

Application of Stuffed Whipple Shield to Robotic Spacecraft

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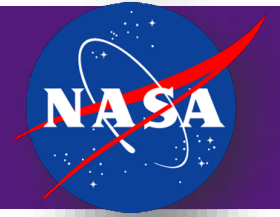
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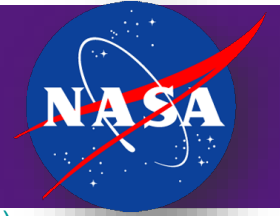
Orbital Debris Services, Code 592





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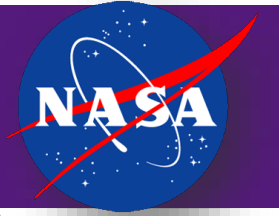
Introduction: The PACE Mission



- The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) spacecraft is designed to improve the ongoing collection of ocean data from space, focusing on phytoplankton production and atmospheric parameters detected on aerosol, clouds, and ocean.
- Its primary payload is the Ocean Color Instrument (OCI), a hyperspectral imaging radiometer.
- Spacecraft is scheduled to launch in early 2024.
- Designed for disposal by controlled reentry.

NASA PACE - Gallery (oceansciences.org)

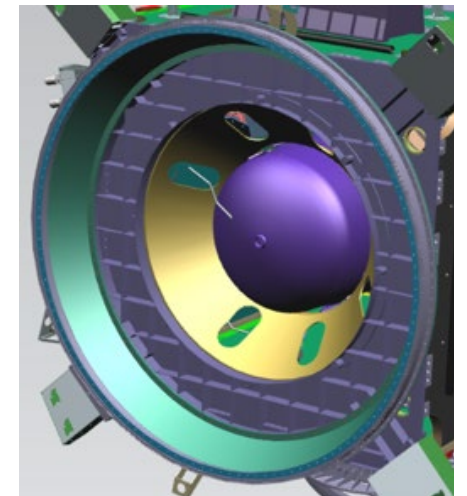
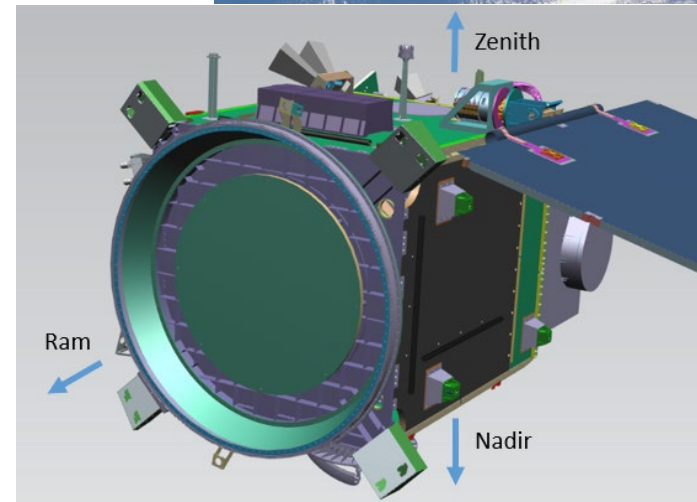




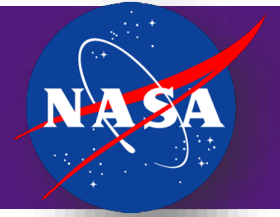
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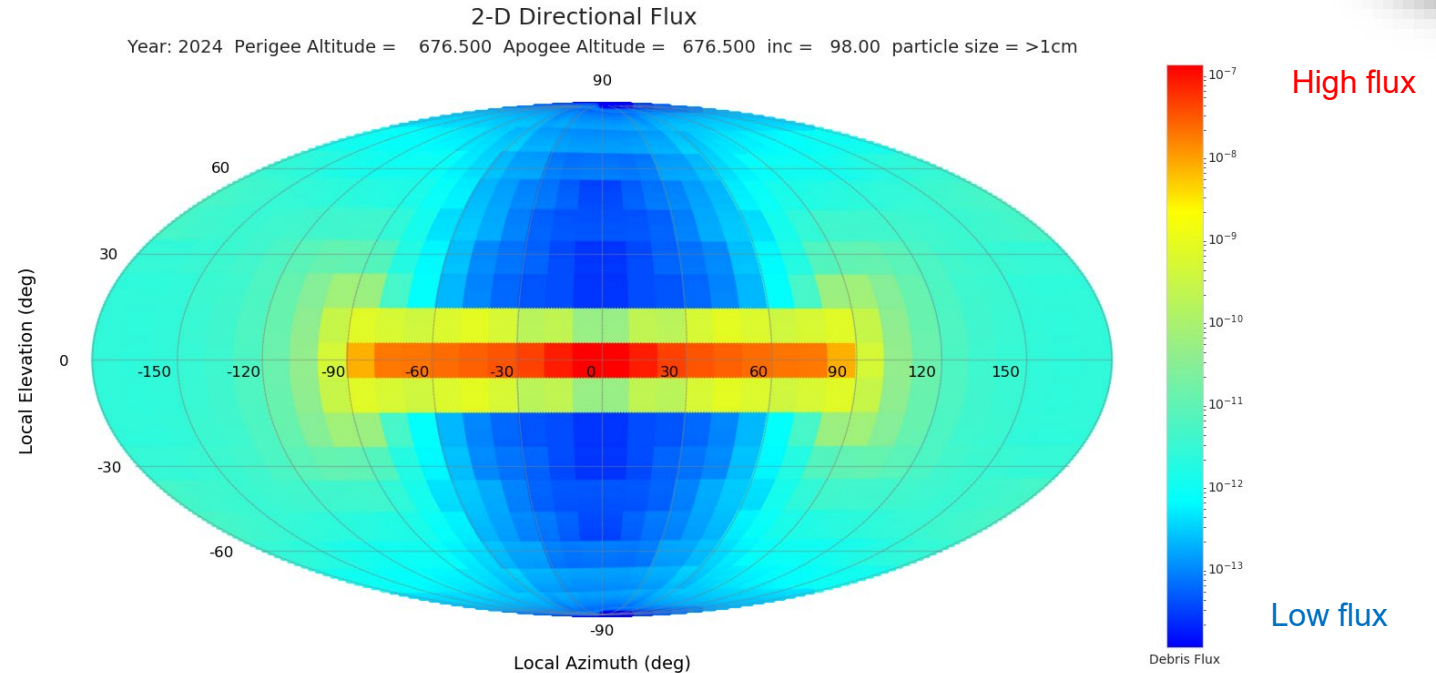
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Orbital Debris Environment and Impact Risk

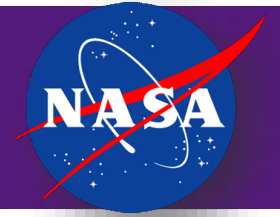


- The ORDEM 3.2 plot of the orbital debris environment at the PACE operational orbit, year 2024, shows highest flux at ram (velocity vector) and port/starboard sides (+/- Y).



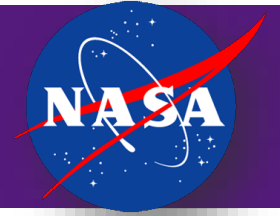
- NASA-STD-8719.14C, *Process for Limiting Orbital Debris*, Requirement 4.5-2. Limiting debris generated by collisions with small objects when operating in Earth orbit: For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, **the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal maneuver requirements is less than 0.01.**

2019 Tank HVI Damage Assessment

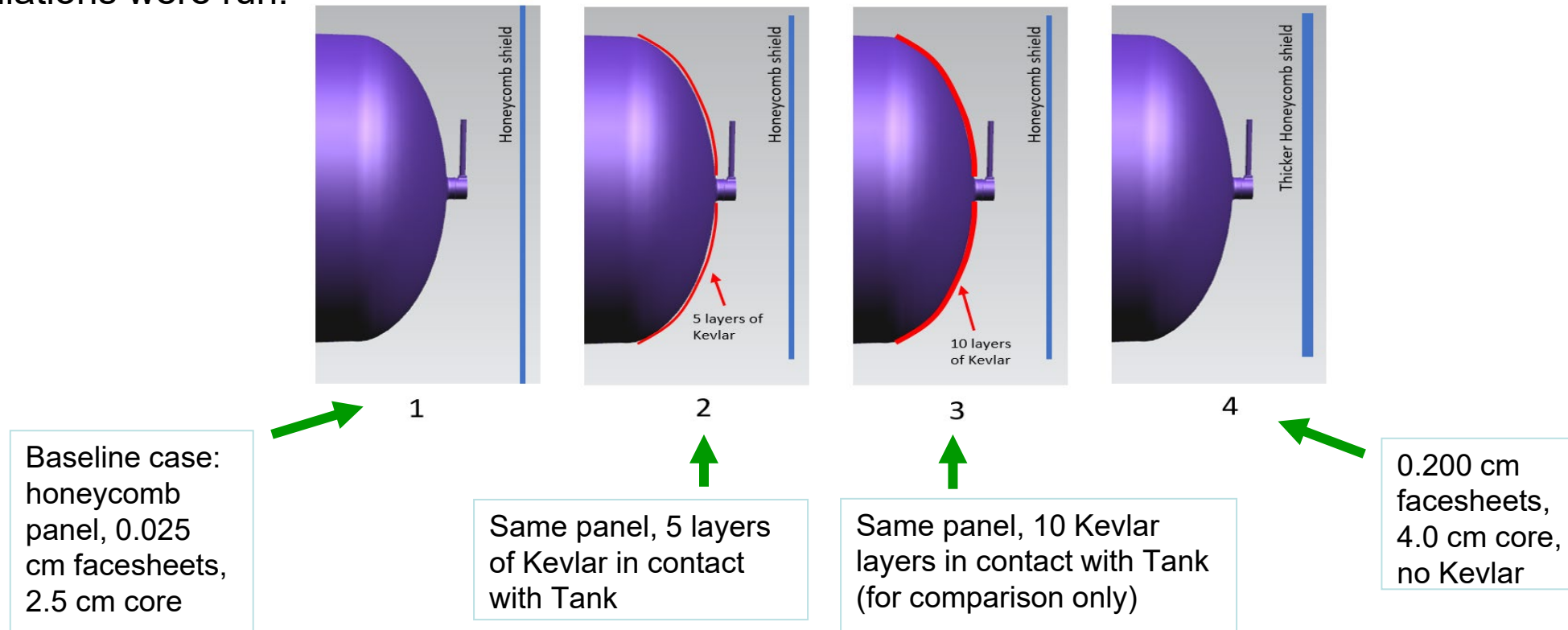


- Pressurized vessels present a challenge for hypervelocity impact (HVI) tests because of their potential to fail catastrophically and to damage adjacent components and structures.
- Since the Apollo era, pressurized tanks have been designed for a penetration depth that should not exceed 25% of the tank wall thickness. For conservatism, the common practice is to limit the penetration depth to 20% of the Tank wall thickness. This makes the Tank particularly vulnerable to micrometeoroids and orbital debris (MMOD) impacts in HVI simulations.
- The original assessment of all reentry-critical components was completed in 2019 using the Bumper3-Sat hypervelocity impact simulation tool. To achieve a total spacecraft risk of less than 0.01, several components were reinforced with typical Whipple shields.
 - The tank ram section was reinforced using a Stuffed Whipple Shield (SWS) adapted for robotic spacecraft. This is the only option that reduced the dome risk to less than 0.001, leaving enough margin for other components in need of protection.

2023 Tank HVI Damage Assessment



- By 2023, the original tools (Bumper3-Sat, ORDEM, and MEM) were already updated. To confirm that the conclusions from the 2019 assessment of the PACE Tank dome remain valid, similar or equivalent simulations were run.



In all cases, the reduced Tank wall is the **critical surface**. Failure is defined as 20% penetration of the Tank wall.

Results for Traditional Whipple Shield Configurations (1 of 2)



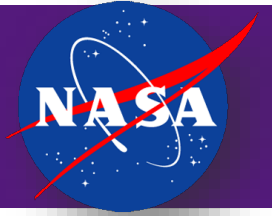
Case	Description	BLE	Probability of Failure (PF)	PF as %	PF as % of 0.01 spacecraft risk	Exceeds 0.01 by itself
1A	Unprotected tank	NNO	0.2467	24.67%	2467%	Yes
1B	Unprotected tank	R	0.2646	26.46%	2646%	Yes
1C	Unprotected tank	TW	0.2974	29.74%	2974%	Yes
2A	5 Kevlar layers on tank	NNO	N/A			
2B	5 Kevlar layers on tank	R	0.0080	0.80%	80%	No
2C	5 Kevlar layers on tank	TW	0.0138	1.38%	138%	Yes
3A	10 Kevlar layers on tank	NNO	N/A			
3B	10 Kevlar layers on tank	R	0.0031	0.31%	31%	No
3C	10 Kevlar layers on tank	TW	0.0035	0.35%	35%	No
4A	2-mm facesheets, 3.8 cm standoff, no fabrics	NNO	0.2213	22.13%	2213%	Yes
4B	2-mm facesheets, 3.8 cm standoff, no fabrics	R	0.2205	22.05%	2205%	Yes
4C	2-mm facesheets, 3.8 cm standoff, no fabrics	TW	0.0089	0.89%	89%	No

- Cases 2A and 3A fail applicability rule for NNO:

$$\frac{\text{Bumper thickness}}{\text{Particle critical diameter}} > 0.20 \text{ and } < 0.25$$

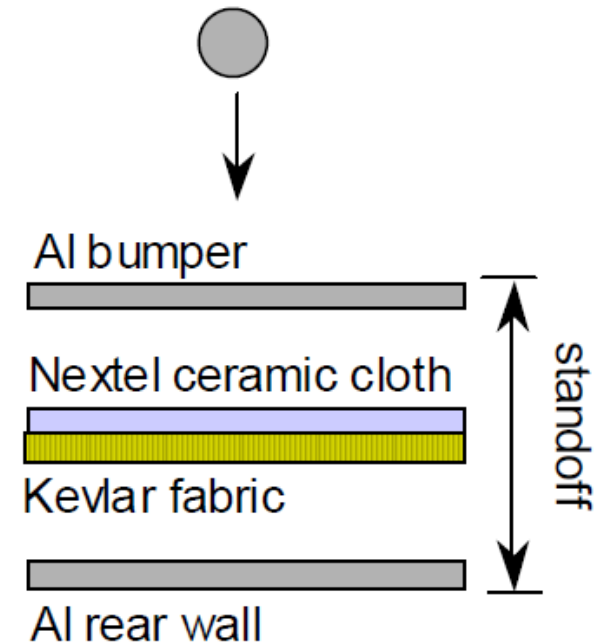
- Valid results for vary from having more than 30% of the allowed risk to failing the Requirement 4.5-2 altogether.
- Conclusion: Typical Whipple Shields are insufficient to keep the risk low enough for spacecraft overall compliance.

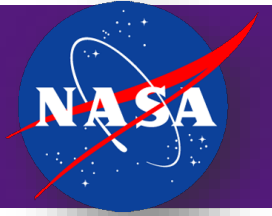
- Ballistic Limit Equations (BLEs):
 - NNO** (New Non-Optimum, based on the Christiansen/JSC equation)
 - R** (Reimerdes' modification of the Christiansen equation, for analysis of thin shields)
 - SRL** (Schäfer-Ryan-Lambert, also know as Triple Wall Equation, where two walls protect the critical surface).
- When applying **NNO** and **R**, the two facesheets are modeled as a single plate.



Human-Rated Stuffed Whipple Shield

- The Stuffed Whipple shield (SWS) consists of two aluminum plates with several layers of Nextel and Kevlar between them.
- The SWS is widely used in the International Space Station (ISS) to protect the crew modules (human-rated).
- **The rear wall is the critical surface.** Failure is defined as penetration of this rear wall, not the surface behind the shield (Damage to anything behind the rear wall, including pressurized tanks, is not defined).
- Several variations exist: rear wall thicker than bumper, internal MLI blanket, aluminum mesh, etc.



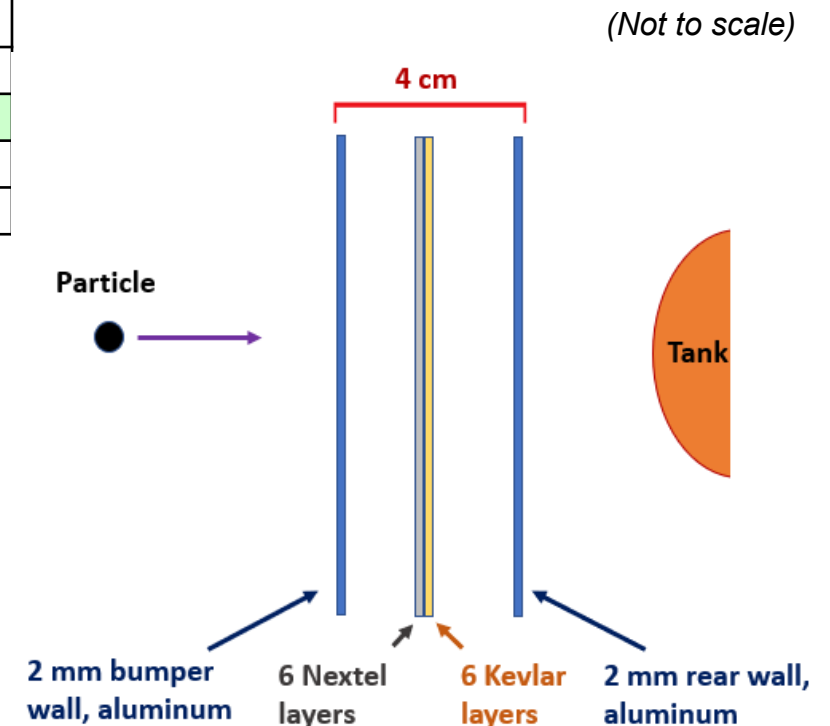


Stuffed Whipple Shield for Robotic Spacecraft

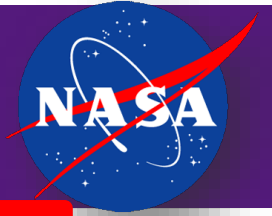
- Simulations using Bumper3-Sat and the Stuffed Whipple Shield BLE, assuming 6 layers of Nextel and 6 layers of Kevlar, showed lower risks compared to traditional Whipple shields:

Case	Bumper Thickness (cm)	Bumper Areal Density (g/cm ²)	Rear Wall Thickness (cm)	Standoff (cm)	Probability of Failure (PF)	PF as percent	PF as % of 0.01
5	0.20	0.8426	0.20	3	0.00166	0.166%	16.6%
6	0.20	0.8426	0.20	4	0.00051	0.051%	5.1%
7	0.25	0.9783	0.25	3	0.00099	0.099%	9.9%
8	0.25	0.9783	0.25	4	0.00038	0.038%	3.8%

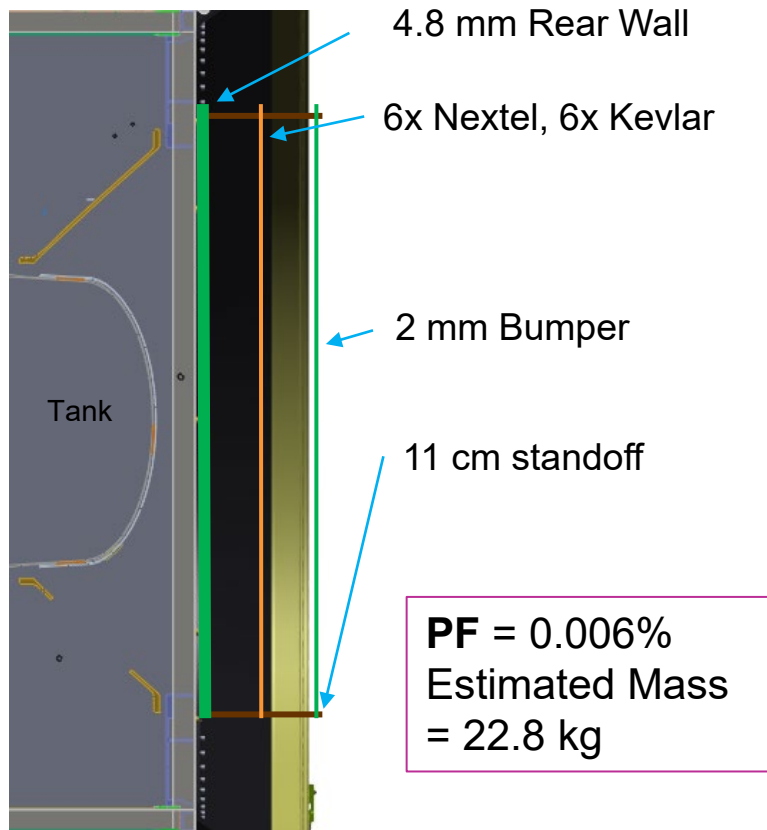
- Case 6 (0.20 cm plates, 4 cm standoff) was selected because it has a Probability of Failure (**PF**) of less than 0.001 but is 3 kg lighter than Case 8 (lowest **PF**). Case 6 balances [performance and shield mass](#).
- Because the failure mode is penetration of the SWS rear wall, the 20% rule for pressurized tanks is not applicable.
 - Results are conservative.



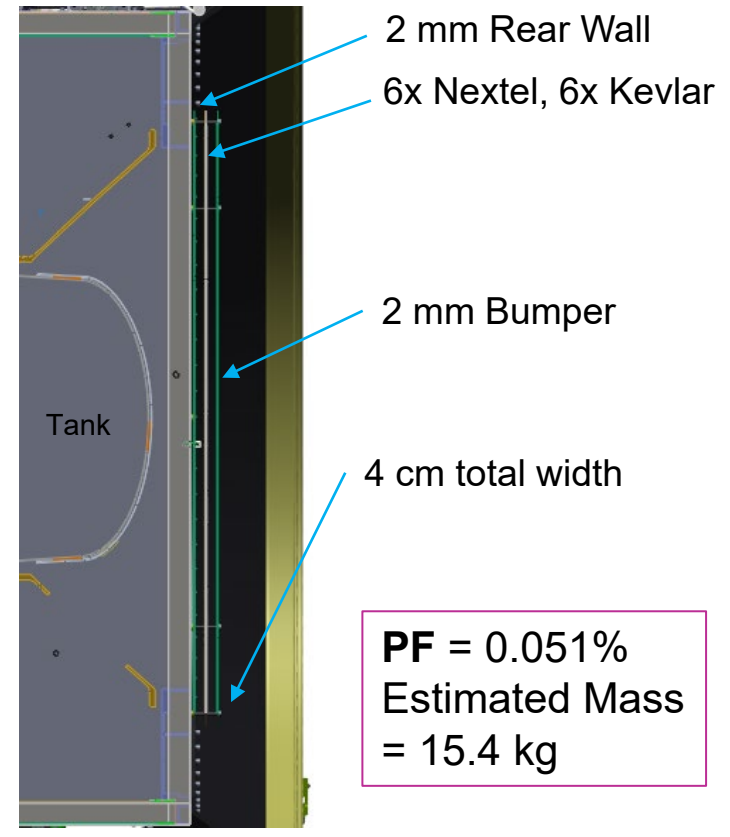
Shield Comparison



For comparison purposes, this is how a typical **human-rated** Stuffed Whipple Shield would look on the PACE spacecraft:

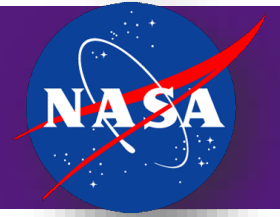


PACE Stuffed Whipple Shield for **robotic** spacecraft:



PF is defined as penetration of the Rear Wall, not in terms of damage to the Tank itself.

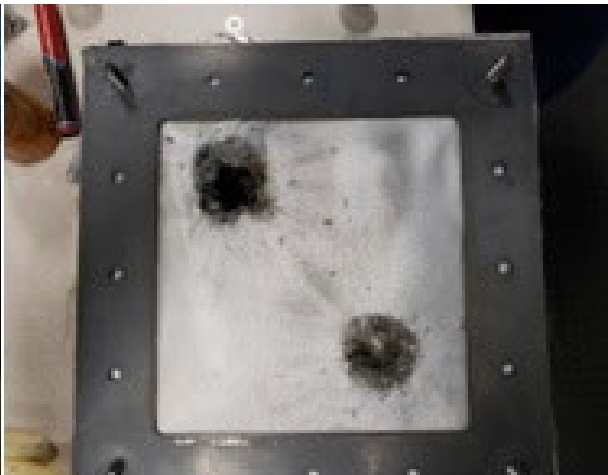
PACE SWS Hypervelocity Impact Test



- In 2019, the PACE SWS configuration was tested at the Remote Hypervelocity Test Laboratory in New Mexico. The tests validated the SWS design.
 - 4.19 mm and 4.59 cm impactors at 7.0 km/s
 - No perforation or detached spall on rear wall
 - Reasonable agreement with the critical diameter of 0.447 cm predicted by the SWS BLE.



Bumper



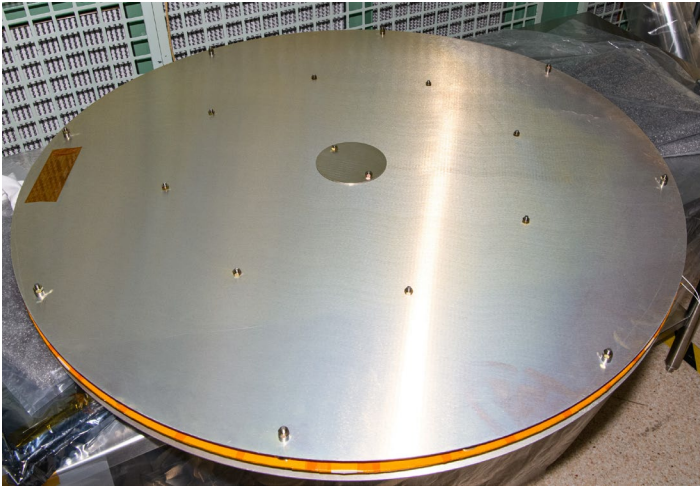
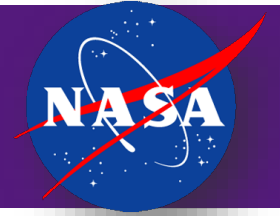
Fabric layers with Nextel facing the Bumper



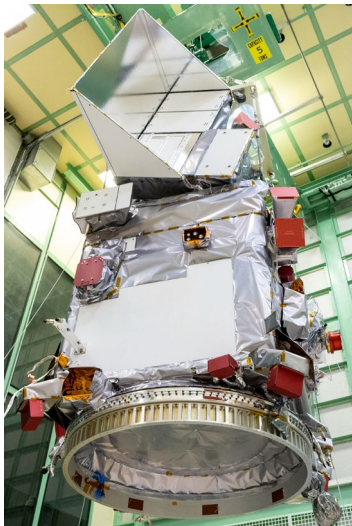
Rear Wall

(Photos used with permission from HVIT)

PACE SWS Integration

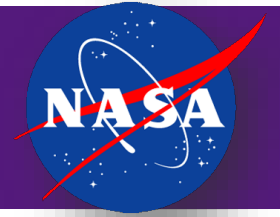


- Photo of the fully assembled Stuffed Whipple shield for PACE, with bumper plate on top, rear wall (plate) at bottom.
- The blanket assembly is in the middle: 6 layers of Nextel AF10 (facing up) and 6 layers of Kevlar KM2+ (behind the Nextel) with Kapton tape covering the borders.
- Stainless Steel spacers separating the plates and the blanket are not shown.



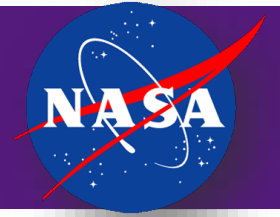
- PACE spacecraft lifted during integration and testing, with the OCI instrument at the top.
- Facing down is the ram section with the Launch Vehicle Adapter and the SWS at the center, covered by Multi-Layer Insulation.

(PACE photos approved for public release)

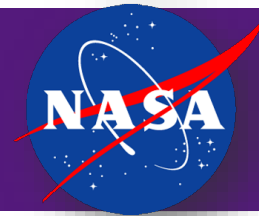


- The Stuffed Whipple shield designed for the ISS can be scaled down for use in robotic spacecraft.
- In most robotic spacecraft, classical Whipple shields and flexible shields provide adequate protection to critical components from MMOD impacts.
- In extreme cases, the location of critical components and thin wall thickness can expose them to a predicted particle flux that may defeat bus panels and traditional MMOD shields. In those cases, the Stuffed Whipple is a viable alternative for robotic spacecraft, as the PACE SWS design demonstrates.

References



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QUESTIONS ?

