Status of NASA Research on Projectile Shape Effects-Impact Simulations

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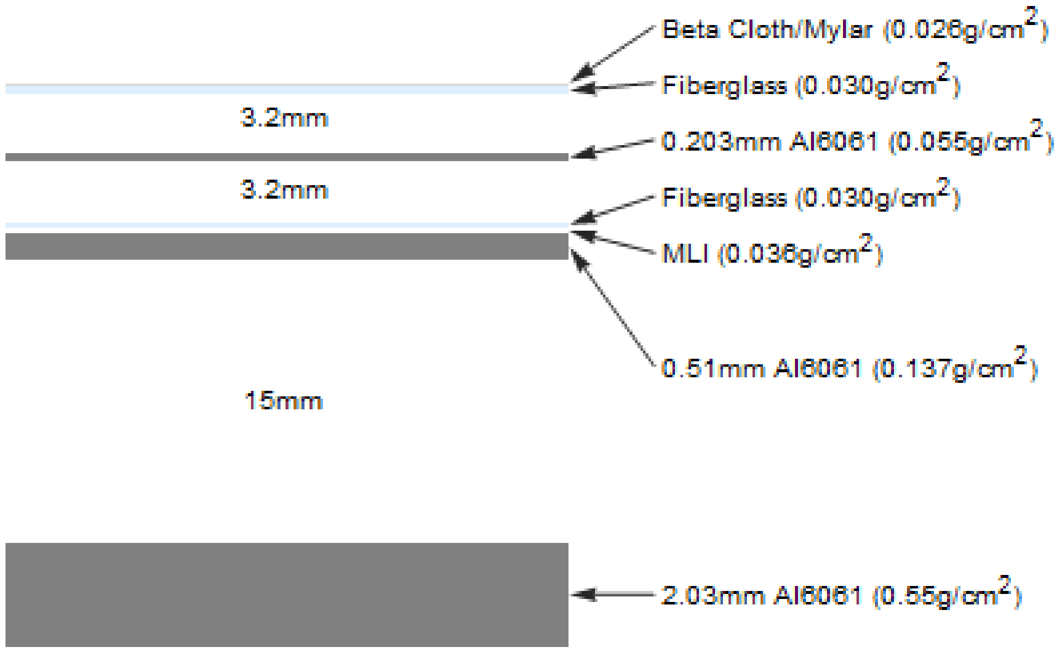
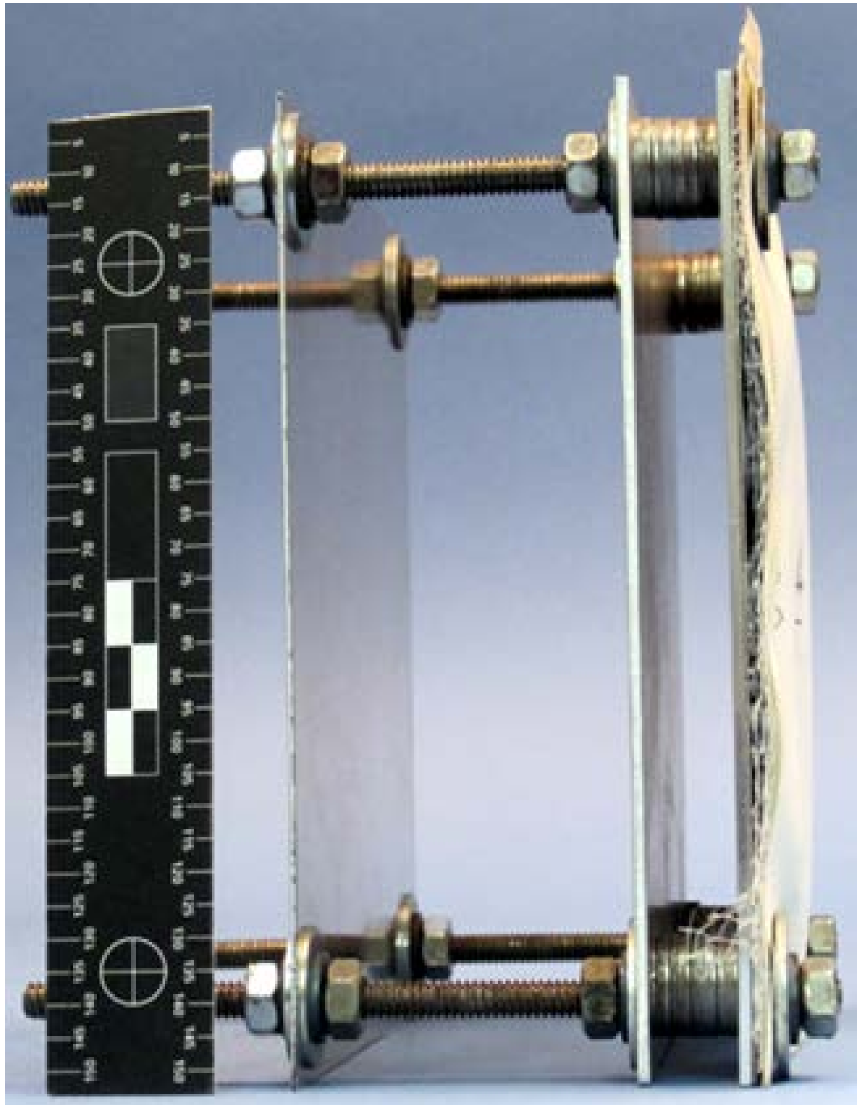
Numerical evaluation of a Whipple shield has yielded a ballistic model for cylindrical projectiles

- A numerical model of a Whipple shield covered with a thermal-blanket that is representative of operational shields has been developed using CTH
  - The shield model has been evaluated against existing test data
  - The projectile model has been developed from preexisting models for graphite-epoxy materials
- The model has been used to identify projectile characteristics at the ballistic limit for spherical and cylindrical projectiles
  - Considered normal impacts of the shield at 7 km/s
  - Varied the angle between the axis-of-symmetry and velocity vector
  - Varied the length to the diameter ratio over a broad range
- The results have been consolidated into a generalized model that can be adapted to existing spherical models

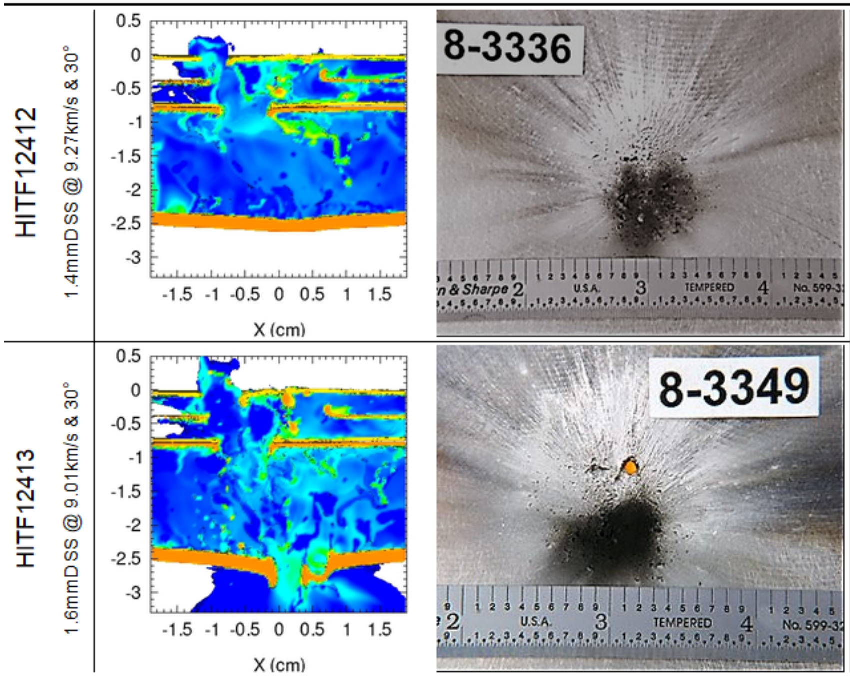
Simulations explored a Whipple shield with an external thermal blanket

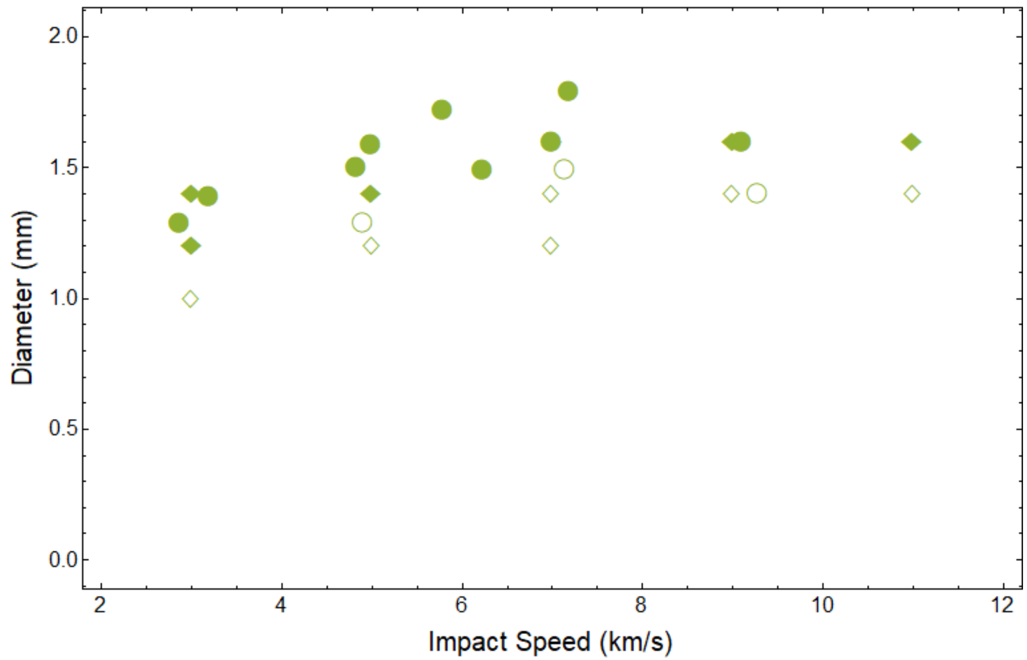


Schematic for numerical simulation (layers scaled by mass; separations to scale), which represents a previously considered shield. [Lyons2013, Davis2013]



Shield model validation using spherical, steel projectiles

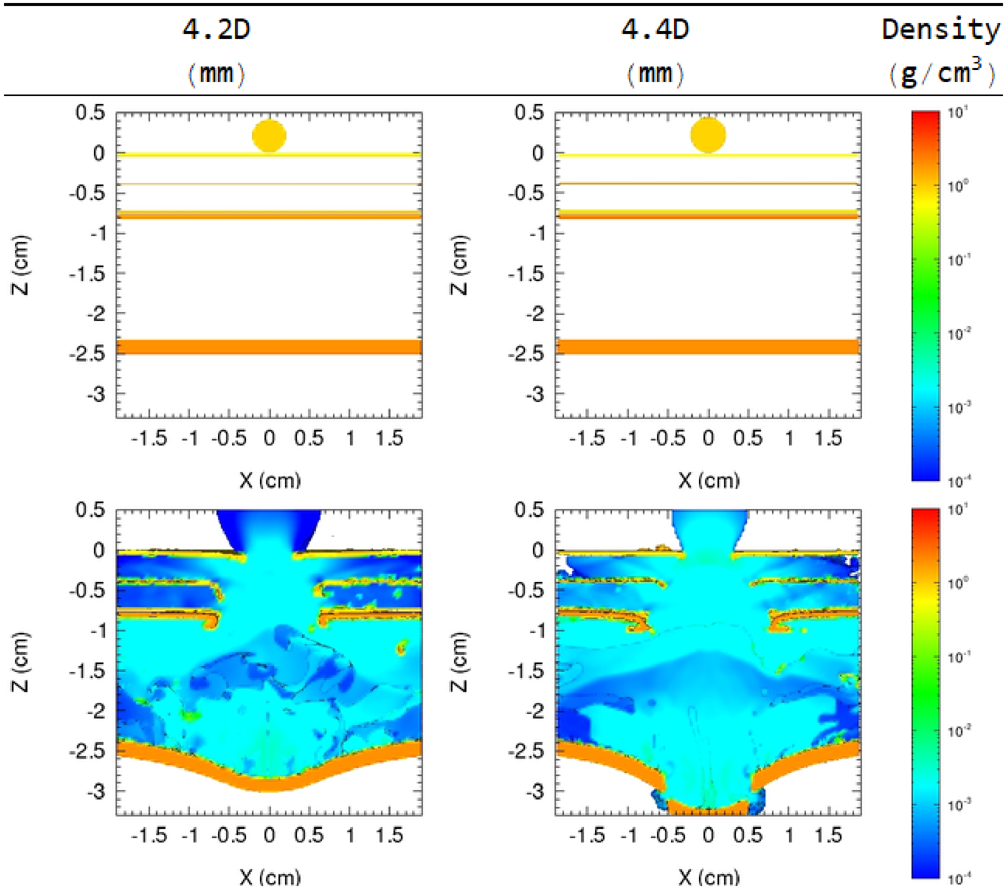




G. I. Kerley, "Equations of State for Composite Materials", KPS99-4, December (1999).
Steinberg, D.J., "Equation-of-state and strength properties of selected materials", UCRL-MA-106439 (1991).
G. I. Kerley, "Theoretical equation-of-state for aluminum", International Journal of Impact Engineering, 5, pp. 441-449 (1987).
G. I. Kerley, "Multiphase equation-of-state for iron", SAND93-0227 (1993).

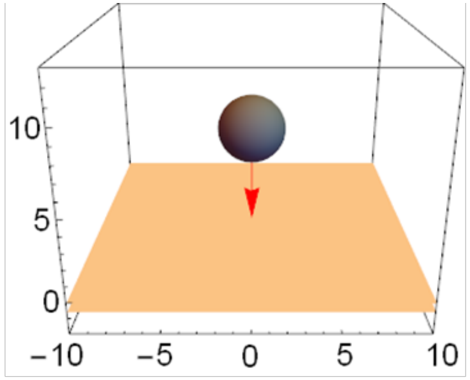
Circles-F. Lyons, NASA Johnson Space Center report 66540 (2013)
Circles-B. A. Davis, NASA Johnson Space Center report 66578 (2013)
Diamonds-J. E. Miller, NASA Jonson Space Center report 67212 (2018)
Open symbols-Intact shield wall
Filled symbols-Perforated shield wall
Circles-Impact tests
Diamonds-Simulation results

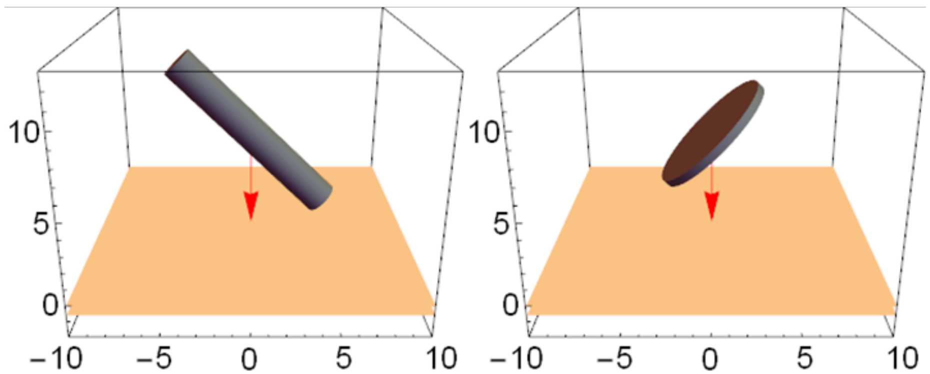
Simulations can be used to augment testing especially in difficult to obtain conditions



Spheres require about four ballistic variables: $\mathcal{B}[\mathcal{D}, U, \theta, \mathcal{M}]$

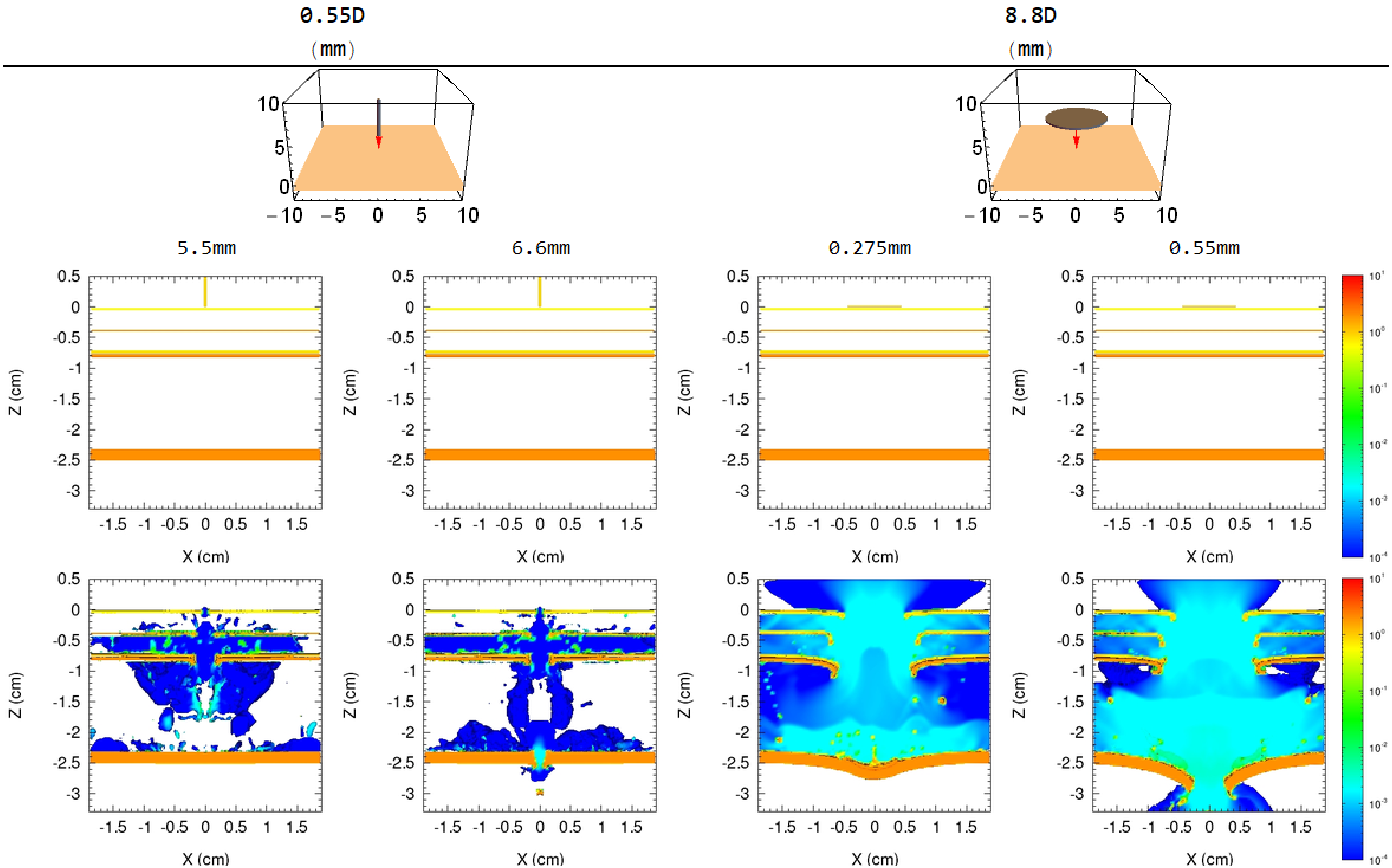
Even extending to axisymmetric shapes adds variables that greatly expand parameter space



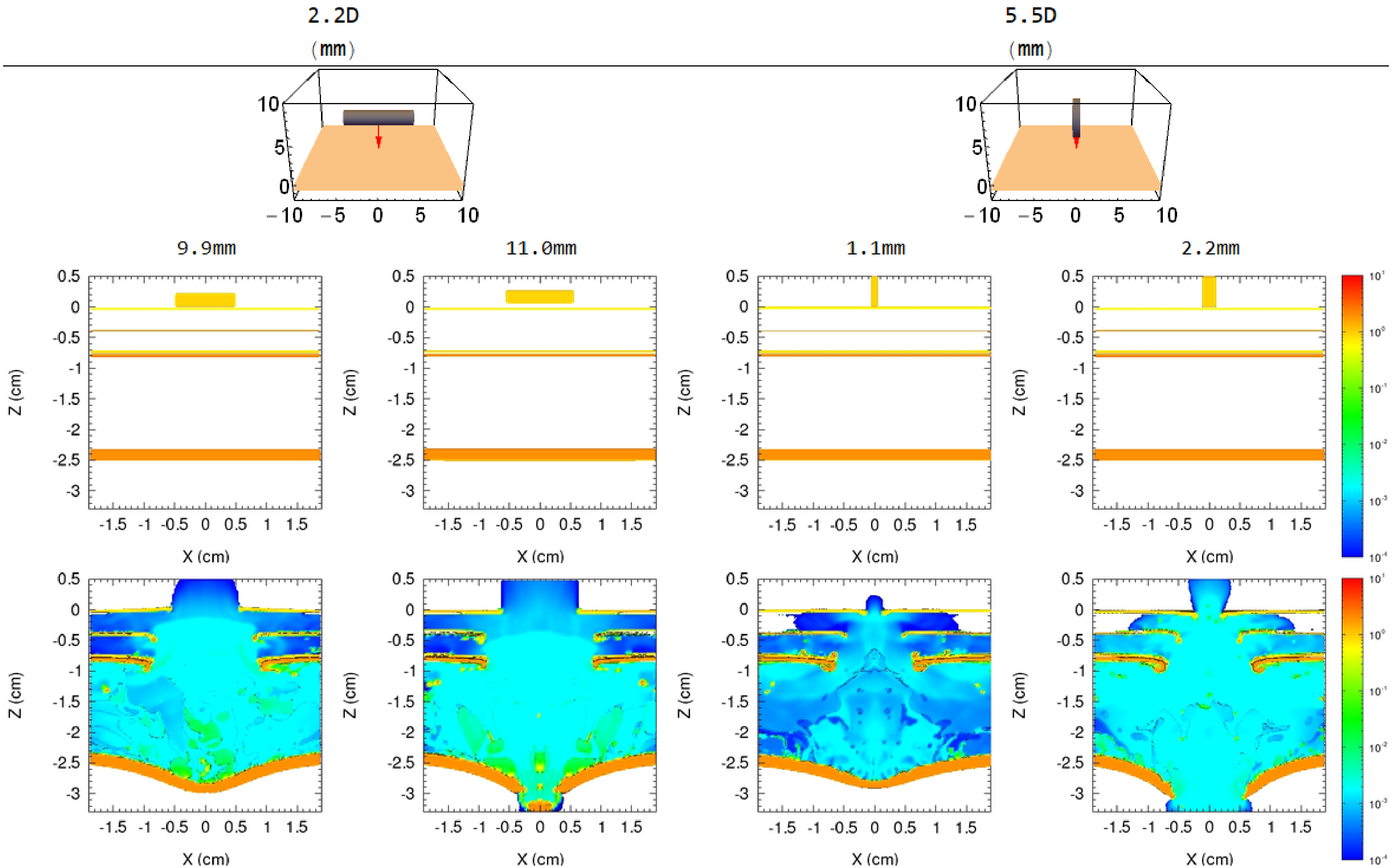


Non-spherical shapes add additional ballistic variables: $\mathcal{B}[\mathcal{D},\mathcal{L},U,\theta,\mathcal{M}, \varphi, \psi]$

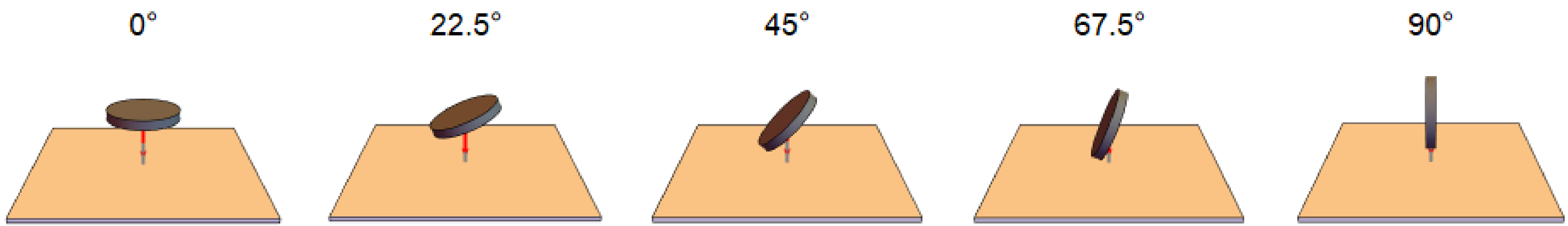
Simulations have identified the critical length of a cylinder aligned to the velocity vector

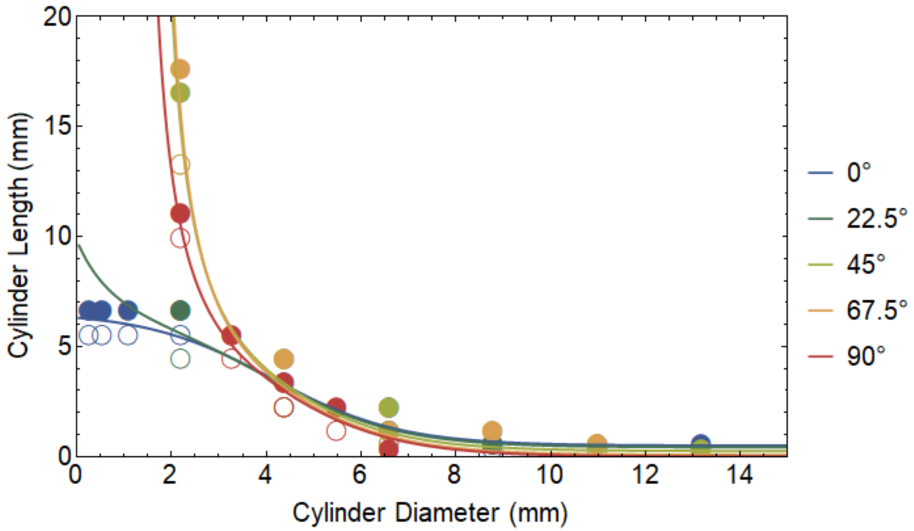


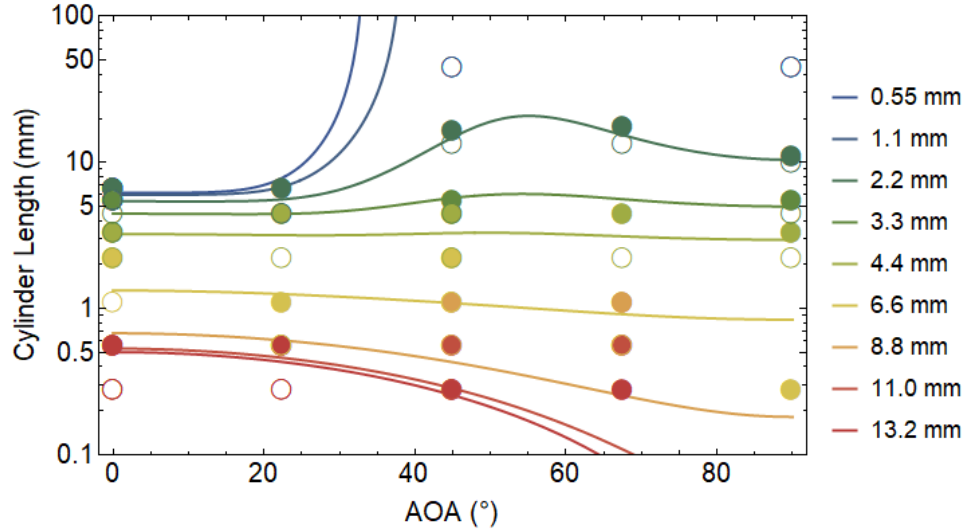
Simulations have identified the critical length of a cylinder rotated orthogonal to the velocity vector



A study has yielded a critical length model based on cylinder diameter and attack angle



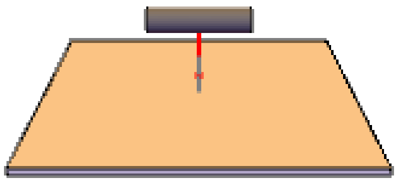


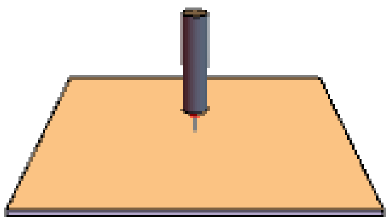


$$L_{Cyl}[D_{Cyl},\alpha]=\left(0.5\,\mathrm{Cos}[\alpha]^2+3.04\,\mathrm{Coth}\left[0.51\left(9.26-26.79\,\mathrm{Sin}[\alpha]+16.33\,\mathrm{Sin}[\alpha]^2+D_{cyl}\right)\right]\left(1-\mathrm{Tanh}[0.37\,(-4.13+D_{cyl})]\right)\right)$$

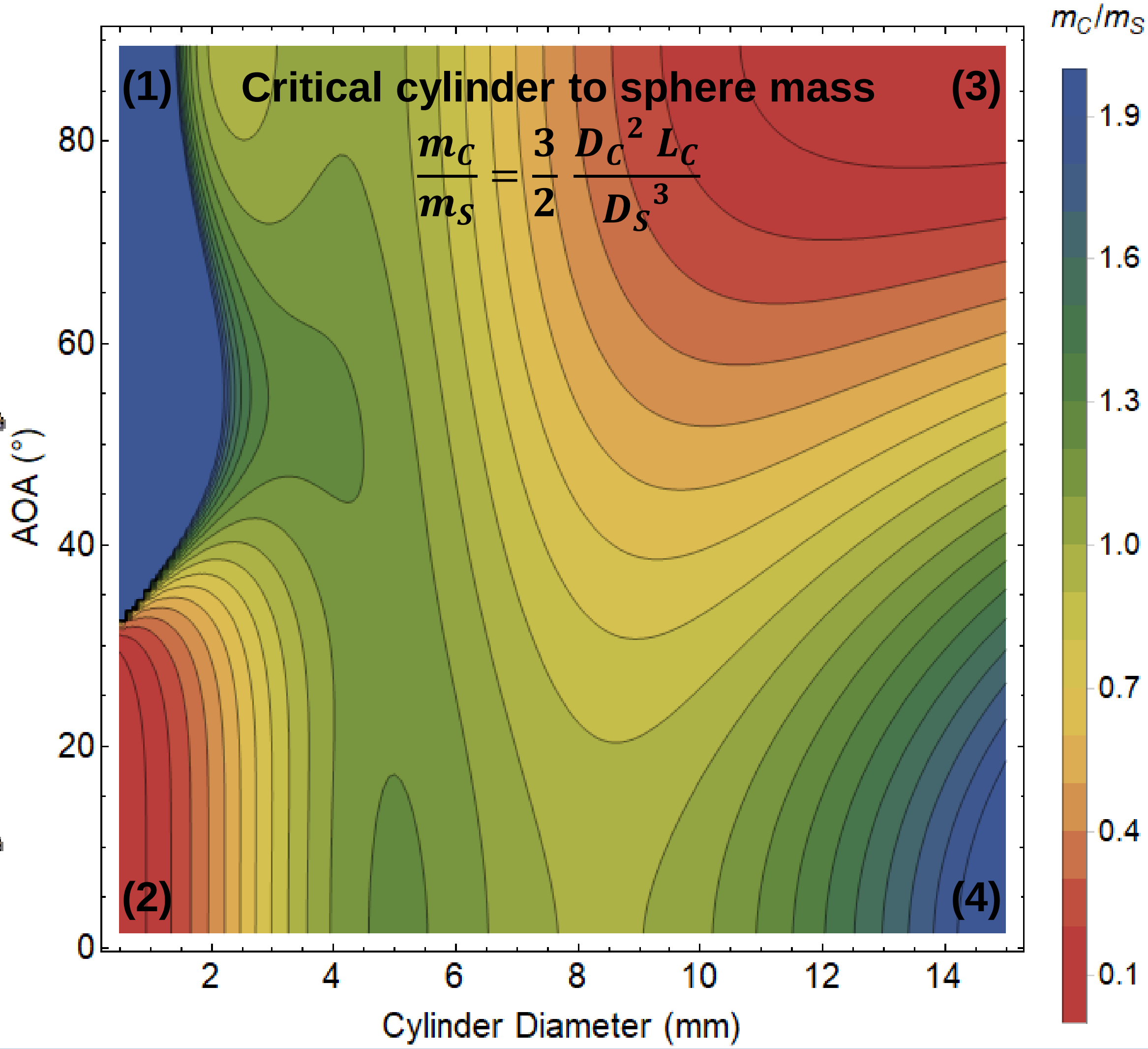
The critical cylinder mass to critical sphere mass highlights regions needing exploration

1) Small diameter orthogonal to the velocity vector

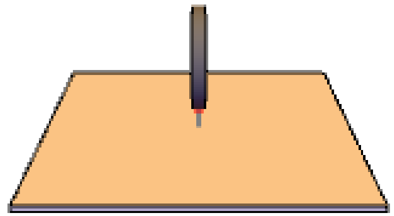


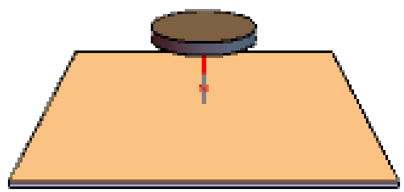


2) Small diameter aligned to the velocity vector



3) Large diameter orthogonal to the velocity vector



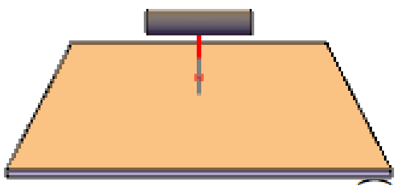


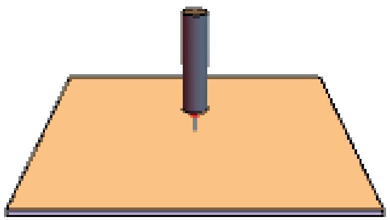
4) Large diameter aligned to the velocity vector

A critical length model allows flexibility to adapting to environment modeling

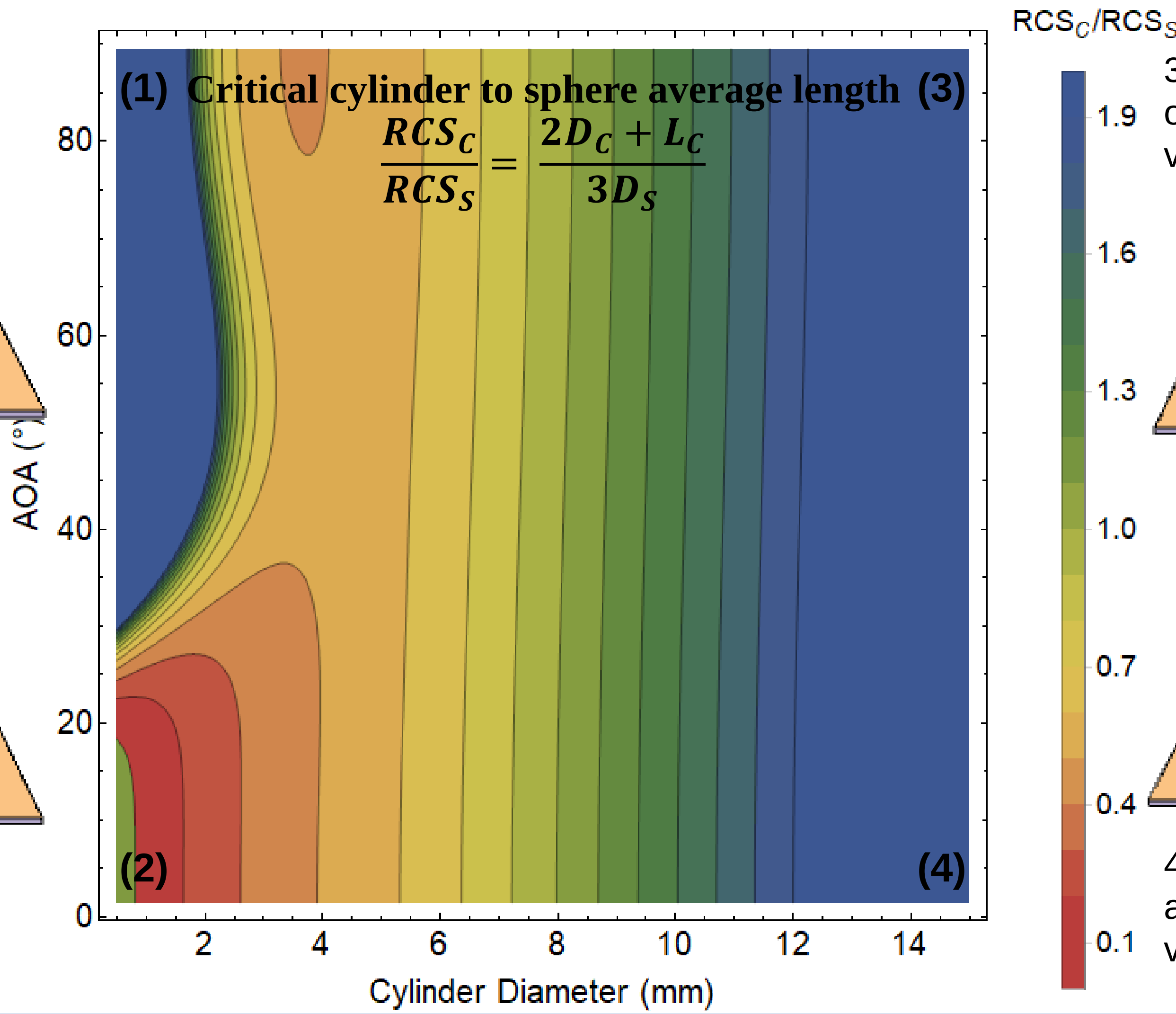
Average length of critical cylinder to critical sphere diameter highlights other areas

1) Small diameter orthogonal to the velocity vector

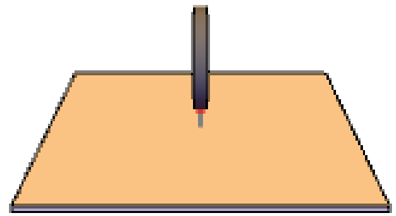


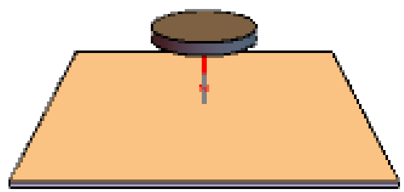


2) Small diameter aligned to the velocity vector



3) Large diameter orthogonal to the velocity vector

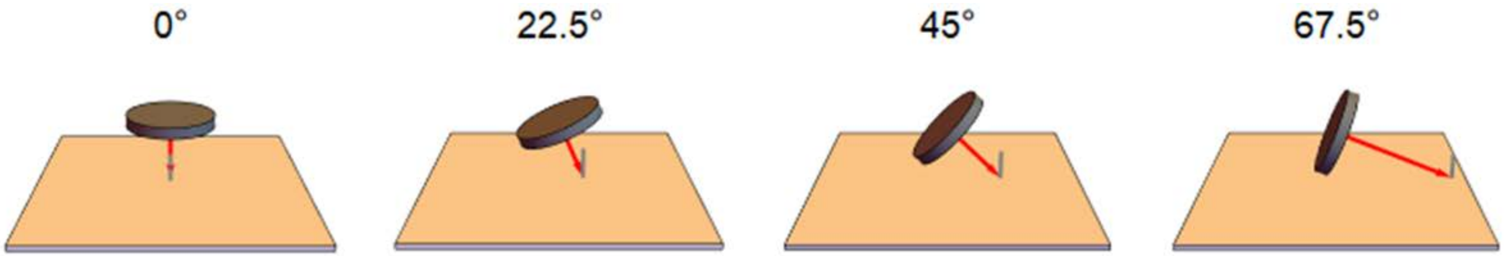




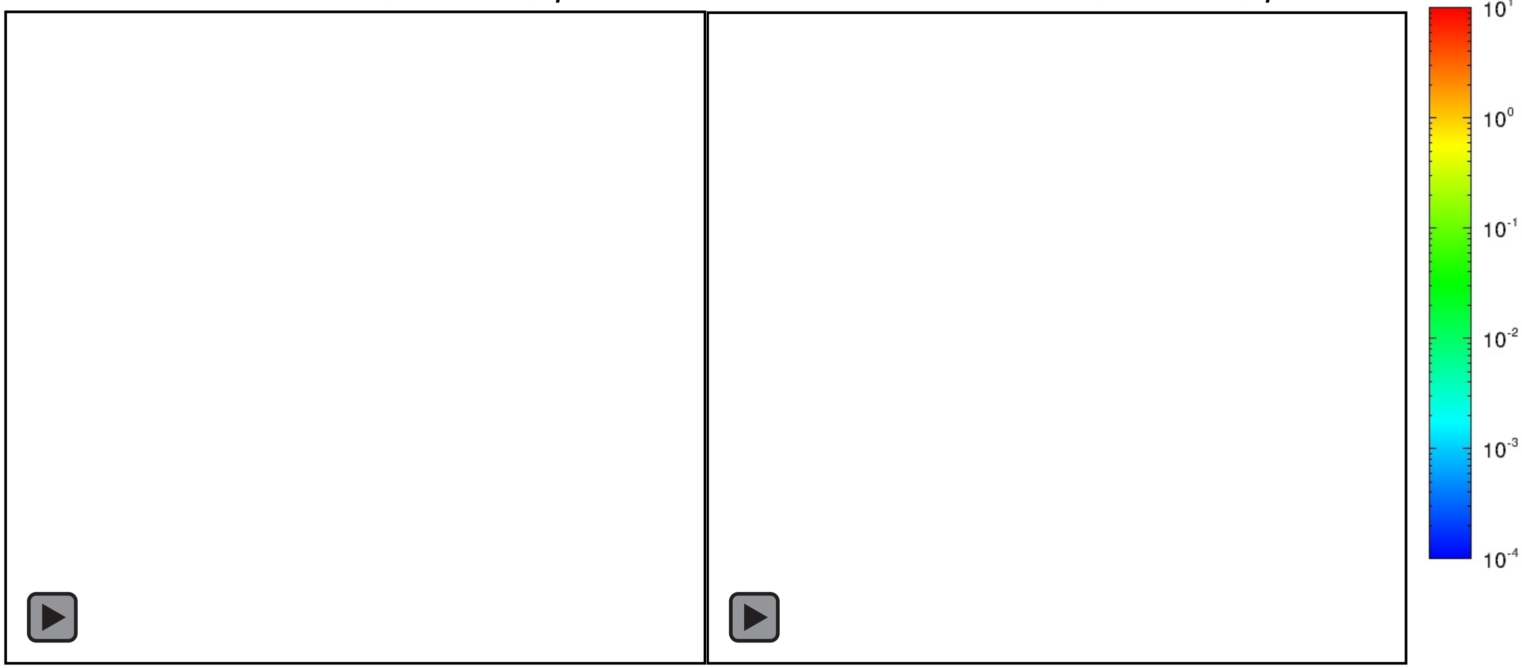
4) Large diameter aligned to the velocity vector

A critical length model allows flexibility to adapting to environment modeling

The critical length model has been adapted for oblique impacts with an angle of attack

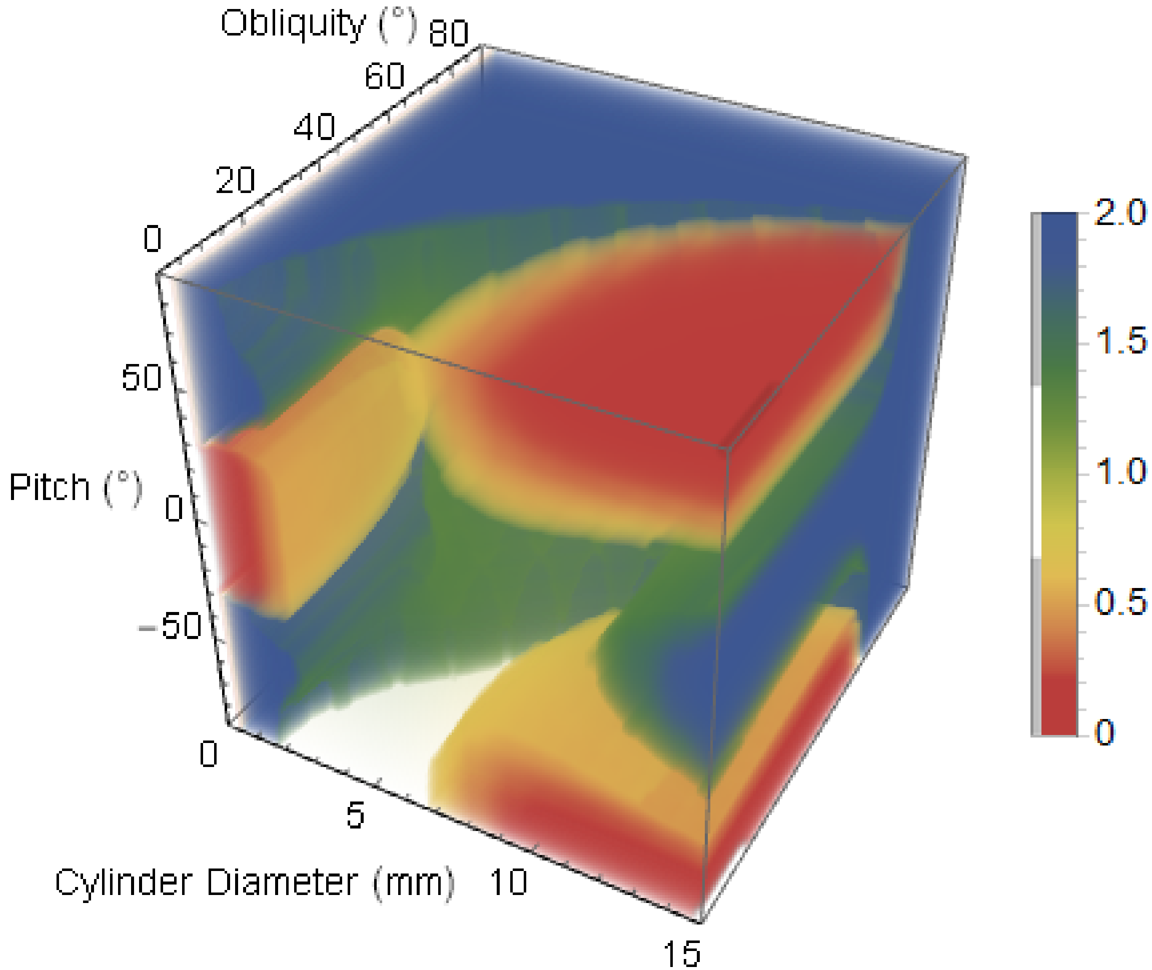


2.2D x 13.2 mm, θ = 45°, ψ = -22.5°   2.2D x 13.2 mm, θ = 45°, ψ = -67.5°



$$L_{Cyl}[D_{Cyl},\alpha,\theta]=\mathrm{Cos}[\sqrt{\alpha\,\theta}\,]^{0.5}\,(0.50\,\mathrm{Cos}[\alpha]^2+3.04\,(1-\mathrm{Tanh}[0.37\,(D_{Cyl}-4.13\,\mathrm{Sec}[\theta]^{1.15})])$$
$$\mathrm{Coth}[0.51\,\mathrm{Cos}[\theta]^{1.21}\,(D_{Cyl}-\mathrm{Cos}[\theta]^{6.22}\,(-9.26+26.8\,\mathrm{Sin}[\alpha]-16.3\,\mathrm{Sin}[\alpha]^2)-4.27\,\mathrm{Sin}[\sqrt{\alpha\,\theta}\,]^{3.42})])$$

The critical cylinder mass to critical sphere mass with obliquity included



$$L_{Cyl}[D_{Cyl},\alpha,\theta]=\mathrm{Cos}[\sqrt{\alpha\,\theta}]^{0.5}\,(0.50\,\mathrm{Cos}[\alpha]^2+3.04\,(1-\mathrm{Tanh}[0.37\,(D_{Cyl}-4.13\,\mathrm{Sec}[\theta]^{1.15})])\,\mathrm{Coth}[0.51\,\mathrm{Cos}[\theta]^{1.21}\,(D_{Cyl}-\mathrm{Cos}[\theta]^{6.22}\,(-9.26+26.8\,\mathrm{Sin}[\alpha]-16.3\,\mathrm{Sin}[\alpha]^2)-4.27\,\mathrm{Sin}[\sqrt{\alpha\,\theta}]^{3.42})])$$

Orbital Debris Fragment Shape Study Forward Work

- Task Plan
  - Assess ballistic limits for cylindrical rod-like and plate-like projectiles impacting thermal protection system (TPS) materials, shielding and spacecraft structures using hydrocode simulations and hypervelocity impact test results
    - Target types/failure criteria:
      1. General and specific single-wall materials (metals and thermal protection materials)
      2. General and specific multi-wall shields (Whipple shield, stuffed Whipple shield, etc)
    - Assess projectile density effects: low-density (graphite-epoxy), medium density (aluminum) and high-density (steel)
    - Assess impact velocity effects
    - Assess projectile orientation effects
    - Assess impact obliquity effects
- Together impact tests and numerical simulations will be used to develop ballistic limit equations for shaped projectiles into a variety of shields.