National Aeronautics and
Space Administration

NASA WG3 MMOD Protection Summary

Interagency Space Debris Coordination Committee (IADC)
May 2012

NASA JSC-KX/Eric L. Christiansen
NASA JSC-ES/Kornel Nagy
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Summary of MMOD Protection Activities

- Shuttle:
  - Performed pre-flight MMOD risk assessments, for vehicle & extravehicular activities (EVA): STS-134, STS-135
  - Performed post-mission MMOD damage inspections of Shuttle vehicle windows, radiators, wing leading edge: STS-134, STS-135
- ISS:
  - Performed post-flight MMOD damage inspections of returned ISS hardware including multipurpose logistics module (MPLM), handrails, and ammonia tank assembly
  - Identified MMOD damage in on-orbit photos
  - Discussing inspection of visiting vehicle thermal protection systems prior to undock
  - Continue damage detection & repair work (joint international working group)
- Multipurpose Crew Vehicle (Orion), Commercial Crew & Resupply Vehicles:
  - Performed risk assessments supported by impact tests to evaluate design options to meet MMOD requirements
    - Failure criteria for thermal protection system defined and included in risk assessment
    - Requirements for ISS missions meet standard allocation for all ISS critical items to maintain ISS crew safety

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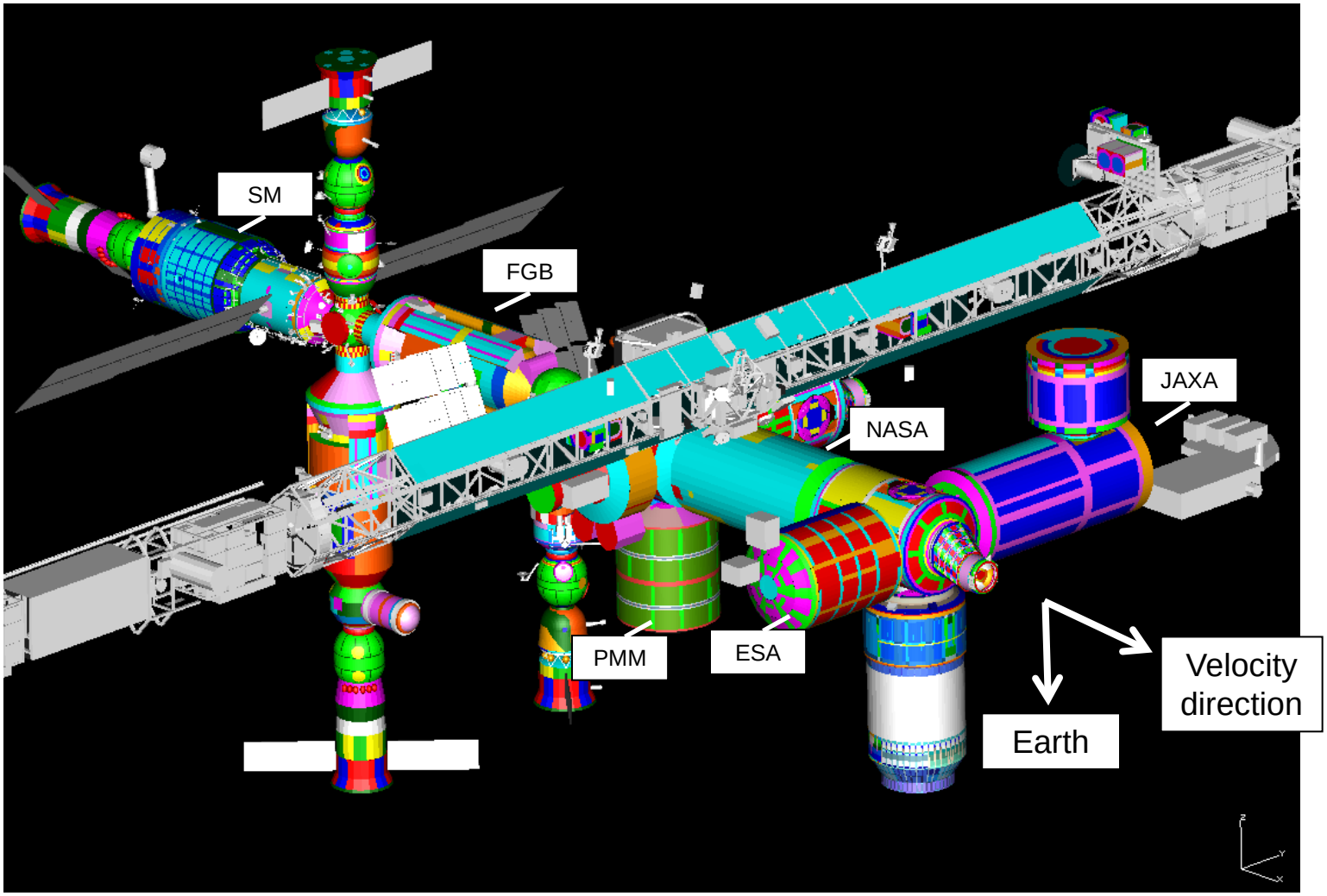
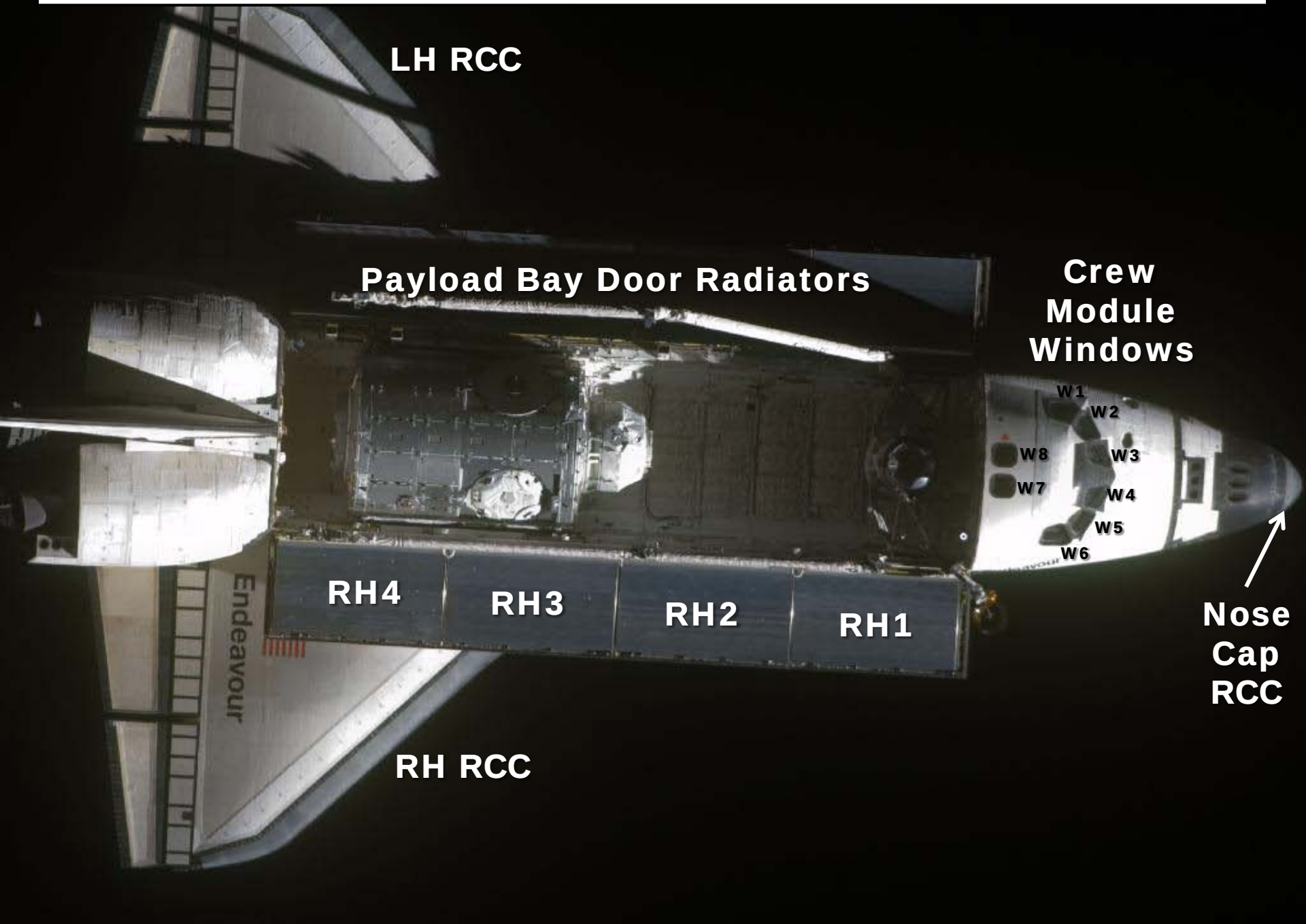
ISS *Bumper* finite element model



Each color represents a different MMOD shield configuration
(~500 different shields protect ISS modules and external pressure vessels)

Orbiter Post Flight MMOD Inspections



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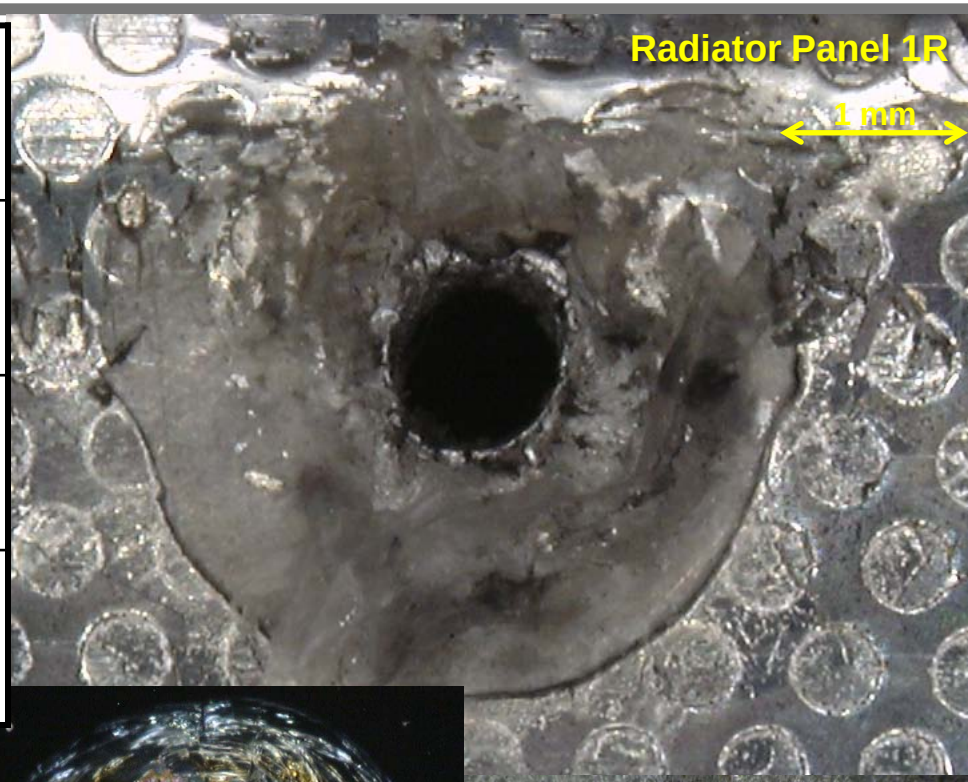
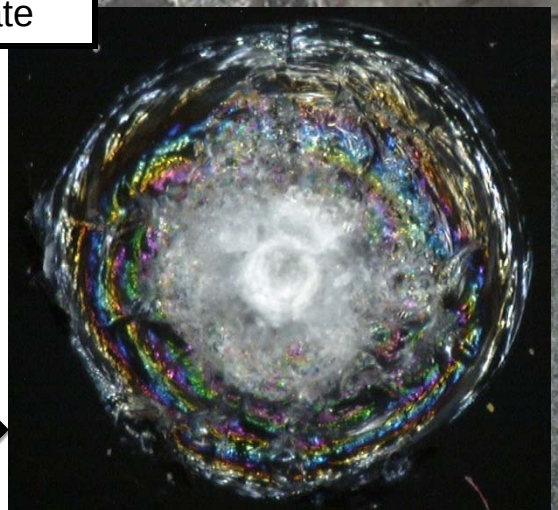
STS-135 MMOD Impact Damage

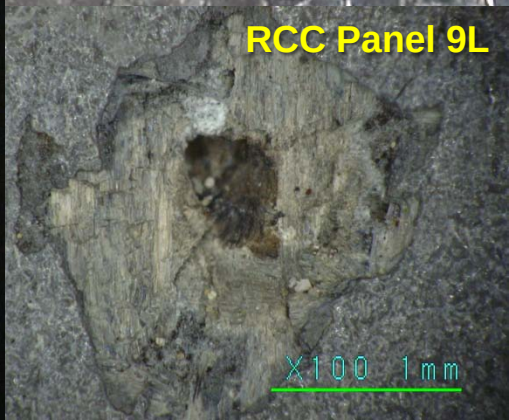
OV-104 Flight 33 – August 2011

	Number of MMOD Impacts	Largest MMOD Impacts
Windows	7 craters	W6: 2.5 x 2.5 mm damage extent
Radiators	3 MMOD damages reported	1 face sheet perforation
RCC	9 MMOD indications	Panel 9L: 2.3 x 1.9mm, depth = 0.4 mm exposed substrate





Window 6 →



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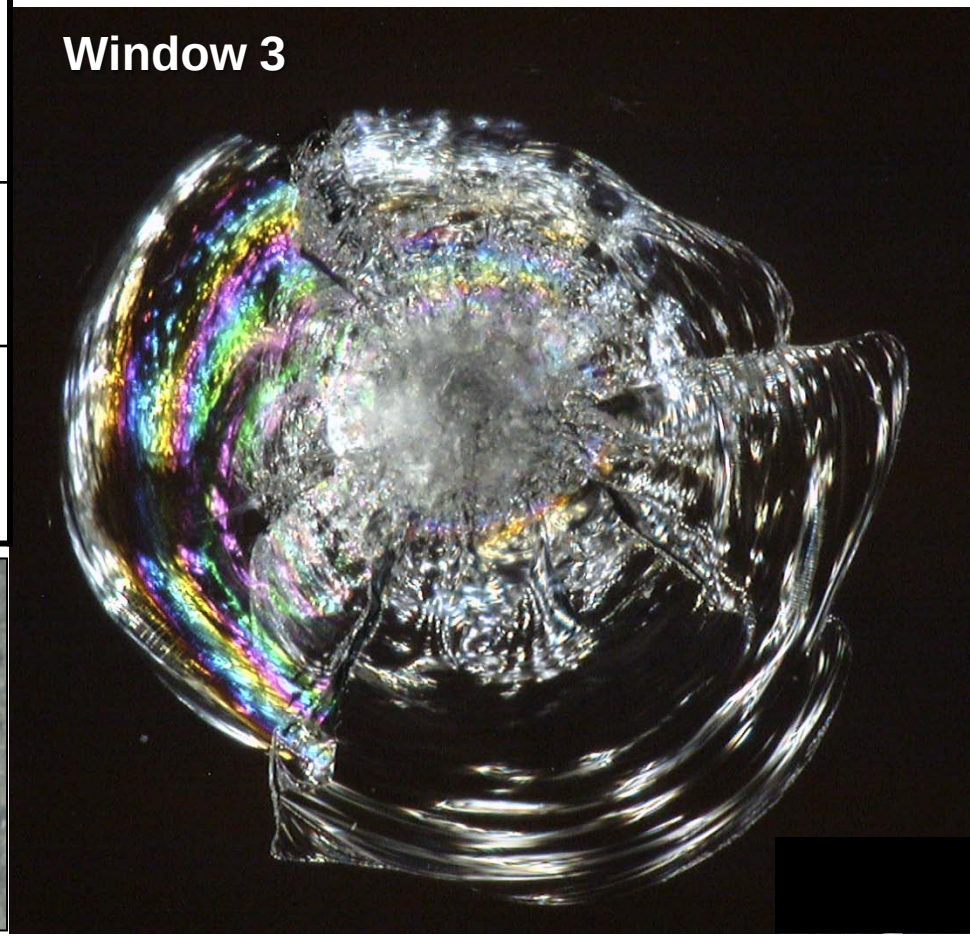
STS-134 MMOD Impact Damage

OV-105 Flight 25 – June 2011

	Number of MMOD Impacts	Largest MMOD Impacts
Windows	10 craters	W3: 3.7 x 3.5 mm damage extent
RCC	13 MMOD indications	Panel 9L: 1.3 x 1.0mm, depth = 0.27 mm no exposed substrate



RCC Panel 9L →

← 2mm →

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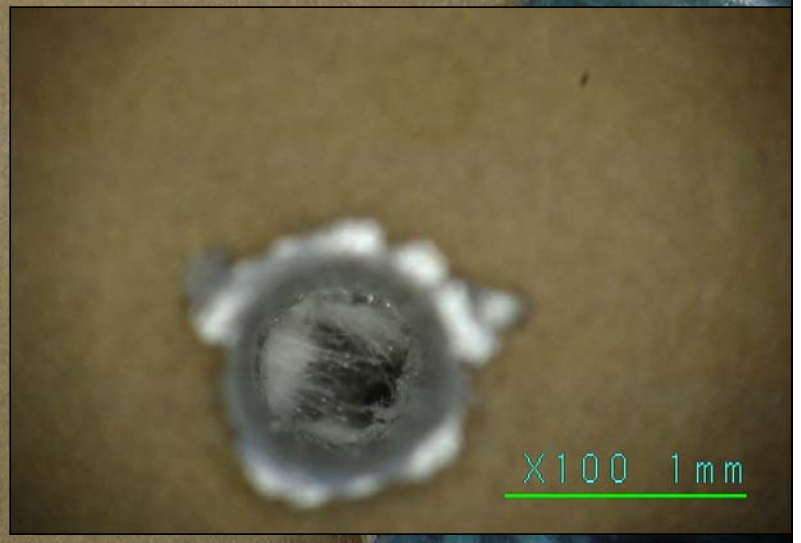
ISS MPLM and PMIA MMOD Impact Damage

Inspected after STS-135	MMOD Exposure	Number of MMOD Impacts	Largest MMOD Impacts
Multi-Purpose Logistics Module (MPLM)	7.0 days on ISS, 5.7 days in payload bay	64 craters between 0.1mm and 0.7mm diameter	0.7mm dia. crater in 0.8mm thick Al bumper
Pump Module Integrated Assembly (PMIA)	8.7 years on ISS	PM: 36 impact features LAPA: 19 impact features	PM: 0.8mm dia. perforation in Al tag LAPA: 1.8 x 1.8mm crater in Al handrail

MPLM grapple fixture coating spall dia. = 0.6 mm



Pump Module ID tag Hole dia. = 0.8 mm

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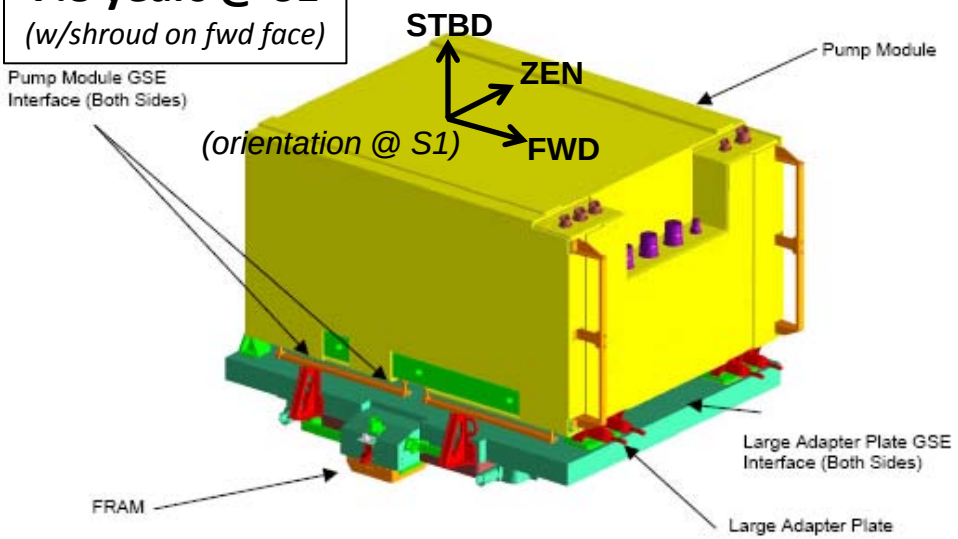
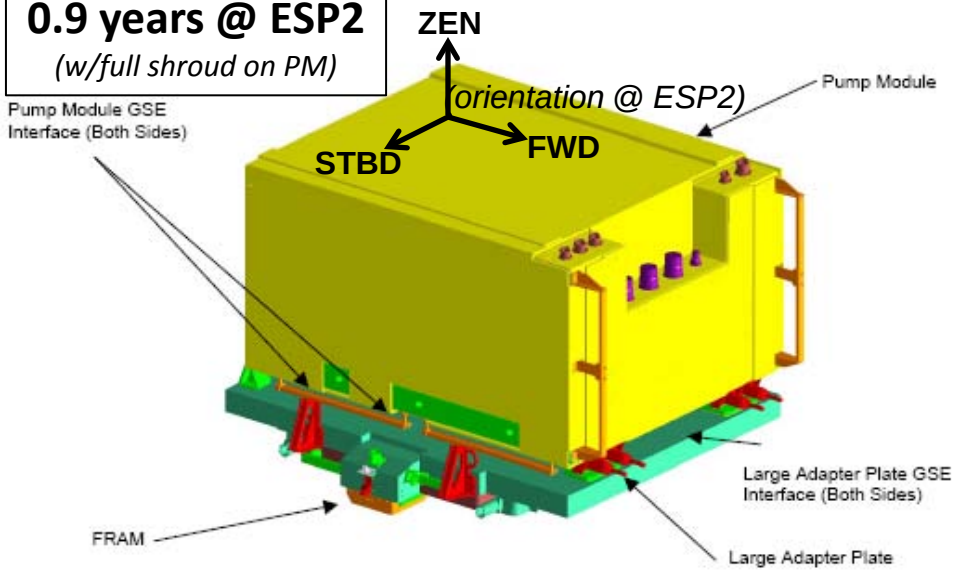
Pump Module Integrated Assembly

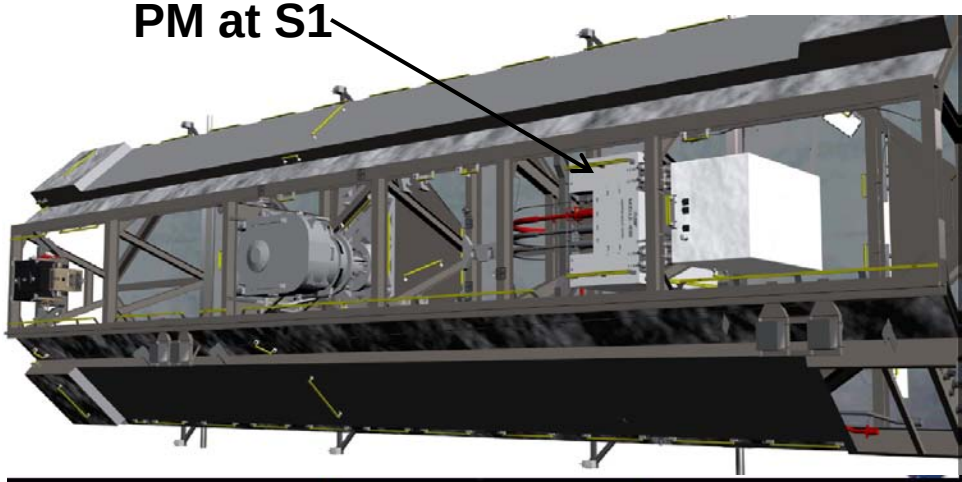
7.8 years @ S1
(w/shroud on fwd face)

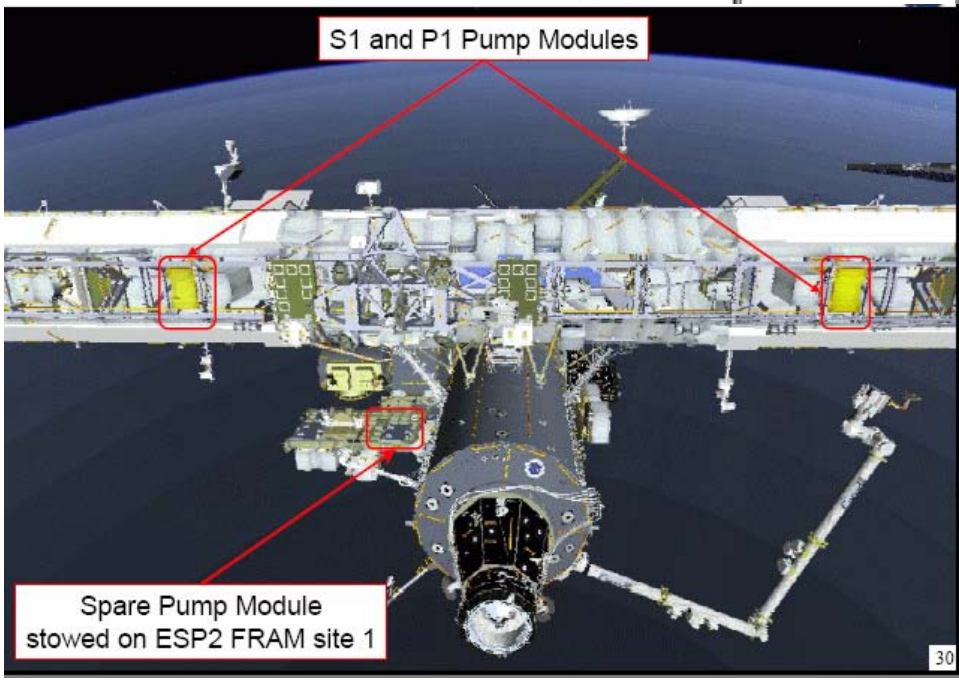


0.9 years @ ESP2
(w/full shroud on PM)



PM at S1





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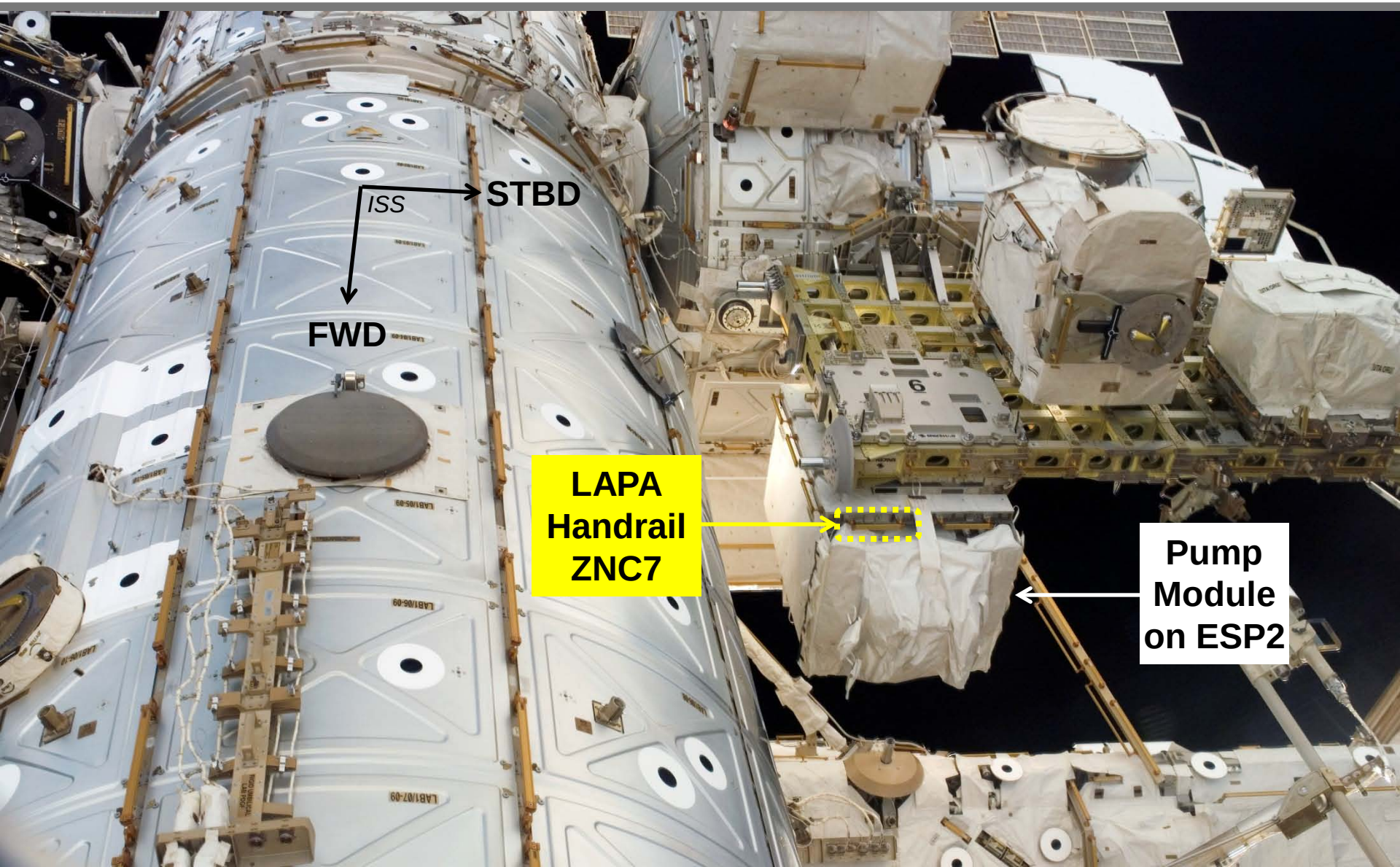
Pump Module Integrated Assembly



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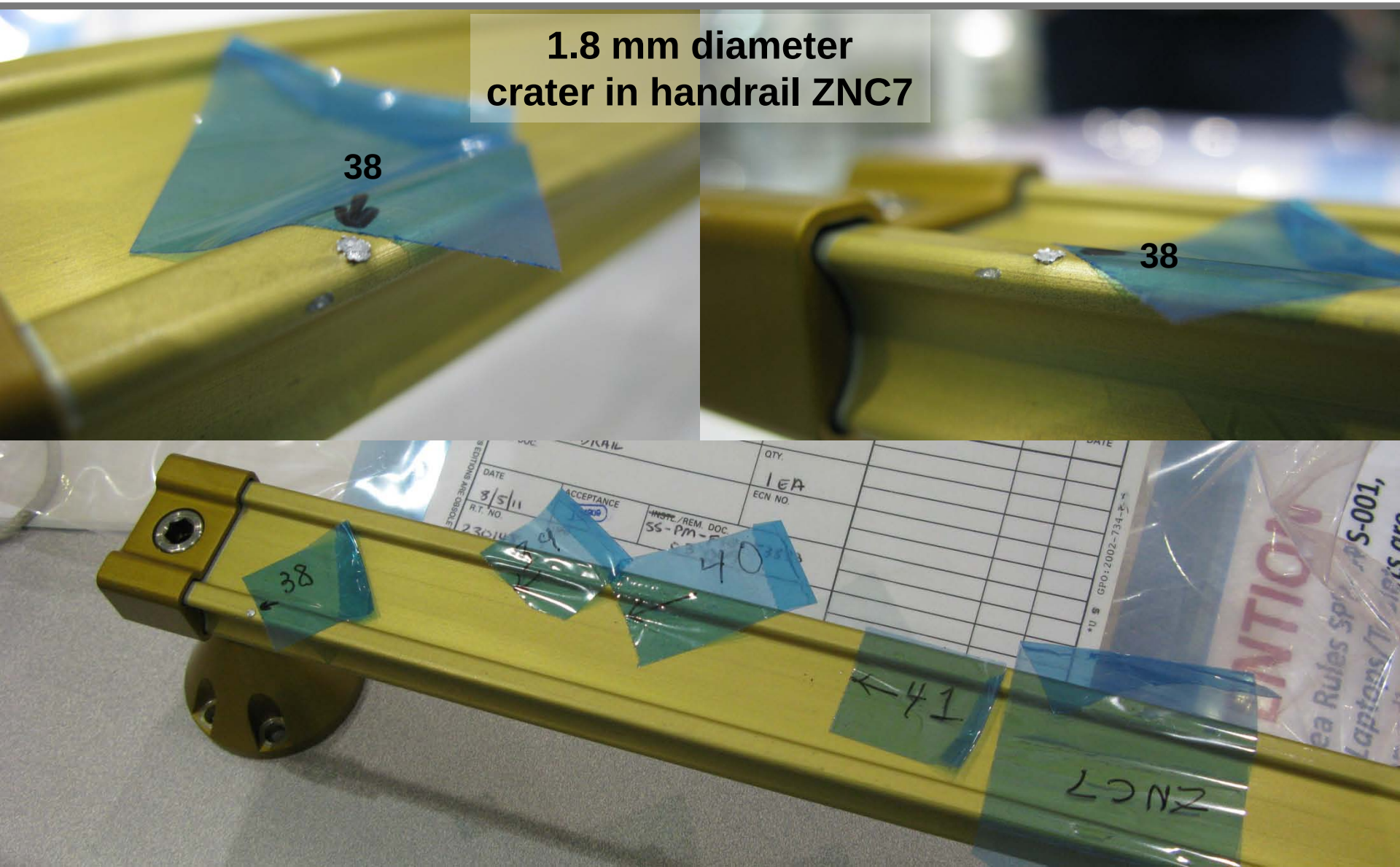
Large Adapter Plate Assembly (LAPA)



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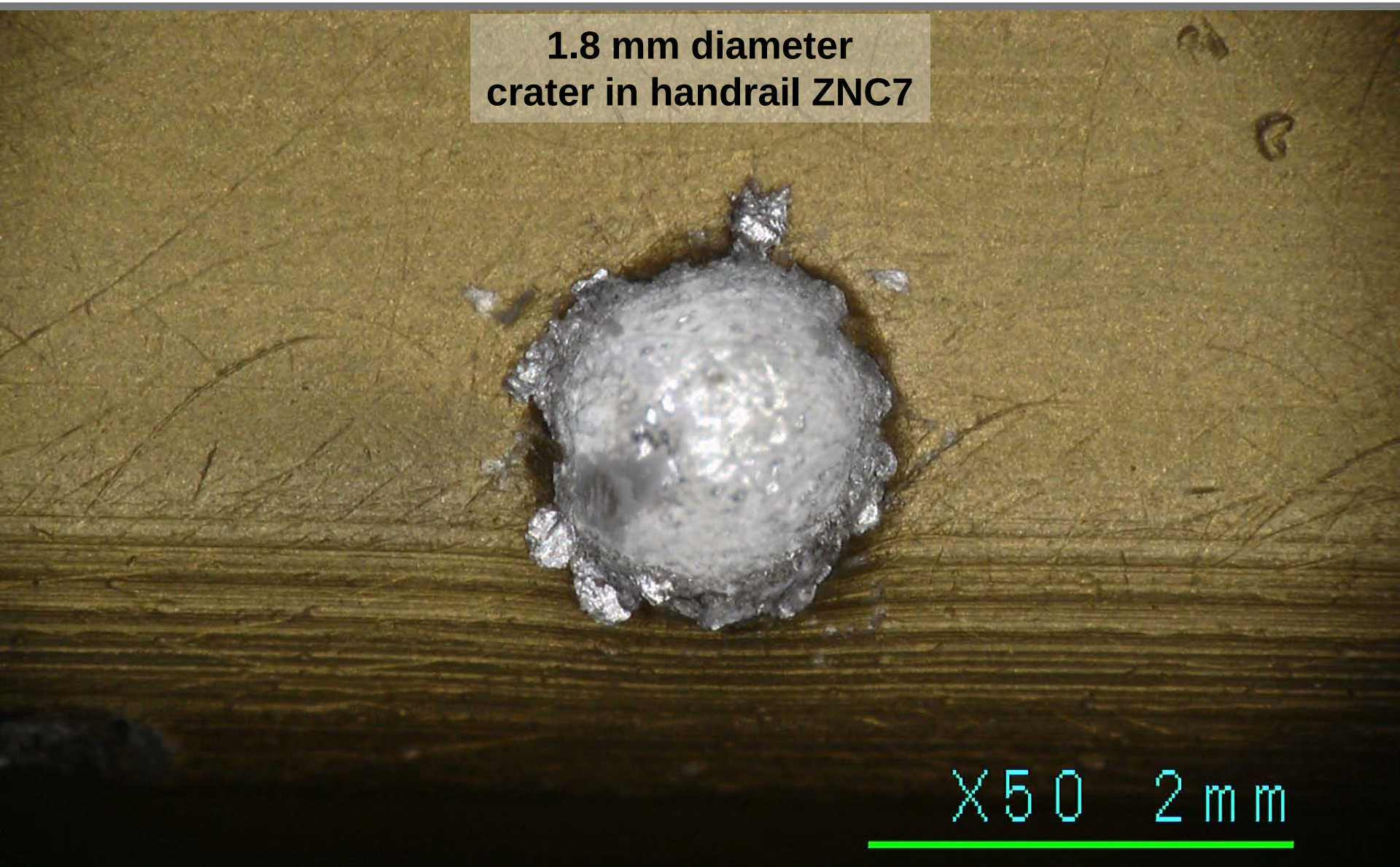
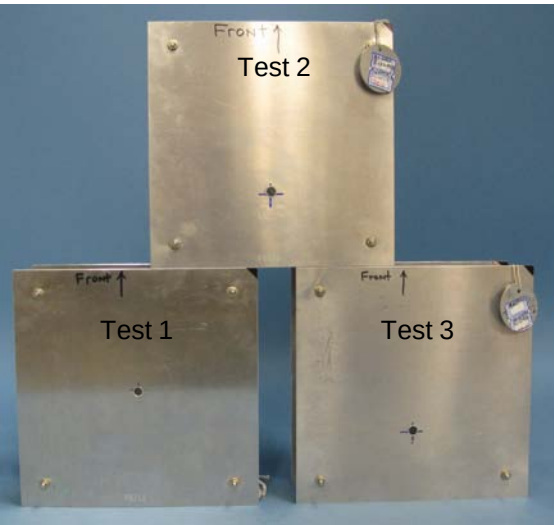
Large Adapter Plate Assembly (LAPA)



IT 29-1: Hypervelocity Facility CNSA-NASA Cross-Calibration

NASA Test Results

Interagency Space Debris Coordination Committee (IADC)
May 2012



NASA JSC-KX/Eric L. Christiansen
NASA JSC/Bruce (Alan) Davis
NASA JSC-ES/Kornel Nagy
NASA JSC/Jim Hyde

Summary

- China Academy of Space Technology (CAST) provided NASA three (3) duplicate test articles and projectiles for cross-calibration with NASA JSC-WSTF hypervelocity launchers
  - Whipple shield: 1mm thick Al 6061 bumper (first shield layer), 70mm spacing, 2.5mm thick Aluminum 5A06 rear wall (second shield layer)
    - Material properties for 5A06 rear wall:
      - tensile strength 320MPa
      - elongation at break 15%
      - yield strength 160MPa
  - Projectile: 3.2mm diameter Al 2027 spheres

- 3 test conditions were specified for the cross-calibration and have been completed using the 3.2mm diameter Al 2027 spheres

  (1) Requested condition: impact speed 5.80 km/s, impact angle 0deg

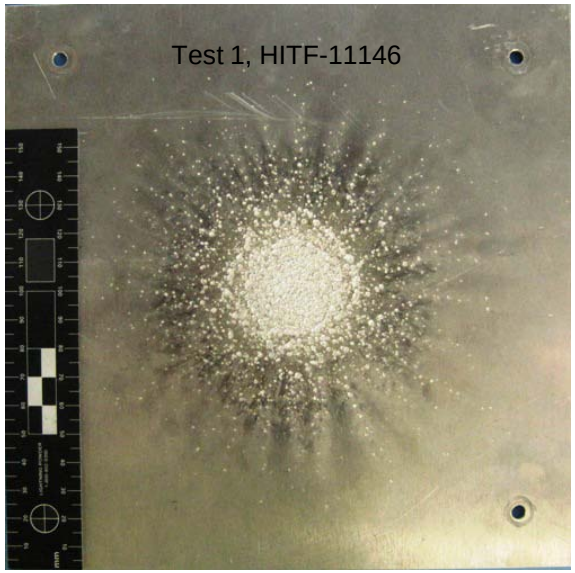
  (2) Requested condition: impact speed 5.50 km/s, impact angle 30deg

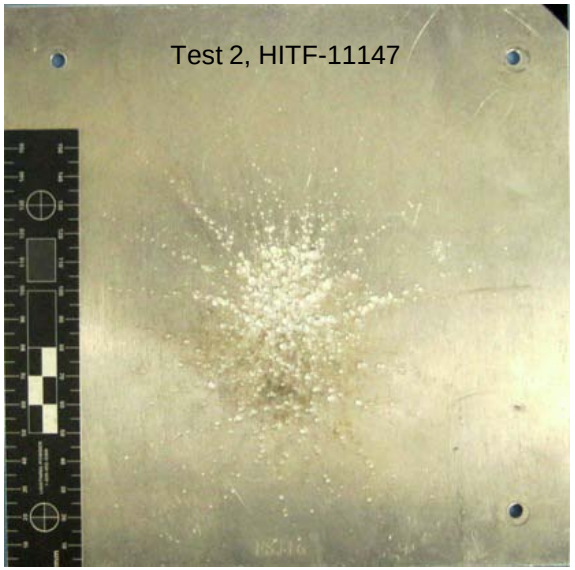
  (3) Requested condition: impact speed 5.00 km/s, impact angle 30deg

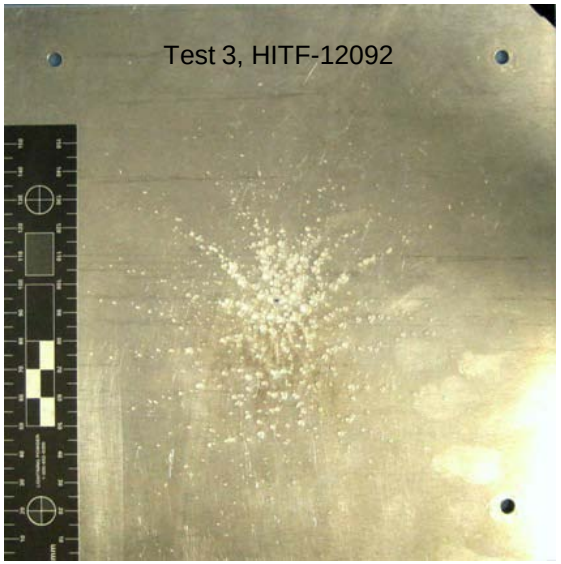
- Comparisons test on US materials completed
  - Similar results to the tests on the CAST test articles (slightly less damage on the US materials in one test)

Test Results Summary

Test number	Projectile impact conditions	Overall damage result	Damage to 1st layer (bumper)	Damage to 2nd wall (rear wall)
#1. HITF-11146	3.2mm Al, 5.77 km/s, 0 deg impact angle	2nd wall passes	Hole inside diameter: 6.8 mm Hole outside diameter: 8.0 mm	Front: Largest crater 1.6 mm diameter and 1.7 mm deep Back: 0.8mm maximum bump height
#2. HITF-11147	3.2mm Al, 5.30 km/s, 30 deg impact angle	2nd wall passes	Hole inside diameter: 7.5 x 6.9 mm Hole outside diameter: 9.2 x 8.4 mm	Front: Largest crater 3.5 x 3.2mm diameter and 1.8 mm deep Back: 0.8mm maximum bump height
#3. HITF-12092	3.2mm Al, 5.01 km/s, 30 deg impact angle	2nd wall fails	Hole inside diameter: 7.4 x 6.8 mm Hole outside diameter: 9.3 x 8.2 mm	Front: 1.4 x 0.8mm hole, largest crater 3.4 x 2.6mm diameter Back: at perforation, 2.1mm bump height

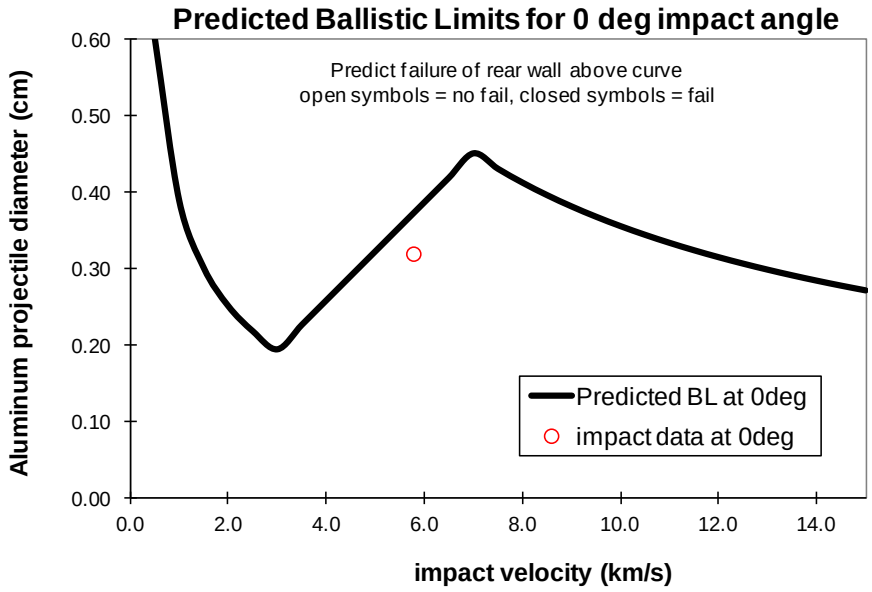


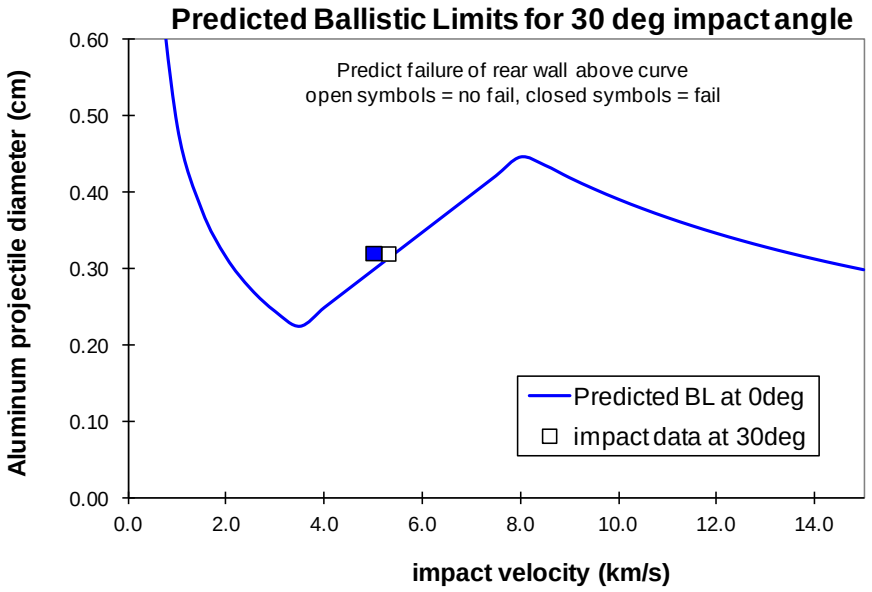




Test results summary

- Impact data versus ballistic limit predictions
  - Used NASA-JSC whipple shield equations provided in Design and Performance Equations for Advanced Meteoroid and Debris Shields, International Journal of Impact Engineering, Vol.14, pp.145-156 (1993)
  - Strength parameter 320 MPa (46ksi)

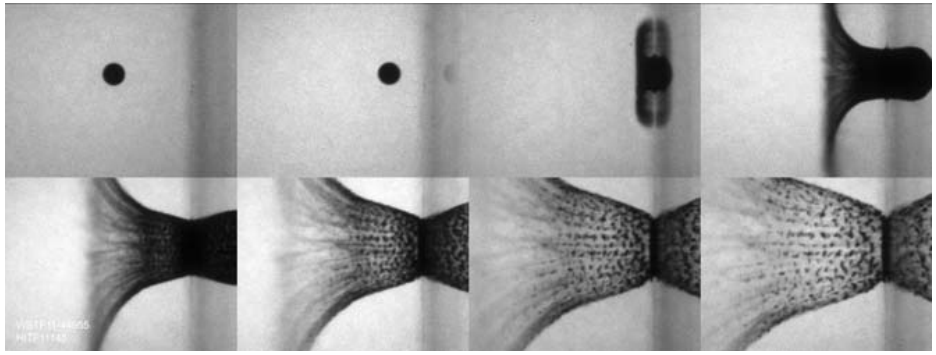




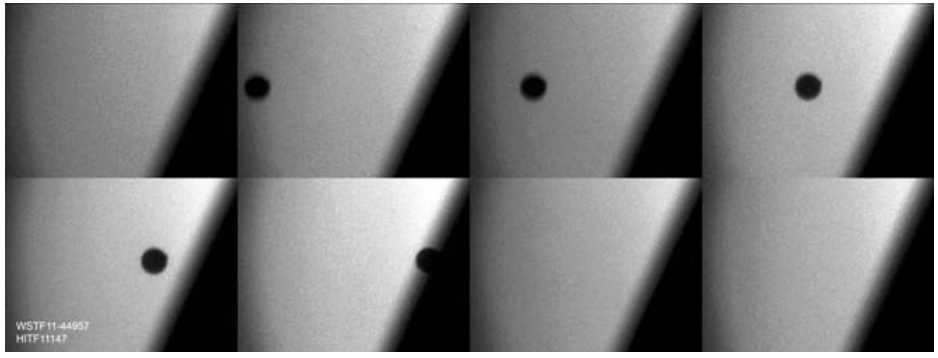
Imagery of projectile just prior to impact

- High-speed camera films capture the projectile in flight just prior to impact

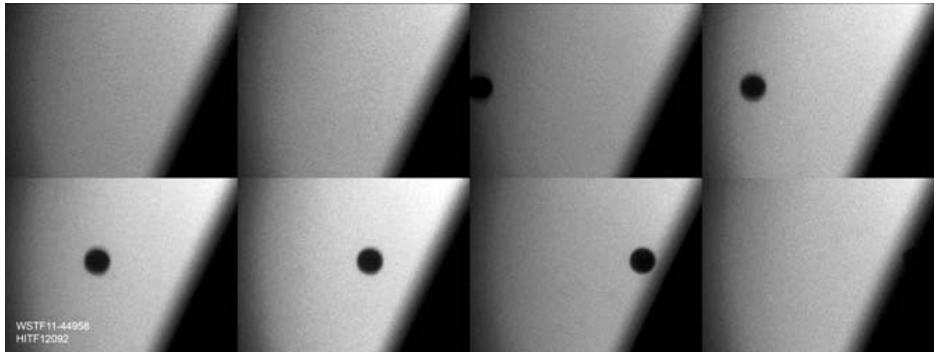
Test 1



Test 2



Test 3



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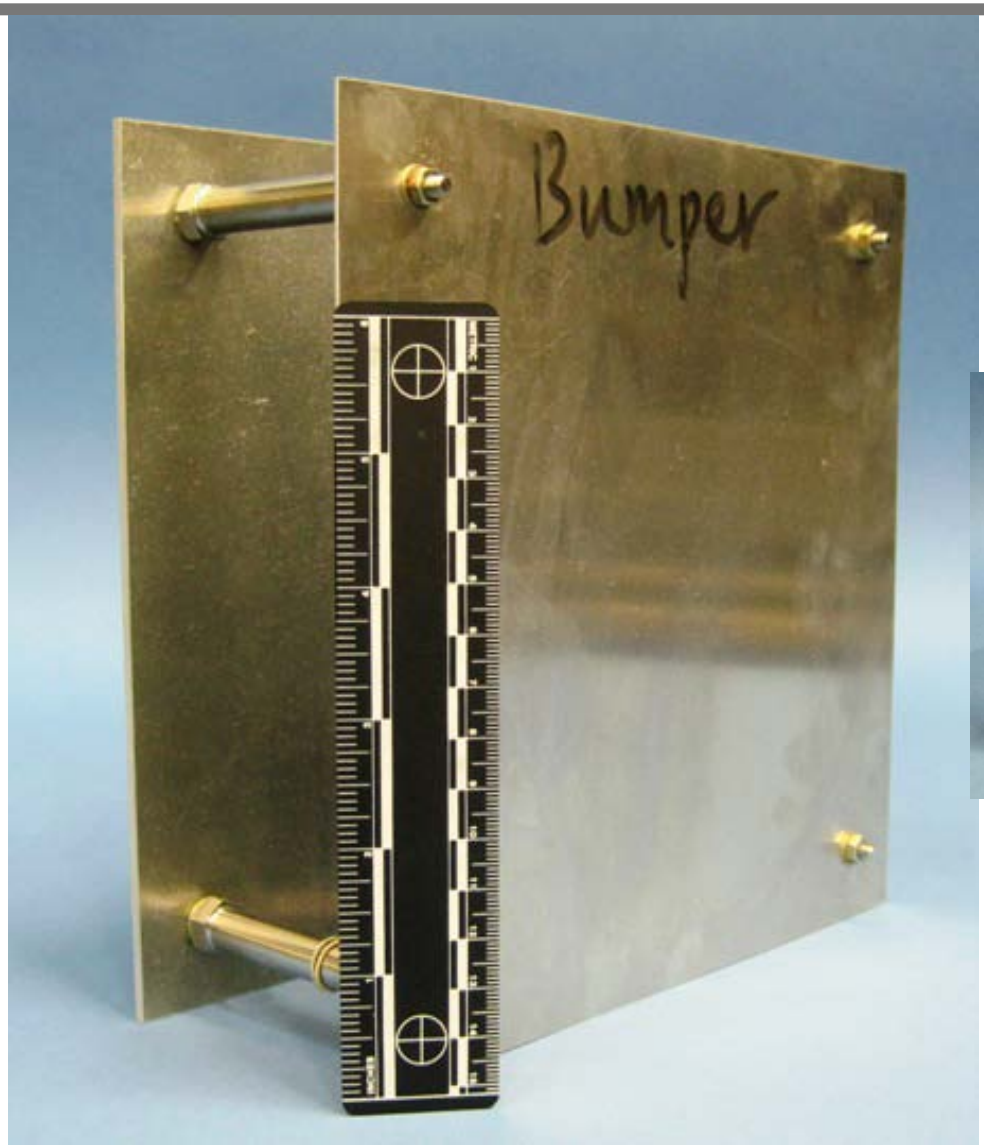
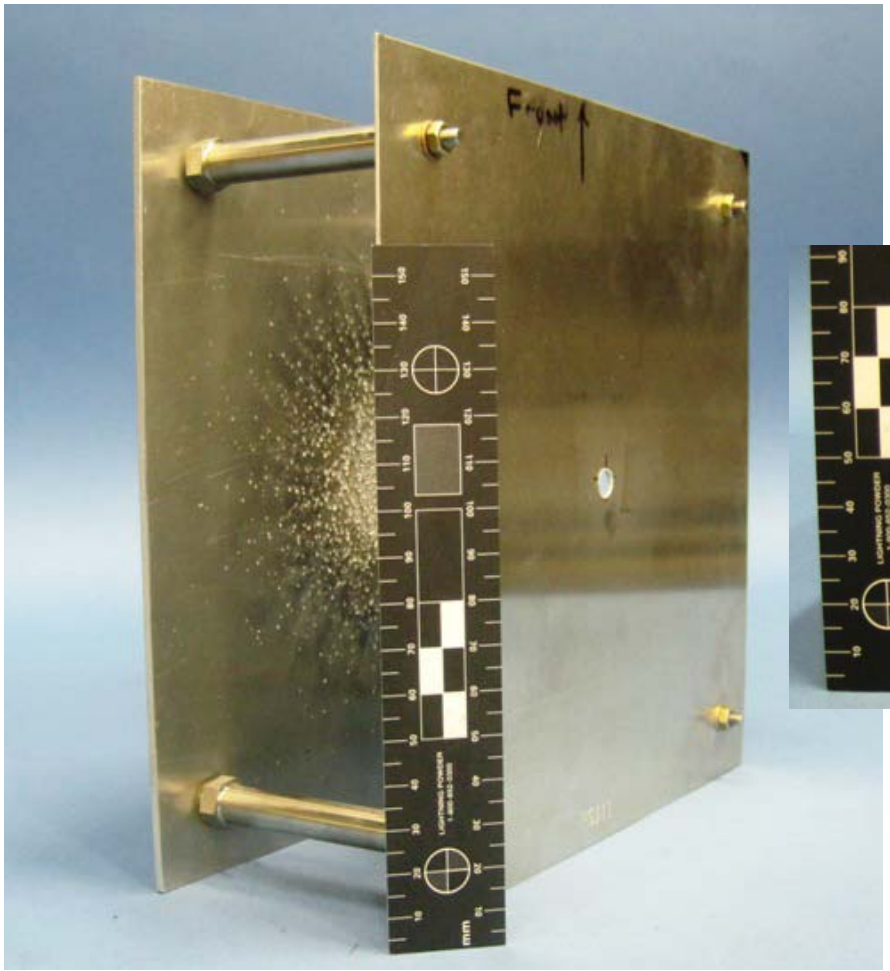
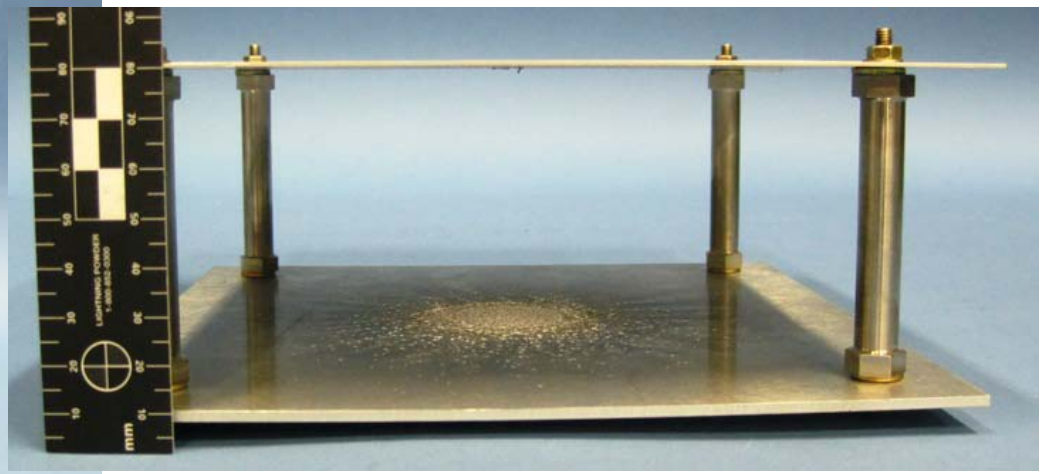
Pre-test photographs of CAST test article



1st test results @ 5.77km/s, 0deg (Provided at IADC-29)

- HITF-11146, 3.2mm AL 2027 projectile, 0.04779g, 5.77km/s, 0deg





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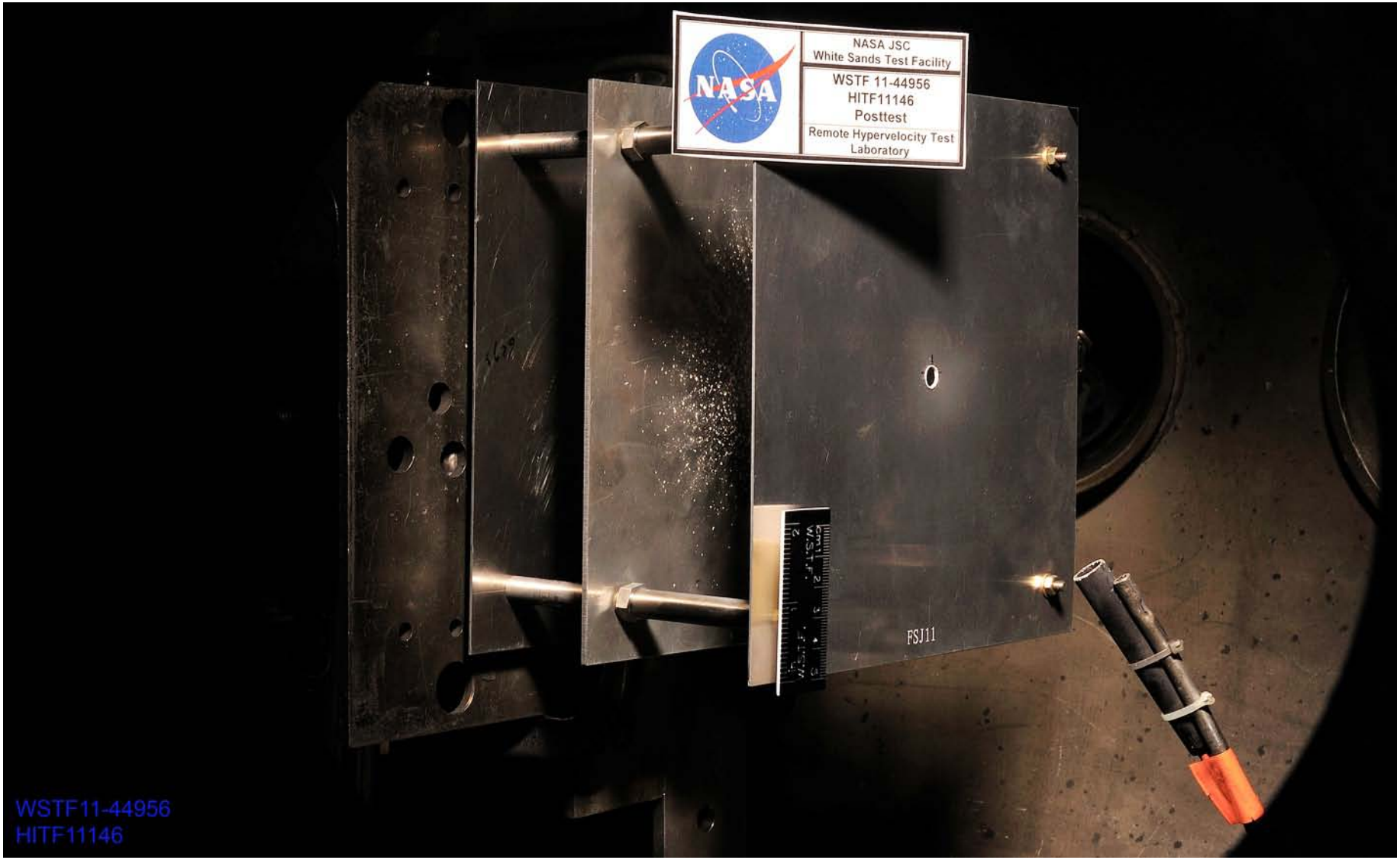
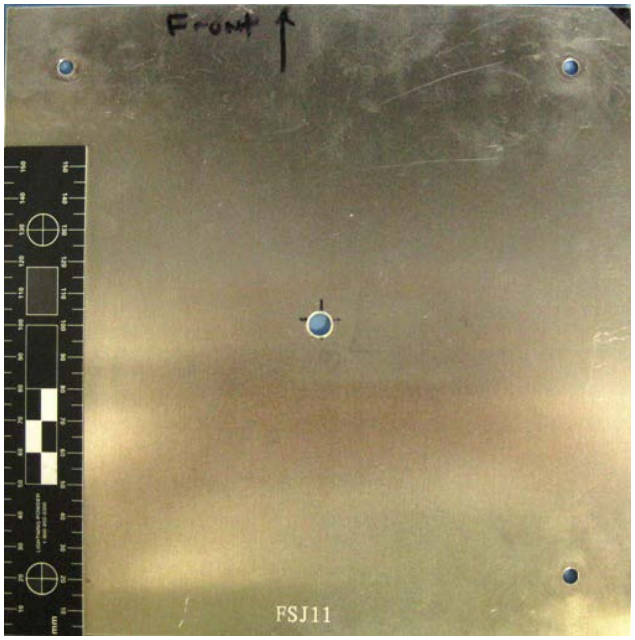
Post-test photograph of CAST test article in target tank

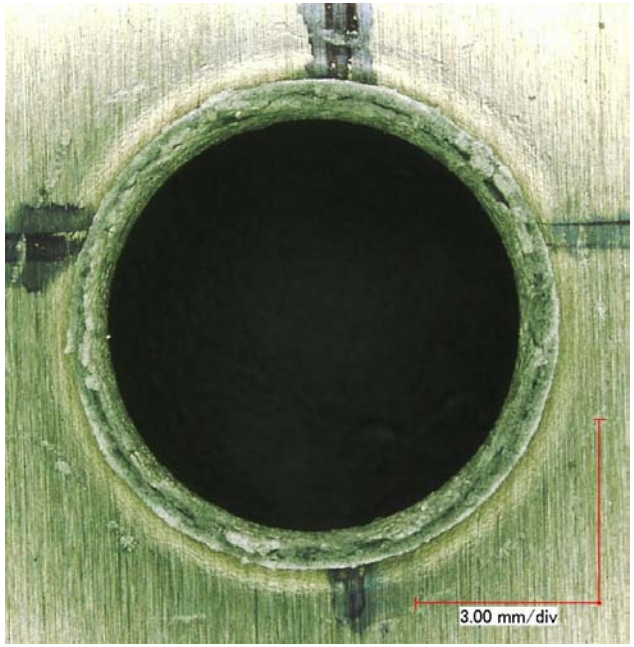


1st test results @ 5.77km/s, 0deg Bumper (1st layer) front/back

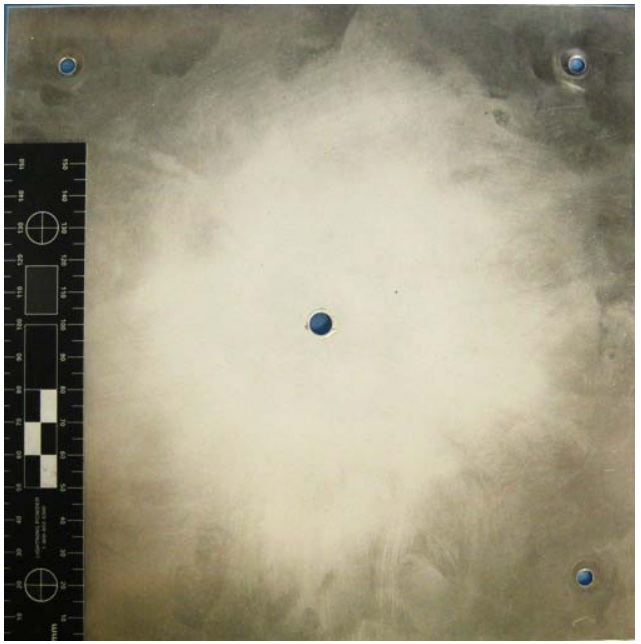
- HITF-11146, 3.2mm AL 2027 projectile, 0.04779g, 5.77km/s, 0deg
  - **1st layer**: through-hole 6.8 mm inside diameter, 8.0 mm outside diameter (including crater lips)



Front



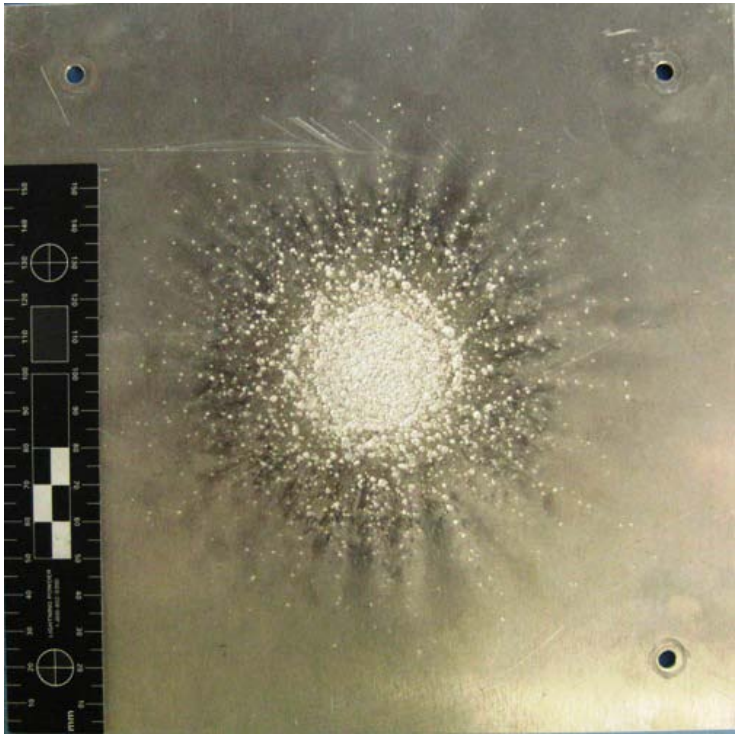
Front, close-up



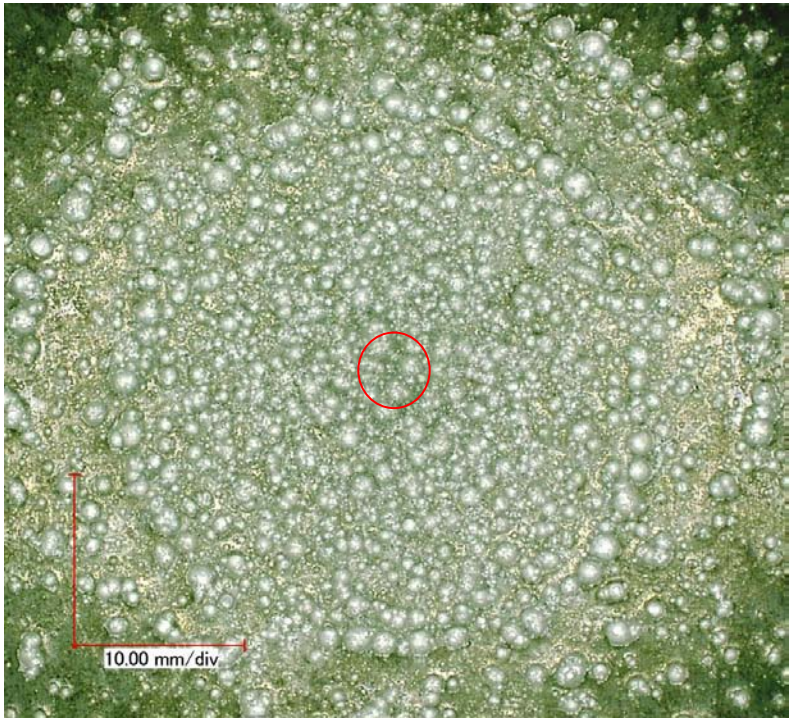
Back

1st test results @ 5.77km/s, 0deg Rear wall (2nd layer) front side

- HITF-11146, 3.2mm AL 2027 projectile, 0.04779g, 5.77km/s, 0deg
  - **2nd layer front side**: multiple craters (no through-holes), maximum crater size 1.6 mm diameter x 1.7 mm deep, circular area of concentrated crater damage within 44 mm diameter, majority of crater damage (>95% of craters) are within130 mm diameter



Front



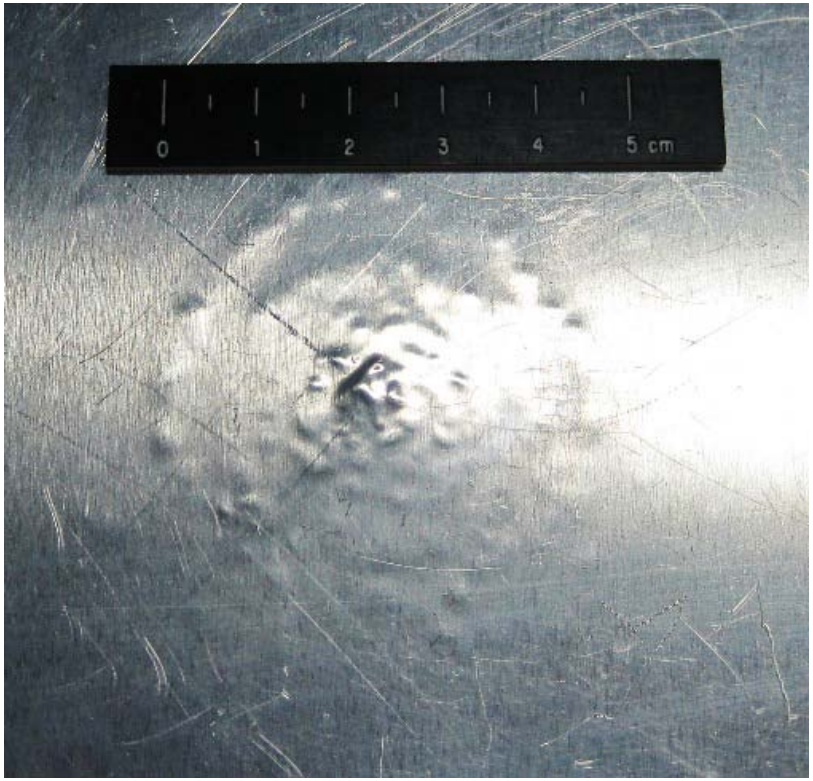
Front, close-up

Deepest penetration within red circle

1st test results @ 5.77km/s, 0deg Rear wall (2nd layer) back side

- HITF-11146, 3.2mm AL 2027 projectile, 0.04779g, 5.77km/s, 0deg
  - **2nd layer back side**: small bumps on back side of plate within 64mm x 66mm area, maximum height 0.8mm, no detached spall present

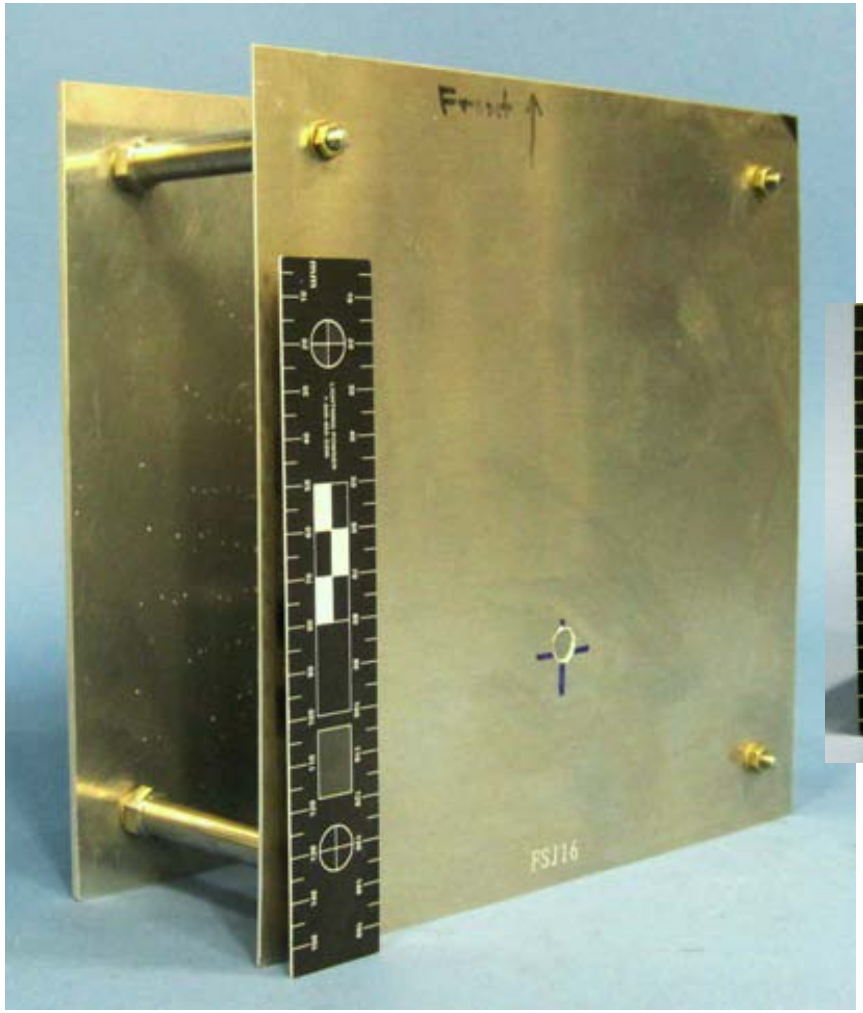
Back



Back, close-up

2nd test results @ 5.30km/s, 30deg (HITF-11147)

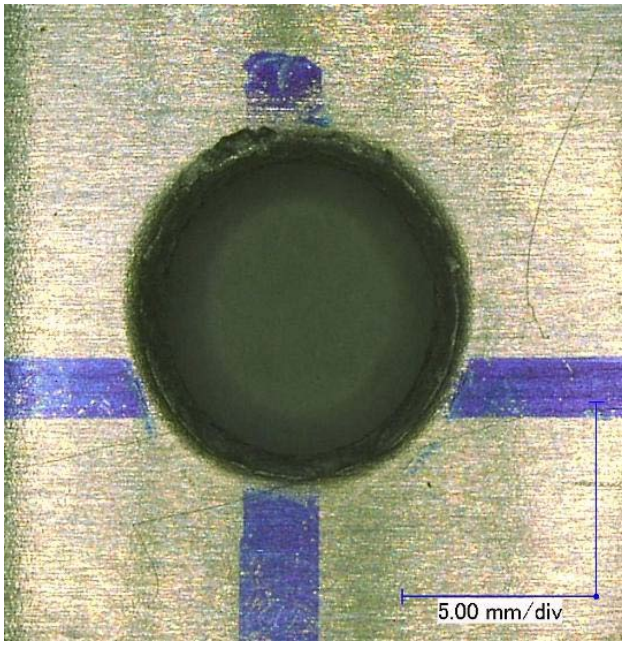
- HITF-11147, 3.2mm AL 2027 projectile, 0.04788g, 5.30km/s, 30deg



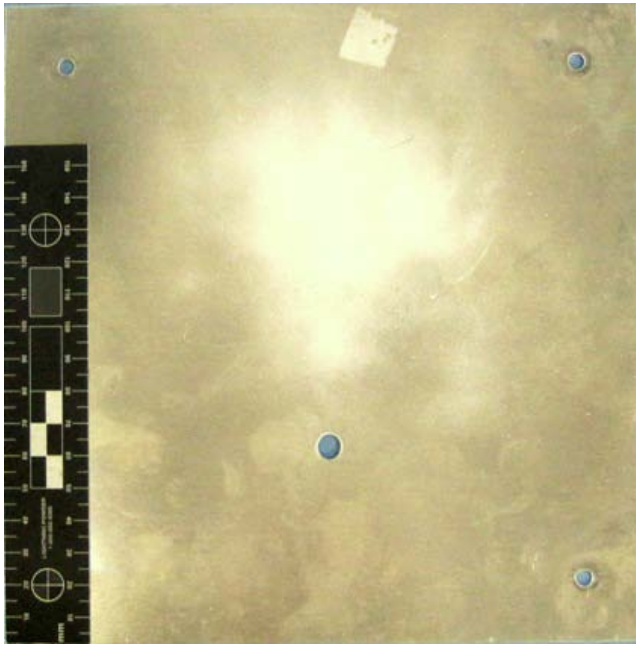
2nd test results @ 5.30km/s, 30deg Bumper (1st layer) front/back

- HITF-11147, 3.2mm AL 2027 projectile, 0.04788g, 5.30km/s, 30deg
  - **1st layer**: through-hole 7.5 x 6.9 mm inside diameter, 9.2 x 8.4 mm outside diameter (including crater lips)

Front
(arrow shows projectile direction of travel)



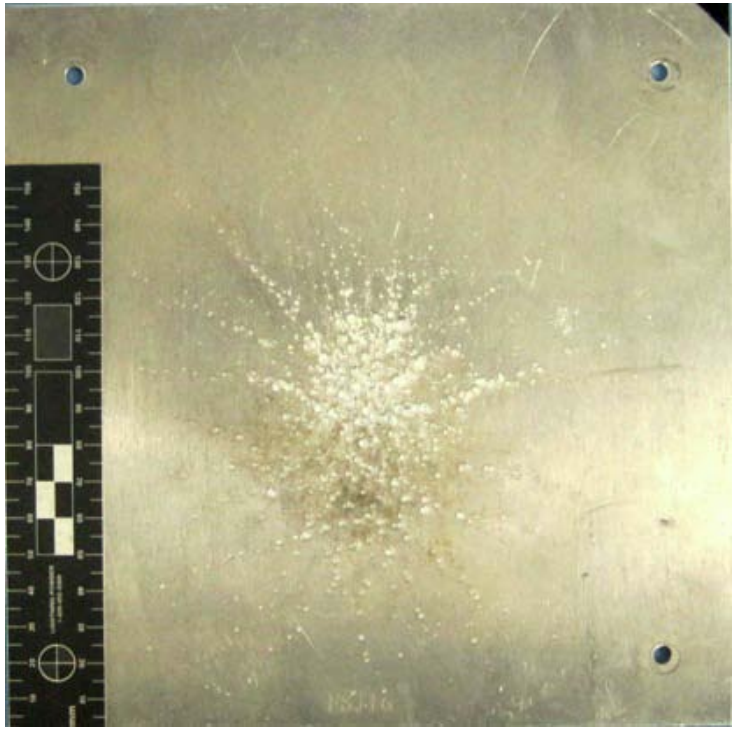
Front, close-up



Back

2nd test results @ 5.30km/s, 30deg
Rear wall (2nd layer) front side

- HITF-11147, 3.2mm AL 2027 projectile, 0.04788g, 5.30km/s, 30deg
  - **2nd layer front side**: multiple craters (no through-holes), maximum crater size 3.5 x 3.2 mm diameter and 1.8 mm deep, concentrated area of crater damage within 44 x 36 mm diameter



Front

Front, close-up

Deepest penetration within red circle

2nd test results @ 5.30km/s, 30deg Rear wall (2nd layer) back side

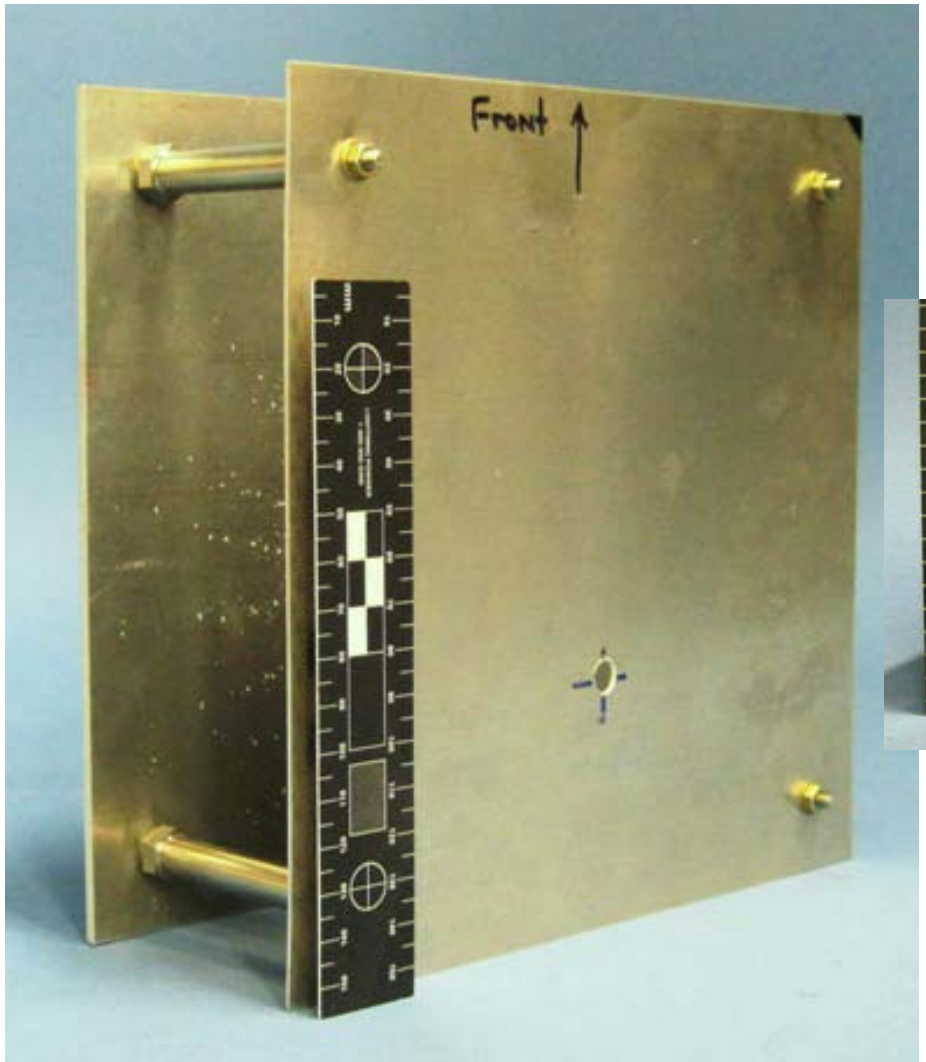
- HITF-11147, 3.2mm AL 2027 projectile, 0.04788g, 5.30km/s, 30deg
  - **2nd layer back side**: small bumps on back side of plate within 65mm x 63mm area, maximum height 0.8 mm, no detached spall present

Back

Back, close-up (oblique view)

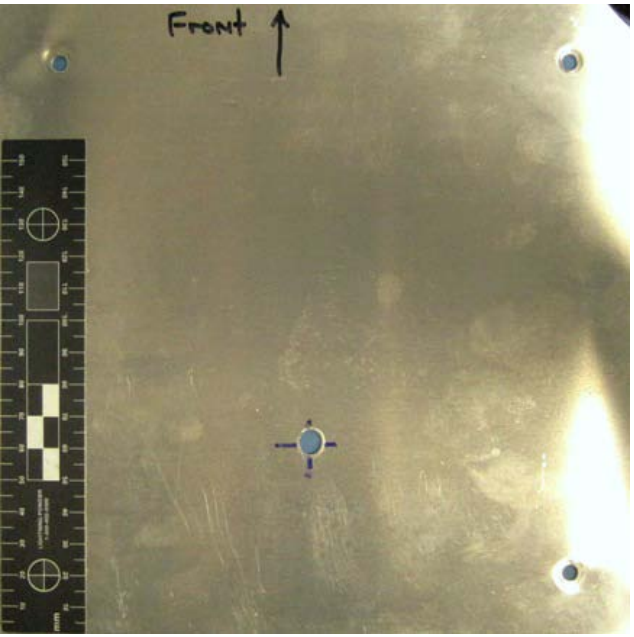
3rd test results @ 5.01km/s, 30deg (HITF-12092)

- HITF-12092, 3.2mm AL 2027 projectile, 0.04767g, 5.01km/s, 30deg

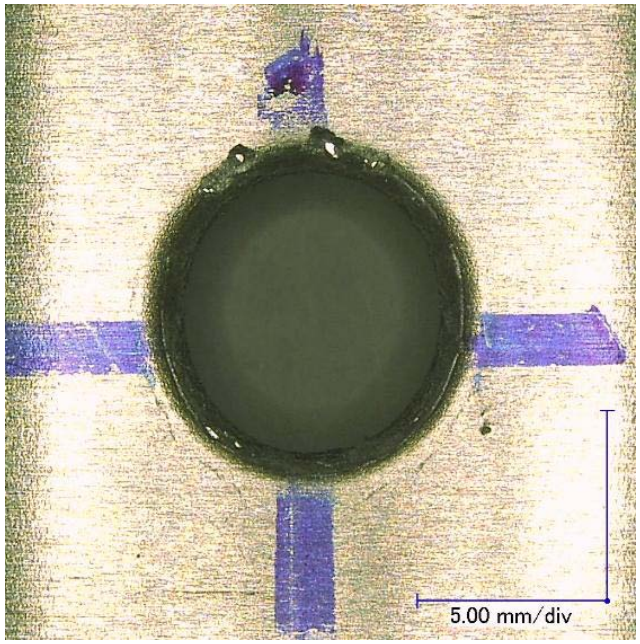


3rd test results @ 5.01km/s, 30deg Bumper (1st layer) front/back

- HITF-12092, 3.2mm AL 2027 projectile, 0.04767g, 5.01km/s, 30deg
  - **1st layer**: through-hole 7.4 x 6.8 mm inside diameter, 9.0 x 8.2 mm outside diameter (including crater lips)



Front
(arrow shows projectile direction of travel)

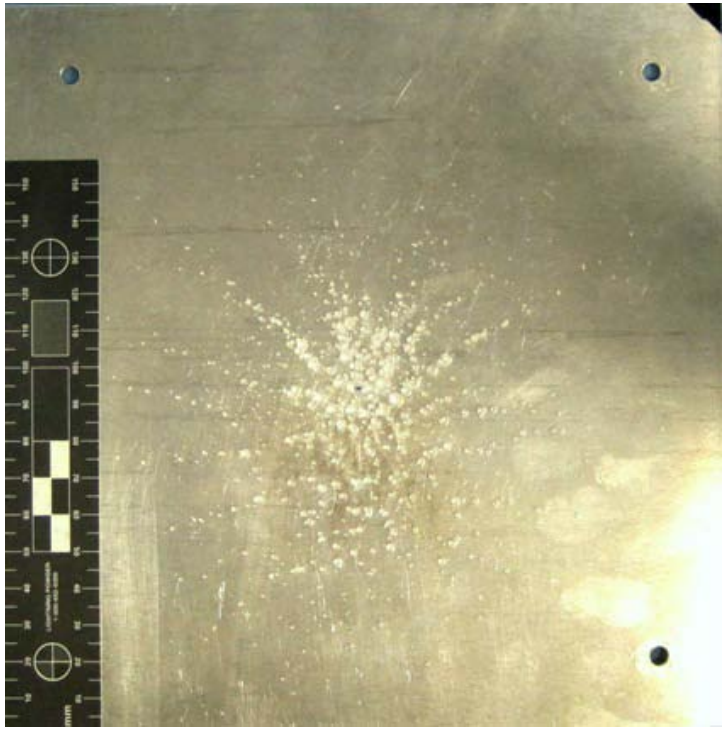


Front, close-up

Back

3rd test results @ 5.01km/s, 30deg
Rear wall (2nd layer) front side

- HITF-12092, 3.2mm AL 2027 projectile, 0.04767g, 5.01km/s, 30deg
  - **2nd layer front side**: One through hole (rear wall failed), multiple craters, hole size 1.4 x 0.8 mm, maximum crater size 3.4 x 2.6 mm diameter, concentrated area of crater damage within 41 x 39 mm diameter



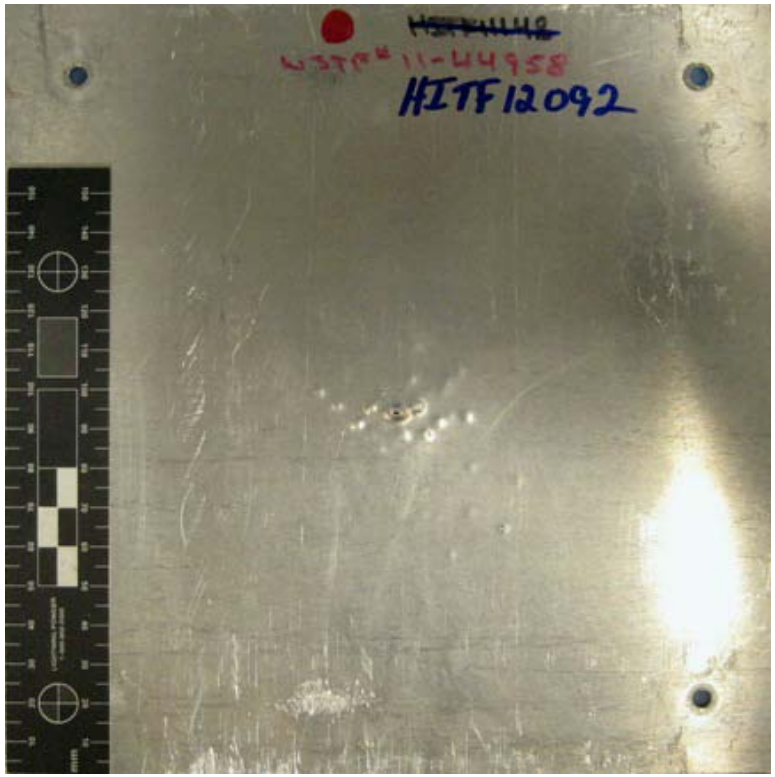
Front

Front, close-up

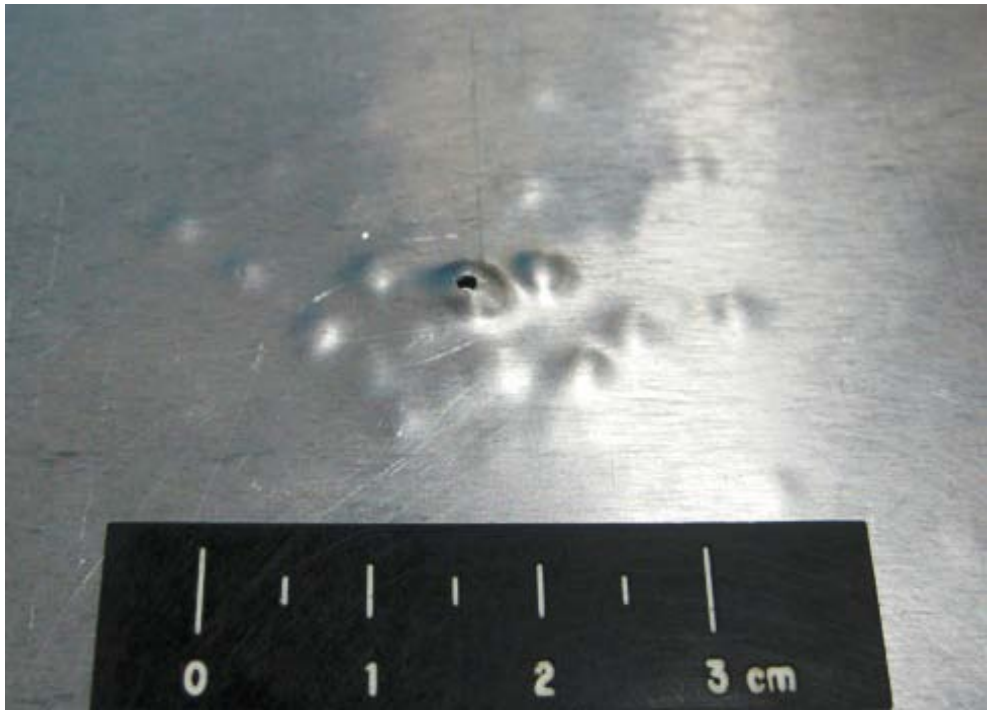
Complete penetration within red circle

3rd test results @ 5.01km/s, 30deg Rear wall (2nd layer) back side

- HITF-12092, 3.2mm AL 2027 projectile, 0.04767g, 5.01km/s, 30deg
  - **2nd layer back side**: small bumps on back side of plate within 63mm x 61 mm area, maximum height of bump at perforation 2.1 mm above surface



Back



Back, close-up (oblique view)

IT 29-2: Hypervelocity Facility CSA-NASA Cross-Calibration

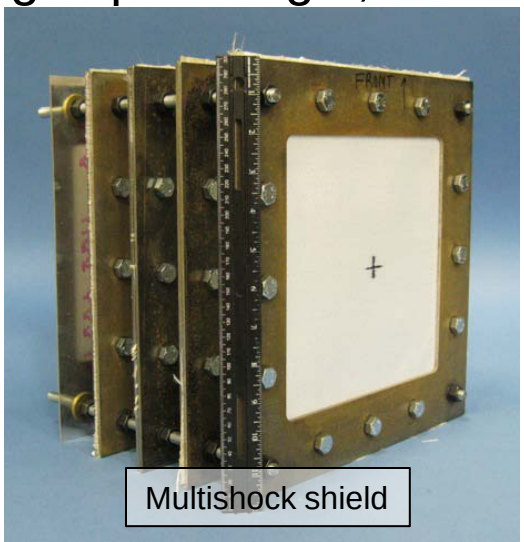
NASA Test Results

Interagency Space Debris Coordination Committee (IADC)
May 2012

NASA JSC-KX/Eric L. Christiansen
NASA JSC/Bruce (Alan) Davis
NASA JSC-ES/Kornel Nagy
NASA JSC/Jim Hyde

Summary

- The Canadian Space Agency provided NASA four different test articles and projectiles for cross-calibration with NASA JSC-WSTF hypervelocity launchers
  - 1 & 2. Two sizes of multishock shield consisting of (4) Nextel ceramic bumpers and an aluminum rear wall
  - 3 & 4. Two sizes of mesh double bumper shields consisting of metallic mesh, aluminum second bumper, kevlar and an aluminum rear wall
  - Projectiles: 3.2mm diameter and 6.4mm diameter Al 2017-T4 spheres
- Test conditions specified for the cross-calibration were 7km/s and 0deg impact angle, and all tests have been completed



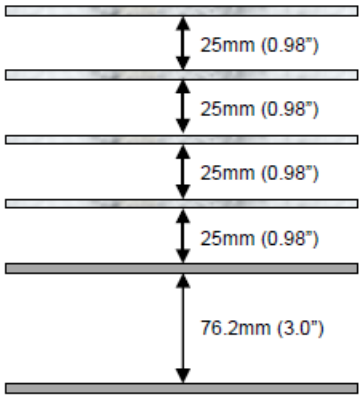
Multishock shield

Mesh Double-Bumper shield

Target configurations

Tested with 0.32cm diameter spherical Al 2017T4 projectile

Multishock shields



0.020" nominal thickness, 6" x 6", Nextel 312 AF-20 (1 layer), areal density 0.0454 g/cm²

0.020" nominal thickness, 6" x 6", Nextel 312 AF-20 (1 layer),areal density 0.0454 g/cm²

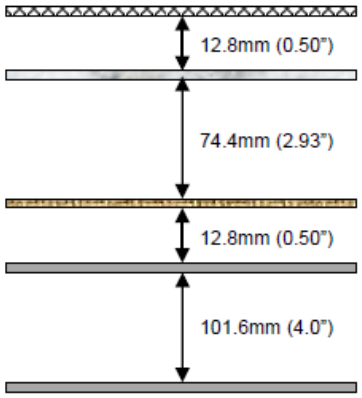
0.020" nominal thickness, 6" x 6", Nextel 312 AF-20 (1 layer), areal density 0.0454 g/cm²

0.020" nominal thickness, 6" x 6", Nextel 312 AF-20 (1 layer), areal density 0.0454 g/cm²

0.025" thick, 6" x 6", Al 2024-T3, density 2.796 g/cm³

0.040" thick, 6" x 6", Al 2024-T3, 2.796 g/cm³

Mesh Double Bumper shields



0.012" nominal thickness, 6" x 6", Al 5000 Series 30 x 30 Wire Mesh (1 layer), areal density 0.037 g/cm²

0.016" nominal thickness, 6" x 6", Al 2024-T3, density 2.796 g/cm³

0.034" nominal thickness, 6" x 6", Kevlar 29 Style 710 (2 layers), areal density 0.066 g/cm²

0.016" nominal thickness, 6" x 6", Al 2024-T3, density 2.796 g/cm³

0.040" thick, 6" x 6", Al 2024-T3, density 2.796 g/cm³

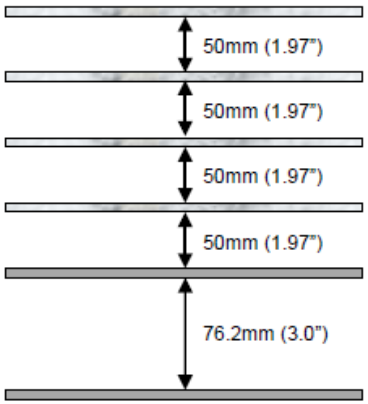
Note, last layer of each shield is an 0.04" (1mm) thick Al 2024-T3 witness plate.

National Aeronautics and Space Administration

Target configurations

Tested with 0.64cm diameter spherical Al 2017T4 projectile

Multishock shields



0.040" nominal thickness, 12" x12", Nextel 312 AF-20 (2 layers), areal density 0.0908 g/cm²

0.040" nominal thickness, 12" x12", Nextel 312 AF-20 (2 layers), areal density 0.0908 g/cm²

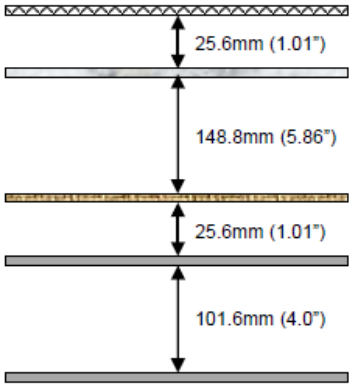
0.040" nominal thickness, 12" x12", Nextel 312 AF-20 (2 layers), areal density 0.0908 g/cm²

0.040" nominal thickness, 12" x12", Nextel 312 AF-20 (2 layers), areal density 0.0908 g/cm²

0.040" thick, 12" x12", Al 2024-T3, density 2.796 g/cm³

0.040" thick, 12" x12", Al 2024-T3, density 2.796 g/cm³

Mesh Double Bumper shields



0.023" nominal thickness, 12" x 12", Al 5000 Series 12 x 12 Wire Mesh (1 layer), areal density 0.057 g/cm²

0.025" nominal thickness, 12" x 12", Al 2024-T3, density 2.796 g/cm³

0.068" nominal thickness, 12" x 12", Kevlar 29 Style 710 (4 layers), areal density 0.132 g/cm²

0.040" thick, 12" x 12", Al 2024-T3, density 2.796 g/cm³

0.040" thick, 12" x 12", Al 2024-T3, density 2.796 g/cm³

Note, last layer of each shield is an 0.04" (1mm) thick Al 2024-T3 witness plate.

Test Results Summary

Test number	Projectile impact conditions	Target Configuration and overall mass per unit area	Damage to bumper layers	Damage to aluminum rear wall
#1. HITF-12001	3.2mm Al, 0.04725g, 6.93 km/s, 0 deg impact angle	Multishock shield 0.36 g/cm^2	1st layer: 5.5 x 4.6 mm hole 2nd layer: 17.0 x 16.7mm hole 3rd layer: 42.9 x 27.5mm hole 4th layer: 45.1 x 33.3mm hole	Bulge, dish (no failure) Impacted area 48mm diameter, bulge is 60mm diameter by 3.5mm high
#2. HITF-12002	6.4mm Al, 0.37406g, 6.86 km/s, 0 deg impact angle	Multishock shield 0.65 g/cm^2	1st layer: 10.0 x 9.8mm hole 2nd layer: 30.1 x 27.3mm hole 3rd layer: 46.7 x 44.3mm hole 4th layer: 65.6 x 50.5mm hole	Bulge, dish (no failure) Impacted area 86mm diameter, bulge is 116mm diameter by 9.4mm high
#3. HITF-12003	3.2mm Al, 0.04725g, 6.85 km/s, 0 deg impact angle	Mesh Double Bumper shield 0.33 g/cm^2	1st layer: 6.3 x 5.9mm hole 2nd layer: 8.9 x 8.7mm hole 3rd layer (last layer of Kevlar): multiple perforations in 54 x 42 mm area, with largest hole 3.9 x 3.8mm	Bulge, dish (no failure) Impacted area 48 x 42mm diameter, bulge is 43 x 37mm diameter by 1.3mm high
#4. HITF-12004	6.4mm Al, 0.37407g, 6.91 km/s, 0 deg impact angle	Mesh Double Bumper shield 0.65 g/cm^2	1st layer: 14.6 x 13.2mm hole 2nd layer: 25.5 x 15.3mm hole 3rd layer (last layer of Kevlar): two perforations in 65 x 41 mm area, with largest hole 53 x 44mm	Bulge, dish with two small perforations (fail) Impacted area 87 x 70mm diameter, bulge is 98 x 95mm diameter by 4.9mm high, largest perforation is 1.7mm x 1.6mm diameter

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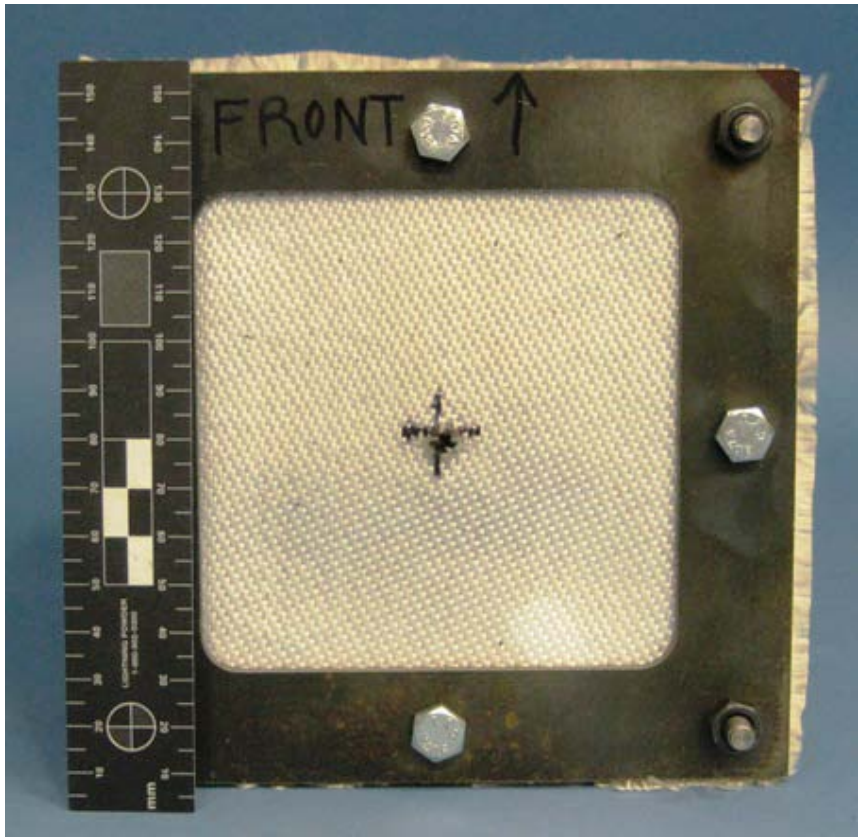
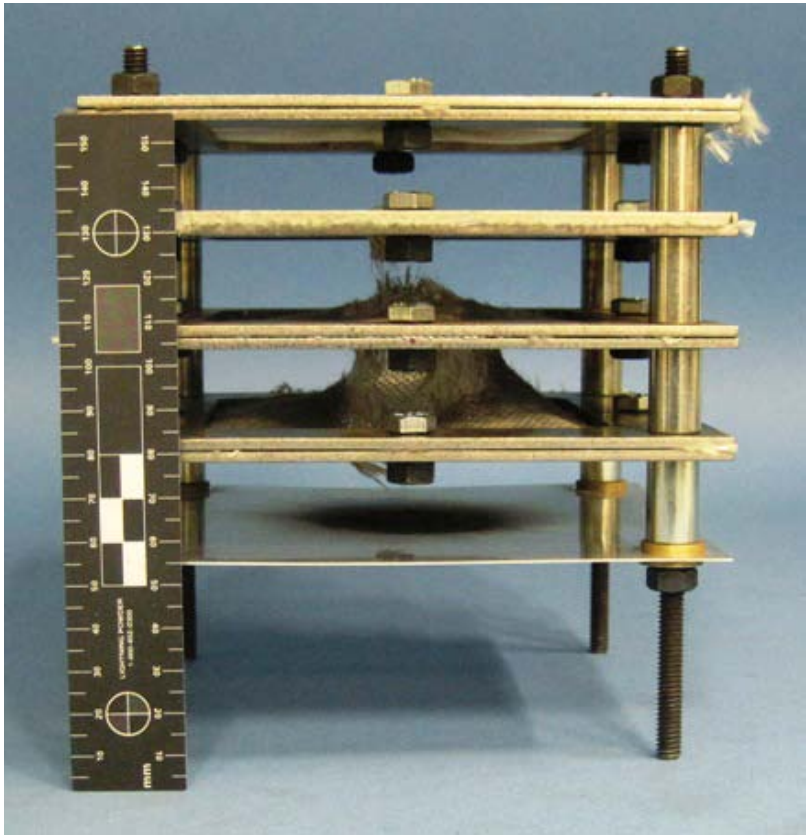
HITF-12001, Multishock 0.36g/cm^2

3.2mm diameter Al 2017T4, 6.93 km/s, 0deg

Front view



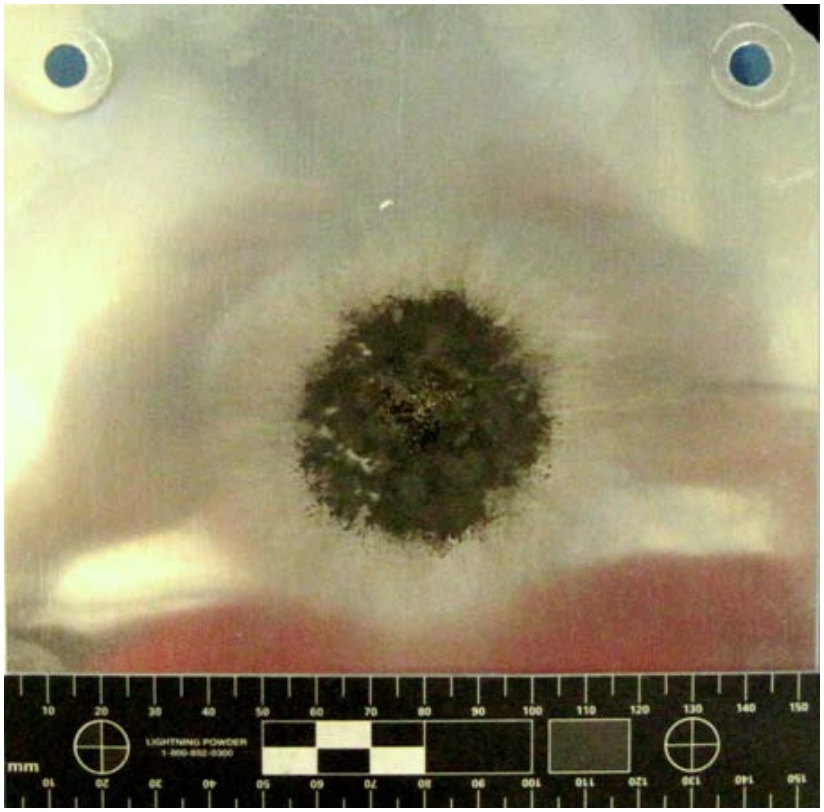
Side view



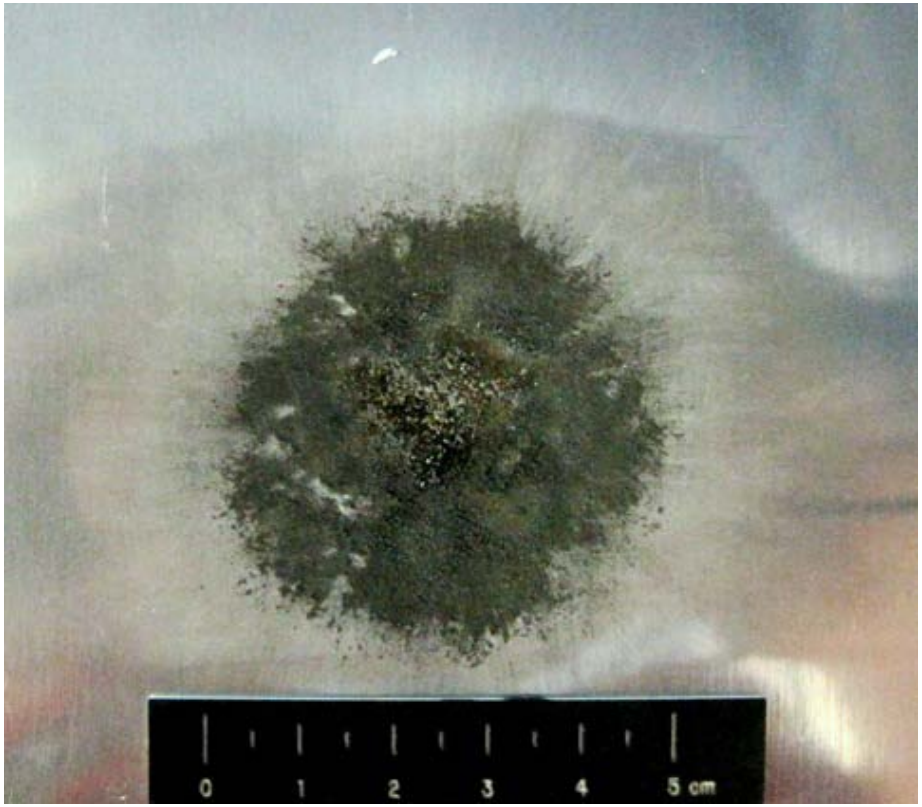
HITF-12001, Multishock 0.36g/cm^2

3.2mm diameter Al 2017T4, 6.93 km/s, 0deg

Rear wall (front)



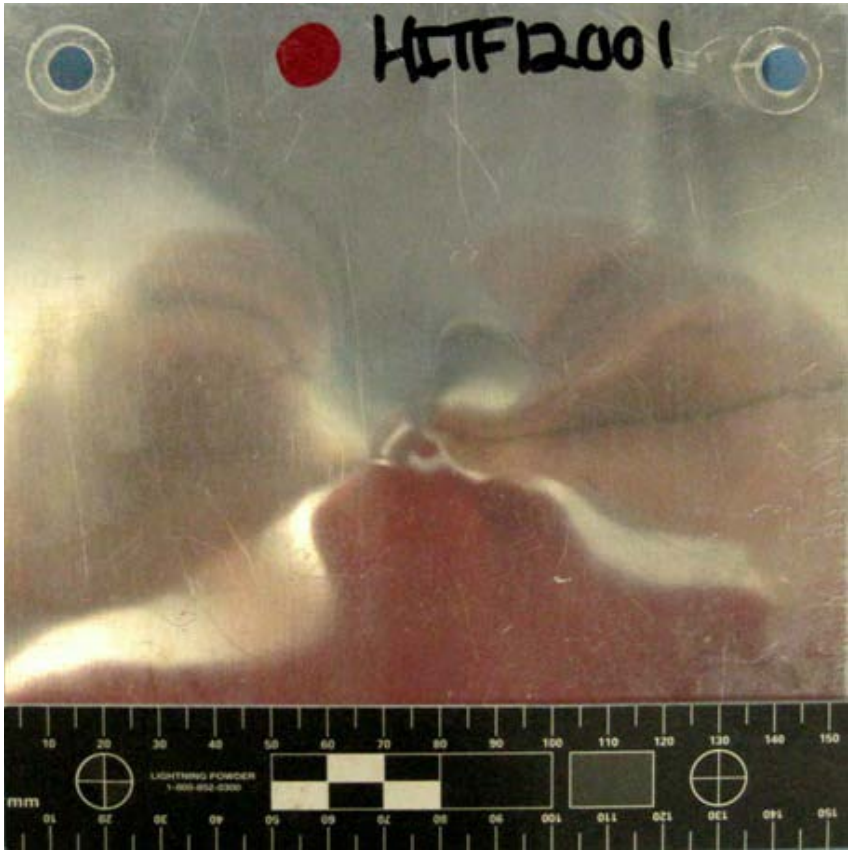
Close-up



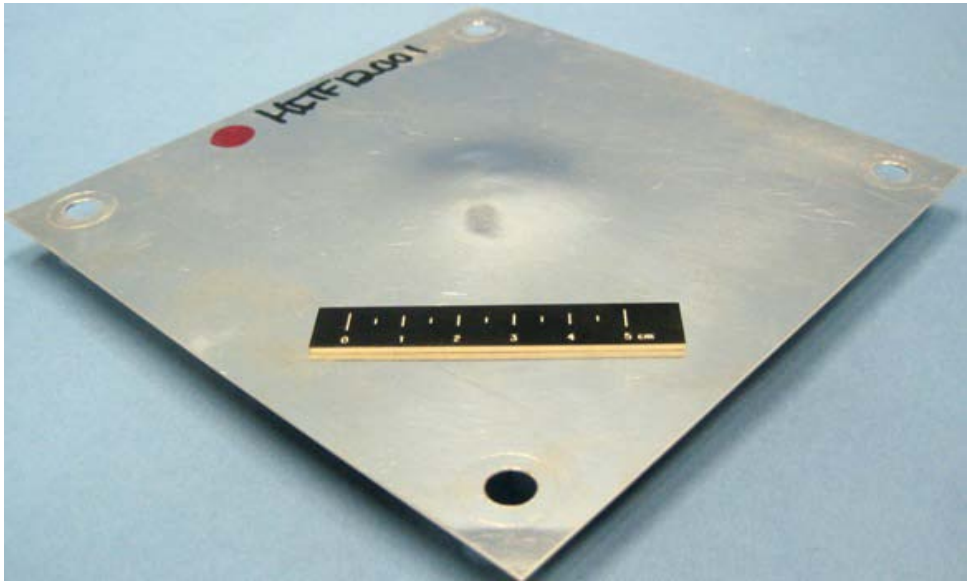
HITF-12001, Multishock 0.36g/cm^2

3.2mm diameter Al 2017T4, 6.93 km/s, 0deg

Rear wall (back)



Rear wall back (oblique)

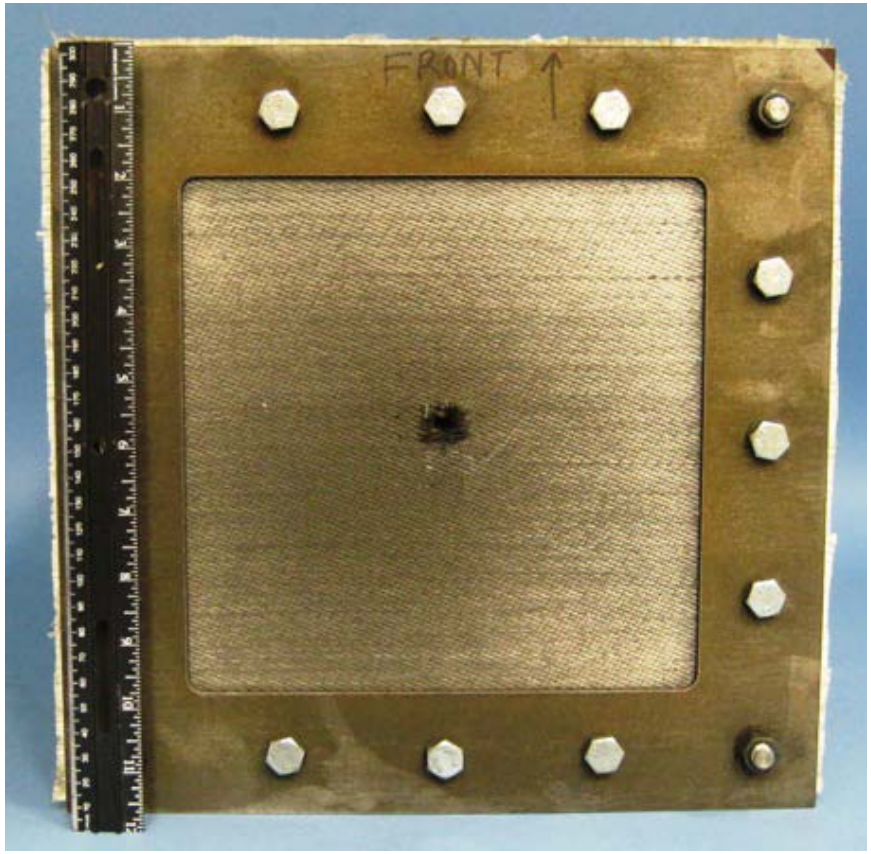


National Aeronautics and Space Administration

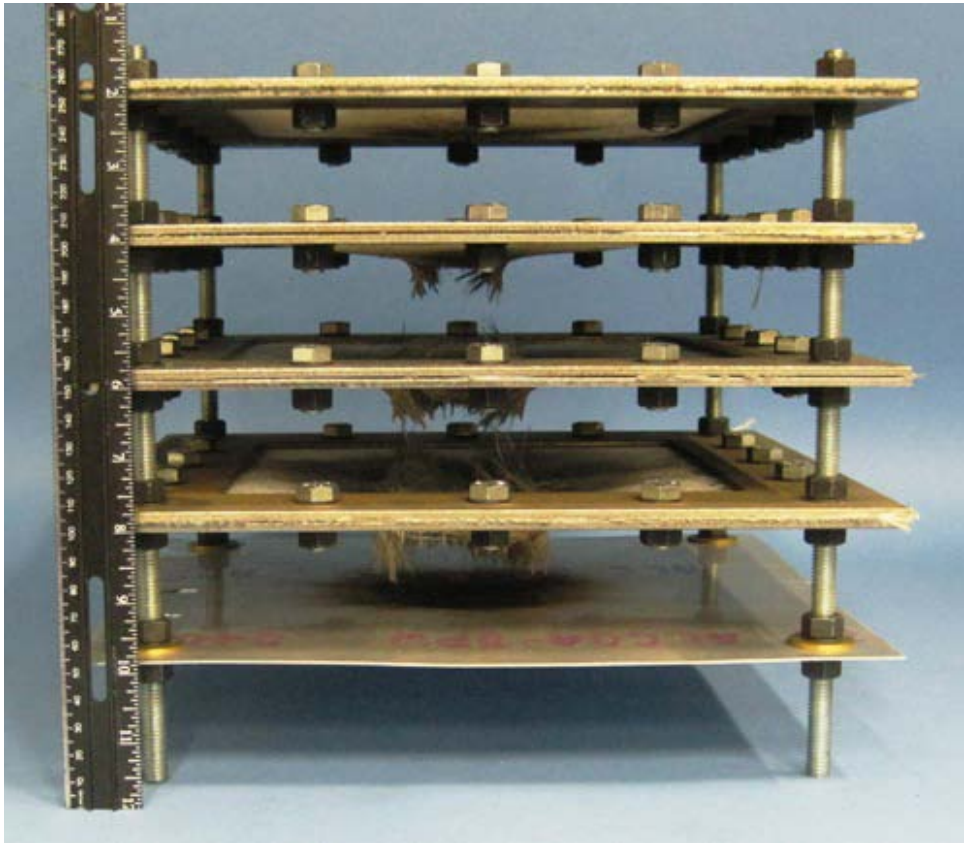
HITF-12002, Multishock 0.647g/cm^2

6.4mm diameter Al 2017T4, 6.86 km/s, 0deg

Front view



Side view

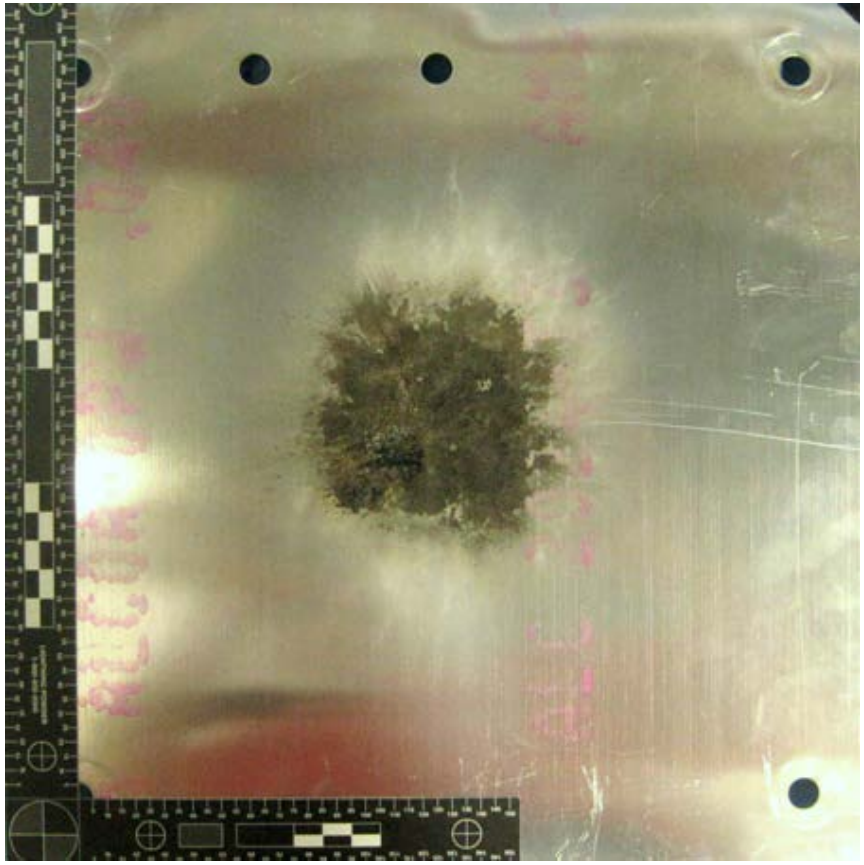


National Aeronautics and Space Administration

HITF-12002, Multishock 0.647g/cm^2

6.4mm diameter Al 2017T4, 6.86 km/s, 0deg

Rear wall (front)

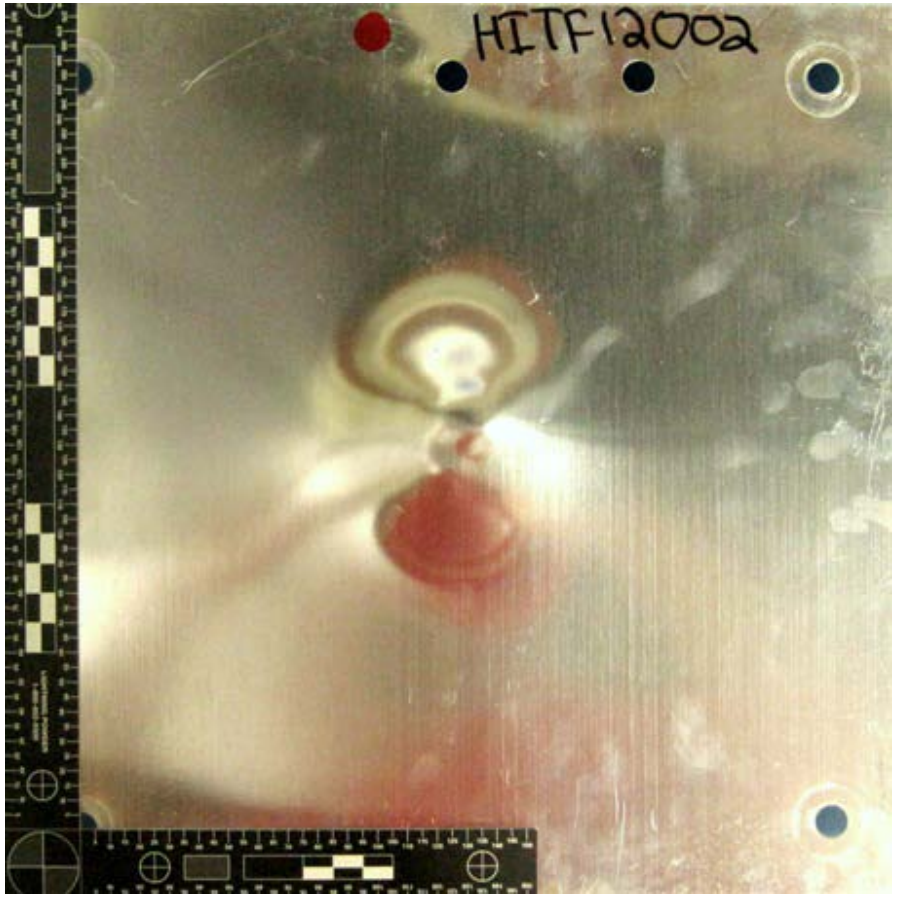


Close-up

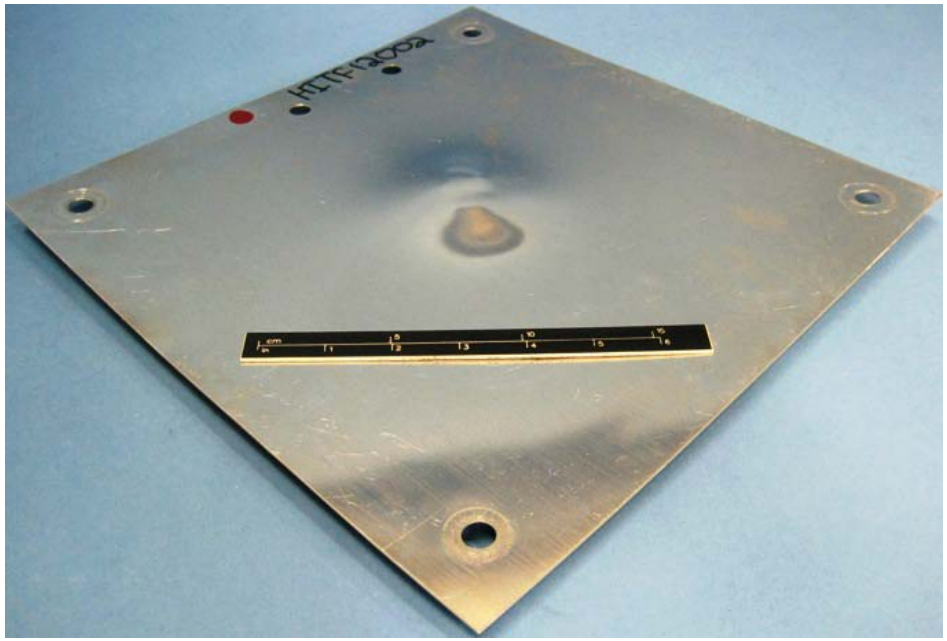
National Aeronautics and Space Administration

HITF-12002, Multishock 0.647g/cm^2
6.4mm diameter Al 2017T4, 6.86 km/s, 0deg

Rear wall (back)



Rear wall back (oblique)

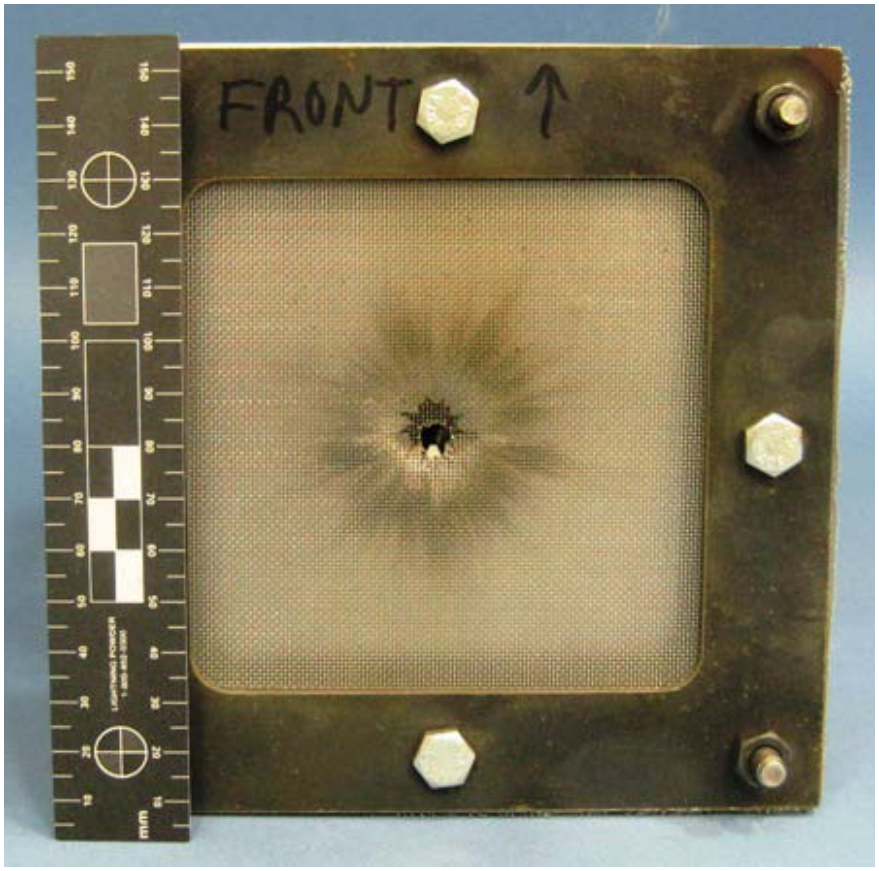


National Aeronautics and Space Administration

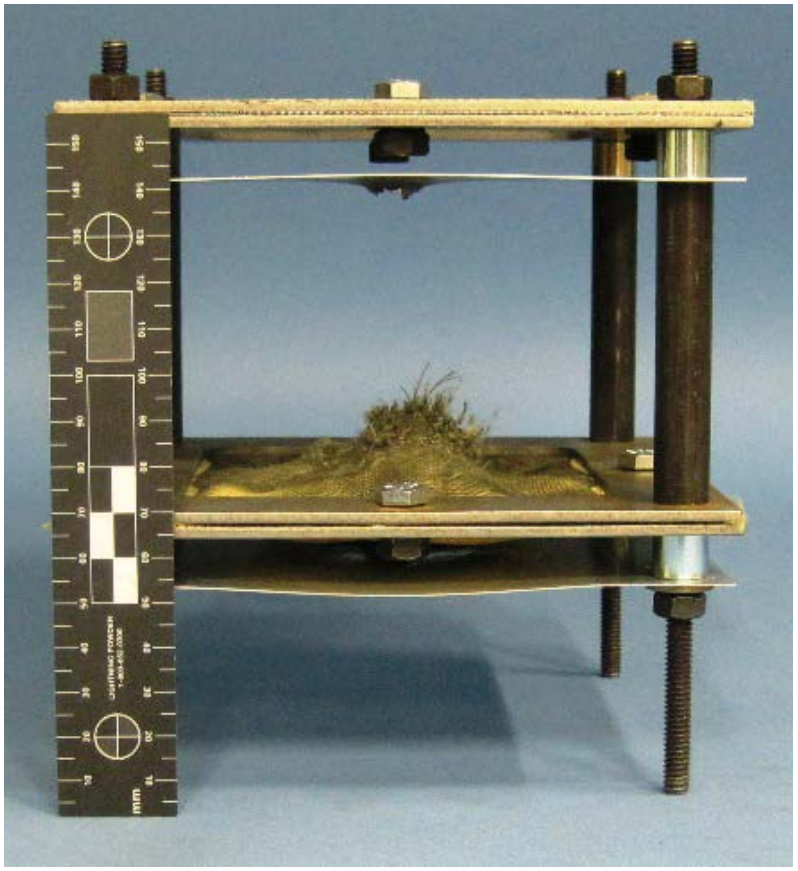
HITF-12003, Mesh Double Bumper 0.33g/cm^2

3.2mm diameter Al 2017T4, 6.85 km/s, 0deg

Front view



Side view

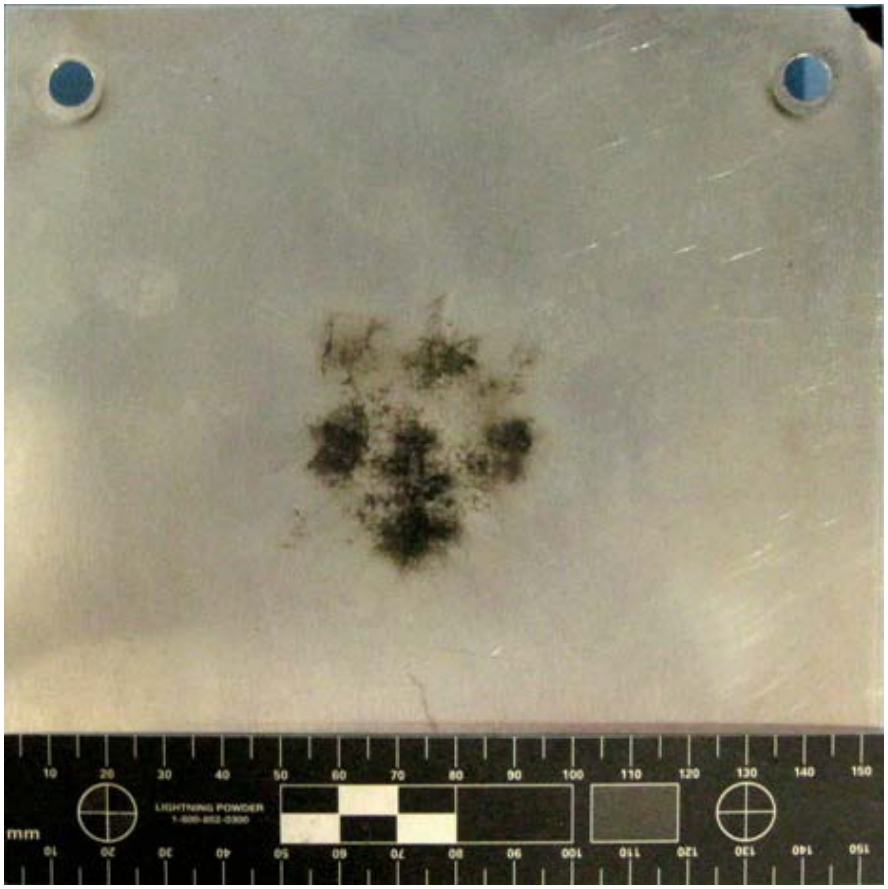


National Aeronautics and Space Administration

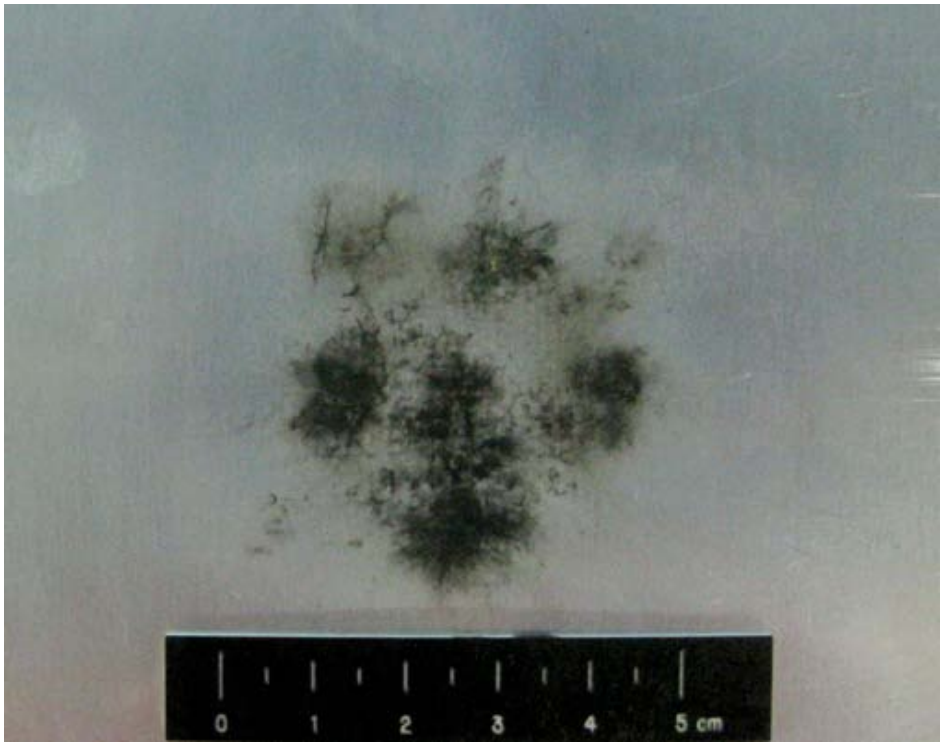
HITF-12003, Mesh Double Bumper 0.33g/cm^2

3.2mm diameter Al 2017T4, 6.85 km/s, 0deg

Rear wall (front)



Close-up



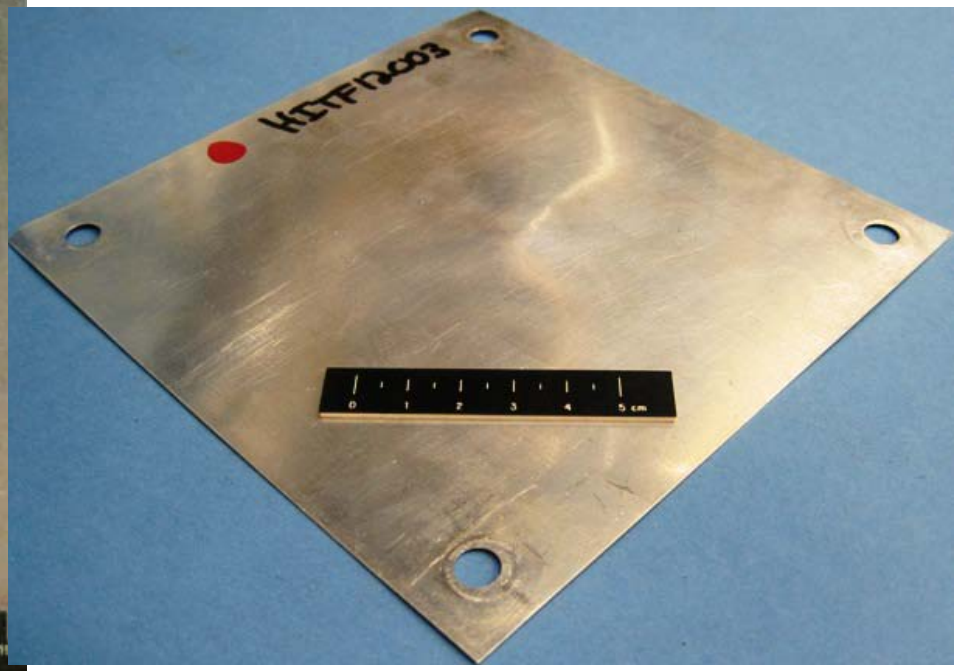
National Aeronautics and Space Administration

HITF-12003, Mesh Double Bumper 0.33g/cm^2

3.2mm diameter Al 2017T4, 6.85 km/s, 0deg

Rear wall (back)

Rear wall back (oblique)

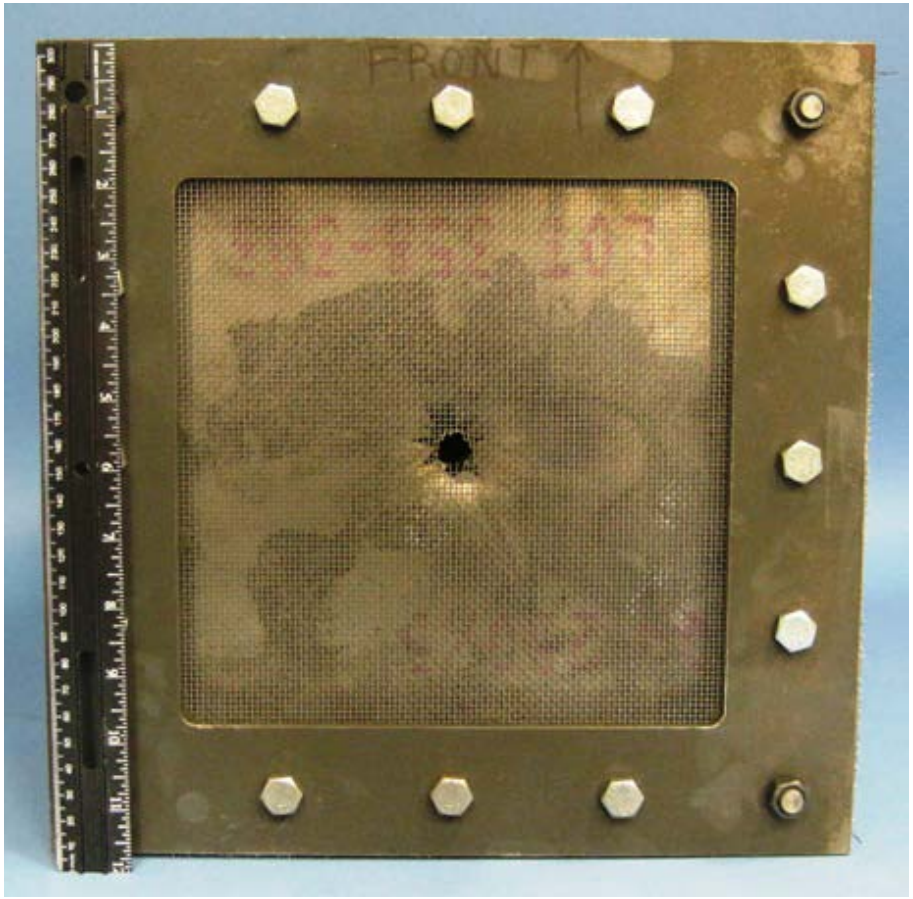


National Aeronautics and Space Administration

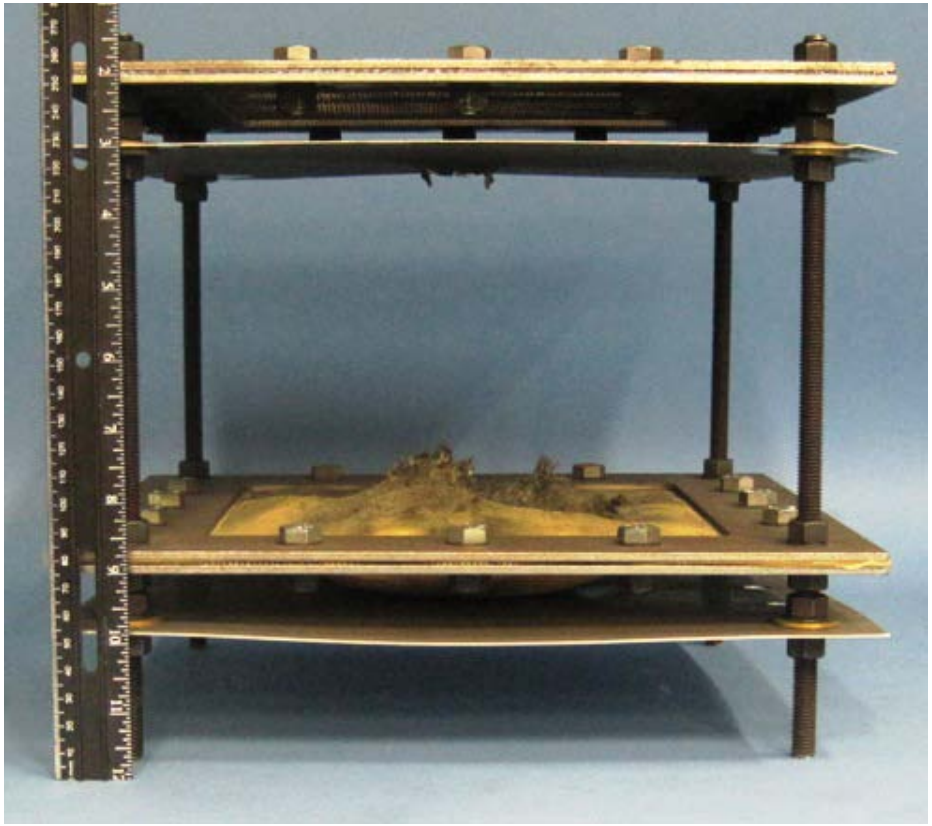
HITF-12004, Mesh Double-Bumper 0.651g/cm^2

6.4mm diameter Al 2017T4, 6.91 km/s, 0deg

Front view



Side view

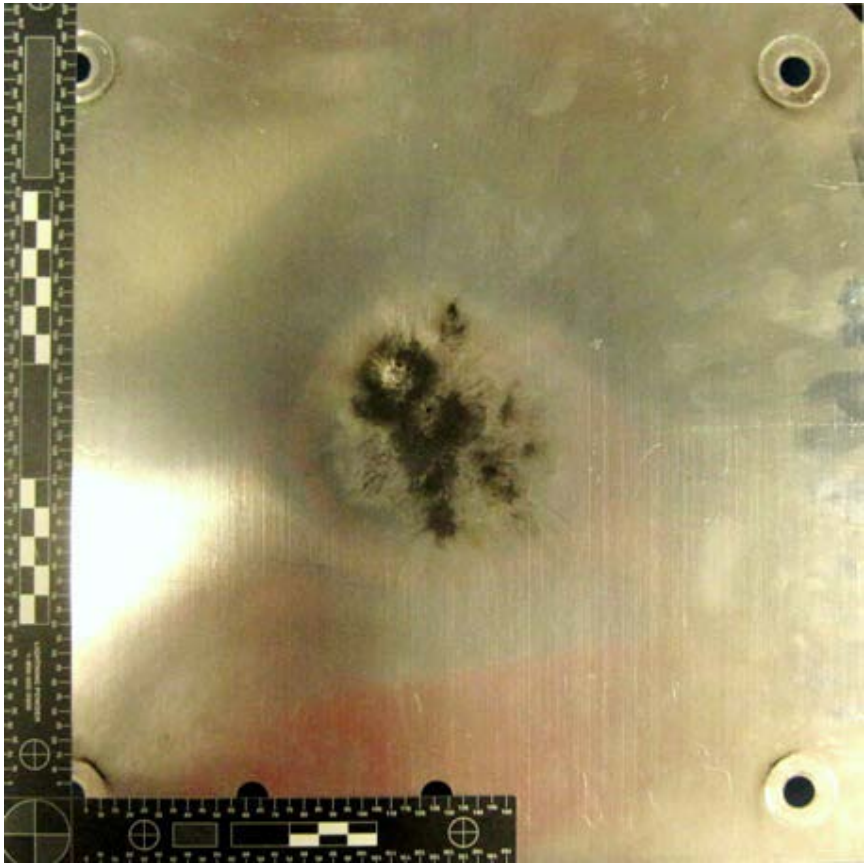


National Aeronautics and Space Administration

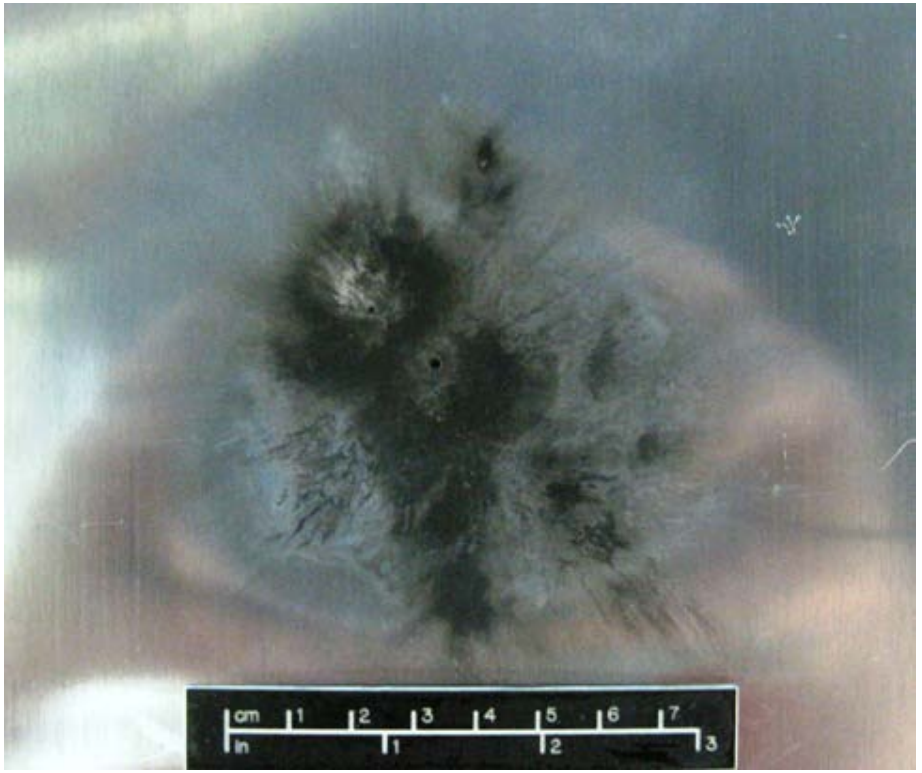
HITF-12004, Mesh Double-Bumper 0.651g/cm²

6.4mm diameter Al 2017T4, 6.91 km/s, 0deg

Rear wall (front)



Close-up

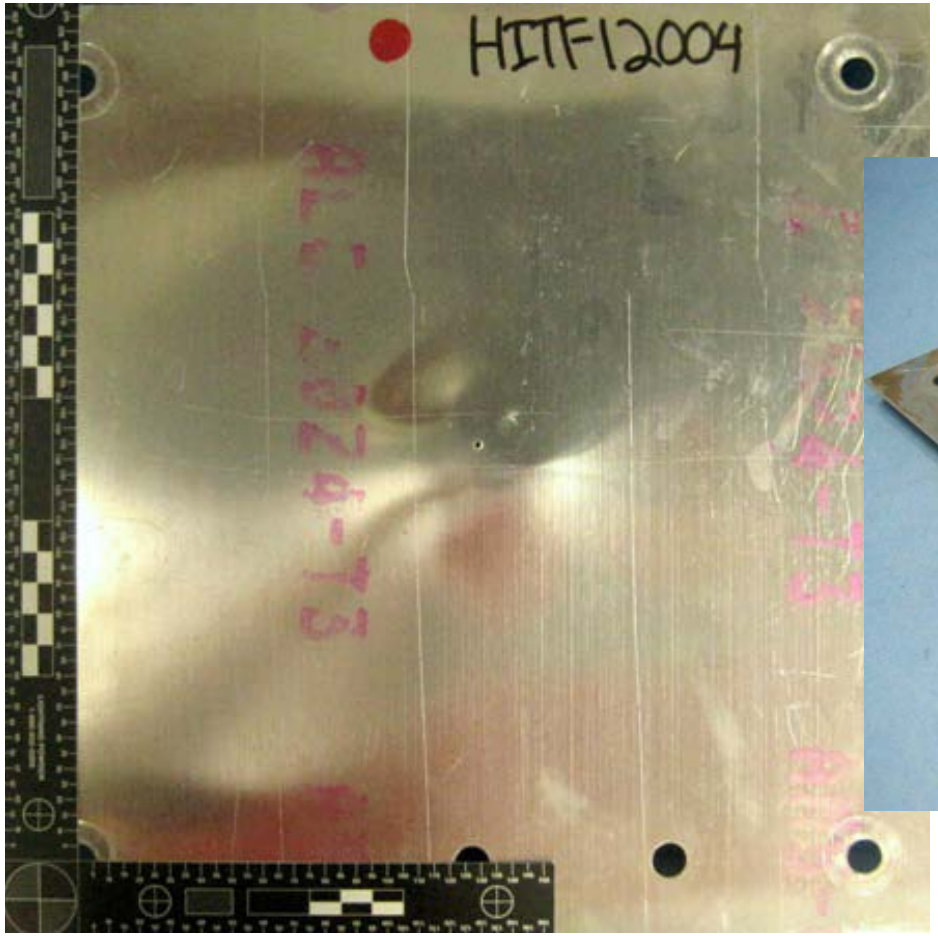


National Aeronautics and Space Administration

HITF-12004, Mesh Double-Bumper 0.651g/cm²

6.4mm diameter Al 2017T4, 6.91 km/s, 0deg

Rear wall (back)



Rear wall back (oblique)