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# *Modeling the Fragmentation of Hypervelocity Impacts on a Dual-Wall Shield*

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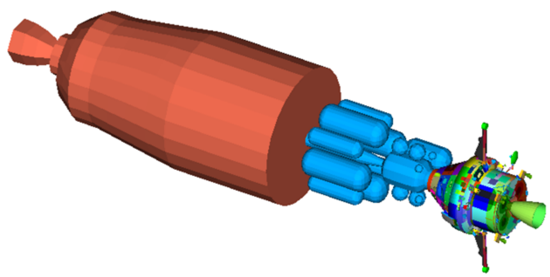
# Background

- Survivability assessments of space hardware require the use of ballistic performance models to predict the performance of a structure over a broad range of impact conditions and configurations
- Hypervelocity impact experiments, hydrodynamic simulations and analytical model development have been performed to improve the dual-wall shield models over a variety of impact conditions
  - Data from over 500 hypervelocity impact experiments on dual-wall shield configurations have been collected and analyzed
  - Hydrodynamic simulations have extended some of these configurations to above the 7-10 km/s threshold of low temperature launches
  - Empirical ballistic performance models have been developed that approximate the data, but extrapolation of the models can lead to incorrect conclusions
- A solution-based ballistic performance modeling approach has been developed here that improves the reliability of the extrapolations

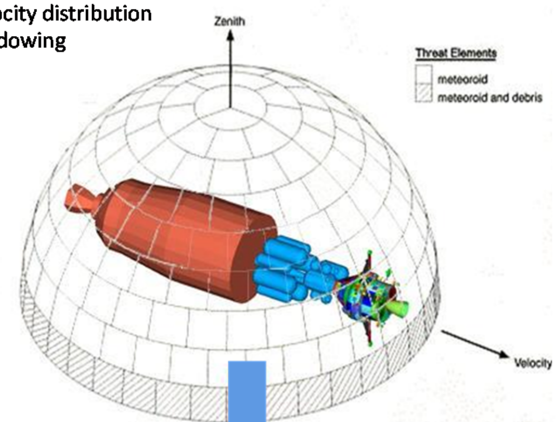
# Survivability Assessment Process

## Spacecraft Configuration (I-DEAS)

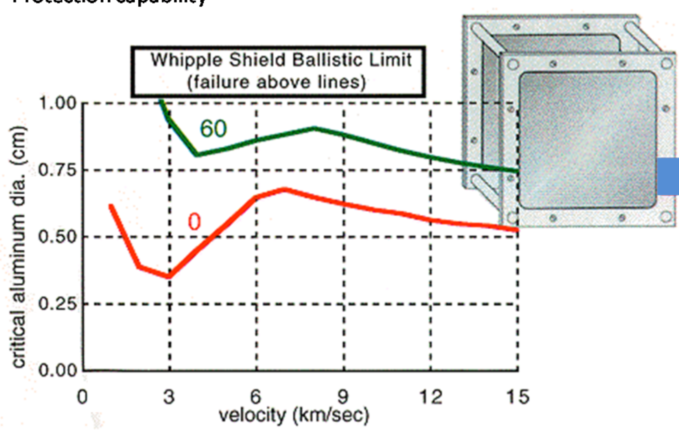


**I-DEAS Finite Element Model**
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions
- Defines MM/OD shield regions

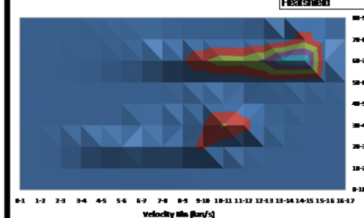
## Meteoroid & Debris Environments (GEOMETRY)
- Threat directions
- Velocity distribution
- Shadowing

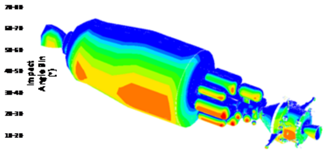



## Critical Particle Diameter Calculation (RESPONSE)
- Protection capability




| CEV - Orion Micrometeoriod and Orbital Debris Theat Assessment | | | |
|---|---|---|---|
| System | Loss of Crew | | |
| | PNCL | LOC | Risk 1-in-X |
| CM Backshell (AETB8) | 0.99960946 | 0.00039054 | 2,561 |
| SM Propellant Tanks | 0.99997665 | 0.00002335 | 42,827 |
| LIDS | 0.99998500 | 0.00001500 | 66,667 |
| SM HP COPV Tanks | 0.99998983 | 0.00001017 | 98,284 |
| Umbilical | 0.99999636 | 0.00000364 | 274,618 |
| CM Docking Hatch (AFRSI) | 0.99999682 | 0.00000318 | 314,021 |
| SM Avionics / ECLSS | 0.99999732 | 0.00000268 | 372,544 |
| CM Other Thermal Barriers | 0.99999764 | 0.00000236 | 423,105 |
| CM Windows | 0.99999767 | 0.00000233 | 429,014 |
| Heatshield | 0.99999836 | 0.00000164 | 609,417 |





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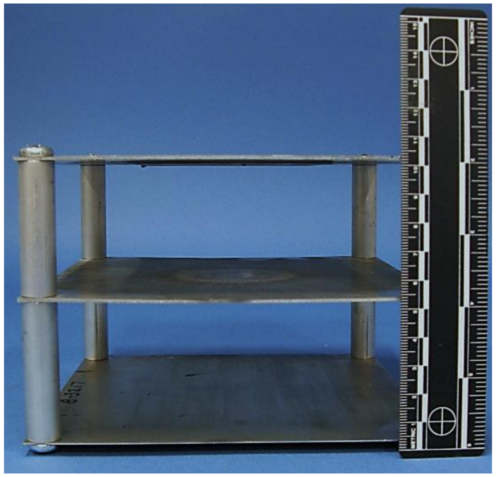
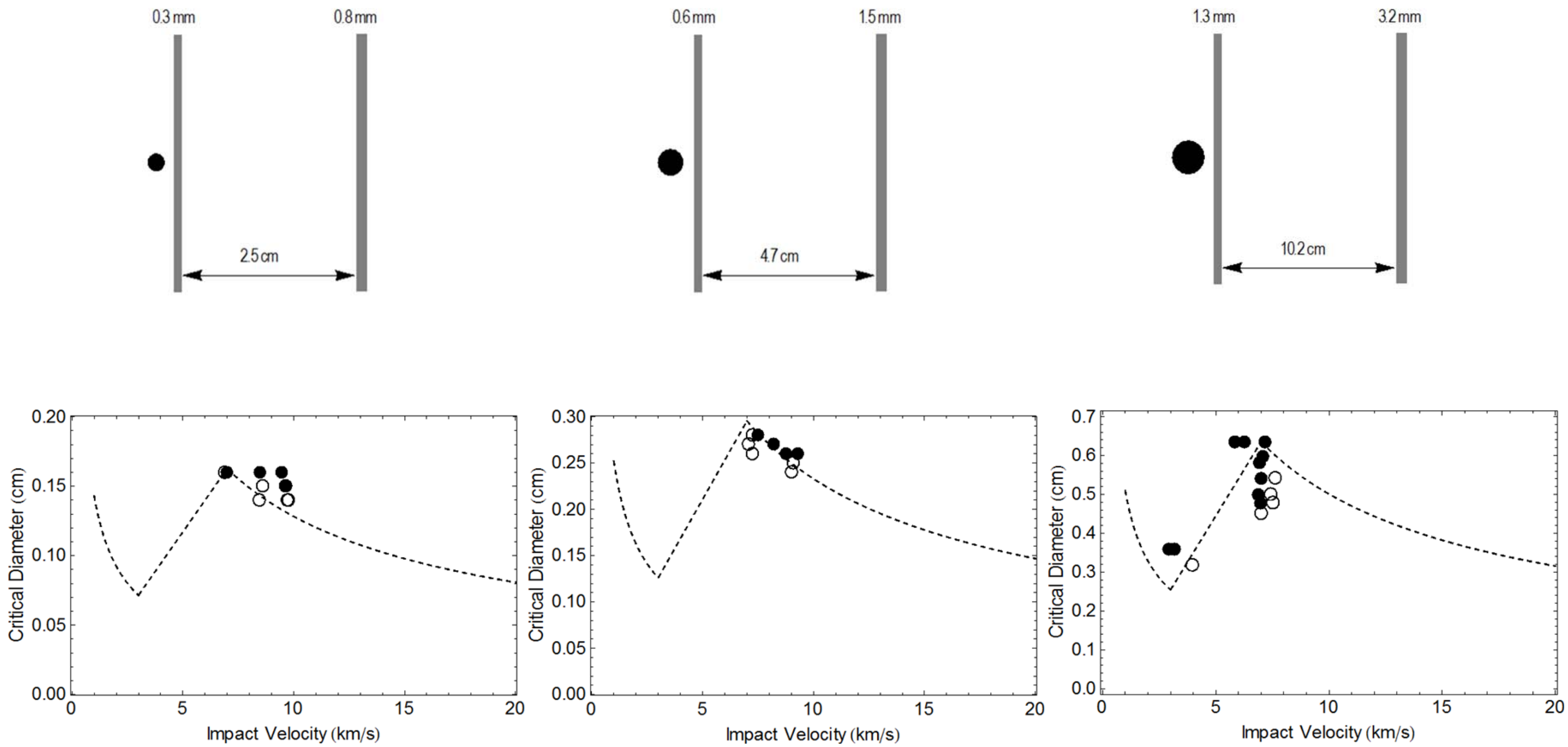
# Hypervelocity Impacts Database

- Spherical projectile launches performed by:
    - UDRI with maximum velocities of ~10 km/s
    - WSTF with maximum velocities of ~8.5 km/s
    - Many others at JSC, MSC, ARC and by contract companies to ~7.5 km/s
- ~500 double wall impacts have been performed
    - Impactors include Cadmium, Copper, Nylon, Glass, Aluminum, Alumina and Steel
    - Impact obliquities from normal to 75° to normal
    - Impact velocities from 3 to 10 km/s



# Empirical Ballistic Performance Models Can Lead to Discrepancies

Aluminum

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**Aluminum dual-wall shows non-linear scale effects**

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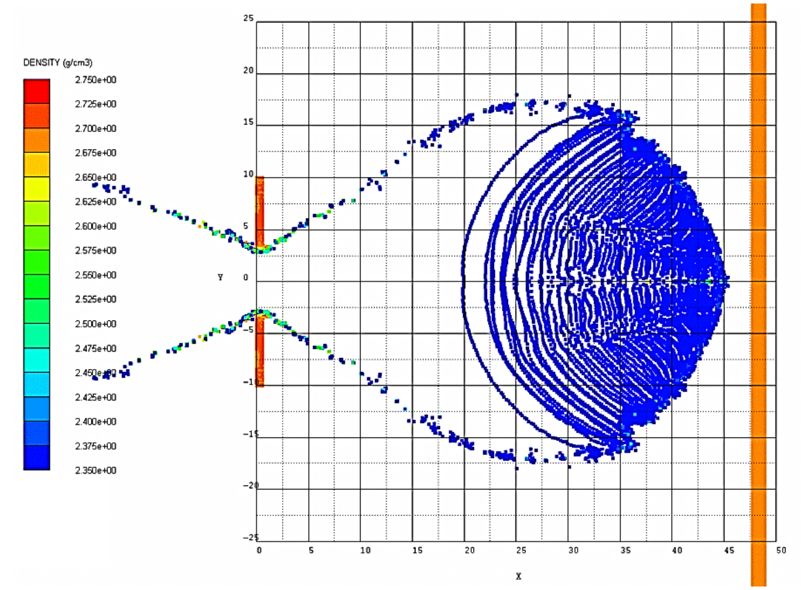
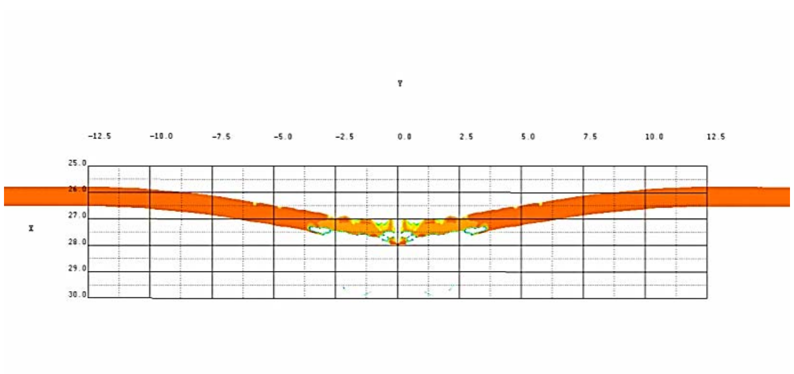
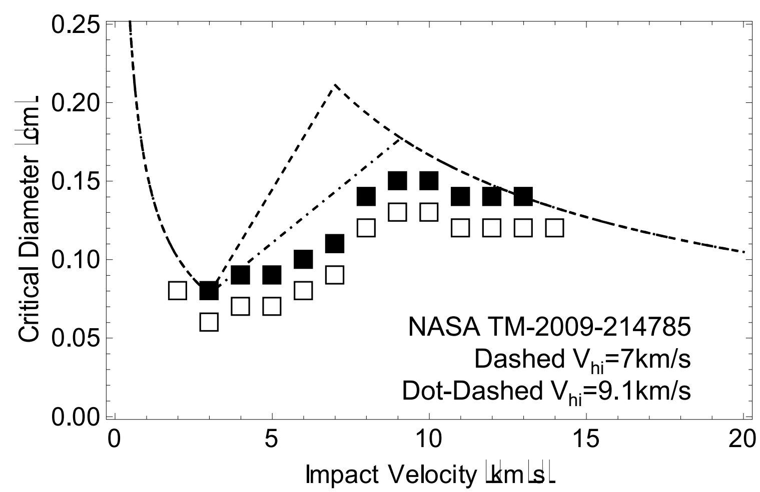
# Hydrodynamic Simulations Extend Impact Conditions Beyond Limits

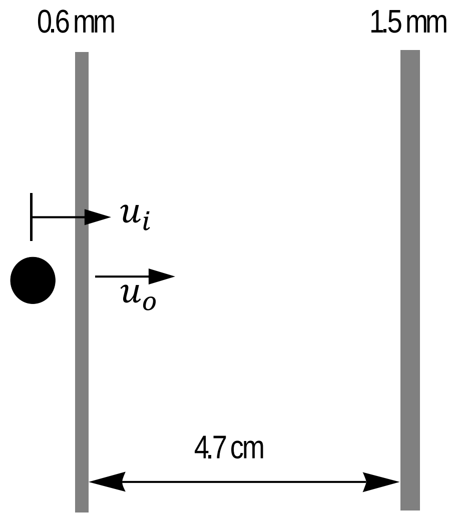
Steel

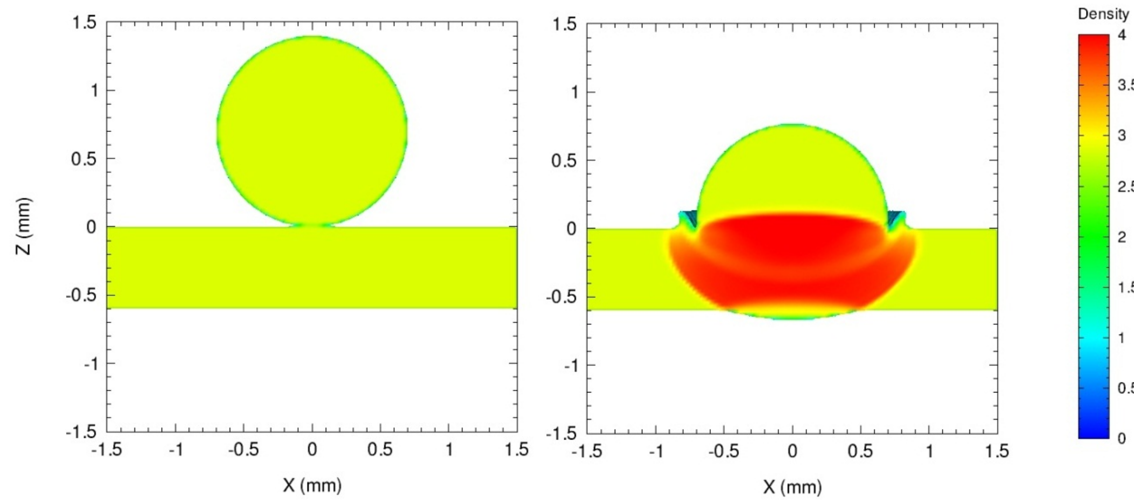



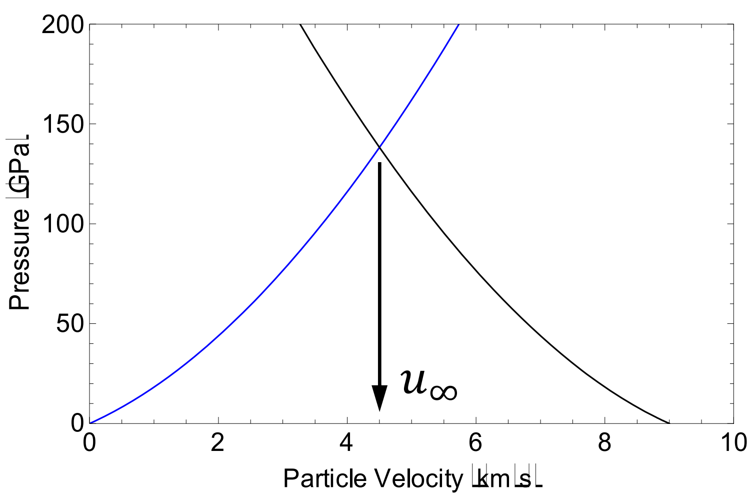





# First Wall Interaction




$$
u_o = \frac{\overline{m_W}}{\overline{m_i} + \overline{m_W}} \left( 1 + \frac{\rho_i (s_i (u_i - u_\infty) + c_i)}{\rho_W (s_W u_\infty + c_W)} \right) u_\infty
+ \frac{\overline{m_i}}{\overline{m_i} + \overline{m_W}} \left( 1 - \frac{\overline{m_W}}{\overline{m_i}} \frac{\rho_i (s_i (u_i - u_\infty) + c_i)}{\rho_W (s_W u_\infty + c_W)} \right) u_i
$$

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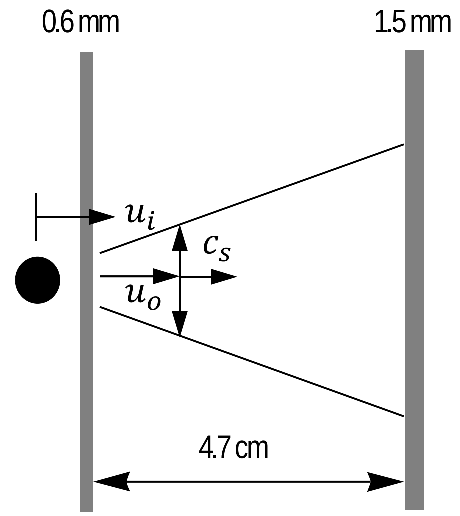
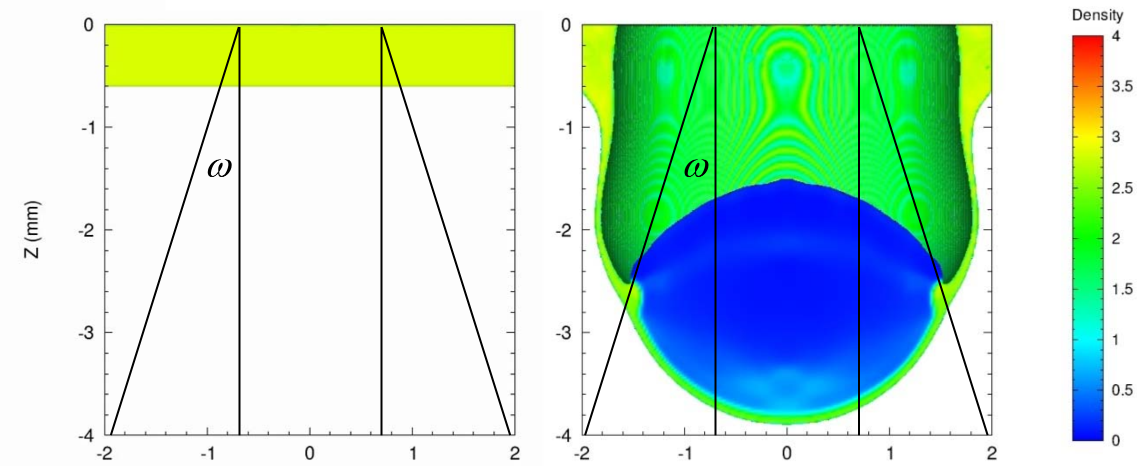
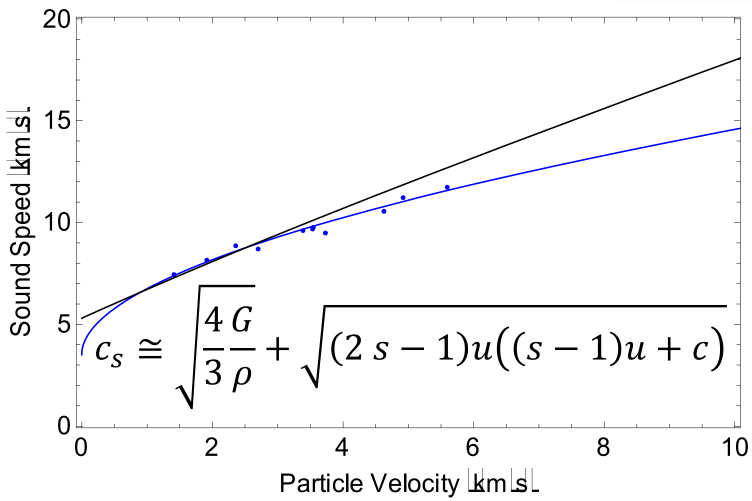
# Expansion Gap

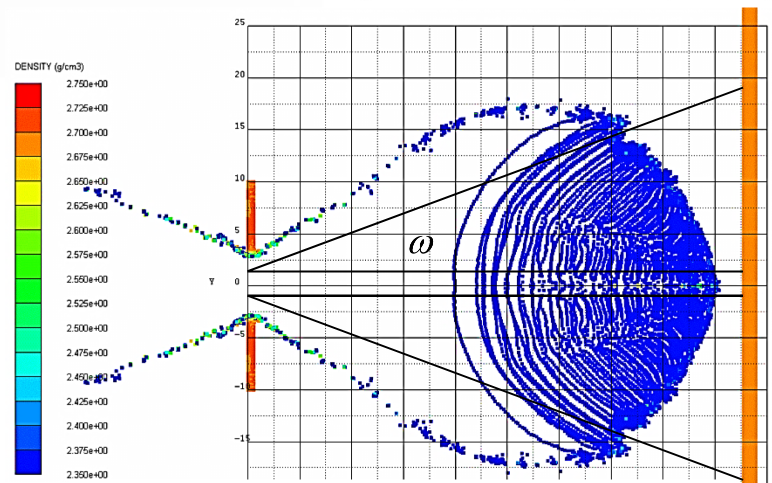



$$\omega = \frac{x - x_o}{z} = \frac{c_s}{c_s + u}\,\frac{\varepsilon_T}{\varepsilon_i} = \frac{c_s}{c_s + u_o}\left(1 - \frac{{u_o}^2}{{u_i}^2} - \frac{E\,d_p}{\rho_i\,{u_i}^2}\left(\frac{\sigma}{K}\right)^2\right)$$



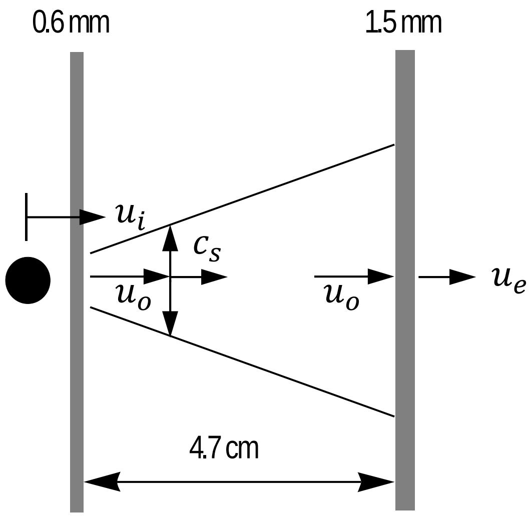




$$c_s \cong \sqrt{\frac{4}{3}\frac{G}{\rho}} + \sqrt{(2\,s-1)u\big((s-1)u + c\big)}$$



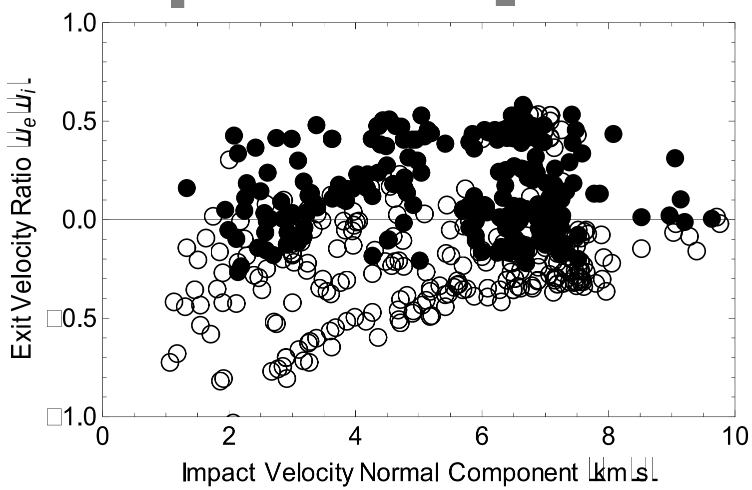

$$\overline{m_o} = \overline{m_i}\left(\frac{r_i}{r_i + \omega_i\,S}\right)^{2/3} + \overline{m_W}\left(\frac{r_i}{r_i + \omega_W\,S}\right)^{2/3}$$

# Second Wall Interaction




$$u_e = \left(u_\infty' + \frac{c_W'}{s_W' + 1}\right)\left(\frac{\overline{m_o}}{\overline{m_o} + \overline{m_W}'}\left(1 + \frac{\rho_W'(s_W' u_\infty' + c_W')}{\rho_i(s_i(u_o - u_\infty') + c_i)}\right)\right)^{\frac{s_W'+1}{2}} - \left(u_F + \frac{c_W'}{s_W' + 1}\right)$$

$$u_F{}^2 = \frac{2}{\rho_W'}\int_0^{\epsilon_F} \sigma(\epsilon, \dot{\epsilon})d\epsilon \approx \frac{2}{\rho_W'}\left(a' + \frac{b'\,\epsilon_F{}^n}{n+1}\right)\left(1 + c'\,Log\left[\frac{\rho_i\,u_o}{2\overline{m_W}'}\right]\right)$$




$$d_i = \frac{3}{2}\left(\frac{\bar{m}_W'}{\rho_i}\left(\sqrt{\rho^*/\rho_i} + \omega_i\,S/r_i\right)^{\frac{2}{3}}\frac{\hat{u}'}{(1 + \hat{R}_W') - \hat{u}'} - \frac{\bar{m}_W}{\rho_i}\left(\frac{\sqrt{\rho^*/\rho_i} + \omega_i S}{\sqrt{\rho^*/\rho_i} + \omega_W\,S/r_i}\right)^{\frac{2}{3}}\right)$$

$$\hat{u}' = \left(\frac{u_F' + \frac{c_W'}{s_W'+1}}{u_\infty' + \frac{c_W'}{s_W'+1}}\right)^{\frac{2}{s_W'+1}} \qquad \hat{R}_W{}' = \frac{\rho_W'\,(s_W' u_\infty' + c_W')}{\rho_i\,(s_i\,(u_o - u_\infty') + c_i)}$$

**Obliquity addressed by correcting lengths to flight path**

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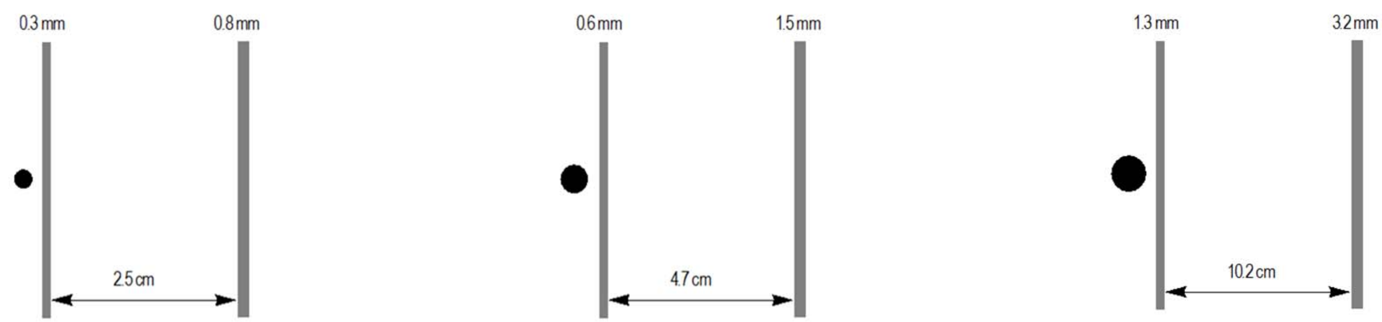
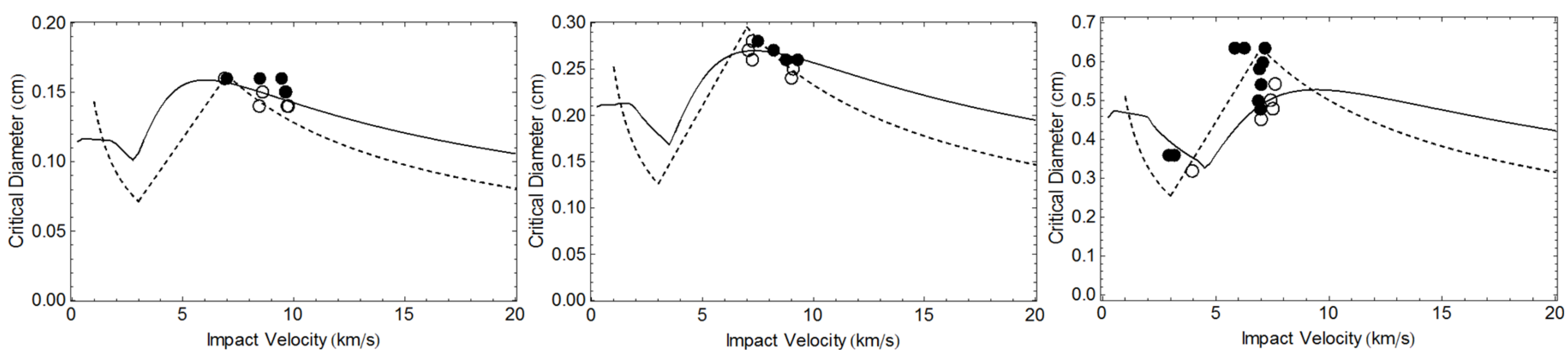
# Solution-Based Ballistic Performance Model Corrects Scale Discrepancies

Aluminum

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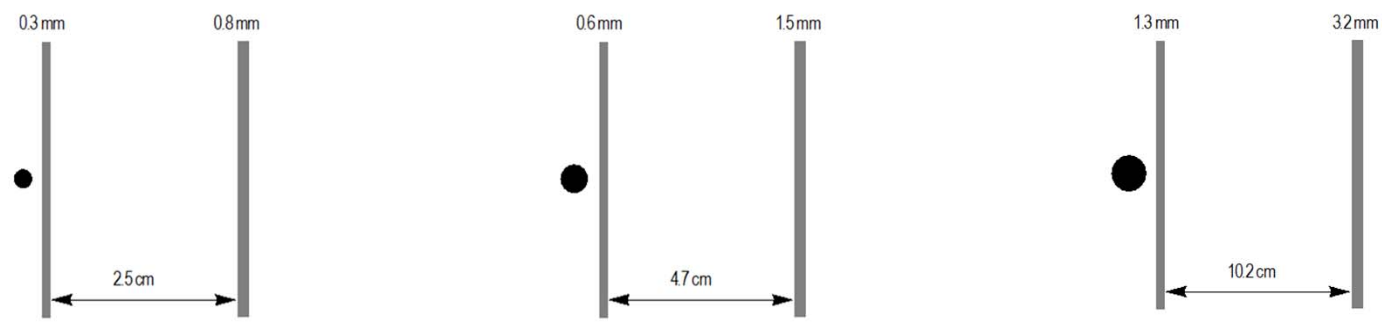
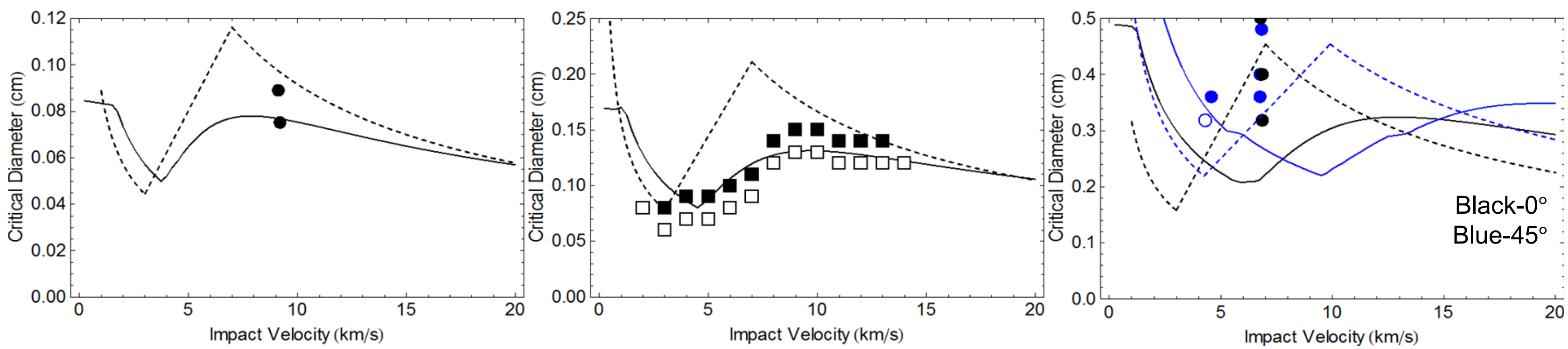
**Simplified solution of hydrodynamic equations resolves scaling effects**

# Extends to Different Impact Conditions

Steel

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**Removal of empirical quantities allows extrapolation to other conditions**

# Summary/Conclusions

- Survivability assessments of space hardware require the use of ballistic performance models to predict the performance of a structure over a broad range of impact conditions and configurations
- Hypervelocity impact experiments, hydrodynamic simulations and analytical model development have been performed to improve the dual-wall shield models over a variety of impact conditions
  - Data from over 500 hypervelocity impact experiments on dual-wall shield configurations have been collected and analyzed
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- A solution-based ballistic performance modeling approach has been developed here that improves the reliability of the extrapolations