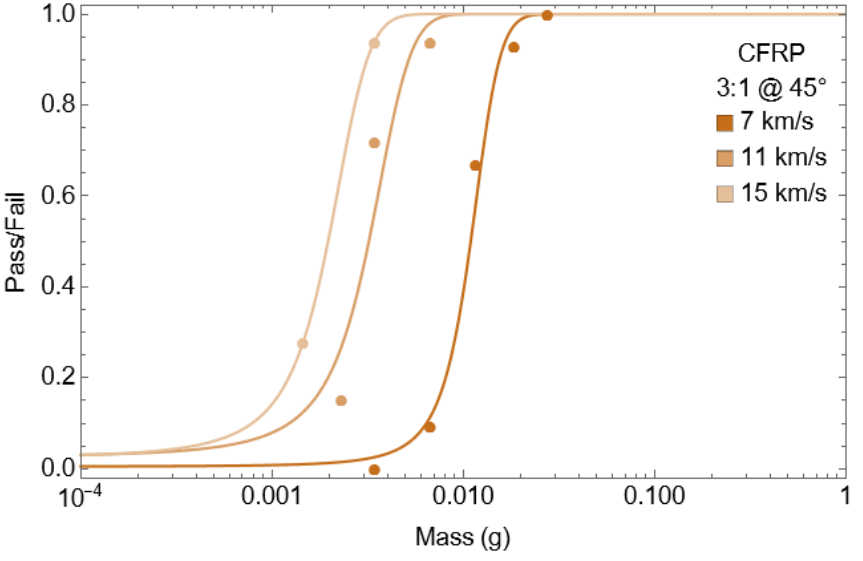


Evaluating for different projectiles at various conditions leads to mean probability of failure

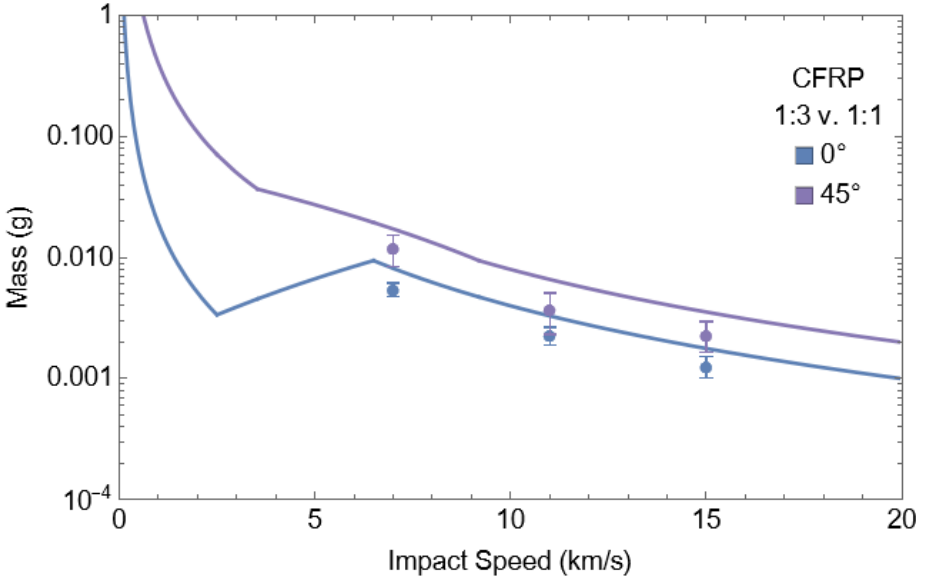


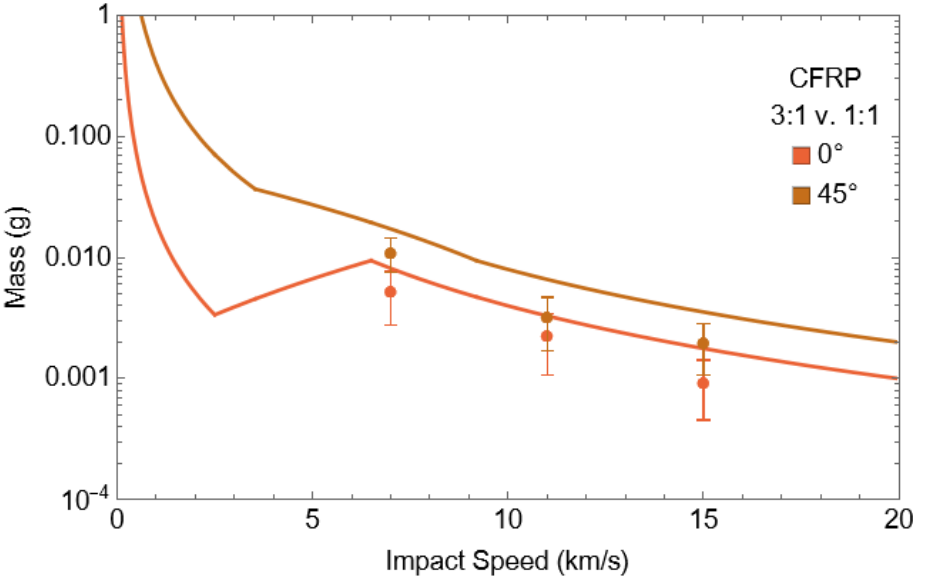




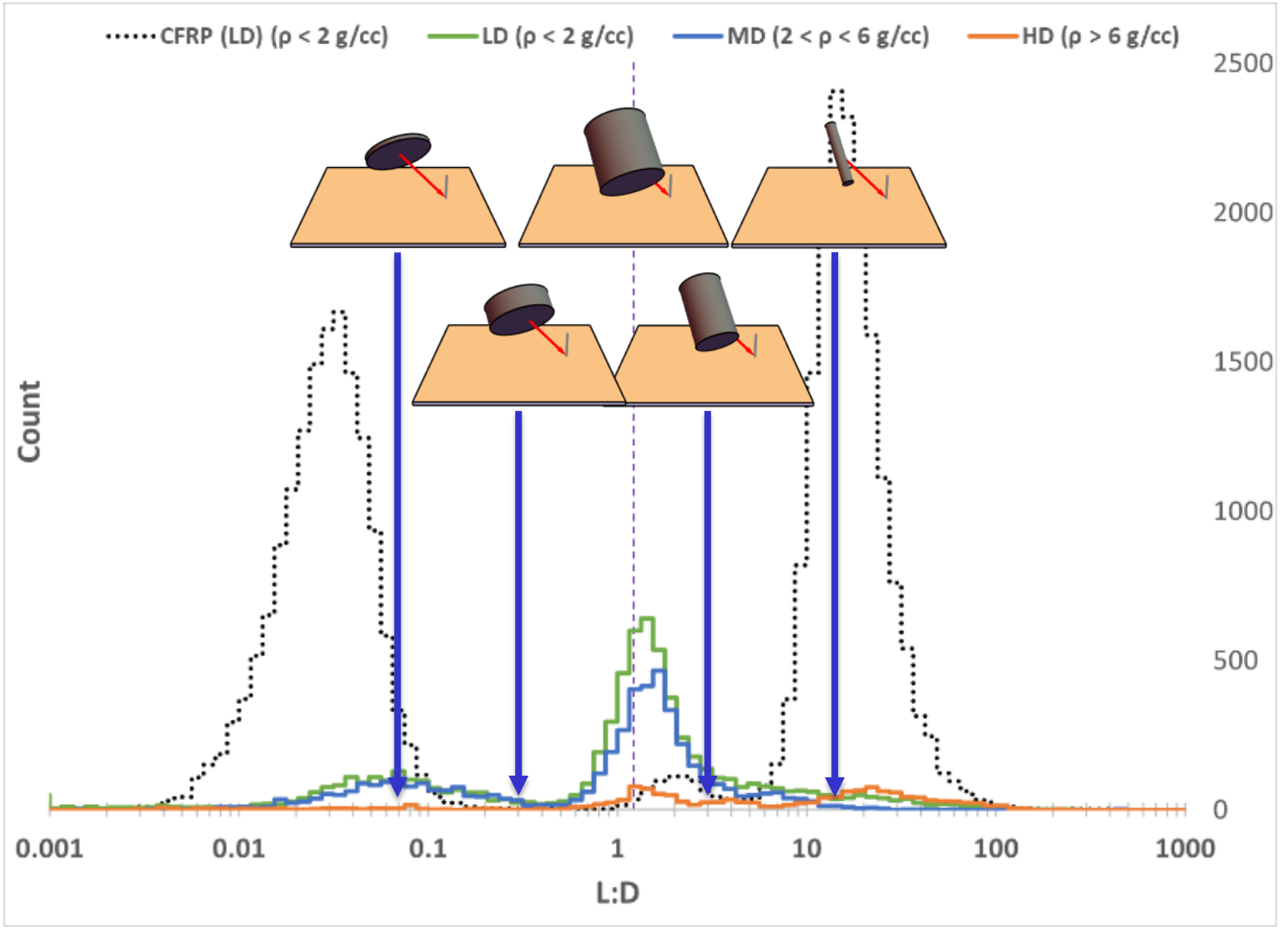


The mean of the probability of failure compared to existing spherical ballistic limit equations



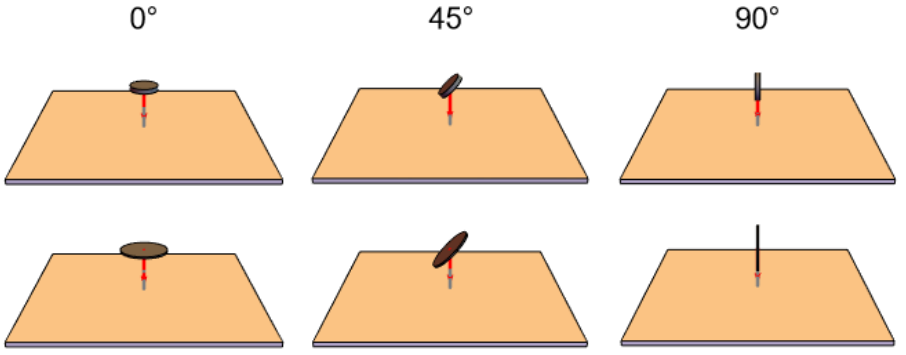


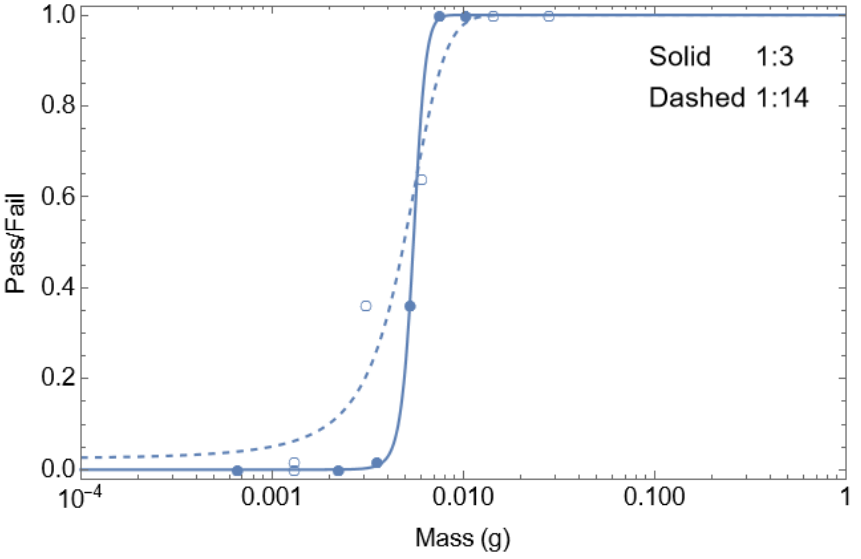
Additional non-spherical aspect ratios and materials can be related to existing equations



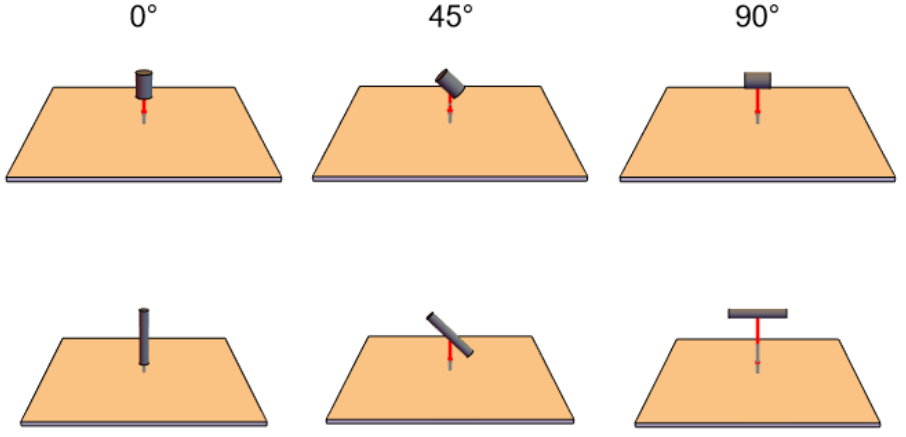
Comparison of length to diameter for CFRP projectiles at 7 km/s and normal impact

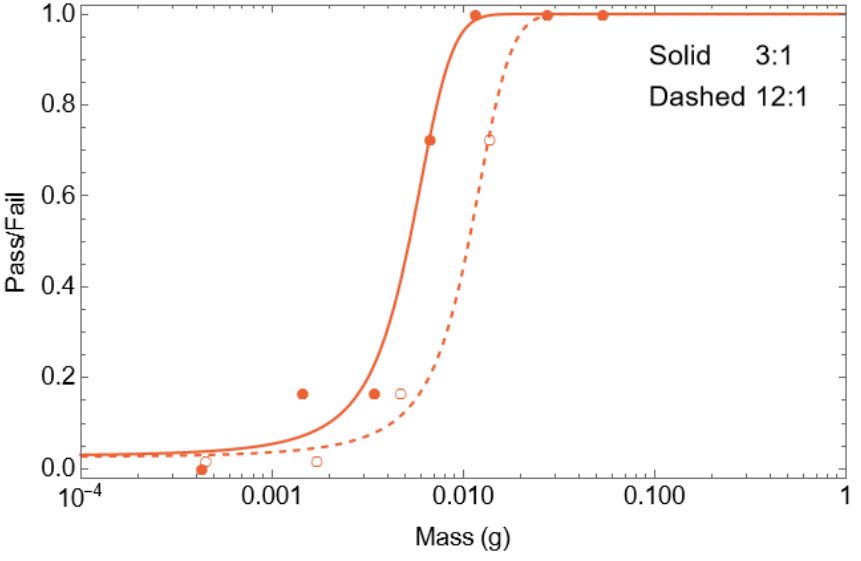
Top - L:D = 1:3 Bottom – L:D = 1:14



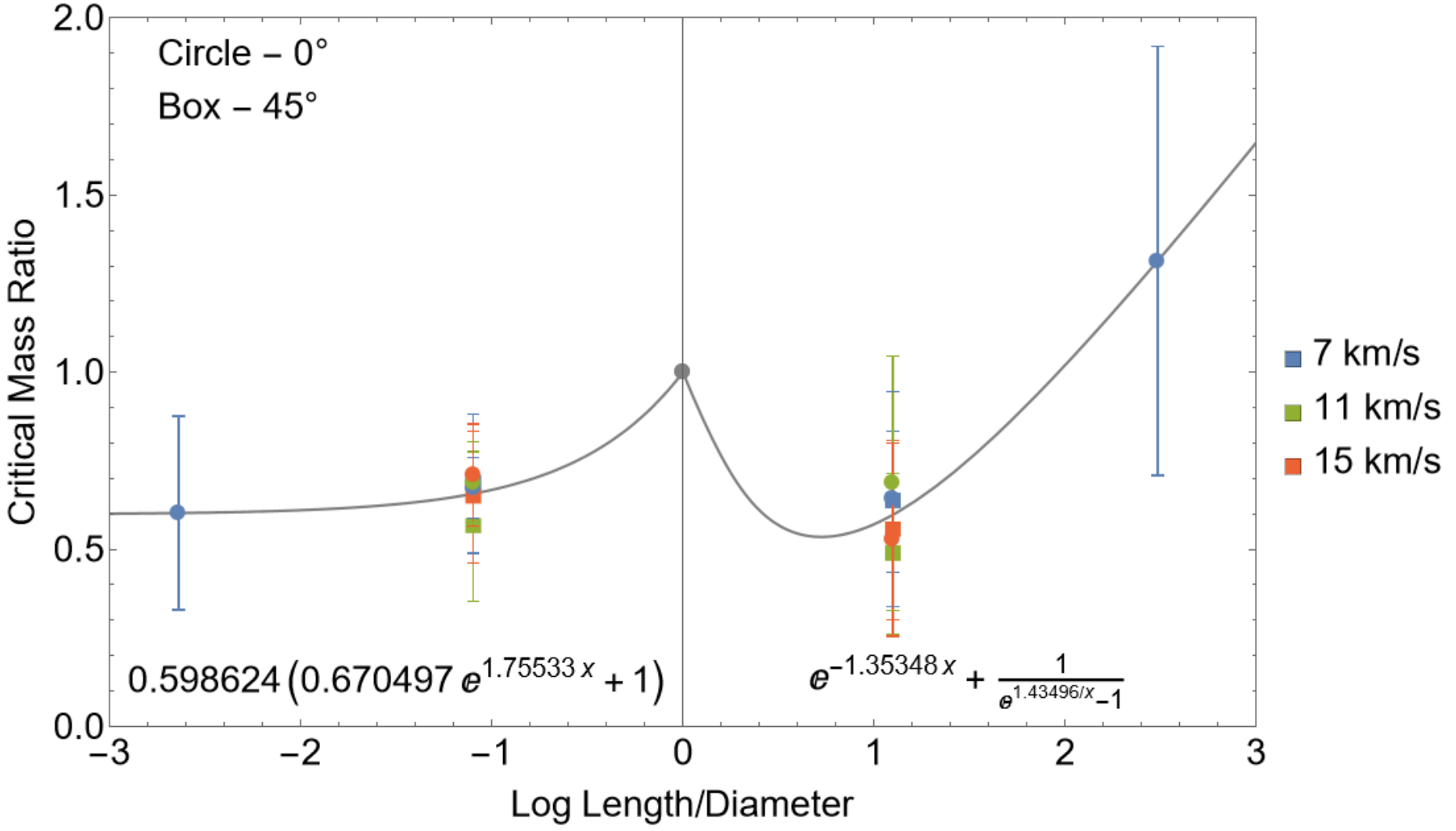


Top - L:D = 3:1 Bottom – L:D = 12:1

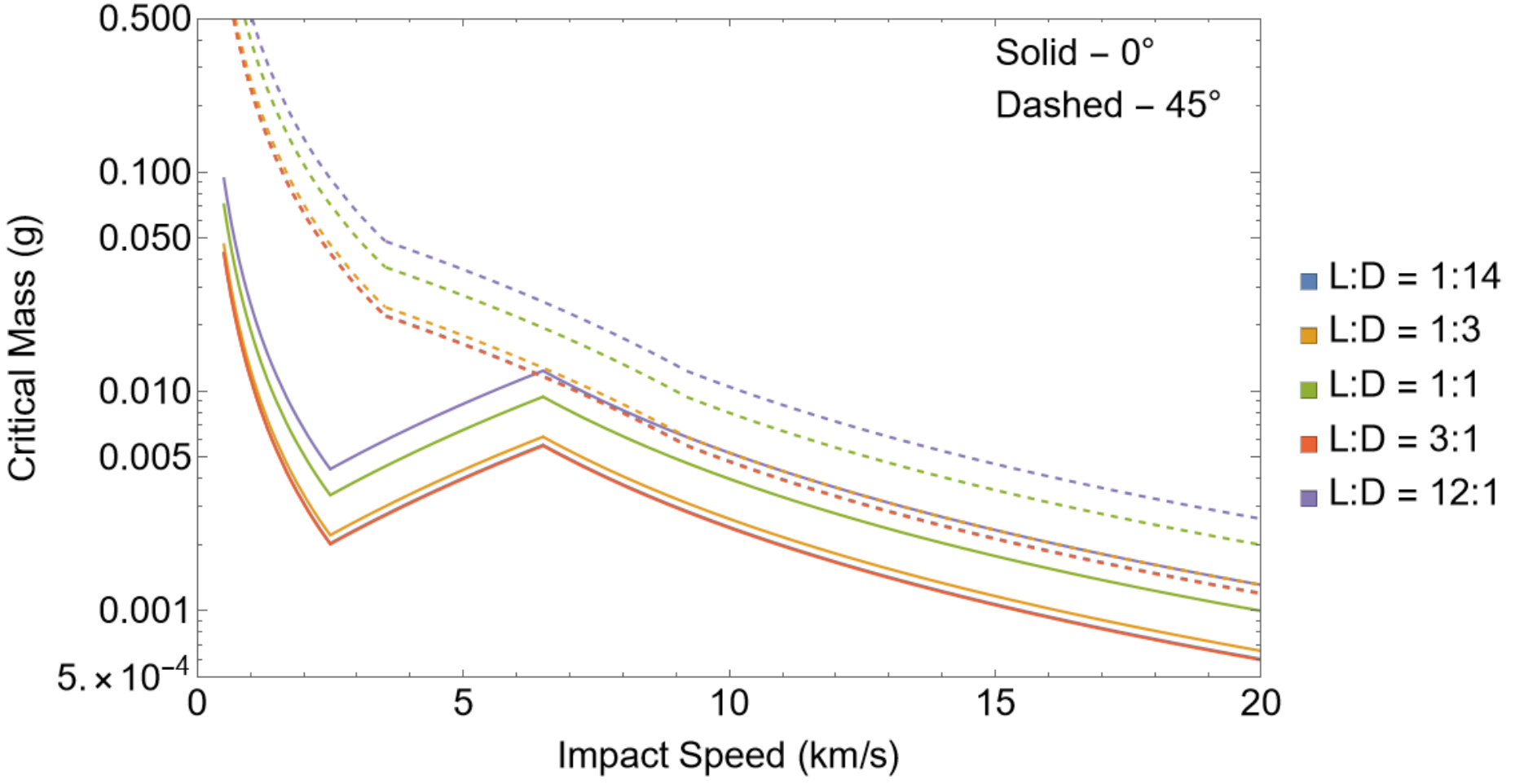




The length to diameter dependence for CFRP for the studied impact speeds and obliquities



The dependence applied to existing equations for Whipple shields of non-spherical projectiles



Forward Work

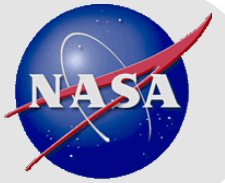


- **Adding in high-density (steel and copper) and medium-density (aluminum) along with high and low fineness ratio (L:D)**
- **Varying Al Whipple shield bumper and rear wall thickness to determine dependence as well as varying separation between the walls for that dependence**
- **Changing to different bumper materials (MLI and composite panels) and different rear wall materials (composite panels, steel, copper, and titanium)**

Forward Work (Cont)



- **So far validation data has been developed for monolithic materials (Ti, SS and Cu), Al Whipple Shields, TPS materials, enhanced MLI blankets and MLI bumper double wall shields**
  - Numerical modeling is progressing on each of these spacecraft shields
  - Future work will consider shield systems like multi-shock shields/stuffed Whipple shields and variations of the double-wall shield with composite panels
  - Future efforts will add aluminum to the projectile set on a subset of these shields



BACKUP

Small changes of projectile orientation result in different results for the same impact conditions

