

EXTENDING THE APPLICABILITY OF THERMAL PROTECTION SYSTEM BALLISTIC LIMIT EQUATIONS BEYOND THE TESTABLE REGIME

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Introduction

Spacecraft typically use some thermal protection system (TPS) in their design, especially those that require high-temperature protection for atmospheric entry.

This includes Earth-entry crew and cargo vehicles, as well as those designed to enter the atmosphere of Mars or other planetary bodies that have an atmosphere.

TPS materials vary, ranging from ceramic tiles or phenolic ablators for heatshields to lightweight multi-layer insulation (MLI) blankets, depending on mission requirements and spacecraft design.

If the TPS is placed on the spacecraft's exterior, it will be susceptible to impacts by meteoroids and orbital debris.

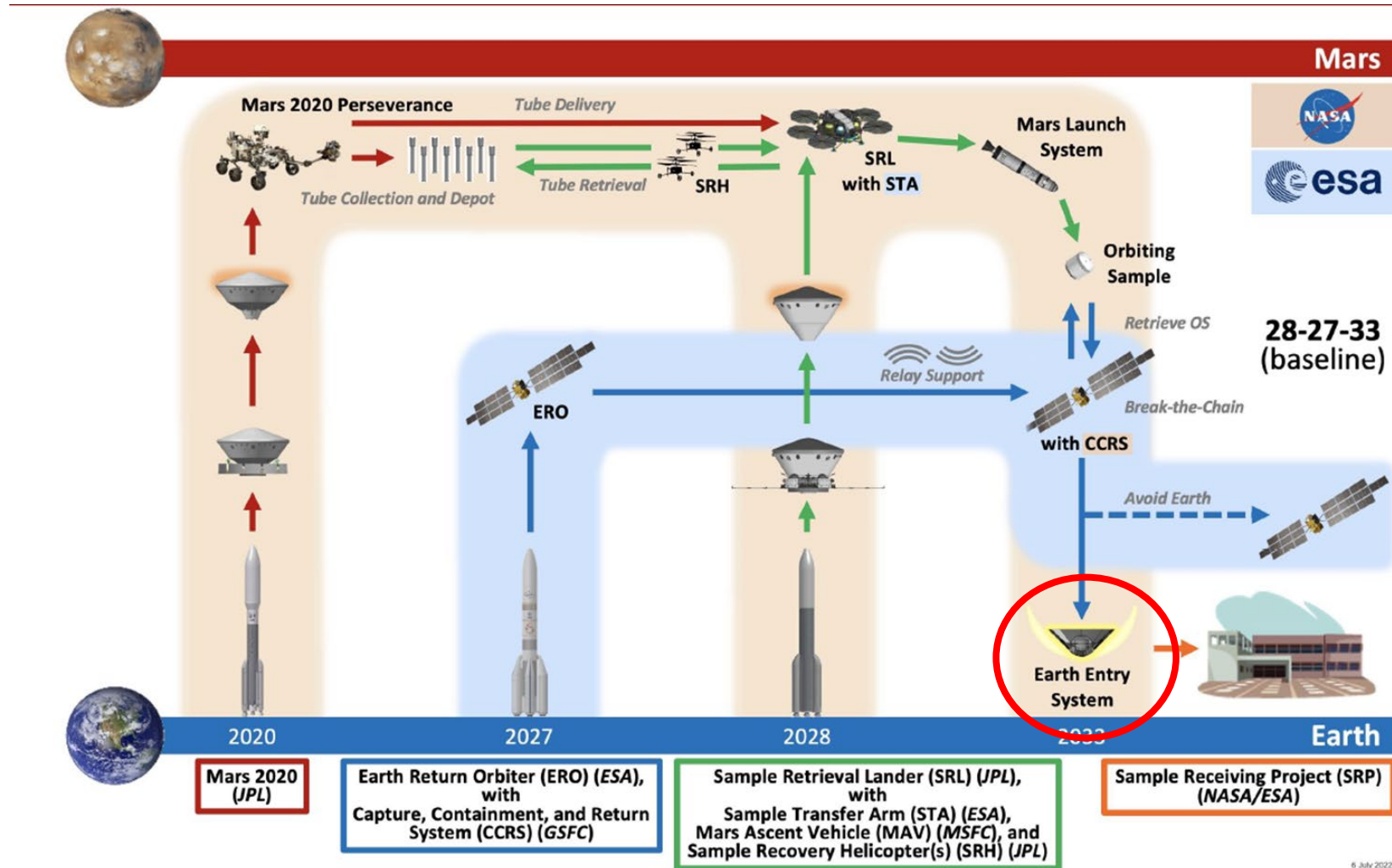
Introduction

These high-speed impacts can damage the TPS to a point where the protection it offers is below acceptable limits.

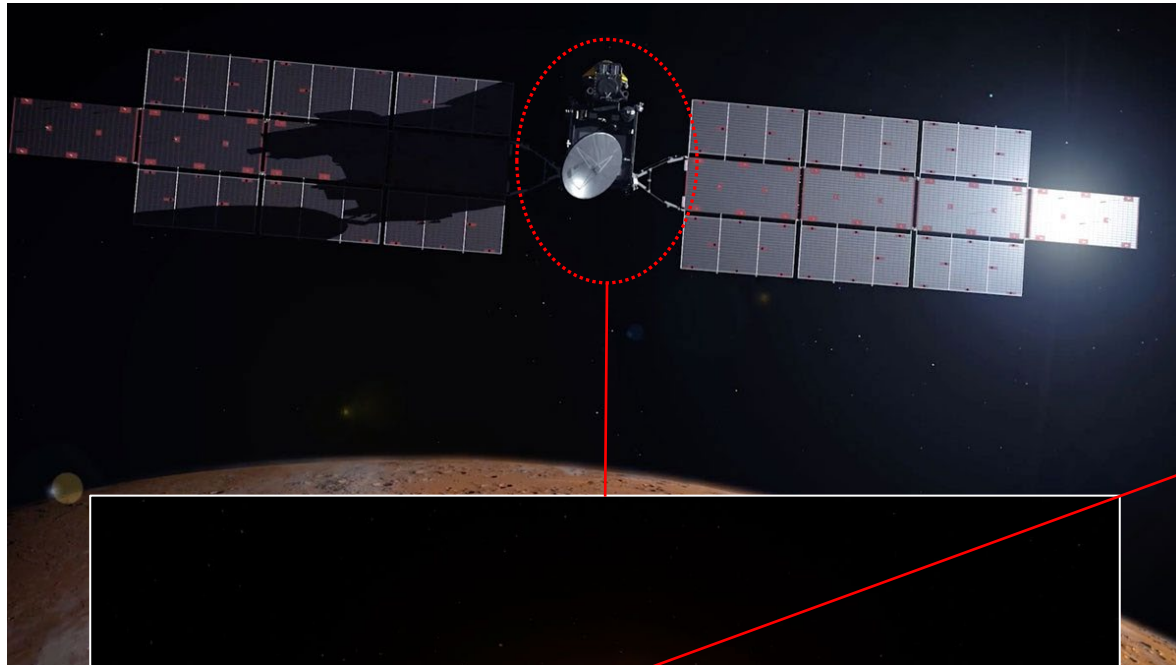
As such, it is important to be able to characterize expected TPS damage levels stemming from such high-speed impacts.

As an example of where this is important is illustrated on the next slide ...

Illustration of the MSR Campaign Assumptions



Notional Earth Entry System Used for Analyses



Earth Return
Orbiter (ERO)

Aftbody

Forebody

Earth Entry System (EES)

The EES contains the Mars samples and has a heat shield for safe entry through the Earth's atmosphere.

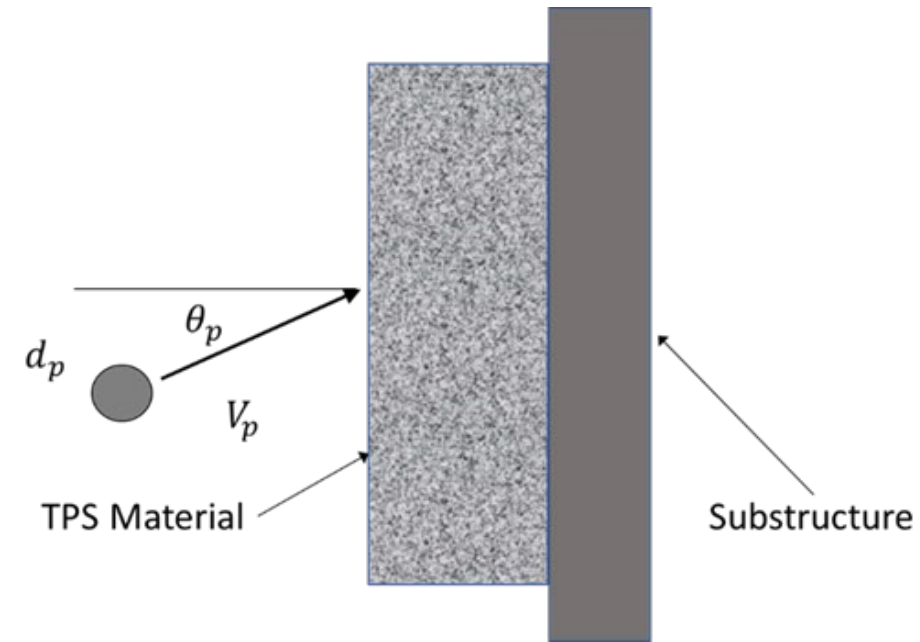


Capture, Containment, and
Return System (CCRS)

In a Recent Study ...

Work was completed to characterize the high-speed impact damage that would be sustained by a Phenolic Impregnated Carbon Ablator (PICA) and SLA-561V (SLA).

Using high-speed impact test data, empirical equations were developed for TPS crater depths, maximum and minimum TPS crater mouth dimensions, and ballistic limit equations (BLEs), with and without a backing substructure.



In a Recent Study ...

The validity of the equations developed was assessed by comparing their predictions against test data.

In nearly all cases, the empirical equations developed were seen to adequately capture

- the magnitudes of the measured damage parameters, and
- whether or not the TPS, or the substructure underlying the TPS, would be perforated by the initial impact.

For example ...

From that Recent Study ...

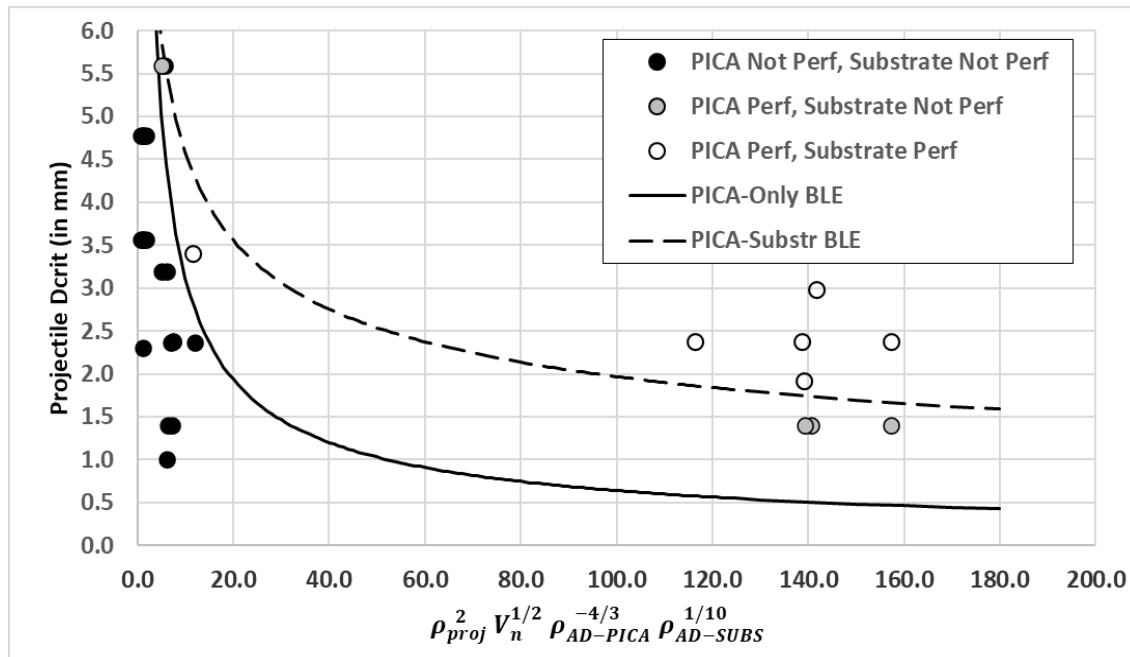


Figure 14. Plots of BLEs and Test Results for PICA and Substructure Perforation

REF: W.P. Schonberg and M.D. Squire, “Predicting high-speed particle impact damage in spacecraft thermal protection systems”, *Journal of Space Safety Engineering*, Vol. 11 (2024) pp. 87–101.

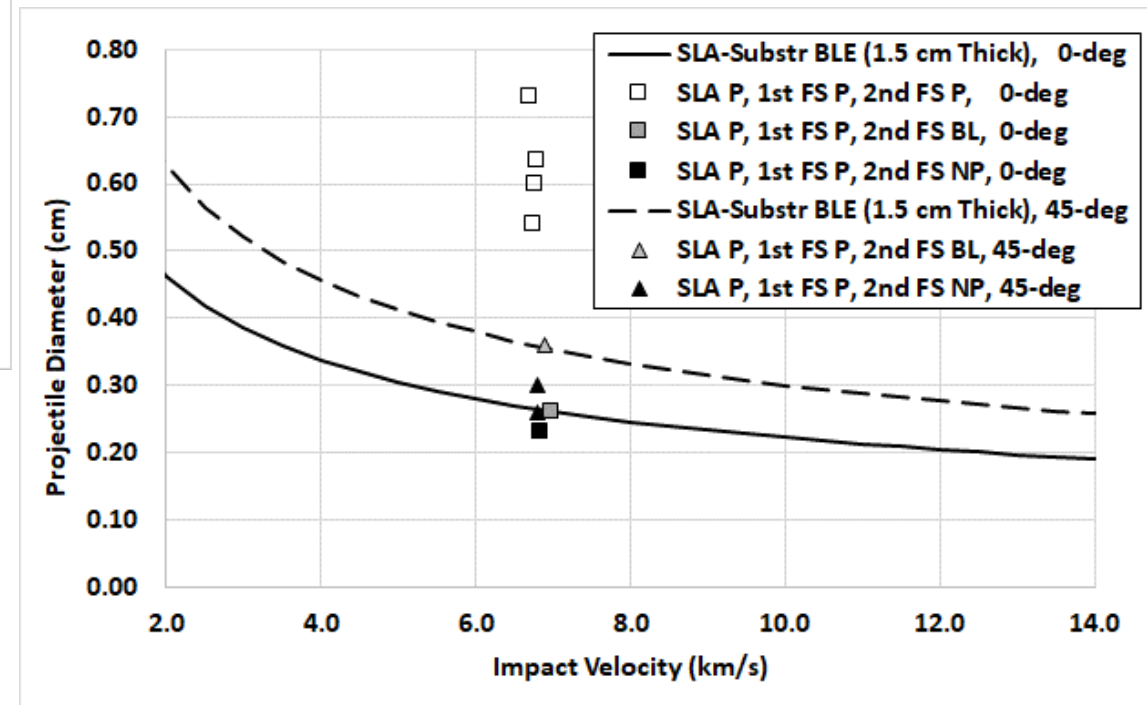


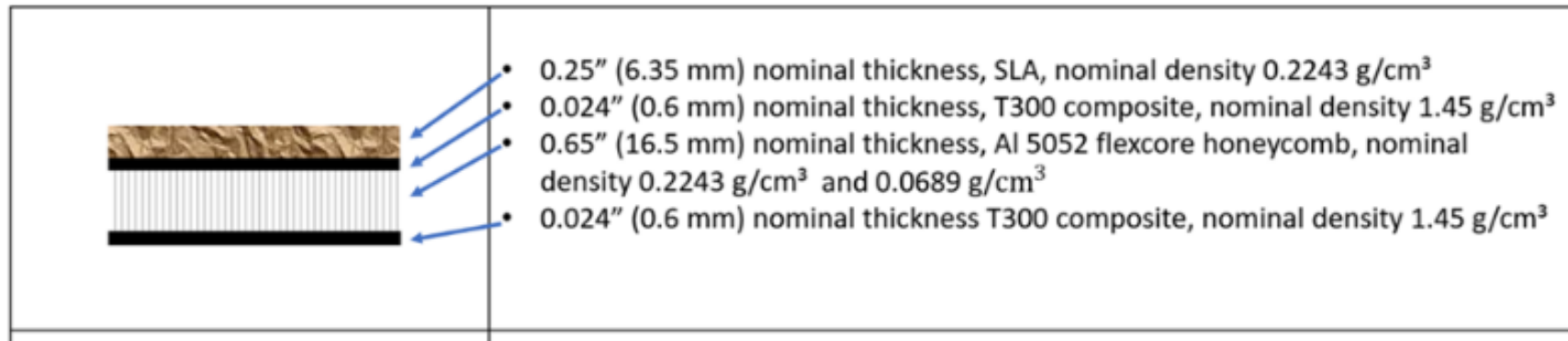
Figure 26. Plots of 0-deg and 45-deg SLA-Substr BLEs and Test Results for Substructure Perforation, 1.5 cm Thick SLA
(P = Perforation, BL = Ballistic Limit, NP = Non-perforation)

In this Study ...

We show how to extend the applicability of the BLE for SLA561V beyond the testable regime (i.e., above an impact velocity of 7 km/s).

This was achieved using the results of a series of hydrocode simulations at impact velocities between 7 km/s and 35 km/s, and at impact obliquities between 30 and 60 degrees.

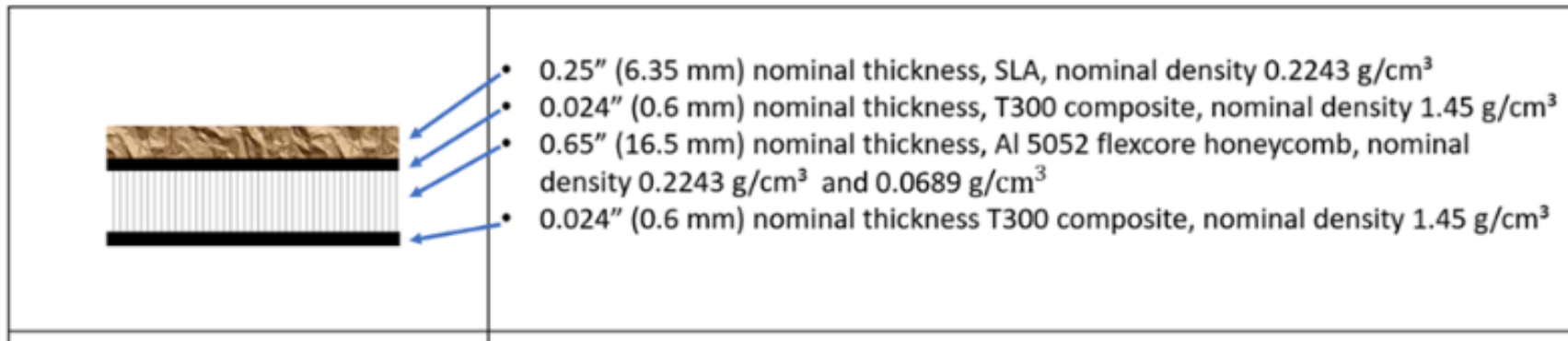
Target configuration:



In this Study ...

Bottom line up front: When predictions from the expanded BLE were compared graphically against the results of the SPHC runs, the positions of the BLE curves were consistent with the data:

- Non-perforation data points were below the curves.
- Perforation data points were above the BLE curves.



So What???

The process and new BLE we developed are sufficiently general and include many of the key parameters that would be used to describe the composition of the selected TPS material and its underlying substructure.

As such, the BLE can be used to compute critical projectile diameters for impact parameters and target constructions other than those used in their development.

A word of caution: Such exercises are not to be undertaken lightly—varying parameters too far from the values used in the development of the equation presented herein could yield results inconsistent with the actual TPS impact behavior.

Methodology

Although the TPS+substructure BLE developed previously showed a good correspondence with the P/NP data from high-speed impact tests, it was only applicable to configurations using the same substructure design.

However, the substructure of interest shown previously consists of a honeycomb sandwich plate with aluminum flexcore sandwiched between two graphite/epoxy plates.

STEP (1): modify the previous TPS+ substructure BLE so that it could take into account the substructure design of interest.

- This was accomplished by including an equivalent facesheet thickness term and a facesheet spacing term, both of which would include the densities of the facesheet and flexcore materials.

Methodology

STEP (2): the plots of the previously developed TPS+substructure BLE are more like that of a single-wall BLE (i.e., monotonically decreasing as velocity increases).

At some point, as velocity increases, the two substructure facesheets should begin to act as a Whipple Shield.

- As such, in addition to adding facesheet thickness and spacing terms, the TPS+ substructure BLE was modified to include an updated velocity-based term to bring out a Whipple Shield-like response.

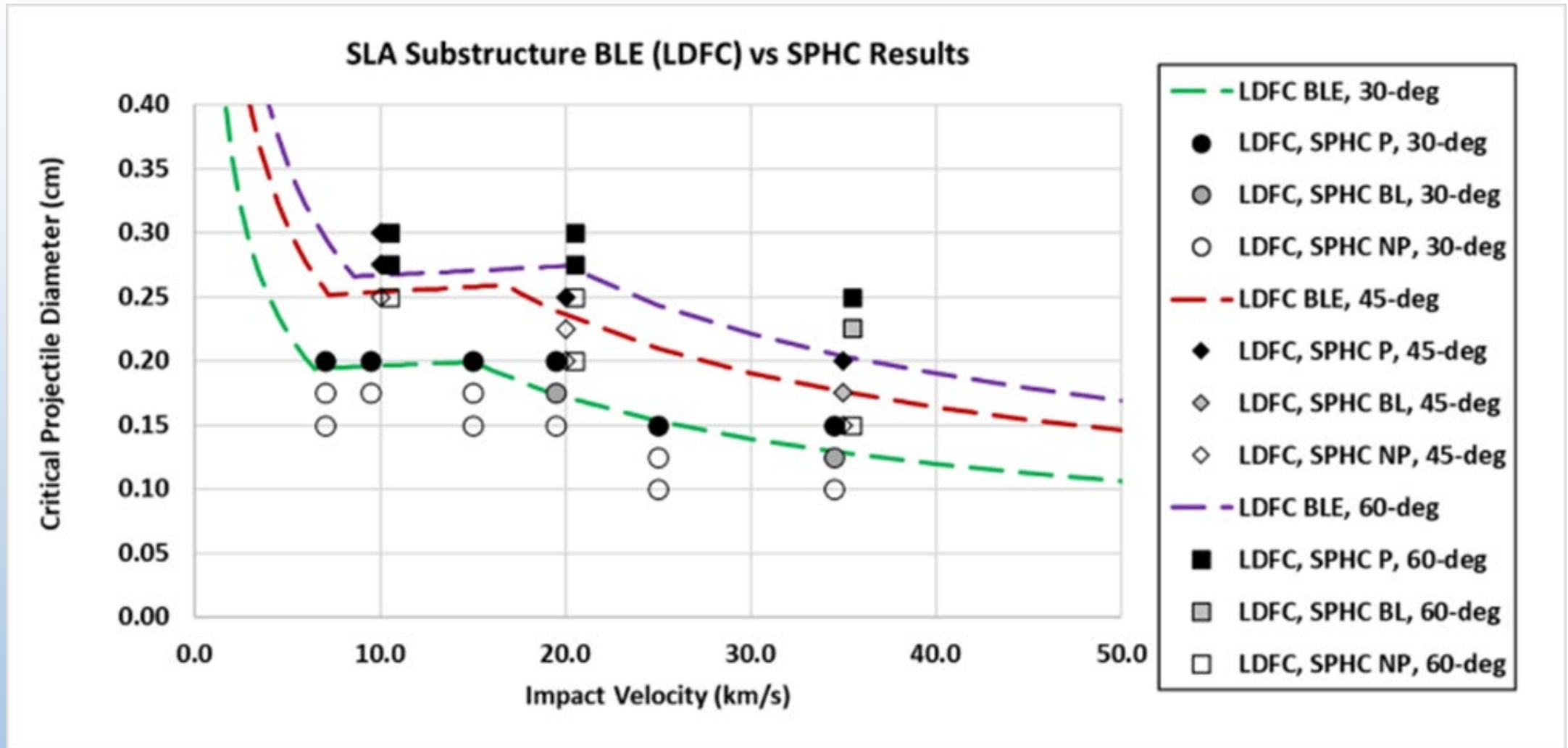
Final Form of the BLE

$$d_{crit} = \left[\left(\frac{C_1}{3.398} \right) t_{SLA} \left(\frac{\rho_p}{\rho_{SLA}} \right)^{-1/2} V_p^{-f(\rho_{HC})} \cos^{-g(t_{eff,Ti})} \theta_p \right]^{\frac{1}{1.46}} \\ * (C * t_{eff,Ti}^A * S_{HC}^B) * K(\theta_p) \quad (1)$$

The various constants and parameters are given in the paper.

Of special note are the constants A, B, and C – since they have different values depending on the impact velocity, it is these constants that bring in the Whipple Shield-like feature of this BLE.

Comparison of BLE and SPHC P/NP Results I



LDFC = Low Density Flex Core (substructure construction)

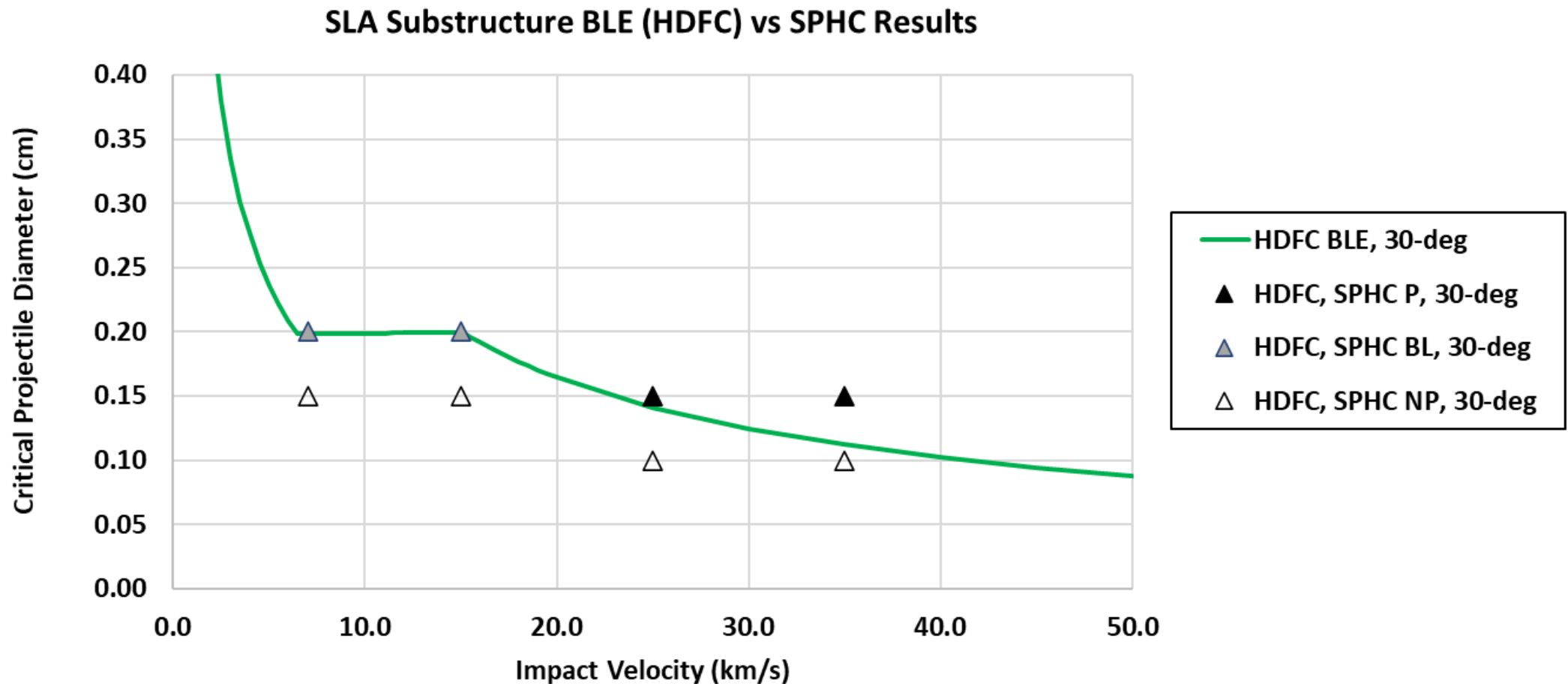
The Next Slide ...

... is BONUS CONTENT!

It's a small way of saying "Thank you" to all who attended this presentation!



Comparison of BLE and SPHC P/NP Results II



HDFC = High Density Flex Core (substructure construction)

Concluding Comments I

Overall, this new / expanded BLE does a reasonable job in predicting whether or not there will be a rear facesheet perforation for each obliquity angle.

Namely, for the most part, the hollow data points, which signify non-perforation impact events, are below the BLEs, while the solid data points, which signify perforation events, are above the BLEs.

It is also important to note that this revised and updated BLE does, in fact, reduce to the BLE developed previously when the parameters of the previously considered substructure are used as input.

Concluding Comments II

Finally, we note that the transition velocities as functions of impact obliquity were determined for this BLE using SPHC results for aluminum projectiles only.

The question that arises is, what should the transition velocities be for other projectile materials?

Unfortunately, we do not yet have any high-velocity results for other projectile materials.

But, for now, it can be assumed that the transition velocity functions are the same for all projectile materials – although this is clearly a point that needs further investigation.