ASSESSING ORBITAL DEBRIS WIRE HARNESS FAILURE FOR THE JOINT POLAR SATELLITE SYSTEM

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This article estimates the likelihood of orbital debris (OD) penetration of wire harnesses aboard the Joint Polar Satellite System (JPSS) using computer hydrocode modeling techniques, combined with an understanding of the orbital debris distribution predicted by NASA's Orbital Debris Model (ORDEM 3.0), and an estimate of redundancy of critical wires in typical 6, 18, and 36 strand cables. Based on the unacceptable risk levels associated with these initial results, the article describes an improved protective blanket design that reduced OD penetration risk to acceptable program levels.

NASA's new orbital debris environment (ORDEM 3.0) includes an order of magnitude increase in particle counts in the 1millimeter size range, and a huge increase in stainless steel particles, which are denser and therefore more penetrating than aluminum particles assumed in prior orbital debris models (Squire et al. 2014). In light of this more challenging environment, the NASA Engineering and Safety Council (NESC) sponsored an independent assessment of the orbital debris protection offered by the Joint Polar Satellite System (JPSS-1) in the summer of 2014.

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The JPSS-1 spacecraft wiring is exposed to orbital debris on the zenith deck of the spacecraft, as shown in Figure 1. Some of this wiring supports critical functions that would be required to ensure reentry of the satellite at the end of its life. As part of its support, several members of our NESC team developed and implemented a generic approach for determining the risk of critical function loss from hypervelocity impact and penetration of critical wire bundles from steel and aluminum orbital debris particles impacting from 7.3 to 14.6 kilometers/second. This initial assessment showed an extremely high likelihood of orbital debris penetration per linear meter of exposed wiring, even accounting for potential redundancies.

Based on this high computed risk of wire failure, the team designed an enhanced orbital debris protection design consisting of betacloth-reinforced multi-layer insulation (MLI) suspended at a 5-centimeter standoff over a 7-layer

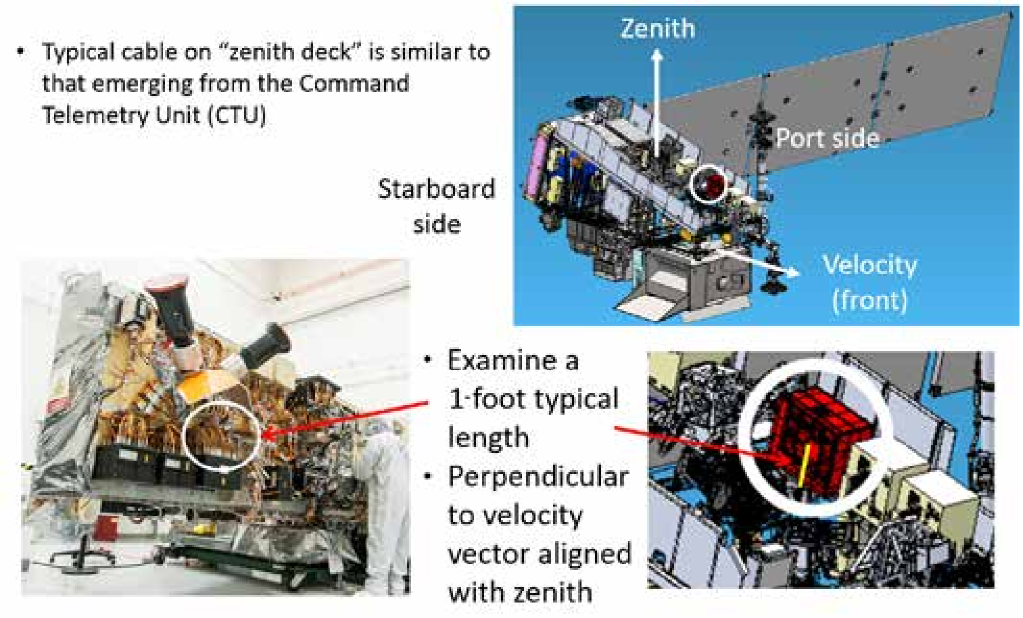


Figure 1. JPSS-1 Wire Harness Geometry, Location and Orientation in SPH Hydrocode Risk Assessment

betacloth and Kevlar blanket, which was draped over the exposed wire bundles. A second Smooth Particle Hydrodynamics (SPH)-based risk assessment was conducted; it also included the beneficial effects from the high (75 degree) obliquity of orbital debris impact and shadowing by other spacecraft components. The result was a considerably reduced likelihood of critical wire bundle failure compared to the original baseline design. This second approach is consistent with earlier wire failure assessments for the James Webb Space Telescope (NASA Engineering and Safety Panel 2008) and other spacecraft such as the Advanced Xray Astrophysics Facility (NASA Presentation 2008), which assumed that any penetration of the shield over the wire bundle caused failure of the bundle.

TASK 1: "GENERIC" RISK ASSESSMENT OF BASELINE MULTI-LAYER INSULATION OVER WIRE BUNDLES

To conduct this effort, our IDA team performed Smooth Particle Hydrodynamics in C computer code (SPHC) hydrocode assessments of orbital debris penetration through a "typical" wire harness (cable) with baseline MLI blanket protection. The SPHC hydrocode is a C language implementation developed by Stellingwerf (1985–1995). In smooth particle hydrodynamics, the "particle" is the analog of the mesh point in a traditional hydrocode. An SPH particle consists of a fixed mass of material at a given position in space, together with a smoothing function, or "kernel," that defines the particle's extent.

Figure 2 shows a typical cable consisting of 36 wires (18 redundant wire pairs), where every wire is considered critical to the function of the cable—that is, if any redundant pair is destroyed. The wires were placed in a hexagonal pattern in order to scale the damage seen in 36 wires to smaller wire bundles (of 18 and 6 wires, respectively). To retain symmetry, the actual hexagonal patterns undergoing hydrocode assessment were of 37, 19, and 7 wires, with damage to the last (deepest) wire neglected in the risk results for the 36-, 18-, and 6-wire strands. The risk assessment considered a one-year exposure to the ORDEM 3.0 orbital debris environment with a zenith/nadir wire orientation. A 5-centimeter standoff of baseline MLI to wire harness (cable) was included in the hydrocode run.

Figures 2 and 3 show typical results from the SPH analyses of the number of wires cut, considering a variety of orbital debris impact materials, velocities and diameters. Note that the expected number of penetrated wires increases with velocity, diameter, and density of the projectile. Figure 4 shows the likelihood of an entire cable failing based on the number of redundant wire failures. As shown, once more than half of the wires (i.e., 19 wires in a 36-wire bundle) are penetrated, there is a 100 percent chance that two redundant wires have been hit, thus "killing" the critical instrument that the wire is feeding. The likelihood of critical instrument failure increases with the number of wires penetrated until unity (100 percent) is reached when penetrating more than half the wires.

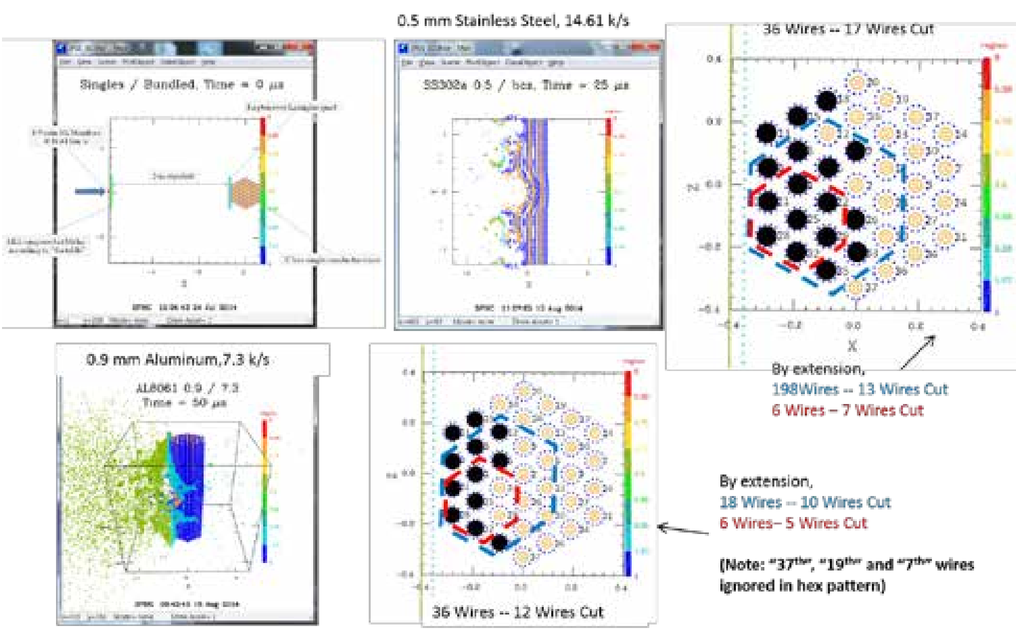


Figure 2. Typical SPH Hydrocode Predictions for Steel and Aluminum Orbital Debris Impacts

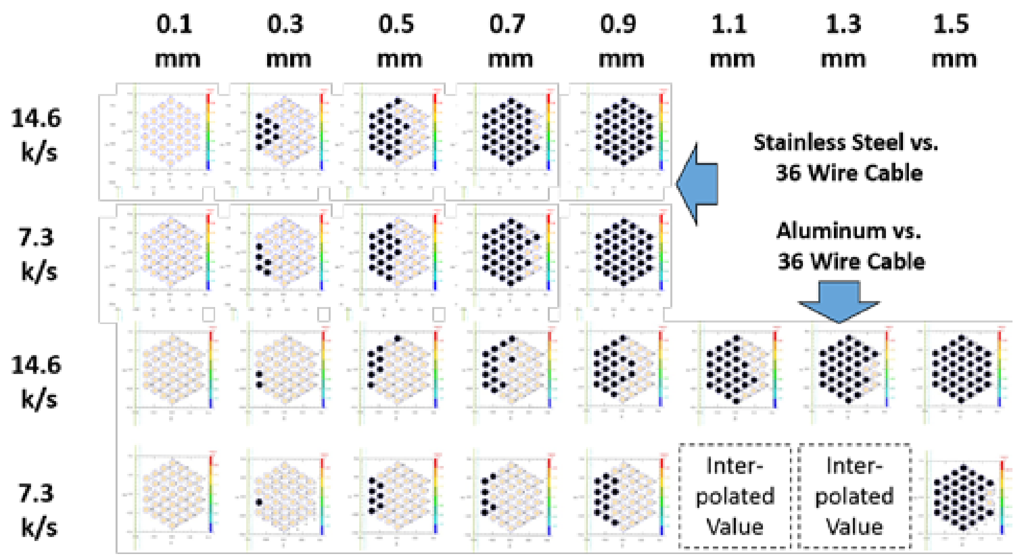


Figure 3. Number of Wires Cut in 36-Wire Bundle for Given Combinations of Orbital Debris Densities, Diameters and Velocities

After we predicted the number of penetrated wires using the SPH hydrocode (and associated it with a probability of cable failure, as shown in Figure 4), we determined the probability of those conditions occurring on orbit using NASA's ORDEM 3.0 (Matney et al. 2014). Larger particles are less likely than small particles to impact a given area on orbit, and we can associate a probability with each size that

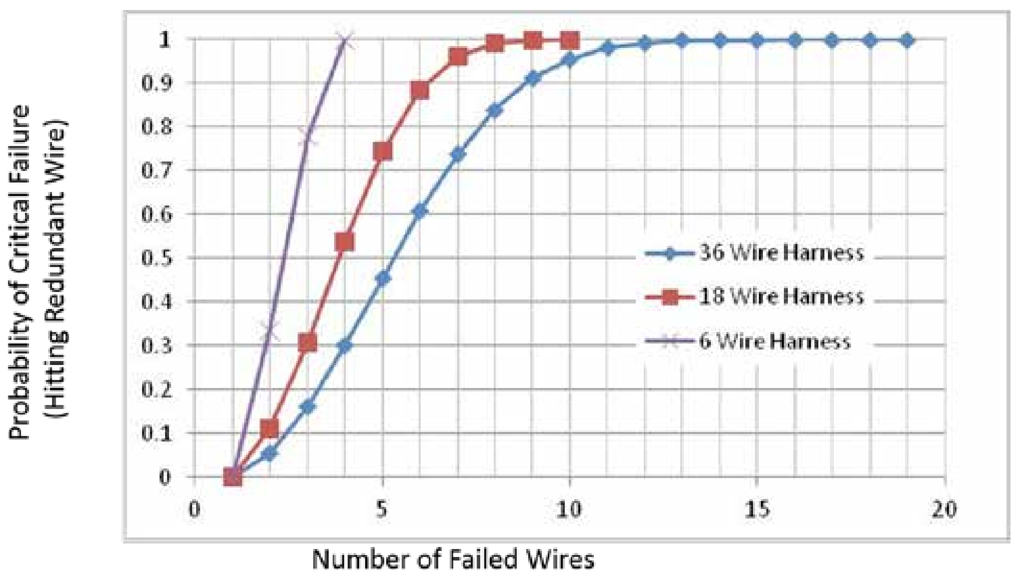
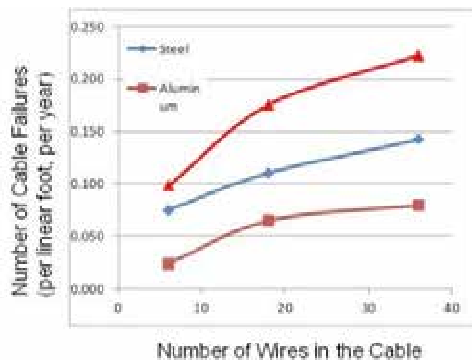


Figure 4. Probability of Critical Failure vs. Wire Harness Size Given Randomly Placed Redundant Wire Failure

causes failure. In this case, we developed an Excel spreadsheet that interpolated the size and velocity of steel and aluminum particles causing from 1 to 36 wire failures based on the hydrocode results and then calculated the likelihood of those particle combinations impacting the cables for a 1-foot length of cable in a year. Figure 5 shows the expected probability of orbital-debris-induced cable failure for a one year exposure of a 1-foot length of 6-, 18-, and 36-strand cables, where every strand within a cable carries a critical function and has a redundant wire somewhere in the cable carrying the same critical function. However, real spacecraft cables are often bundled together, shadowing one another, and are located in orientations and locations where other spacecraft components shadow them. They also often carry less than critical functions. Table 1 shows that considering these potential effects of shadowing, position, and criticality can lower the likelihood of critical cable failure (for the 8-foot cable example) by a factor of 20. However, even this risk is too high, considering that hundreds of feet of cabling would be exposed to the orbital debris environment.



Bundle Size	Steel	Aluminum	Total
6	0.075	0.024	0.099
18	0.111	0.065	0.176
36	0.143	0.080	0.223

Figure 5. Cumulative Number of Cable Failures for Three Cable Sizes (1-Foot Length, Zenith/Nadir Orientation, 1-Year Exposure)

Table 1. Effect of Shadowing and Reduced Criticality on a Typical 8-Foot Cable

Cable	Length (ft)	Baseline n Fails	Portside Shadowing	Front (0 deg) Shadowing	45 deg Shadowing	Bundle Shadowing	Criticality	Realistic n fails
1	2	0.446	0.5	0.46	0.84	1	0.5	0.043084
2	2	0.446	0.5	0.46	0.84	0	0.5	0
3	2	0.446	0.5	0.46	0.84	1	0.5	0.043084
4	2	0.446	0.5	0.46	0.84	0	0.5	0
	Baseline n fails	1.784					More realistic n fails in 8 ft	0.086
	Failure per foot	0.223					Failures per foot	0.011
							Unshadowed baseline vs Realistic	20.7

TASK 2: EVALUATING AN ENHANCED MICROMETEOROID AND ORBITAL DEBRIS SHIELD

Based in part on the high computed risk of a critical wire bundle failure from the generic approach, the program decided to implement an enhanced micrometeoroid and orbital debris (MMOD) protection design consisting of betacloth-reinforced MLI suspended at a 5-centimeter standoff over a 7-layer betacloth and Kevlar blanket, draped over the exposed wire bundles, as shown in Figure 6. It is noteworthy that 99.5 percent of orbital debris approaches from within the X-Y (orbital) plane and that orbital debris approaching from the Y axis (from the "front" as viewed by the spacecraft) makes up nearly 50 percent of this flux. This threat would impact the deck at 14.6 kilometers per second (km/sec) and impact the blanket at 75 degrees obliquity, relative to the exposed wires on the zenith deck. The ultimate objective was to develop a design that prevented penetration of the blanket from 3mm aluminum spheres and 2mm steel spheres considering these "worst case" impact conditions shown in Figure 6.

As shown in Figure 7, SPHC analyses showed that the enhanced shield was capable of preventing penetration of a 3mm aluminum and 2.12mm orbital debris particle at the stated conditions. By preventing penetration of the blanket from these particle sizes, the wires are automatically protected to at least that degree.

Once we determined the ballistic limit of the blanket for the worst case orientation (and highest orbital debris flux), we calculated the exposed area for the blanket (and wiring beneath it) using the configuration shown in Figure 8. The JPSS-1 spacecraft features radiators on the "sides" of the spacecraft that block much of the orbital debris from approaching the spacecraft from angles at 15 degrees or more from the velocity vector. A cardboard model and a simple digital camera were used to estimate the amount of shadowing achieved on the surface of the spacecraft.

Table 2 shows that there is only a 5.3 percent probability that one or more orbital debris penetrations of the enhanced shield over the zenith deck wiring will occur in the expected 7-year operation of the JPSS-1 spacecraft. Most of this risk results from penetration by stainless steel particles, due to their lower ballistic limit and higher flux on the enhanced wiring shield.

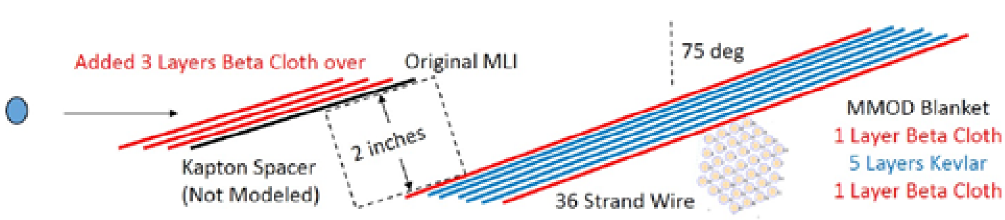


Figure 6. Enhanced Shield Configuration For Defeat of 3mm Aluminum Orbital Debris Particles

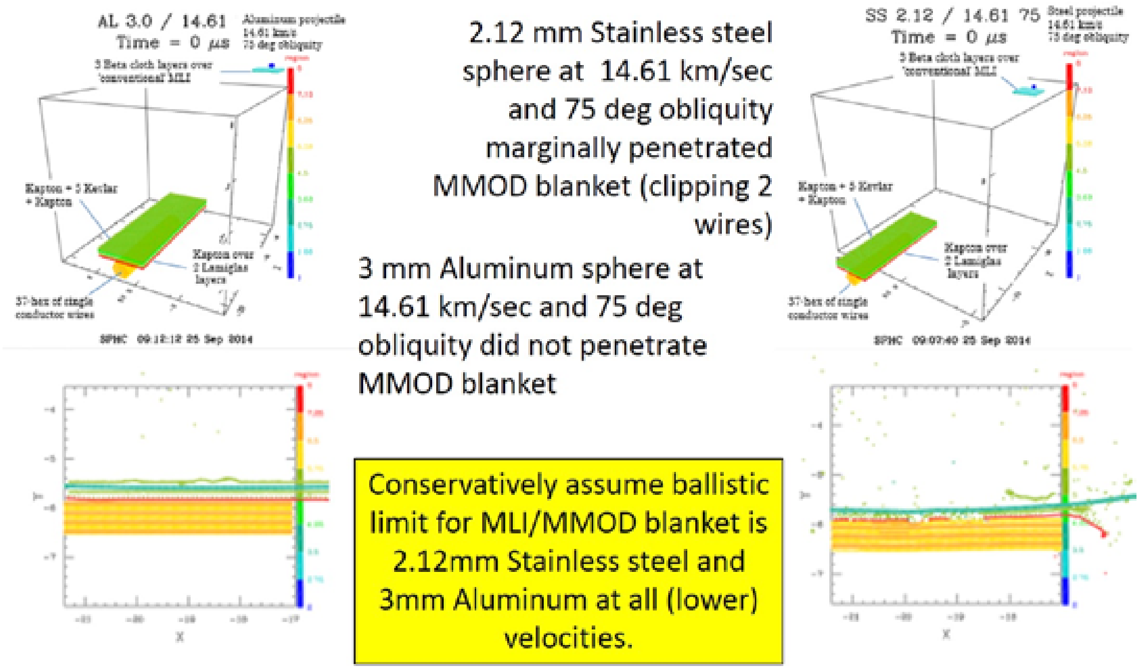
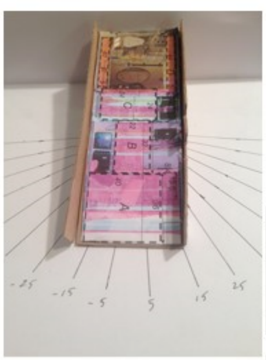
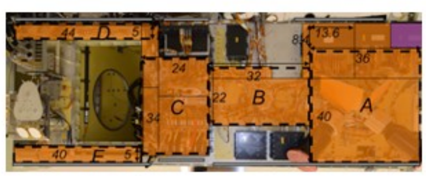


Figure 7. Hydrocode Evaluation of Enhanced MMOD Shield for Steel and Aluminum Orbital Debris



Orbital Debris Approach Angles



Example: 25 Degree Approach Angle

		Exposed Area Including Shadowing by Approach Direction (m^2)									
Region	Surface Area	0 deg	5	15	25	35	45	55	65	75	85
A	0.930	0.241	0.239603	0.233331	0.219177	0.098527	0.042508	0.013805	0.005134	0.000639	0.000218
B	0.454	0.118	0.117139	0.114073	0.053577	0	0	0	0	0	0
C	0.527	0.137	0.135775	0.105777	0	0	0	0	0	0	0
D	0.142	0.037	0.036606	0.035648	0	0	0	0	0	0	0
E	0.129	0.033	0.033278	0	0	0	0	0	0	0	0
	Obliquity	75	75.1	75.5	76.4	77.8	79.5	81.5	83.7	86.1	88.7
	Total Area	0.57	0.56	0.49	0.27	0.10	0.04	0.01	0.01	0.00	0.00

Figure 8. Exposed Areas of Wire Harness by Approach Angle

Table 2. Total Estimated Risk of Blanket Penetration by Steel and Aluminum Orbital Debris Particles

Steel risk with shadowing

		Steel		7 years
Approach	BL for N	Pen Flx	Area	N pens
5	2.120	0.003448	0.562	0.013563491
15	2.120	0.001757	0.488	0.006000823
25	2.120	0.000942	0.272	0.001792875
35	2.120	0.000688	0.098	0.000472185
45	2.120	0.000549	0.042	0.000161411
55	2.120	0.000484	0.013	4.40532E-05
65	2.120	0.000462	0.005	1.61581E-05
75	2.120	0.000471	0.0006	1.97961E-06
85	2.120	9.55E-05	0.0002	1.33696E-07
		Total Port		0.0221
		Total Stbd		0.0221
		Total		**0.0441**
		Ppen		**0.0431**

Aluminum risk with shadowing

		Aluminum		7 years
Approach	BL for N	Pen Flx	Area	N pens
5	3.000	0.000678	0.562	0.002668771
15	3.00	0.000503	0.488	0.001718317
25	3.000	0.000259	0.272	0.000493157
35	3.000	0.000184	0.098	0.000126244
45	3.000	0.000149	0.042	4.38661E-05
55	3.000	0.000129	0.013	1.17334E-05
65	3.000	0.000116	0.005	4.07175E-06
75	3.000	0.000114	0.0006	4.80279E-07
85	3.000	6.57E-05	0.0002	9.19177E-08
			Total Port	0.0051
			Total Stbd	0.0051
			Total	**0.0101**
			Ppen	**0.0101**

Total Risk ~ 5.3% probability of 1 or more MMOD blanket penetrations in 7 years.

SUMMARY AND CONCLUSIONS

Two approaches were pursued to evaluate the risk from orbital debris penetration of exposed JPSS wiring. In the first case, a "generic" approach considering normal impact of the baseline MLI over wires resulted in an evaluation of wire damage that was very conservative, in that it did not initially consider the effects of obliquity or shadowing by other spacecraft components and adjoining wiring and could not be sufficiently refined to account for the exact wiring bundle design, including redundancy. This resulted in an unacceptably high risk, according to JPSS program management.

In the second case, an enhanced orbital debris shield was added over the wires and evaluated to provide less than a 5.3 percent probability of blanket penetration in 7 years. However, shield penetration should not be equated to critical wire failure. The figure of 5.3 percent "risk" of shield penetration is an upper bound for critical wire failure risk, for the following reasons:

- Penetration of the wires below the blanket would require a larger (and less likely) orbital debris particle, thus lowering computed risk compared to the blanket itself.
- Actual wire coverage is less than the coverage of the MMOD blanket (lowering critical wire risk).
- There is a higher ballistic limit of the shield at other approach angles since that debris approaches at a lower velocity.

- Not every wire is critical, and many wires are redundant.
- Many of the critical wires are placed below other wires, so more shadowing is likely than was accounted for in this assessment.

Considering these factors, the probability of critical wire failure on the zenith deck could be well beneath 1 percent.

EPILOG

The NASA-IDA team was awarded the NASA Group Achievement award, chosen by the NESC Director “in recognition of outstanding accomplishment through the coordination of individual efforts that have contributed substantially to the success of NESC’s mission.”

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