Debris Shielding Technology Progress

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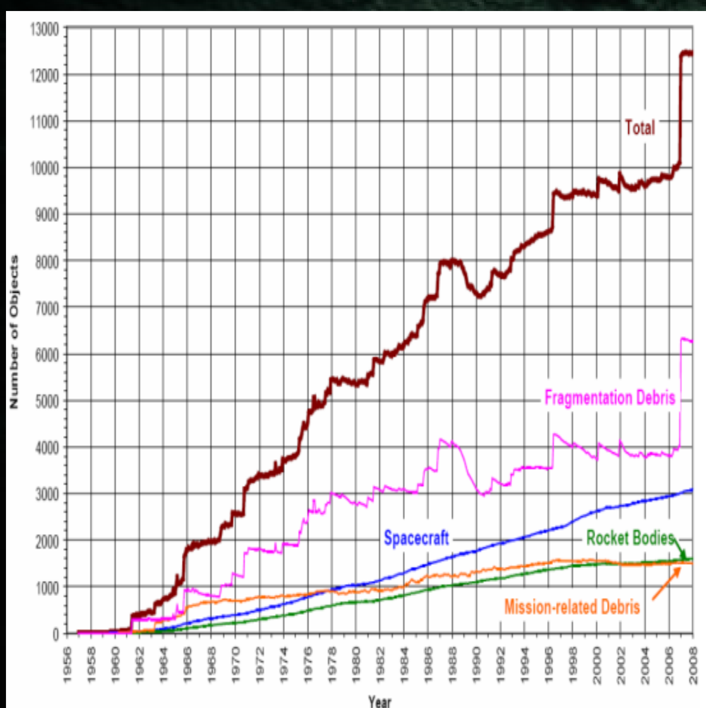
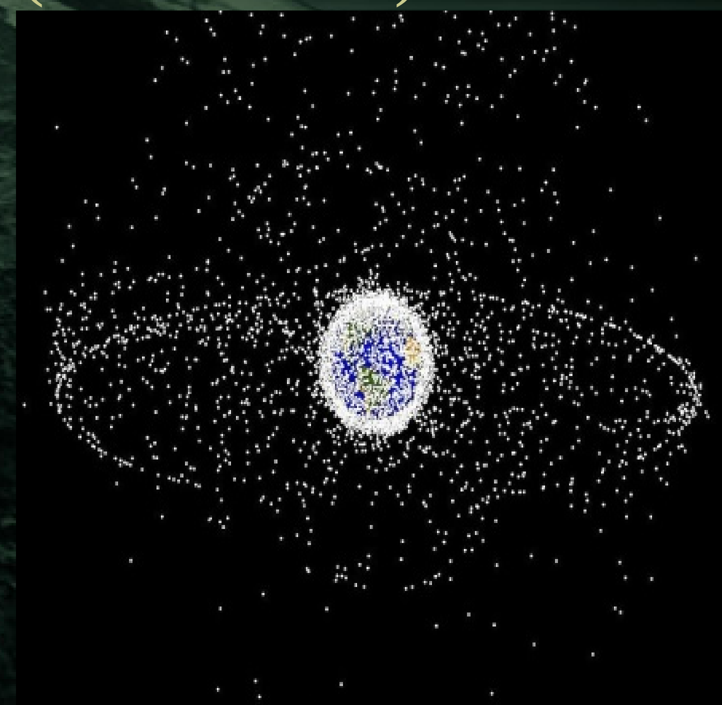
1 Debris Shielding And Ballistic Limit Equations(BLEs)

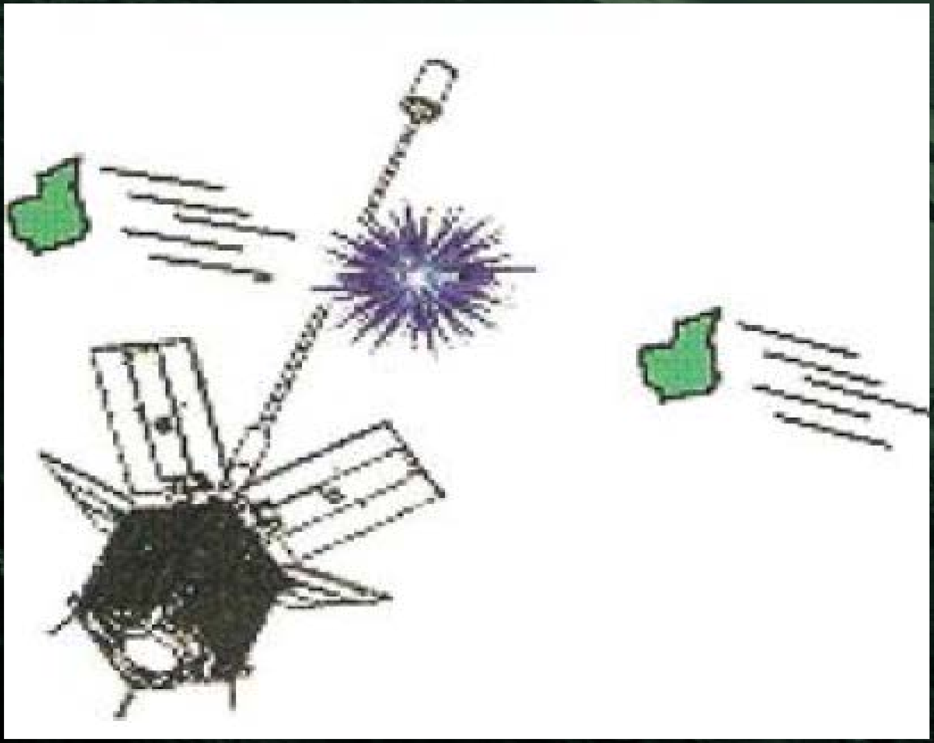
1 Debris Shielding

As we know, it is possible that the on-orbit spacecr-afts being encountered hypervelocity impact by mi-crometeoroid or orbital debris(i.e. MMOD).



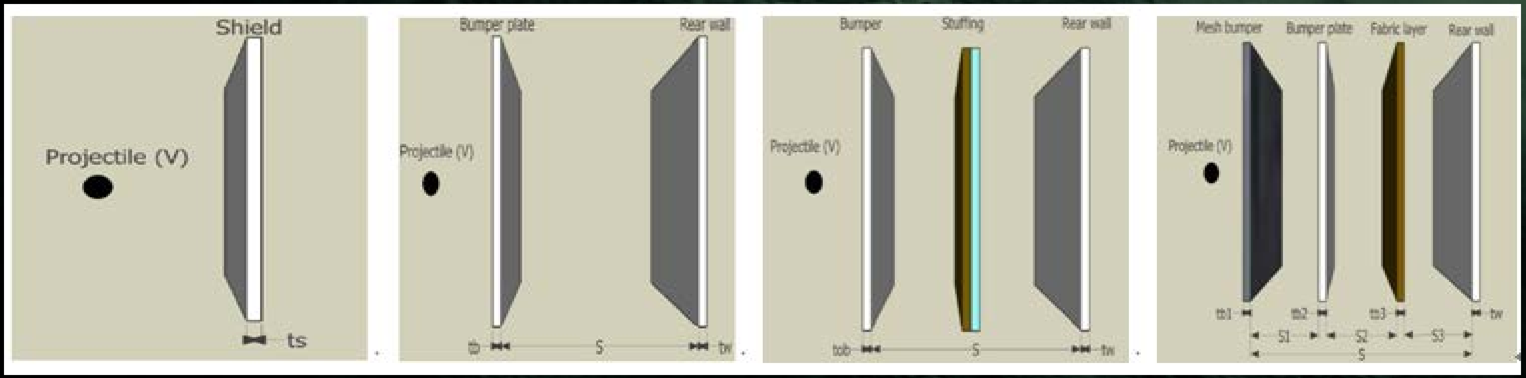


In 1996, Arianne rocket remains hit the gravity gradient pole of French satellite CERISE, which led directly to the failure of the CERISE.



In order to decrease the probability of spacecraft failure caused by MMOD, space maneuver is needed to avoid MMOD if the MMOD has dimensions larger than 10cm, but for MMOD with dimensions less than 1cm, MMOD shields are needed for spacecrafts.

Classical structure and MMOD shields are Single Wall , Whipple shield, Stuffed Whipple shield and Mesh Double-Bumper shield.



2 BLEs

Ballistic limit equations research is an important part of hypervelocity impact research.

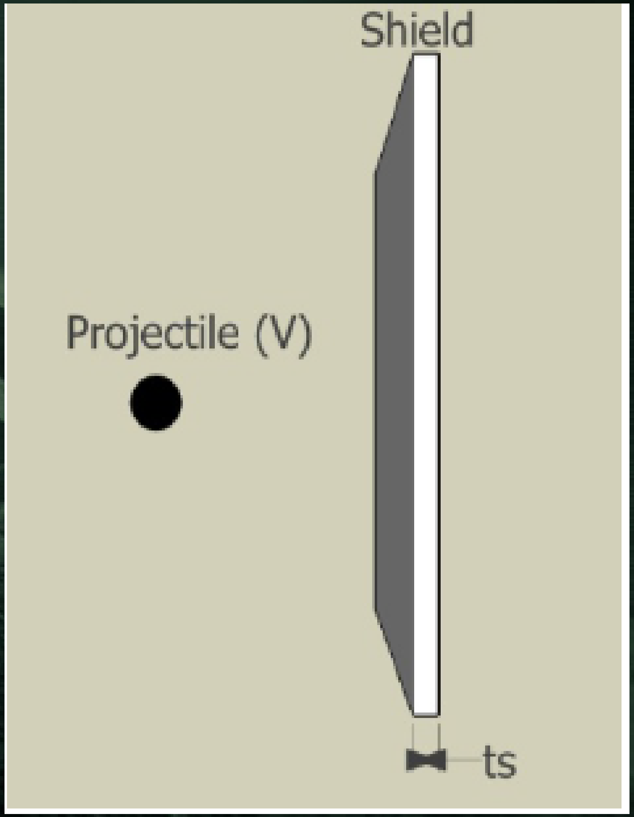
Ballistic limit equations are developed to define impact conditions (i.e. particle size, particle density, impact velocity, and impact angle) that results in threshold failure of specific spacecraft components or subsystems.

$$d_c = f(\rho_p, \rho_t, t, V, \theta, \sigma_y)$$

2 Single Wall

The schematic diagram of a single wall is shown on the right.

Early spacecrafts didn't have shielding structures, they just used the bulkheads or skins of spacecrafts (i.e. Single Wall) to prevent the MMOD impact.

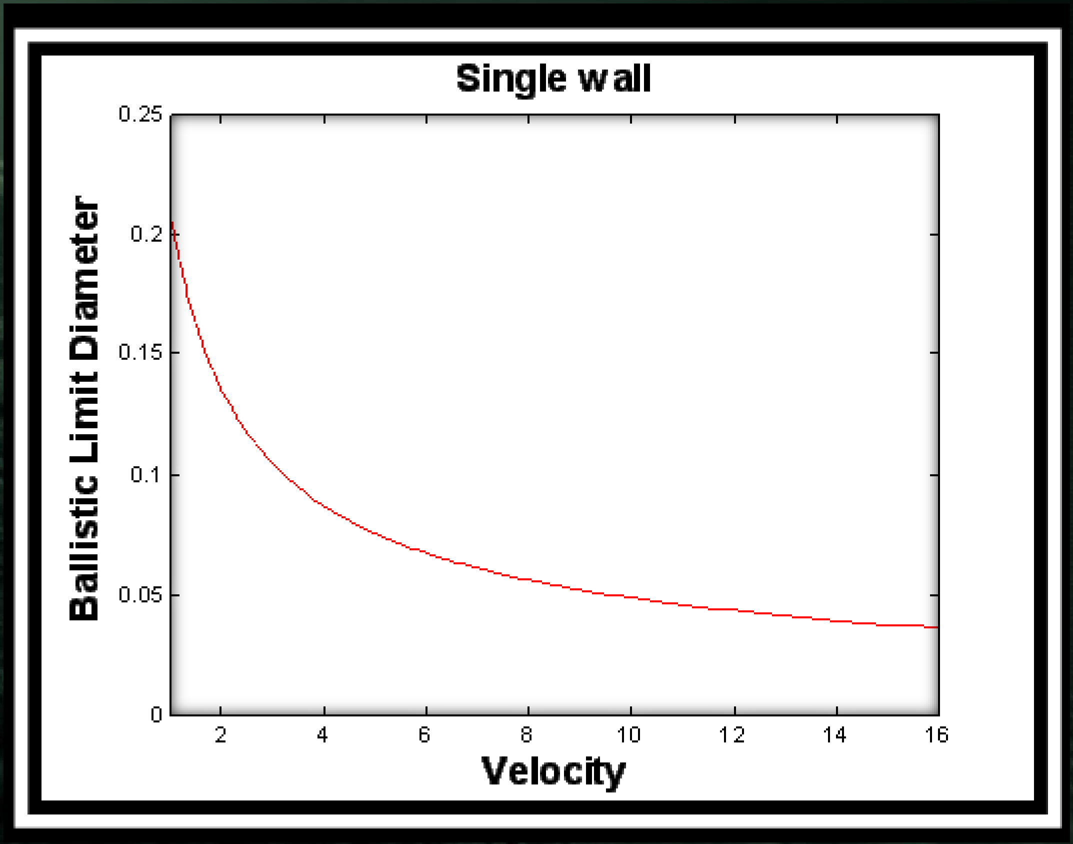


In order to conduct size design and to evaluate the performance of the shield, many institutions have conducted hypervelocity impact investigations since the middle of 1960s, and many ballistic limit equations were derived, one kind of such equations for single wall is given below.

$$d_c = \left[\frac{t}{k} * \frac{BH^{0.25} \left(\frac{\rho_t}{\rho_p} \right)^{0.5}}{K \left(\frac{V}{C} \right)^{\frac{2}{3}}} \right]^{\frac{18}{19}}$$

According to the BLE, we can plot out the ballistic limit curve (BLC) that describes the shielding performa-nce.

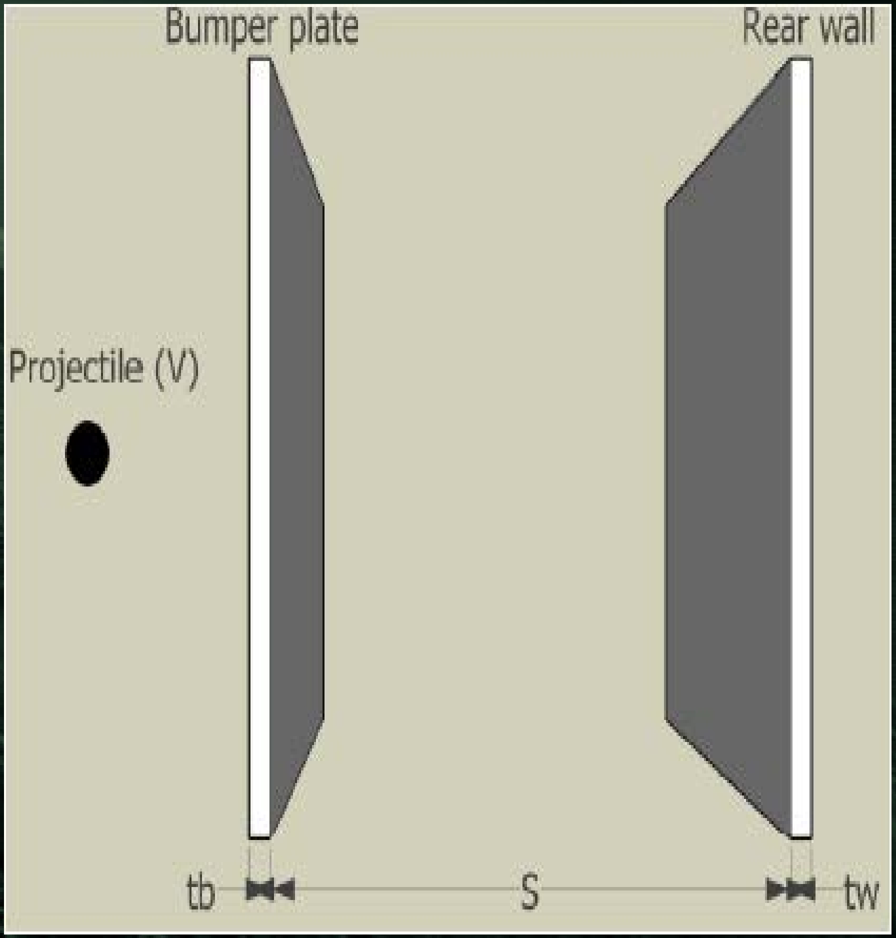
It can be seen that the critical diameter of projectile (MMOD) decreases with the increasing projectile velocity.



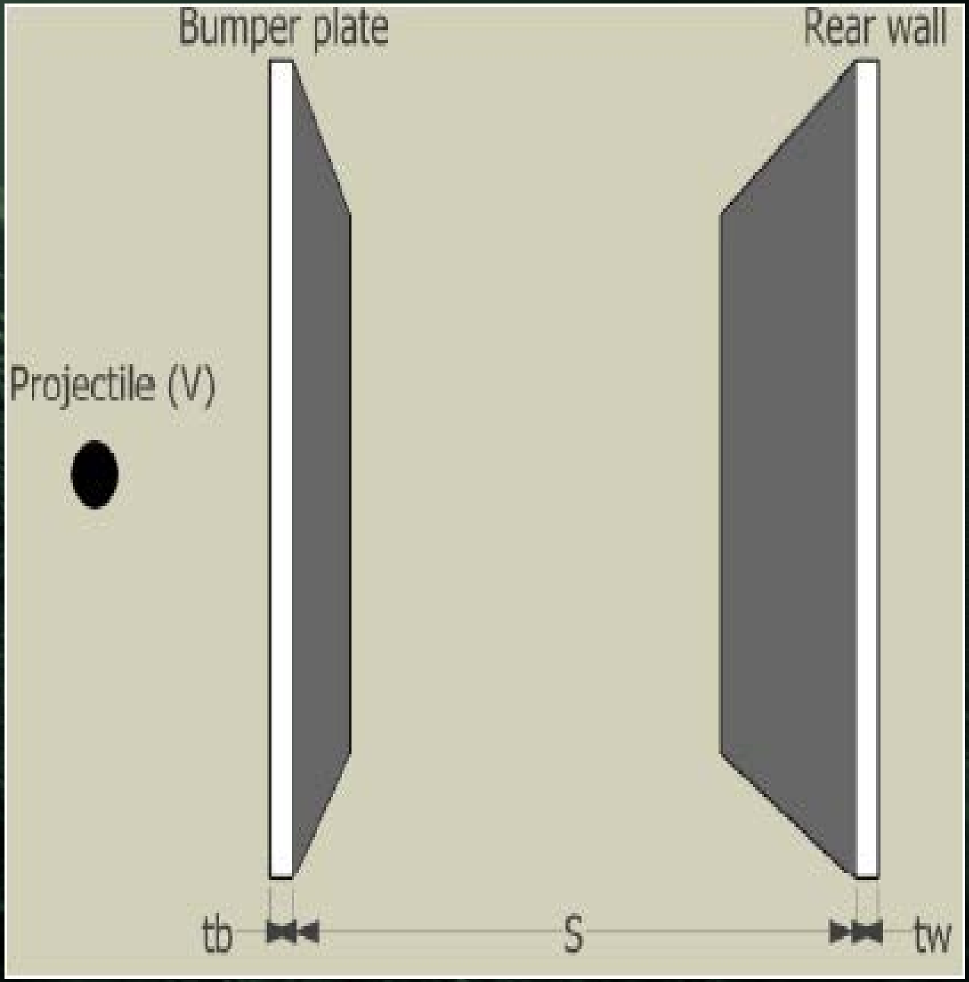
3 Whipple shield

Sometimes, the single wall can not achieve the probability of non-penetration (PNP) of the spacecraft, so another kind of shield named Whipple shield was proposed to fulfill the PNP requirement.

The schematic diagram of a Whipple shield is shown on the right.



Whipple shield consists of a single bumper, standoff, and the spacecraft structur-e that is to be protected. As an additional bumper plate is added, the shielding performance is much better than single wall.



The BLEs that describe the shi-elding performance of Whipple shield is given below.

Low Velocity Region

For $V_n < 3km/s$

$$d_p = \left(\frac{t_w\left(\frac{\sigma_w}{40}\right)^{0.5} + t_s}{0.6(\cos\theta)^{5/6}\rho_p^{0.5}V^{2/3}}\right)^{18/19}$$

High Velocity Region

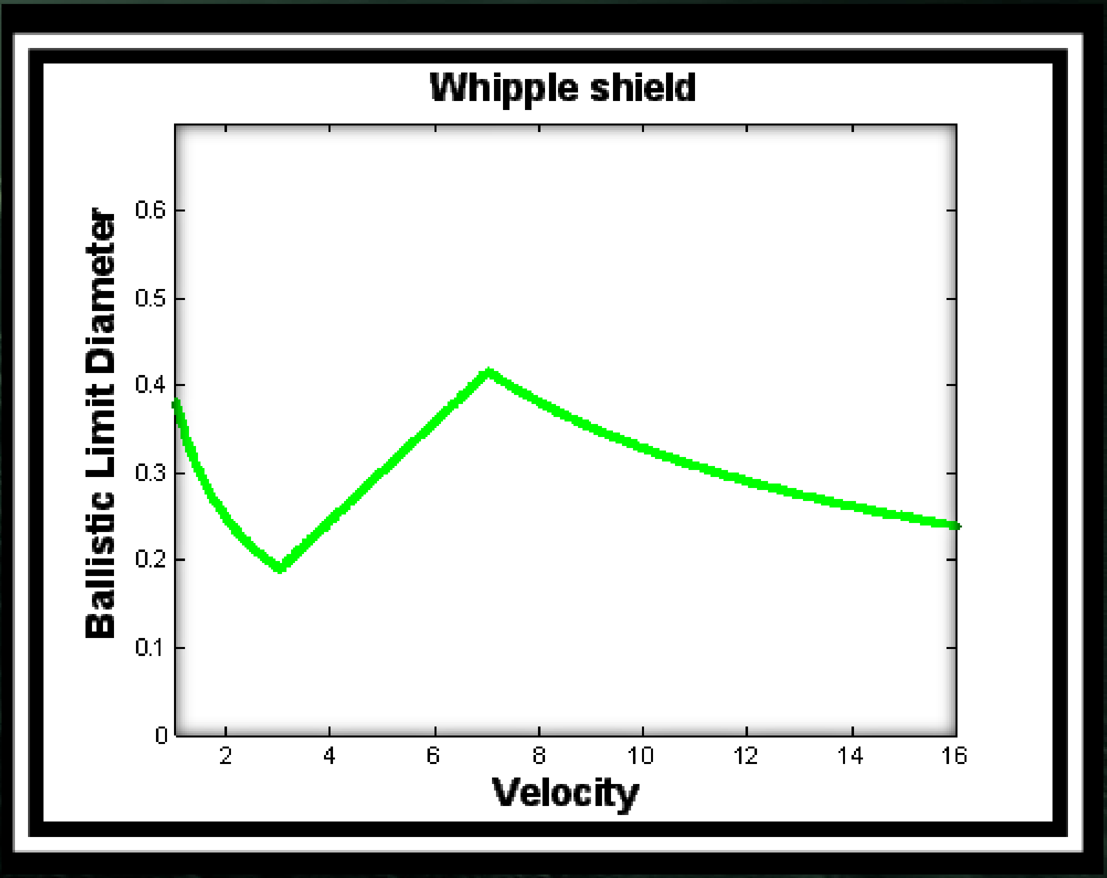
For $V_n > 7km/s$

$$d_p = 3.918 t_w^{2/3}\rho_p^{-1/3}\rho_b^{-1/9}V_n^{-2/3}S^{1/3}\left(\frac{\sigma_w}{70}\right)^{1/3}$$

Linear Interpolation is used between low and high velocity regions.

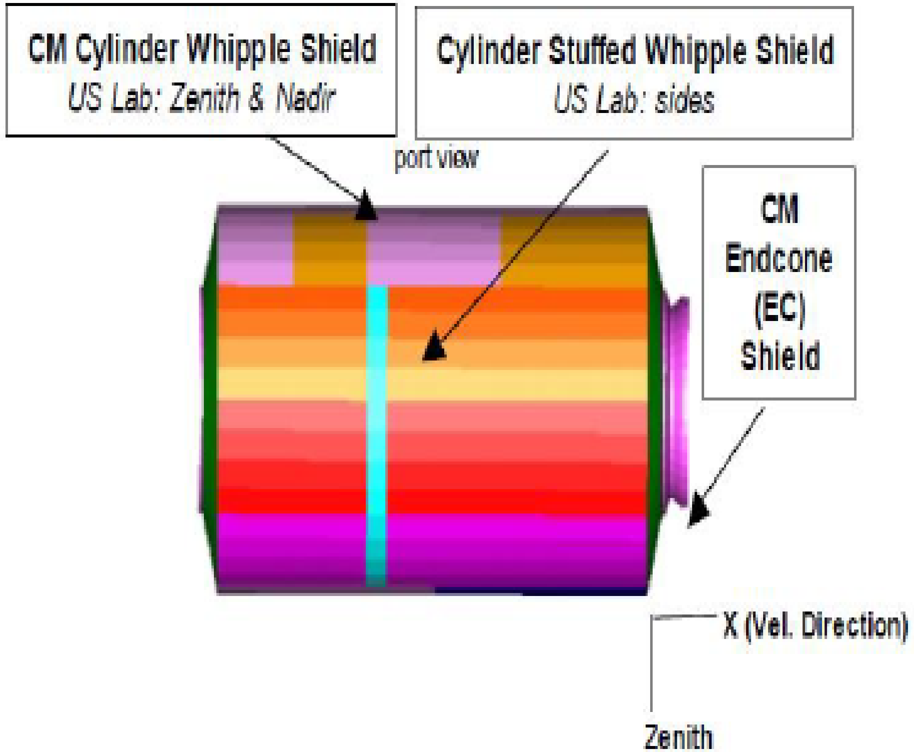
The figure on the right shows the BLC of Whipple shield.

There are three phases during a hypervelocity projectile impact onto a double-plate structure. The three phases are ballistic, shatter, and melt/vaporization .



The U.S. Laboratory module for the International Space Station awaiting to be covered by a debris shield blanket.

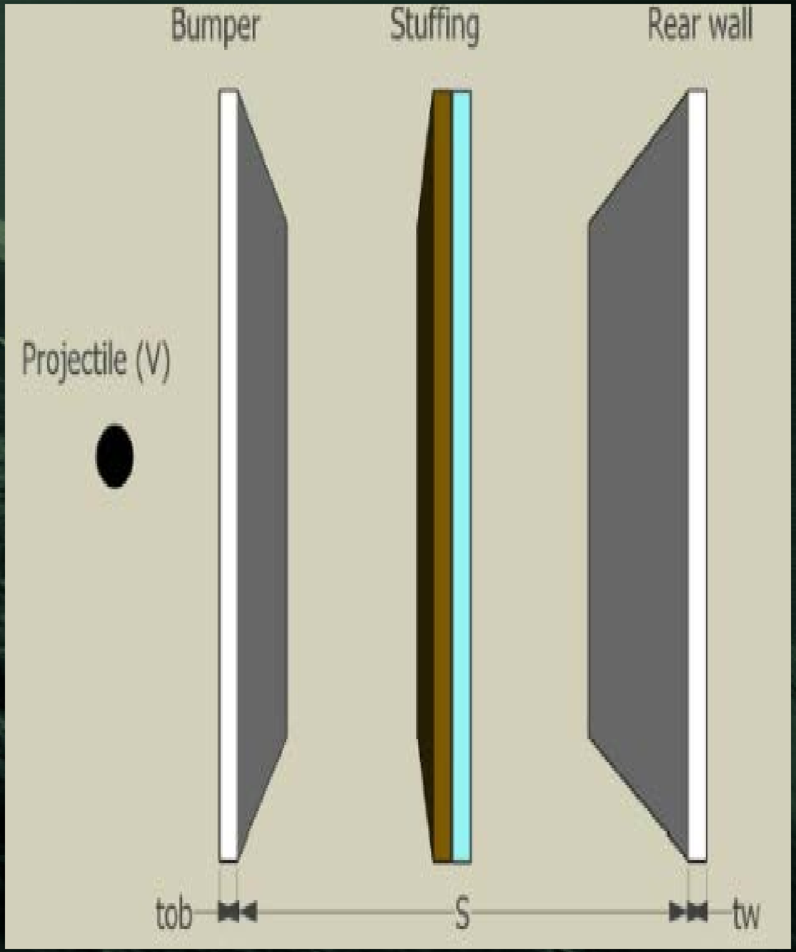
These two figures give a case that the Whipple shield is used in the U.S. laboratory module



4 Stuffed Whipple shield

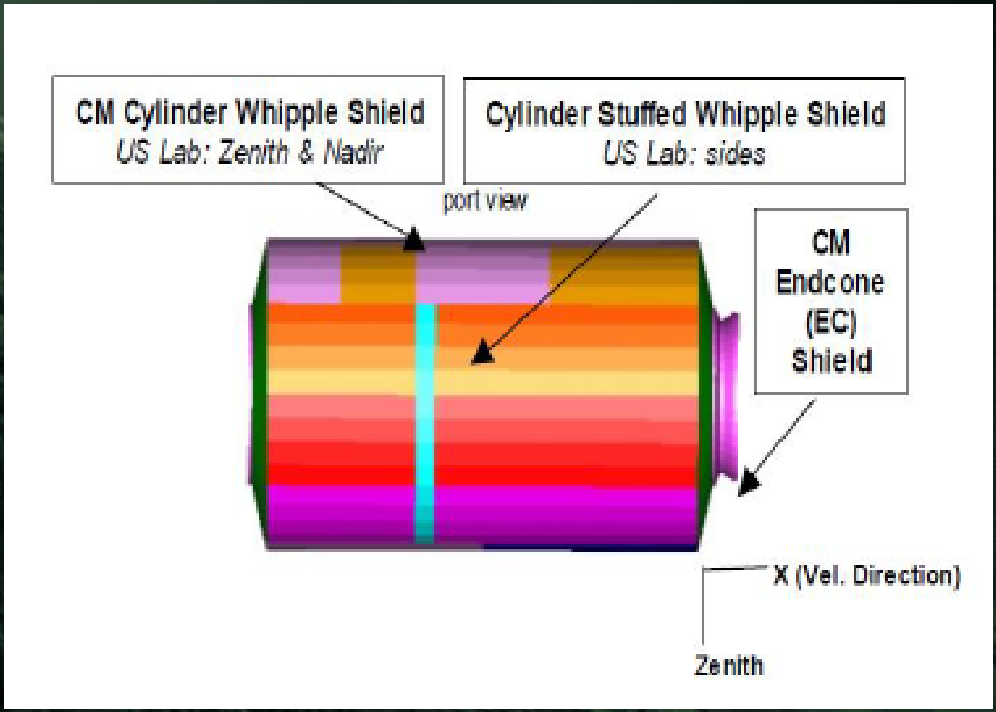
In order to improve the protection of spacecrafts, an extra intermediate layer is added between the bumper shield and the backup wall of the Whipple shield, thus transforming it into a Stuffed Whipple shield.

intermediate layer consisting of advanced materials, e.g., ceramic cloth (Nextel) backed up by high-strength cloth (Kevlar), or cloth epoxy panels.



The Stuffed Whipple shiel-
ds provide better protection than double-aluminum bu-
mper shields of equal weig-
ht, it is particularly effecti-
ve if shield standoffs are short (i.e. shield spacing to projectile diameter ratios of 15 or less).

Nextel/Kevlar Stuffed Whipple (SW) shields protect sections of ISS that are exposed to the highest concentration of orbital debris and meteoroid impacts.



The BLEs that describe the shielding performance of Stuffed Whipple shield is given on the right.

Low Velocity Region

For $V \leq 2.6/(\cos\theta)^{0.5}$

$$d_c = 2.35 \frac{\left(t_w \left(\frac{\sigma_y}{40}\right)^{0.5} + 0.37 A D_b\right)}{\left((\cos\theta)^{4/3}\right)\rho_p^{0.5} V^{2/3}}$$

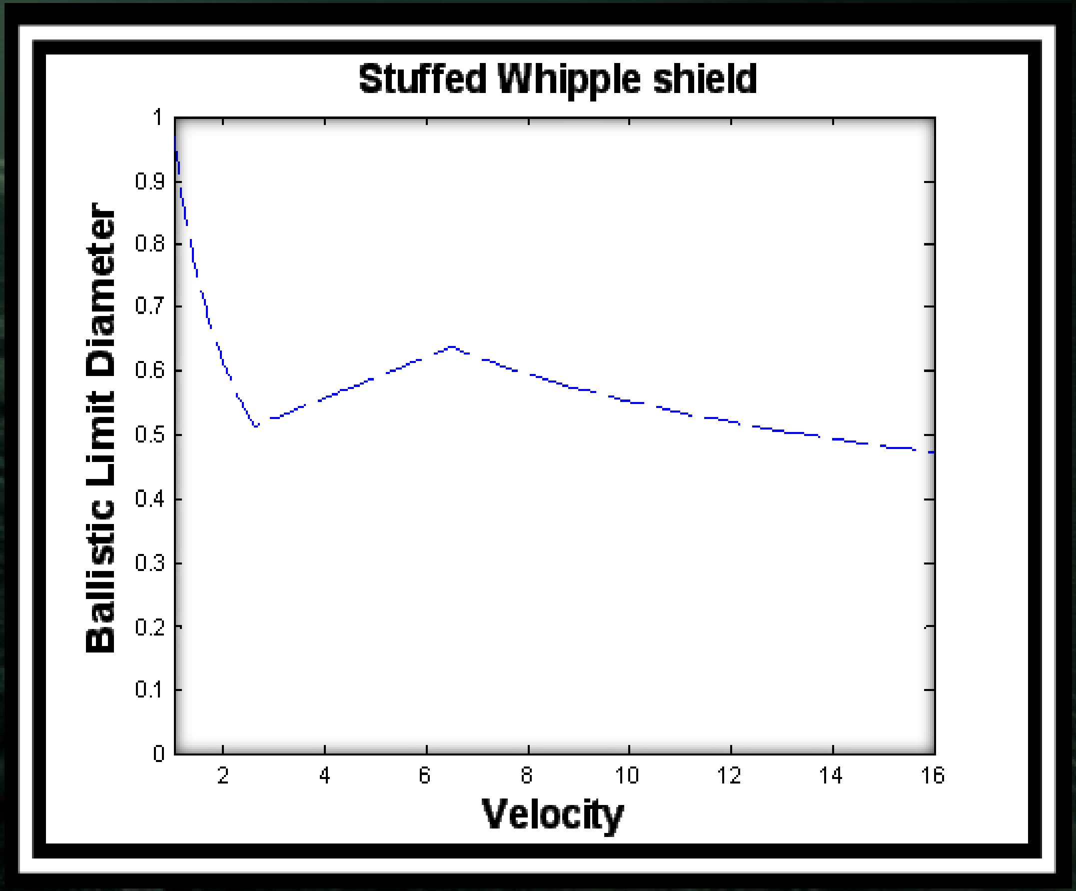
High Velocity Region

For $V \leq 6.5/(\cos\theta)^{3/4}$,

$$d_c = 0.321 \frac{(t_w \rho_w)^{1/3} S^{2/3} (\sigma_y/40)^{1/6}}{\rho_p^{1/3} V^{1/3} (\cos\theta)^{1/2}}$$

Linear Interpolation is used between low and high velocity regions.

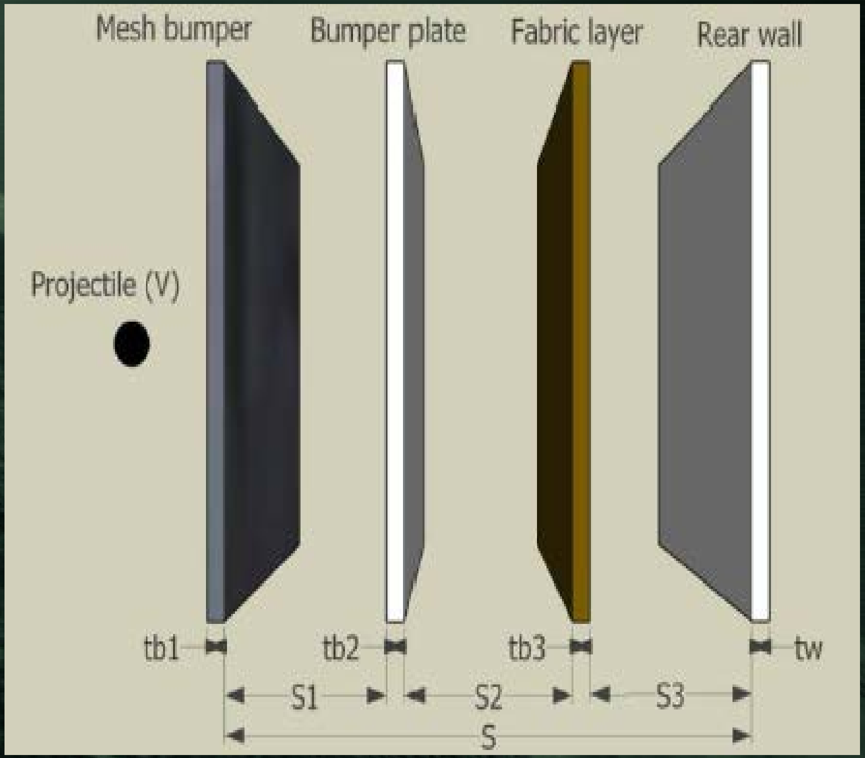
The BLC of Stuffed Whipple shield is shown on the right.



5 Mesh Double-Bumper shield

In order to provide better shielding performance than Stuffed Whipple shield, Mesh Double-Bumper shield (MDB) was proposed.

The schematic diagram of a Mesh Double-Bumper shield is shown on the right.



Hypervelocity impact testing of the MDB shield have demonstrated weight savings of approximately 30% to 50% at light gas gun velocities compared with conventional dual-sheet aluminum Whipple shields at normal impact angles.

The BLEs that describe the shielding performance of Mesh Double-Bumper shield is given below.

Low Velocity Region

For $V \leq \frac{2.8}{(\cos\theta)^{0.5}}$ km/s:

$$d_c = 2.2 \frac{\left(t_w \left(\frac{\sigma_y}{40}\right)^{0.5} + 0.37(AD_b + AD_f)\right)}{\left((\cos\theta)^{5/3} \rho_p^{0.5} V^{2/3}\right)}$$

Where $AD_b = AD_{mesh} + AD_{b2}$, $AD_{b2} = 0.093 d_p \rho_p$, $AD_f = c_f d_p \rho_p$

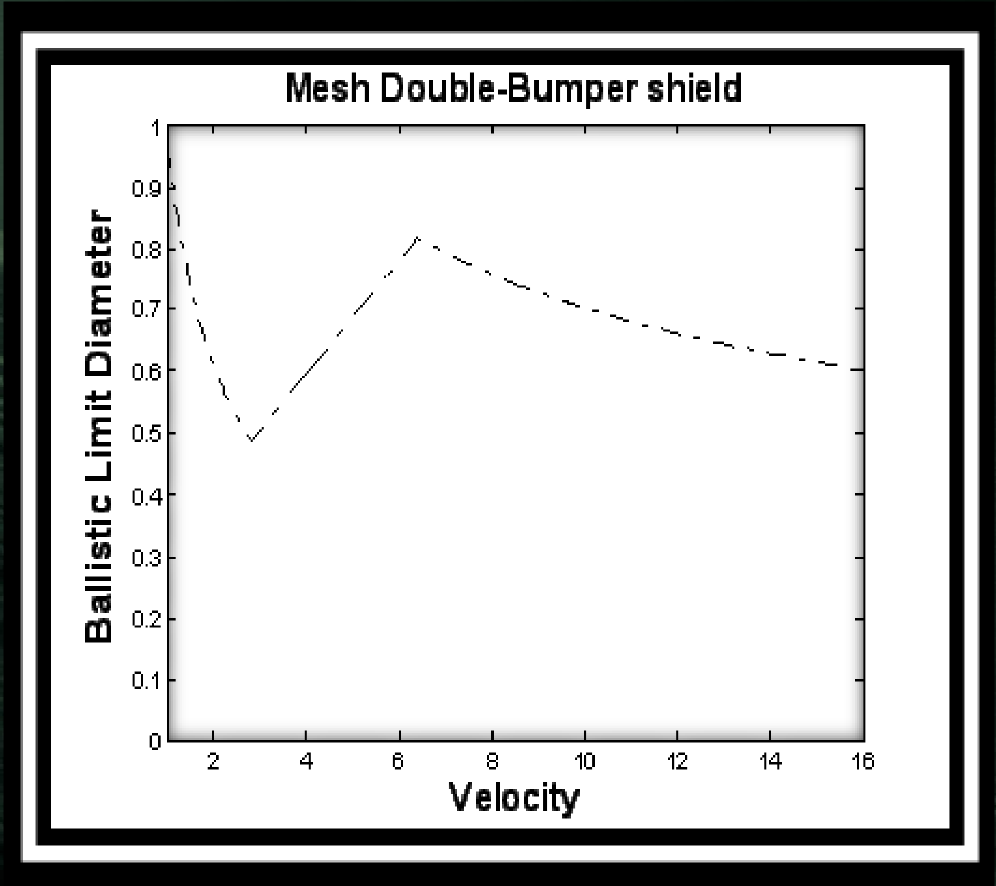
High Velocity Region

For $V \geq \frac{6.4}{(\cos\theta)^{\frac{1}{3}}}$ km/s:

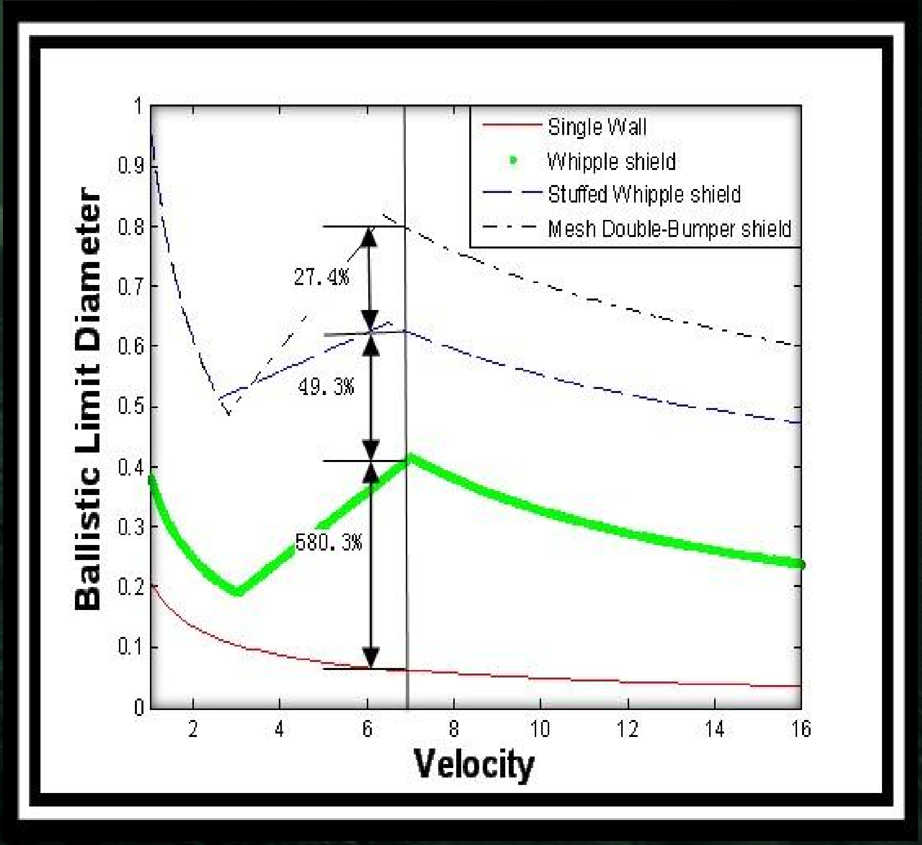
$$d_c = 0.6 \frac{(t_w \rho_w)^{1/3} S^{1/2} (\sigma_y/40)^{1/6}}{\rho_p^{1/3} (V\cos\theta)^{1/3}}$$

Linear Interpolation is used between low and high velocity regions.

The BLC of Mesh Double-Bumper shield, shown in this figure, which is also similar to that of Whipple shield.



The highest curve is the BLC of Mesh Double-Bumper shield, which illustrates that the shielding performance of Mesh Double-Bumper shield is the best (in the condition that the area density of each shield is the same). The second and the third one is Stuffed Whipple shield and Whipple shield respectively, the last one is Single wall.

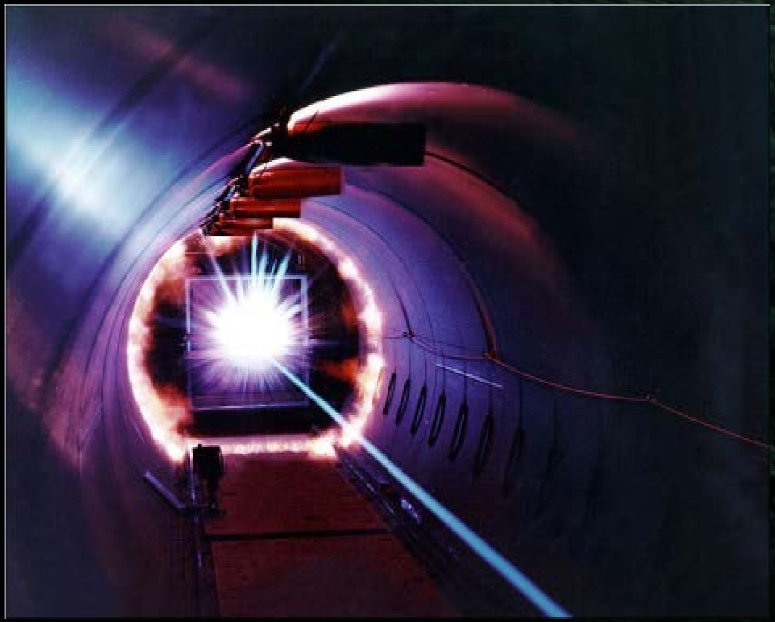


6 Research Methods To Obtain Ballistic Limit Equations of Shields

The methods that are used to obtain the ballistic limit equations are laboratory experiments and numerical simulations.

1 Laboratory Experiments

Laboratory experiments use light gas gun to launch hypervelocity projectiles onto the shield structures.



Through laboratory experiments, we can know well about the shielding performances of spacecraft shields, and we can also conduct optimal design for the shielding structures.

Under normal circumstances, the MMOD velocities have a range of 1~16km/s, but the projectile launched by light gas gun only has a velocity less than 8km/s. Besides, the costs of using laboratory experiments are very high.

2 Numerical Simulations

In order to overcome the deficiencies of laboratory experimen-ts, numerical simulations are used to model the MMOD impa-cts, and to obtain BLEs.

Advantages :

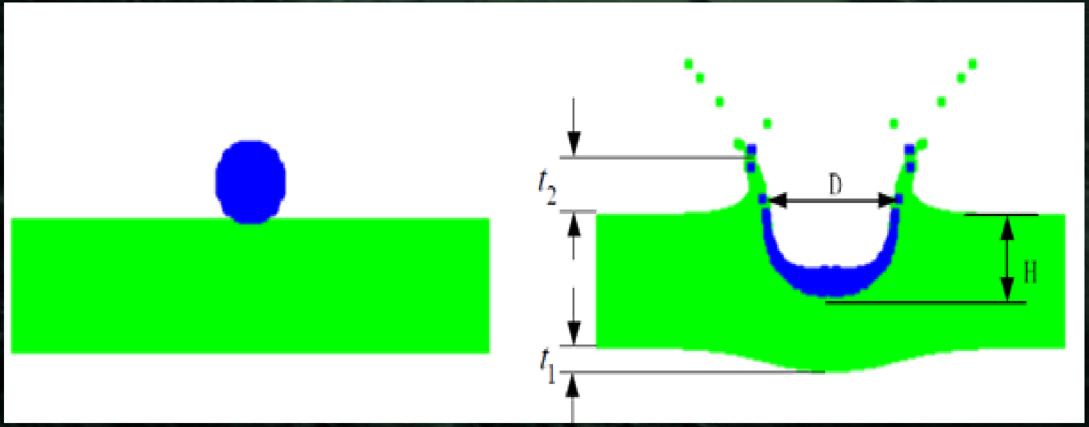
● simulate the hypervelocity impact in the whole speed range

● cost little

● time saving

Simulation results must be verified by laboratory experiments.

Usually, numerical simulations are combined with laboratory experiments to model the hypervelocity impacts.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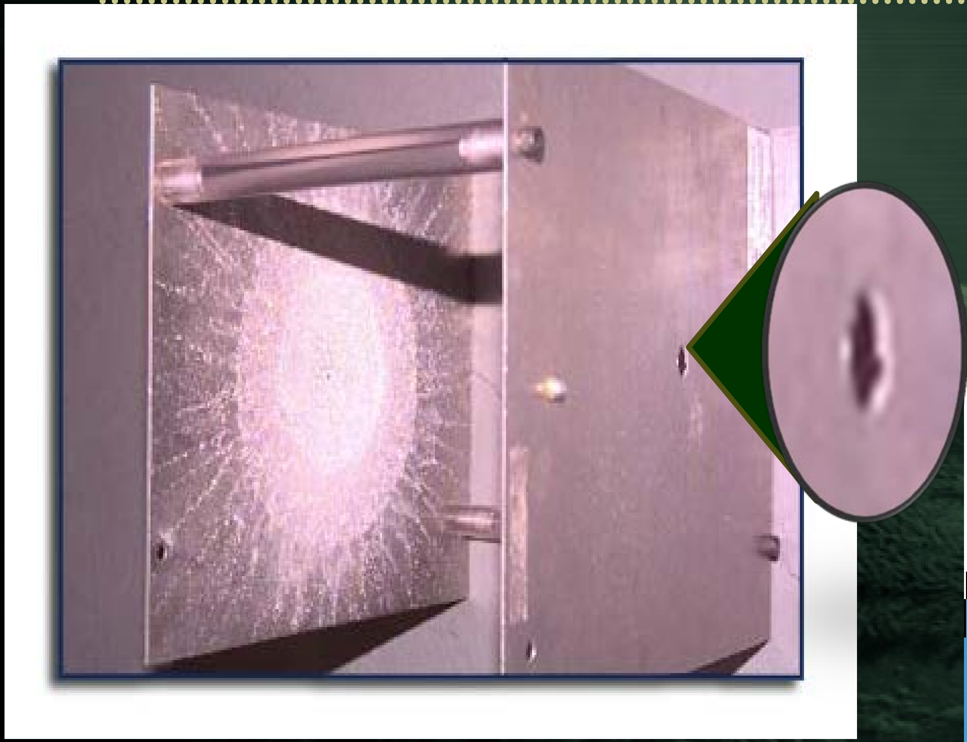
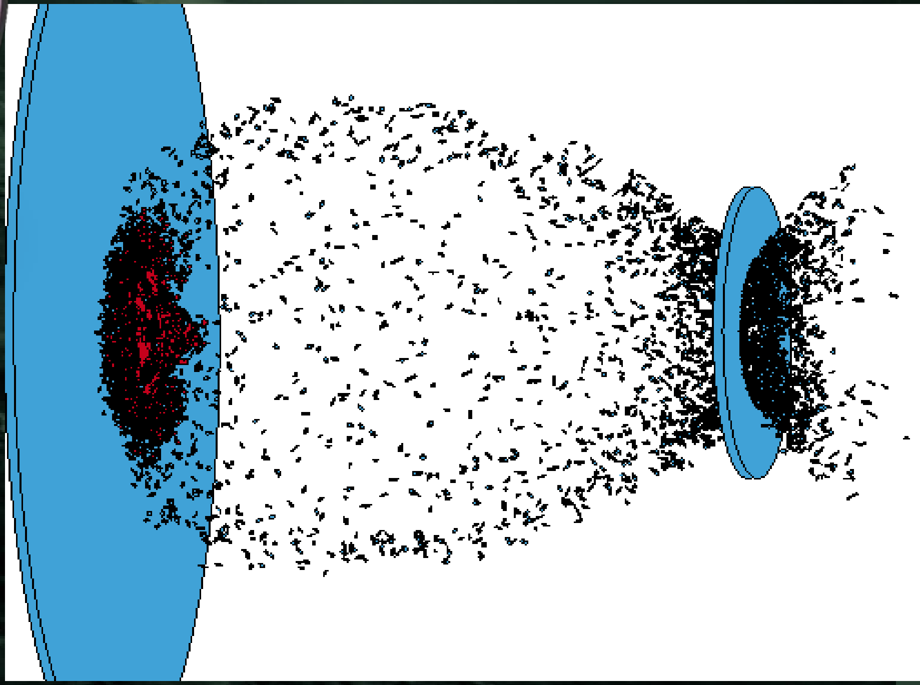
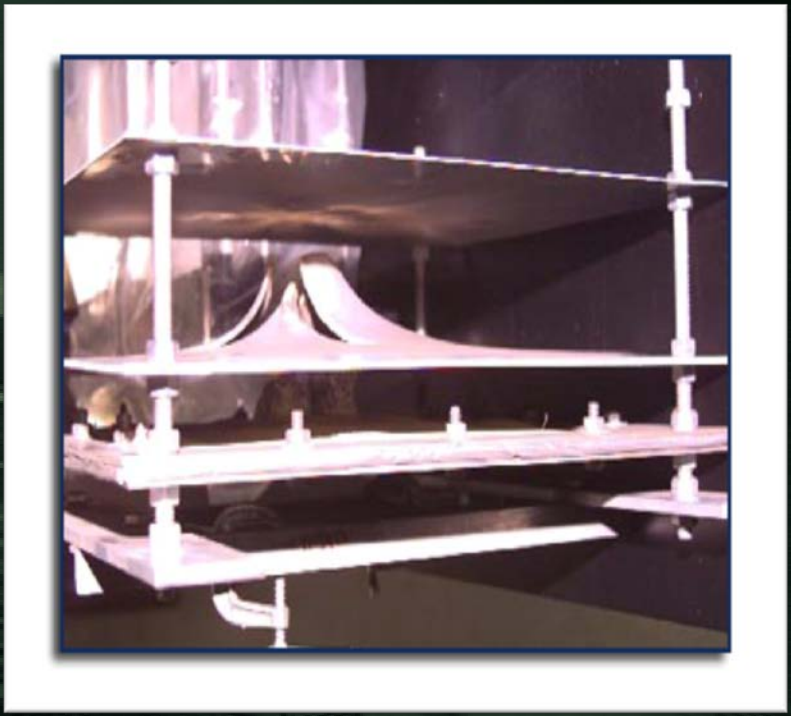
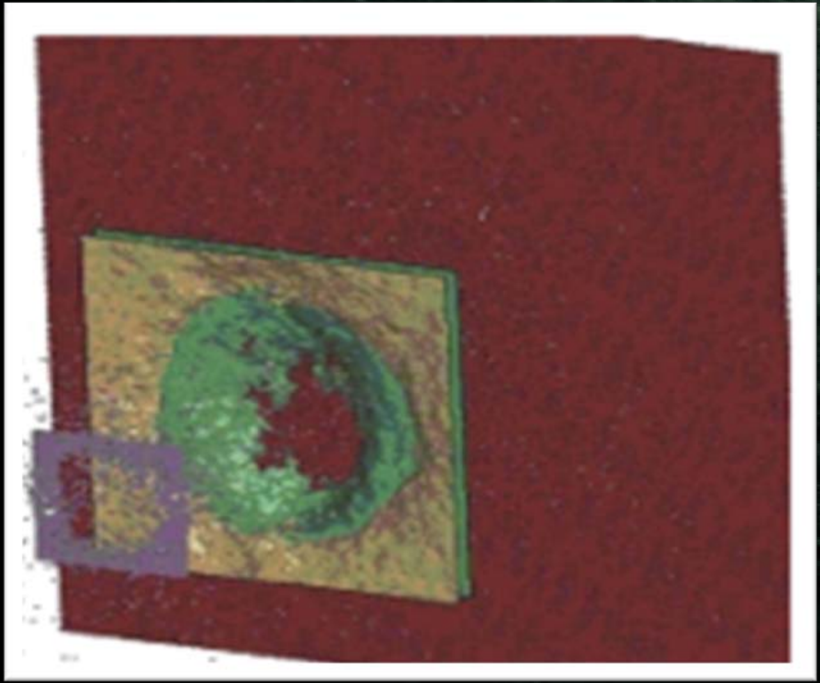
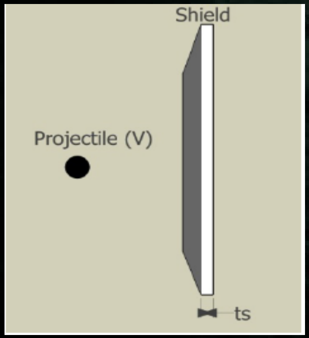



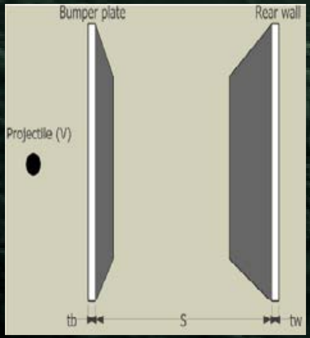


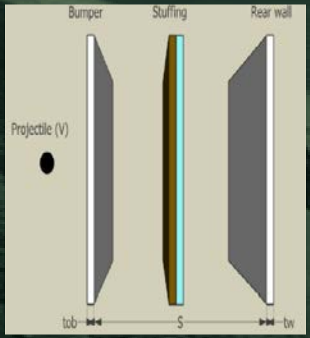


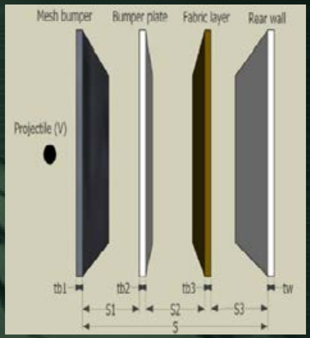
7 Shielding Technology Summary

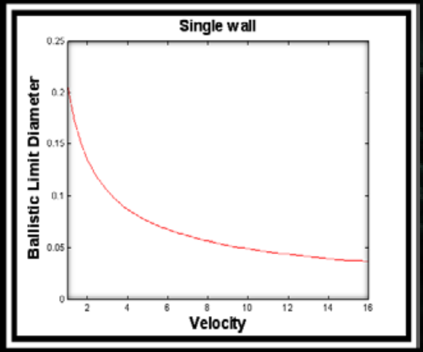
- Single wall (since the first satellite launched in 1957)
- Whipple shield (proposed in 1947, recognized at the beginning of Apollo program)
- Stuffed Whipple shield Mesh Double-Bumper shield (proposed in 1990s)

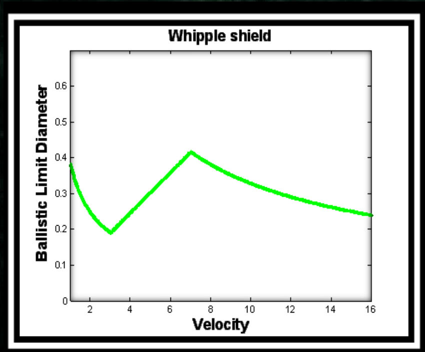


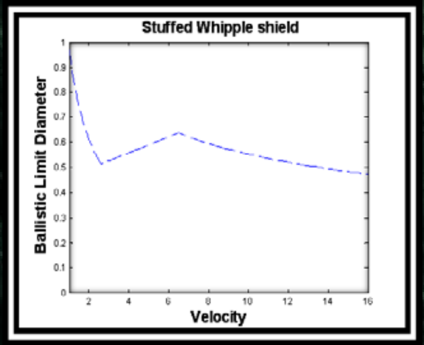


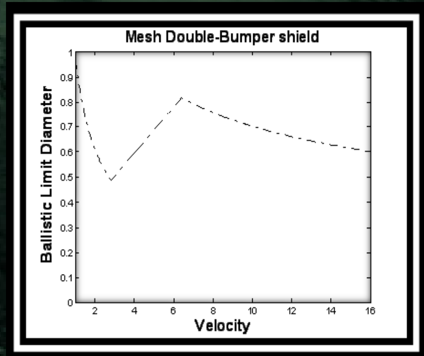










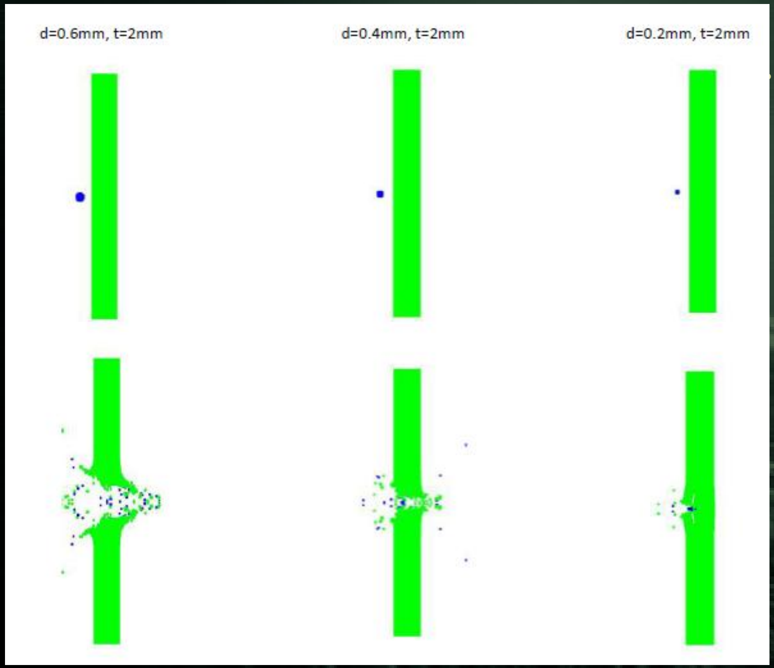


8 What Our Group Is doing

1 Analyze the form of ballistic limit equations
Single wall
Whipple shield,
Stuffed Whipple shield
Mesh Double-Bumper shield
2 Design simulation tests

3 Research simulation technology
FEM (i.e. Finite Element Model)
SPH (i.e. Smoothed Particle Hydrodynamics)

4 Conduct the establishment of ballistic limit equations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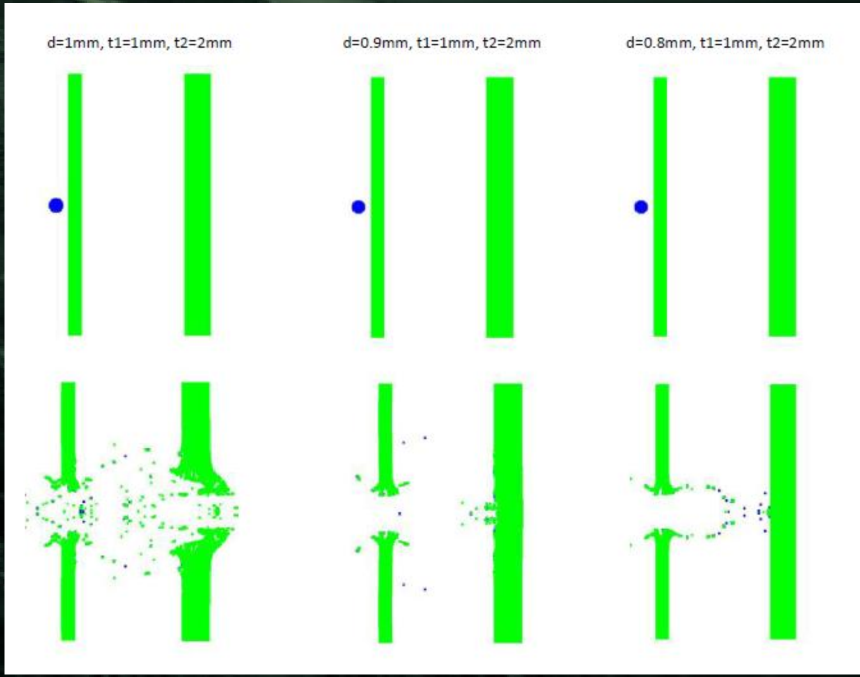
d=0.4mm, t=2mm
d=0.2mm, t=2mm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d=0.8mm, t1=1mm, t2=2mm

Thank you