High Velocity Impact Performance of a Dual Layer Thermal Protection System for the Mars Sample Return Earth Entry Vehicle

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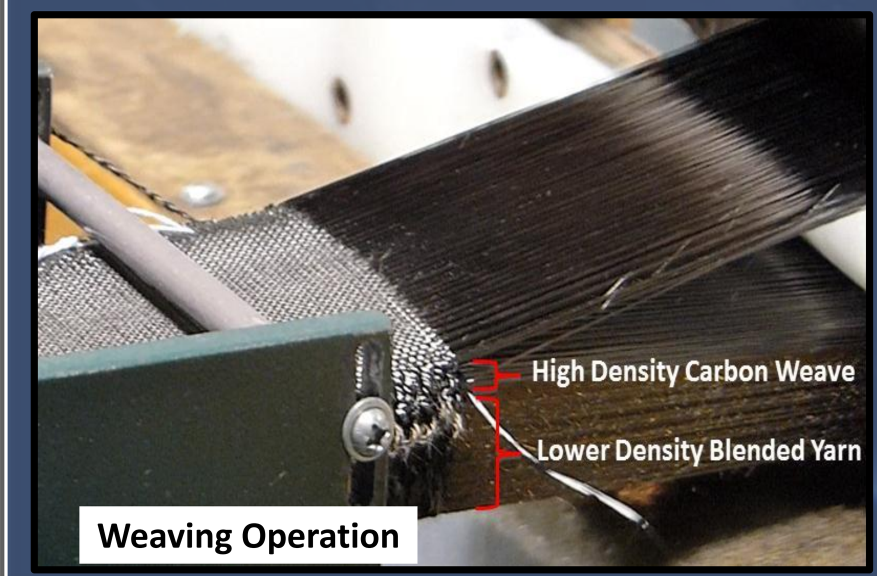
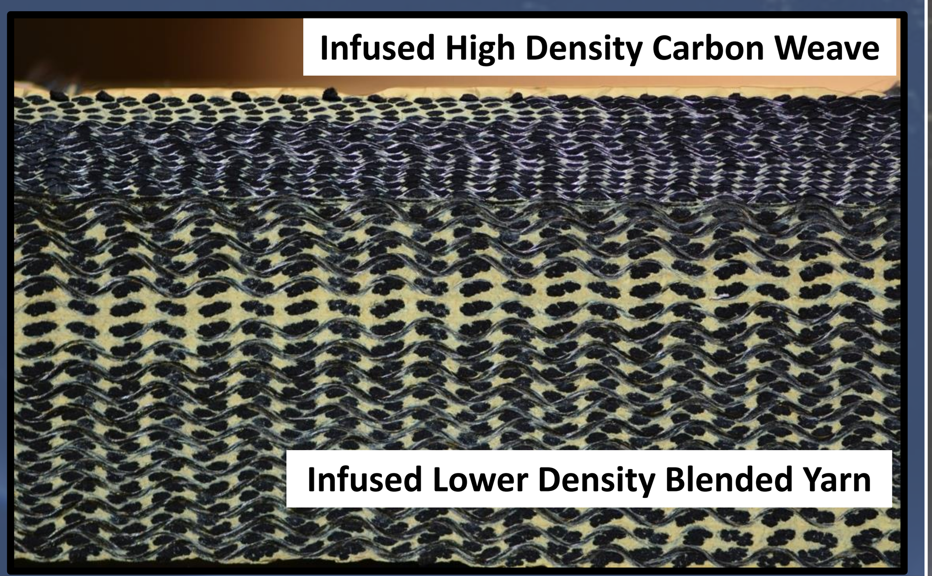
What is HEEET?

- Heat Shield for Extreme Entry Environment Technology (HEEET) is a Dual-Layer 3-D woven material infused with a low density phenolic resin matrix
- **Recession Layer (RL)**
  - Layer-to-layer weave using fine carbon fiber - high density for recession performance
- **Insulating Layer (IL)**
  - Layer-to-layer weave with carbon phenolic blended yarn - lower density for insulative performance
  - Arc jet tests have shown IL-alone aerothermal capability as well
  - ~30% more recession measured compared to RL





Hypervelocity Impacts and Ballistic Limit Equations

- Hypervelocity impacts (HVI) are characterized by projectile velocities that exceed the local speed of sound in the target material. Such impacts result in stresses at the shock front that far exceed the failure stresses of both the target and projectile.
- The result is a "flow" of material in the region of the shock front, well-described by the equations of hydrodynamics. It has been shown that increasing velocities (up to a threshold) result in more fluidic behavior at the shock front[5]
- As velocity increases, craters go from being more ellipsoidal (greater depth than diameter) to nearly hemispherical[3] [5]
- Hypervelocity impact damage can be characterized by Ballistic Limit Equations (BLEs) which predict penetration depth as a function of projectile kinetic energy, target material properties, and projectile material properties[1]
- BLEs are semi-empirical, based on test generated data. The HEEET BLE is

$$P_{HEEET} = 0.787d\left(\frac{\rho_p}{\rho_{HEEET}}\right)^{\frac{1}{2}} V_n^{\frac{2}{3}}$$

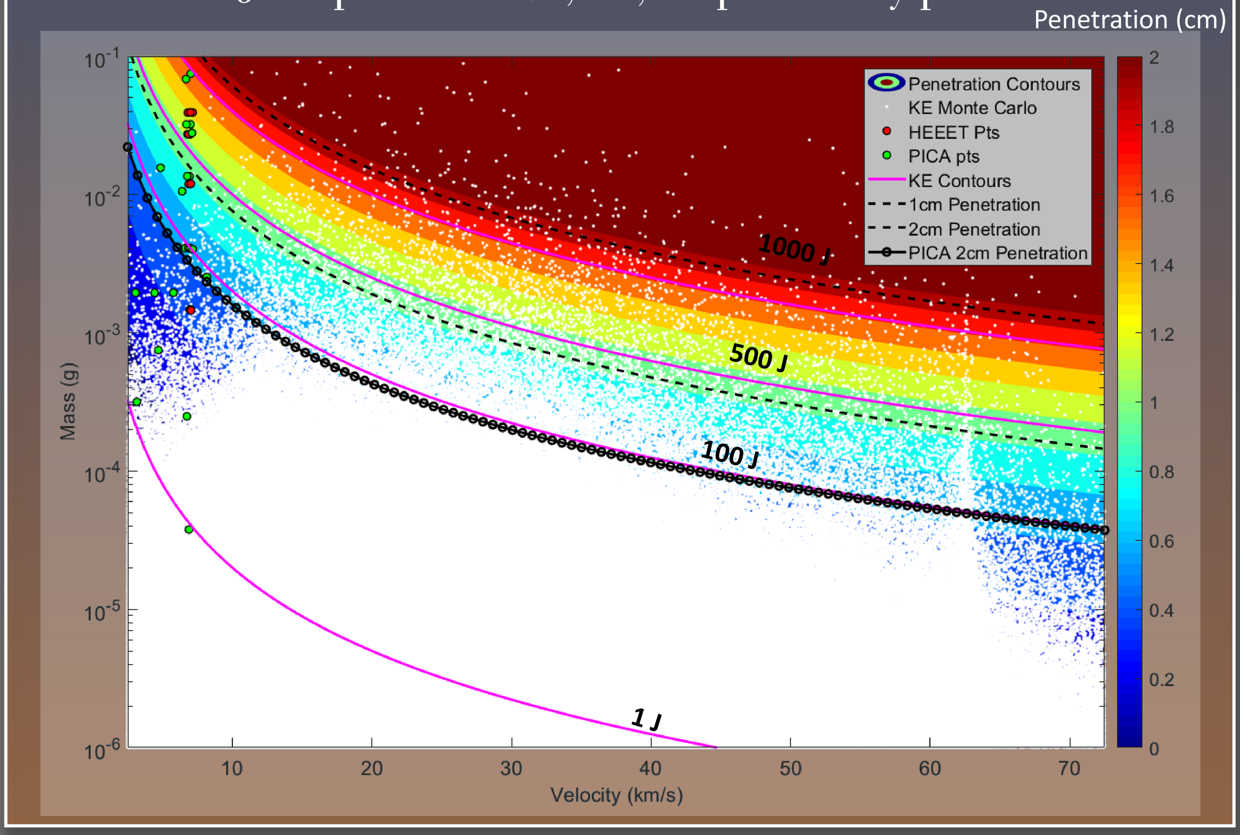
- A common format is based on Blast Wave Theory, which predicts a crater volume proportional to the kinetic energy deposited in the target material by the projectile[2] [3] [4] [5], therefore

$$Volume_{Crater} \propto KE_{Projectile}$$

- Since crater volume is constant for a given amount of energy, as crater volume increases, penetration depth decreases for constant projectile kinetic energy
  - Therefore the BLE predicts impact depth for low velocity shots should bound higher velocity impacts with equivalent kinetic energy

Expected Micormeteoroid Environments

- A 10 million point Monte Carlo simulation of Micrometeoroid (MM) impacts encountered along the MSR-EEV trajectory provides impact energy likelihoods
- Three energies were selected to test at
  - 500 J – represents ~1/100,000 probability particle
  - 1400 J – represents ~1/500,000 probability particle
  - 15000 J – represents ~1/1,000,000 probability particle



Whipple Shields

- Whipple Shields are a thin outer layer meant to break up an incoming particle before it interacts with your vehicle
- Testing this year will evaluate if a thin RL will provide any Whipple Shield effect to the underneath IL
- Standoff distance does play a signification role in the effectiveness of a Whipple Shield, meaning RL layer effectiveness against MM/OD damage will likely be small
  - Increasing RL thickness coupons will be evaluated against IL-only control samples

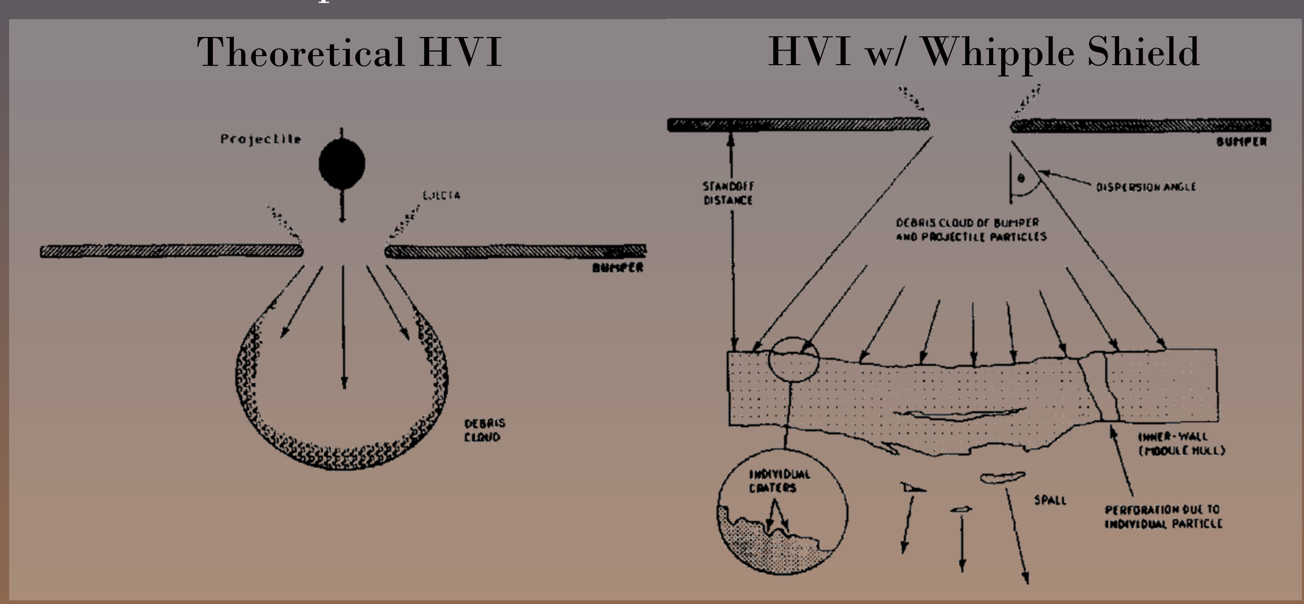
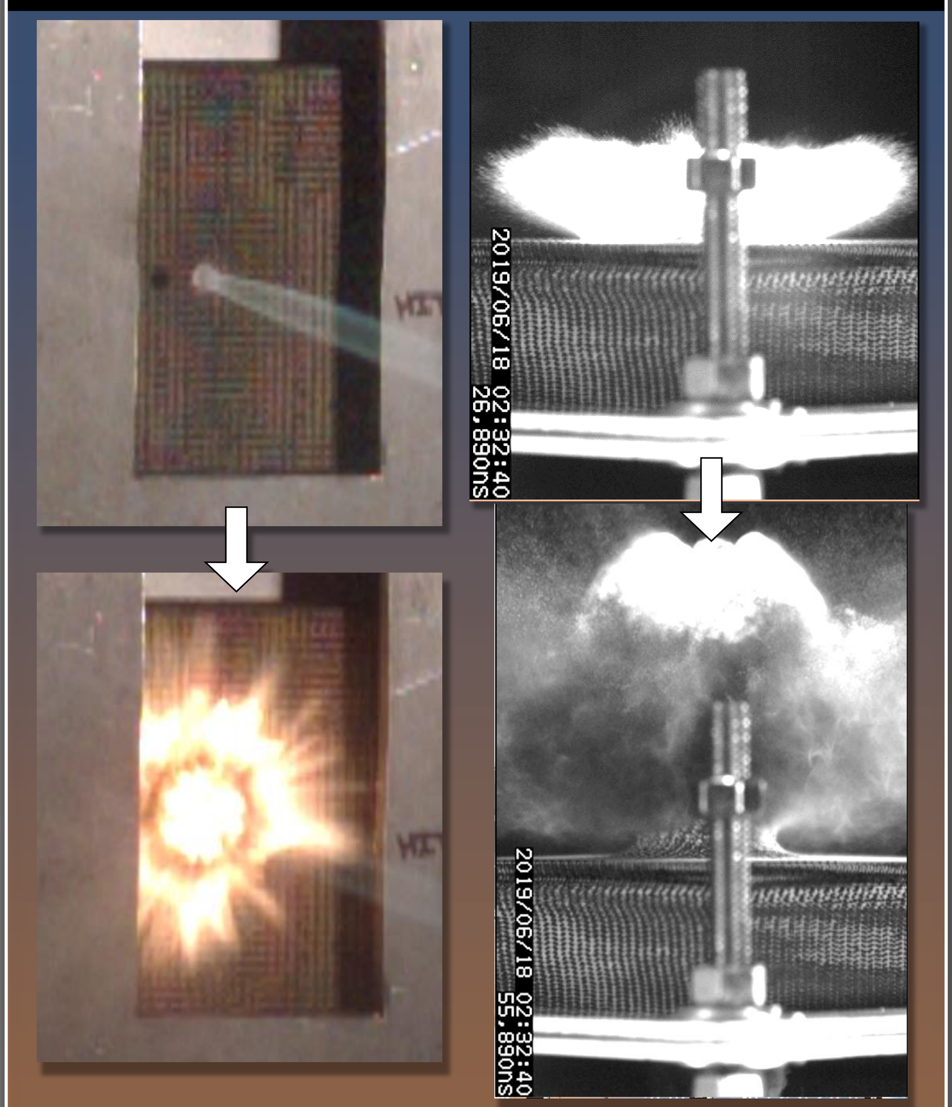


Figure 1: Effects of a Whipple Shield on HVI[6]

In-Test Photos

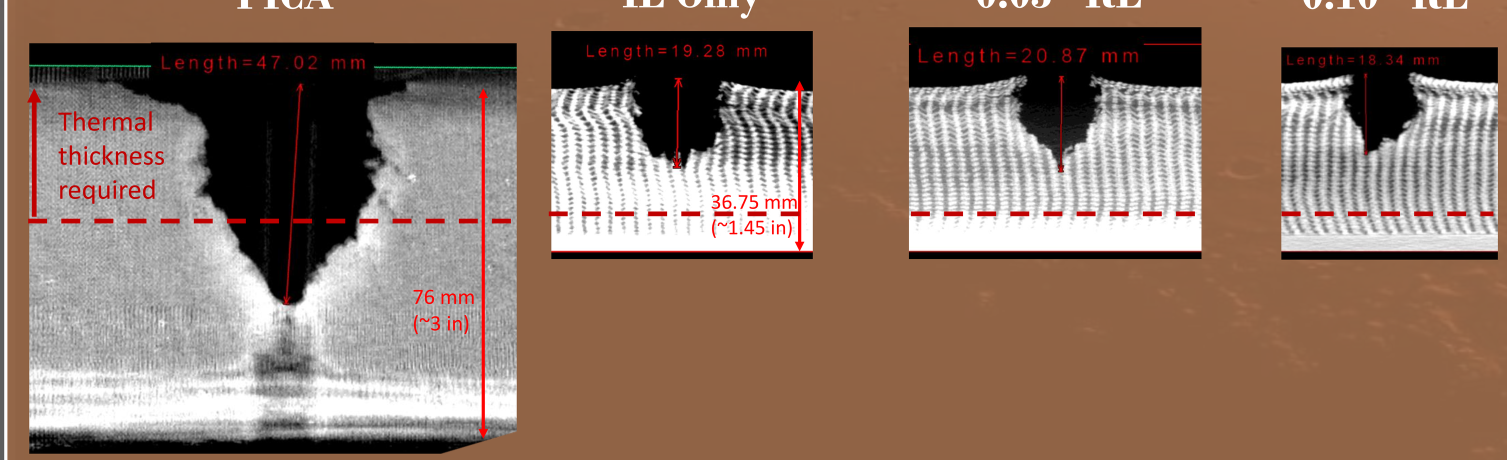


1400 J Nylon Test   15000 J Al Test

High Velocity Impact Testing (HVIT) Performance

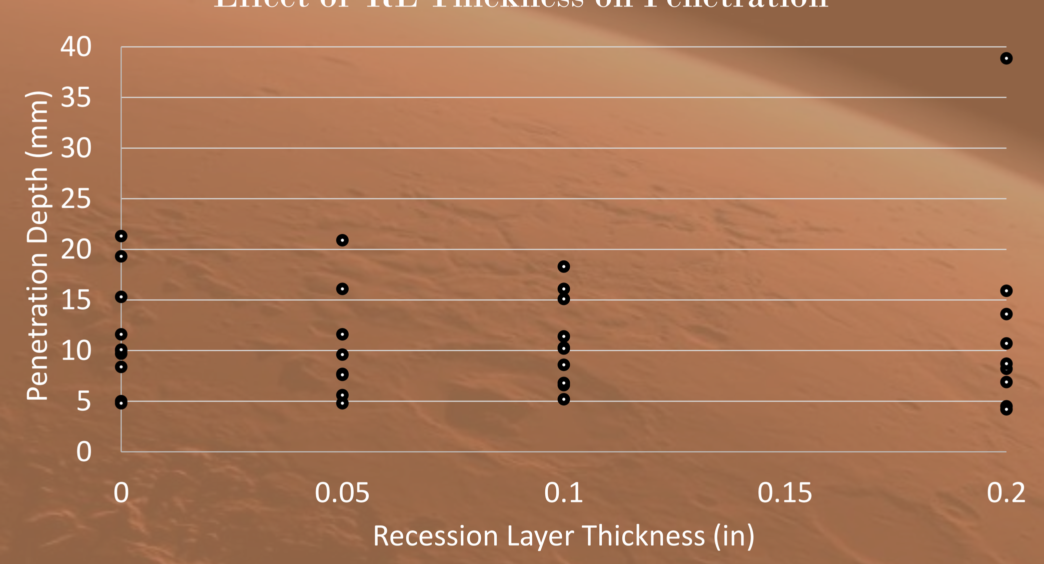
Nylon	4.78 mm	~6.7 km/s	Normal	~1400 kJ
Projectile	Diameter	Velocity	Impact	Energy

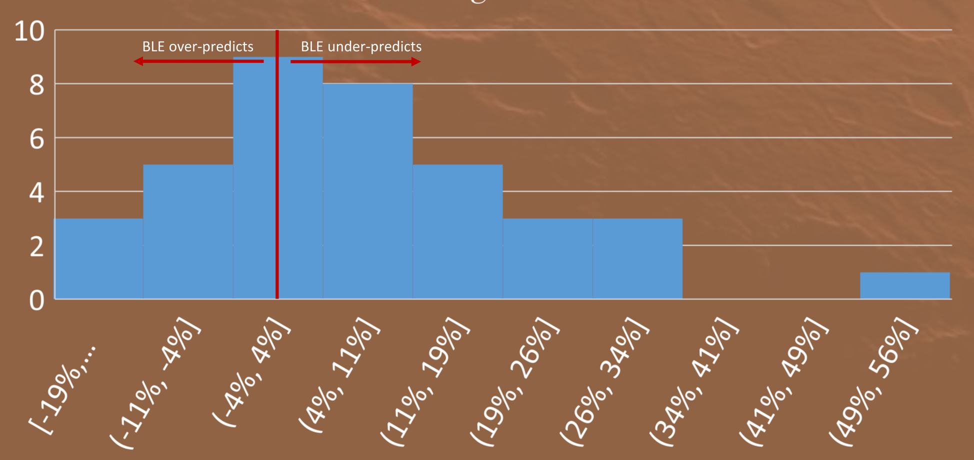
*CT Images are to scale



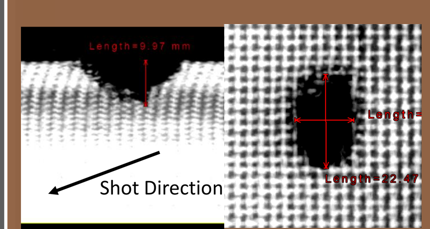
	PICA	IL Only	0.05" RL	0.10" RL
Depth	47 mm	19.3 mm	20.9 mm	18.3 mm
BLE Depth	48.3 mm	15.6 mm	13.6 mm	13.7 mm
BLE Error	3%	23%	54%	33%

- RL thickness does not appear to have a substantial effect on penetration depth
- Existing HEEET BLE is based on RL testing and not expected to represent IL impacts well. A new IL-relevant BLE is in work





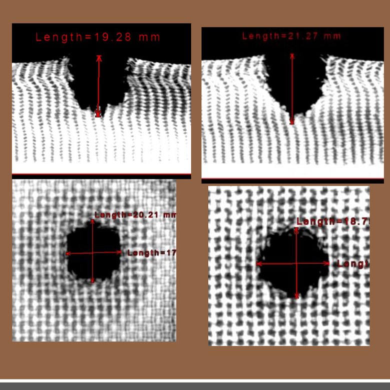
Effects of a Shallow Angle Impact



Depth	10 mm
BLE Depth	7.8 mm
BLE Error	28%

- As expected, shallow shots create higher aspect ratio craters with significantly less depth. There also appears to be less of a surface "bubble" around the crater

Effects of Projectile Density



	Nylon	Aluminum
Depth	19.3 mm	21.3 mm
BLE Depth	15.6 mm	18.3 mm
BLE Error	23%	16%

- Depth measurement would imply little sensitivity to projectile density, but the impacting Al projectile is ~33% smaller

References
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Conclusions

- A thin Recession Layer does not yield a significant improvement in measured crater depth, meaning it is not a mass-efficient mitigator for MM/OD damage
- 1400 J impacts (representing ~1/500,000 particle) on HEEET IL are likely flyable, pending thermal analysis
- 15000 J impacts (representing ~1/1,000,000 particle) on HEEET yield un-flyable damage
- HEEET Insulation Layer alone provides significant MM/OD robustness for ~3x the density of heritage PICA
- HEEET BLE (to be updated with new test data) was formed off of full scale RL coupons (~.50" RL) with about half the data points in this test series. This explains the poor predictions the current BLE generates
- A new IL-only HEEET BLE will be generated from the results of this test series