Impact Testing of Orbiter Thermal Protection System Materials

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Background

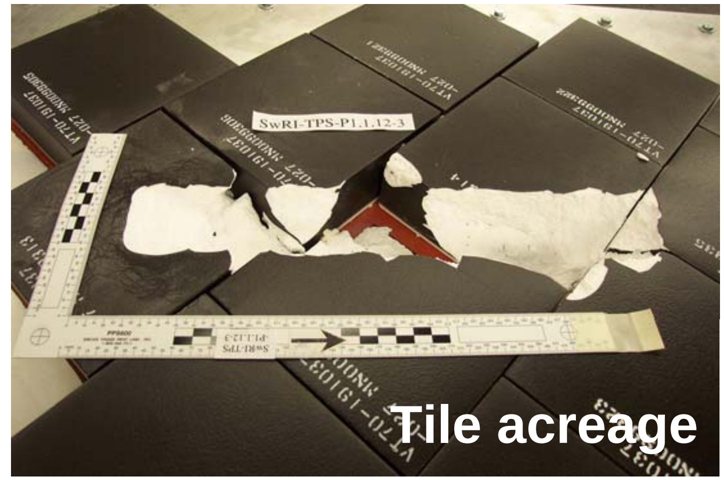
- In February 2003, the Columbia vehicle and crew were tragically lost during re-entry.
- The accident occurred because critical damage to the thermal protection system (TPS) was incurred during ascent to orbit.
- Impact of the port ET bipod with panel 8L of the Orbiter wing leading edge created a breech in the TPS.
- During re-entry, hot gases flowed through the TPS breech and into the wing structure.
- Subsequently, the Orbiter disintegrated over the United States.
- Since the accident, the Orbiter Damage Assessment Team (DAT) has performed extensive impact testing of the Orbiter TPS
  - Over 750 impact tests on tile
  - Over 300 impact tests on RCC
- Impact testing has enabled development of damage equations
  - Critical input to quantifying loss of vehicle and crew risk
  - Used to decide if observed damages are safe for re-entry

CAIB Recommendations

- ***R3.3-2 Initiate a program designed to increase the Orbiter's ability to sustain minor debris damage by measures such as improved impact-resistant Reinforced Carbon-Carbon and acreage tiles. This program should determine the actual impact resistance of current materials and the effect of likely debris strikes.***

- ***R3.8-2 Develop, validate and maintain physics-based computer models to evaluate TPS damage from debris impacts. These tools should provide realistic and timely estimates of any impact damage from possible debris from any source that may ultimately impact the Orbiter. Establish impact damage thresholds that trigger responsive corrective action, such as on-orbit inspection and repair, when indicated.***

TPS tile and LESS RCC impact testing



Orbiter Ascent Impact Test Facilities

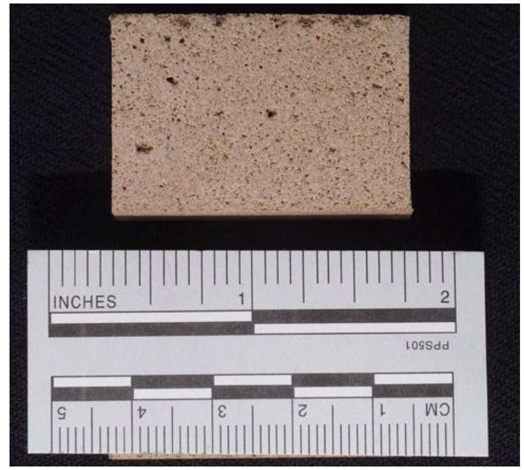
- **Southwest Research Institute – full scale RCC testing and foam impact testing on TPS tile**

- **NASA**
  - **White Sands Test Facility – ice impact testing on TPS tile**
  - **Kennedy Space Center – ablator impact testing on TPS tile**
  - **Glenn Research Center – material property characterization and ET test program**

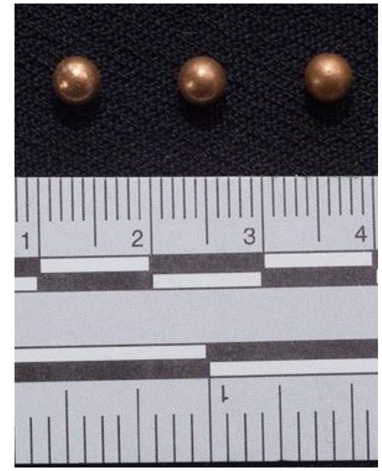
Various projectile materials

Standard Density
Ice (Clear Ice)

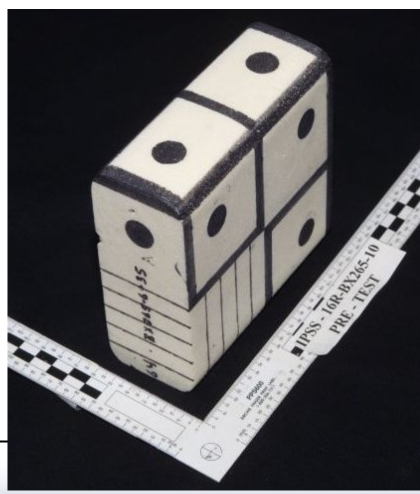
Low Density
Ice



Ablator from
the SRB's

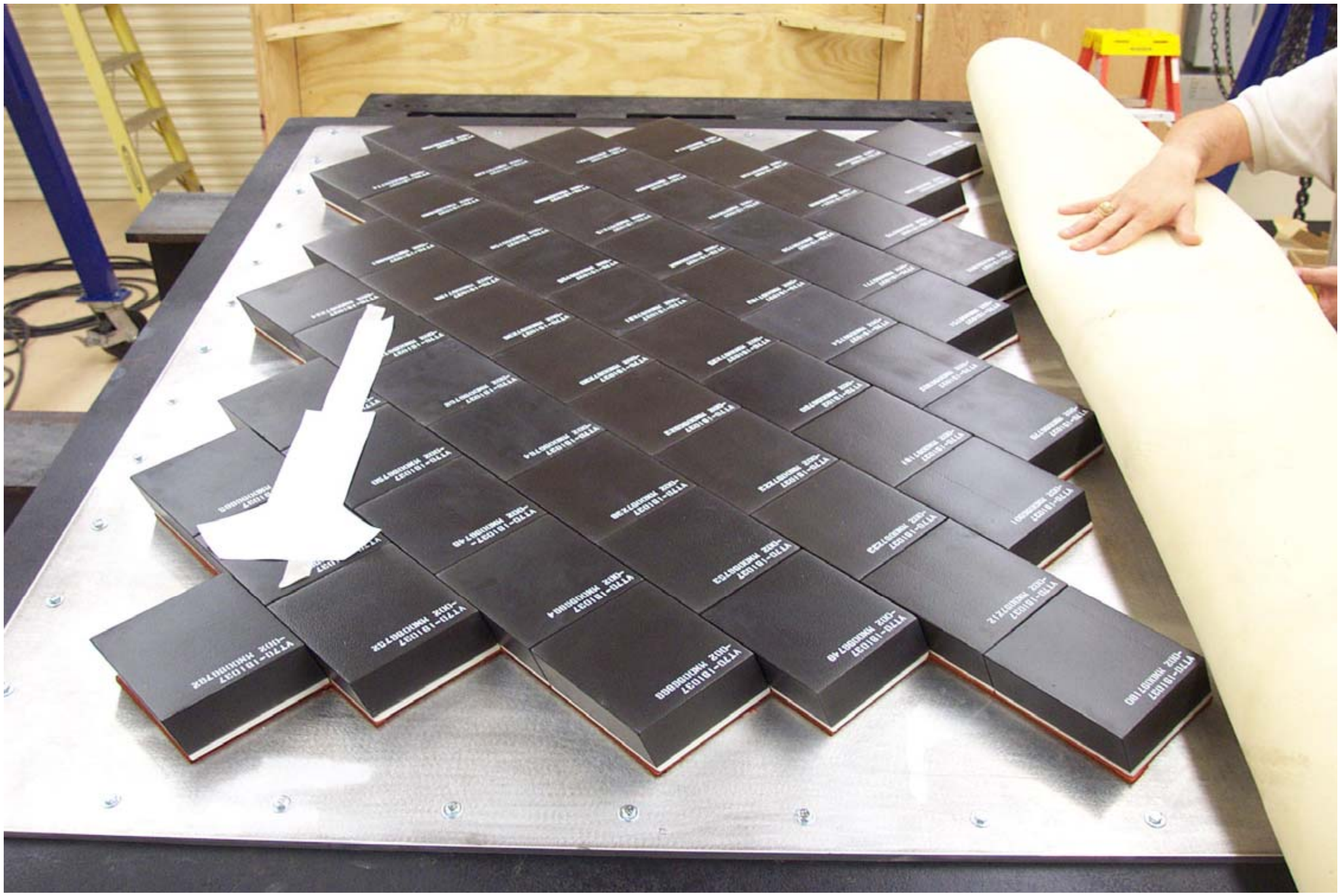


Metal from
the Launch
Pad Structure
(BB's)



ET Foam (1/10th the size of
that tested during the Investigation

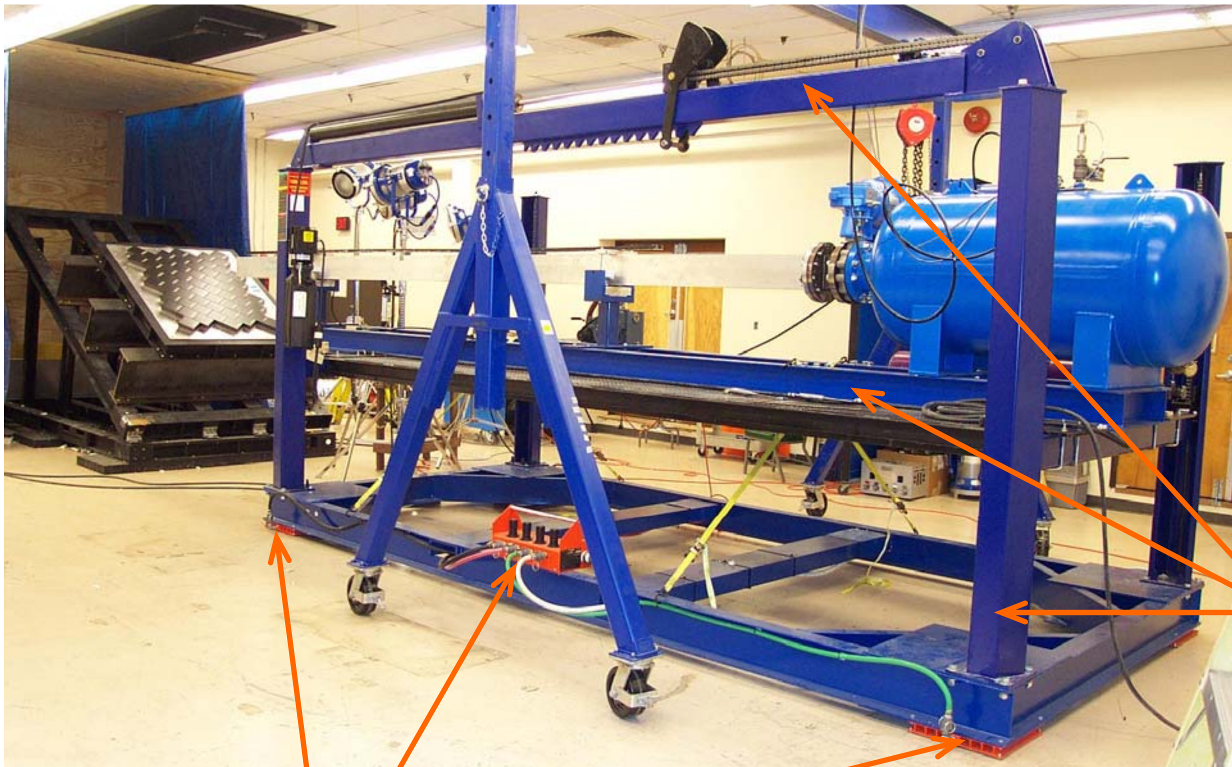
Thermal Protection System (TPS) Tile Array



Acreage Tile Testing Summary

- **Characterize damage due to debris impacts on acreage tile**
  - **Support development of an empirical damage prediction model**
    - “Simple” or “Rapid response” model
  - **Provide data for validation of analytical models**
    - “Detailed models” – CTH & LS-DYNA
- **3 test facilities to conduct 764 total impact tests**
  - **SwRI (Foam), WSTF (Ice & Metal), KSC (Ablator)**
  - **398 Foam, 198 Ice, 120 Ablator, and 48 Metal**
- **SwRI’s role in this task was limited to impacting the TPS tiles with ET foam—approximately 52% of the total tests.**

Compressed gas guns



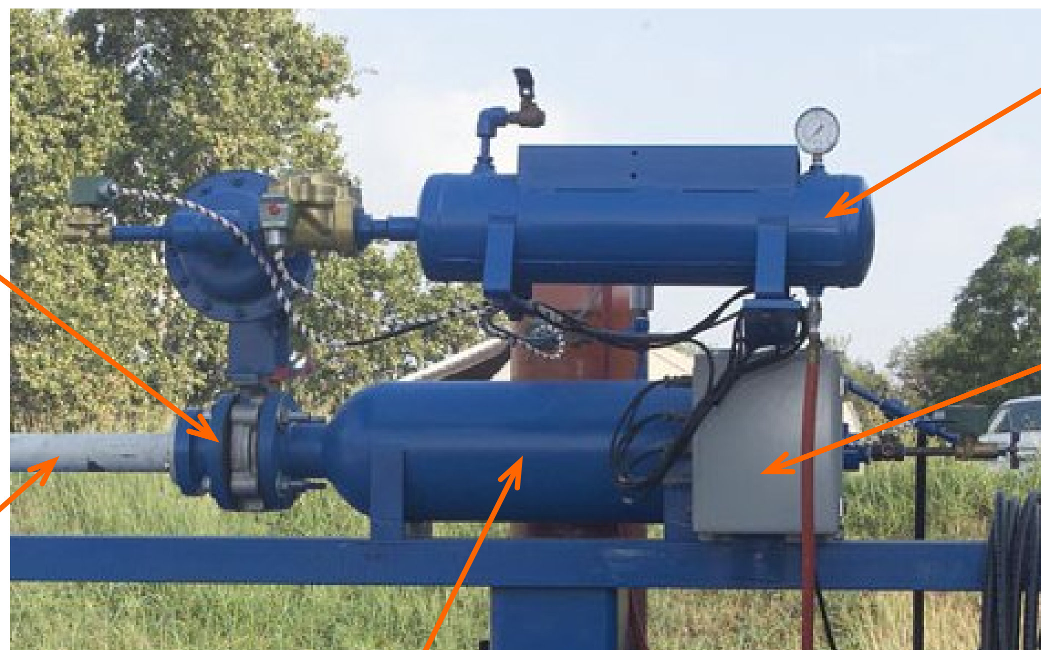
Hydraulic Car Lift for Height Adjustment

Air Bearings for X, Y, and Yaw Adjustment

Compressed Gas Guns

All compressed gas guns work the same:

- Tank to store high pressure Nitrogen or Helium
- Fast acting valve used to fire the gun
- Mounted on car/bus lift for vertical adjustment
- Mounted on air bearings for x-y and yaw adjustment



Fast Acting Valve

Barrel

Valve Air Supply Tank

Gun Controls

Pressure Tank

Small Compressed Gas Gun (3 Gallon Tank)

Used to launch Ice (Low and Regular Density) and ablator 300 – 800 fps

½” x 1” Rectangular, 2” Diameter, and 2” x 2” Square 11-foot Barrels

Medium Compressed Gas Gun (150 Gallon Tank)

Used to launch ET Foam 600 – 1800 fps

20-foot aluminum barrels with rectangular cross sections

Large Compressed Gas Gun (500 Gallon Tank)

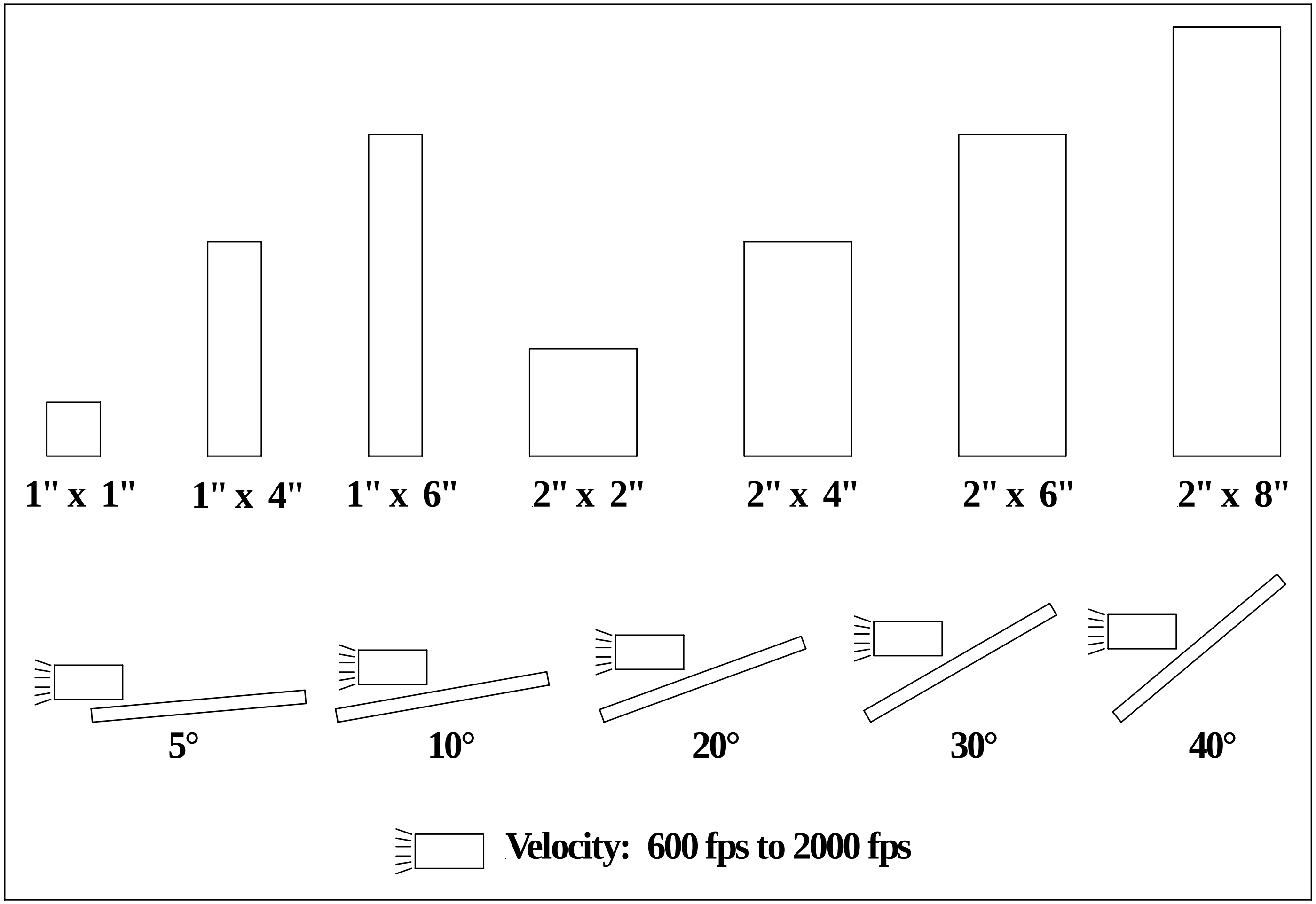
Used to launch ET Foam 800 – 2000 fps

35 and 40-foot Steel and Aluminum Barrels with rectangular cross sections

BB Gun

Used to launch BB's at RCC Panels 0.34 grams BB's 300 – 600 fps

Various foam cross-sections and impact angles



Observed Damage Types

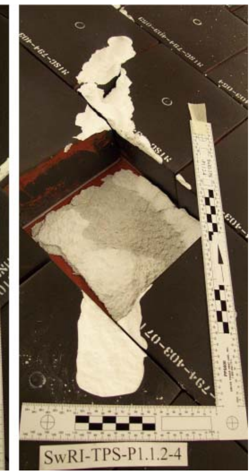
Coating Damage

Surface Damage

Multiple Tile Cratering

Full Depth Cratering

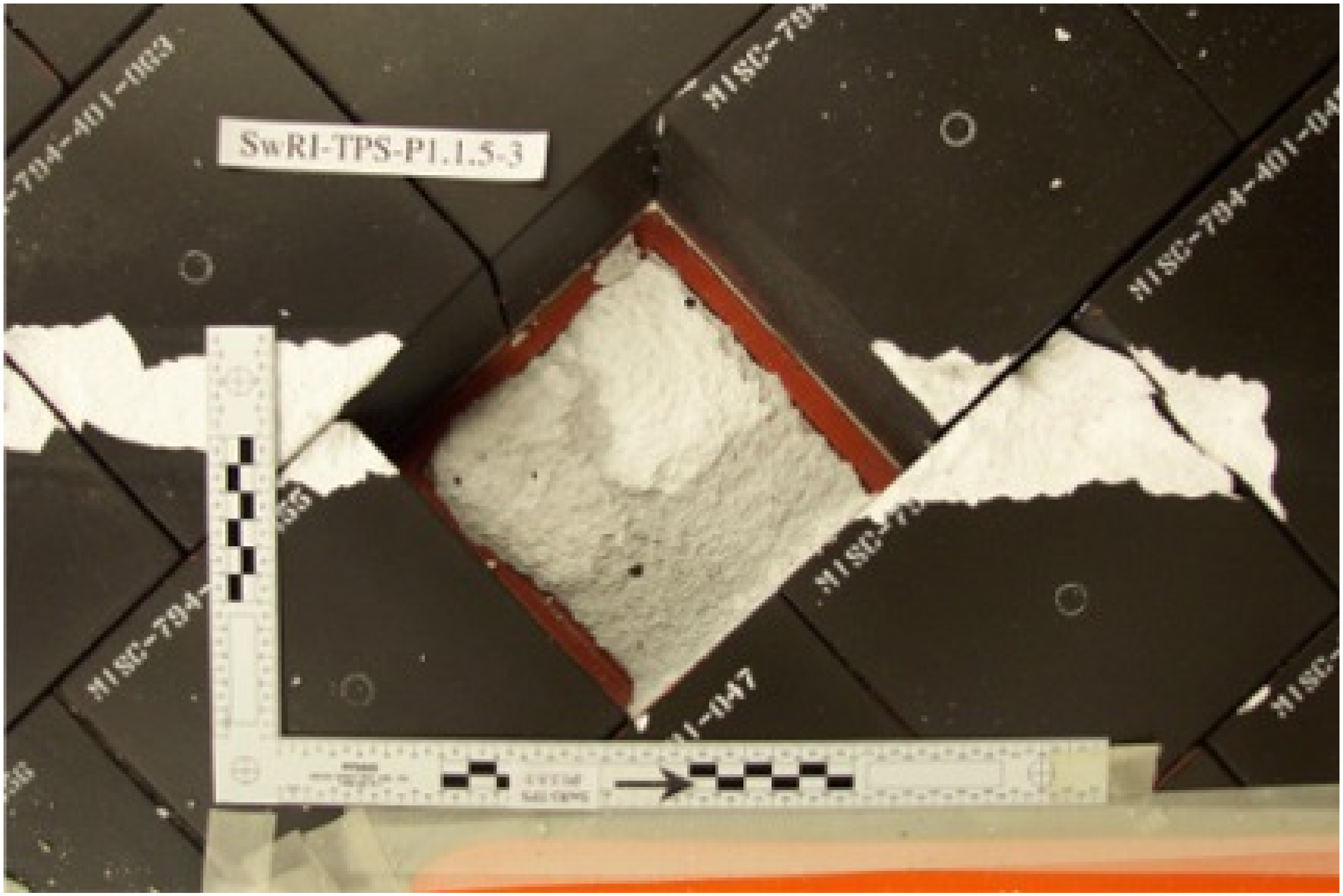
Complete Tile Loss



Cracking, minor coating removal | **Surface damage, significant coating removal** | **Crater Damage** | **Full-Depth Cratering** | **Complete Tile Loss**

Spectrum of increasing damage

Acreage testing has demonstrated new failure modes



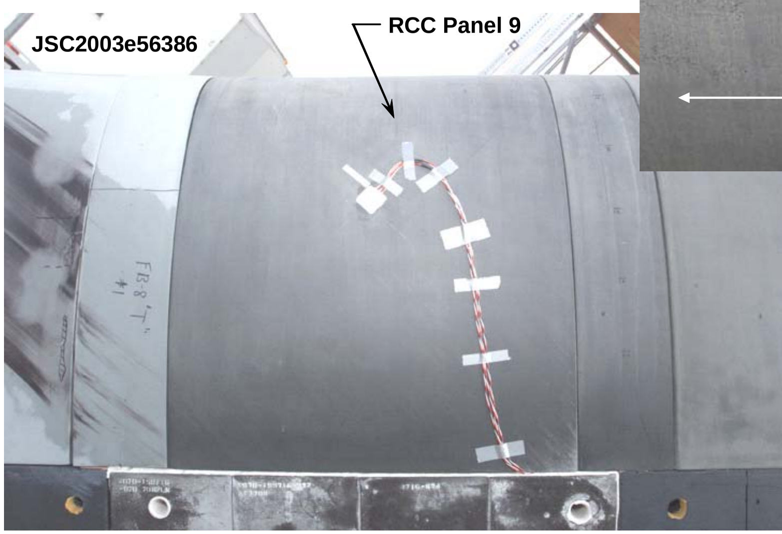
Wing Leading Edge Panel (RCC Panel)

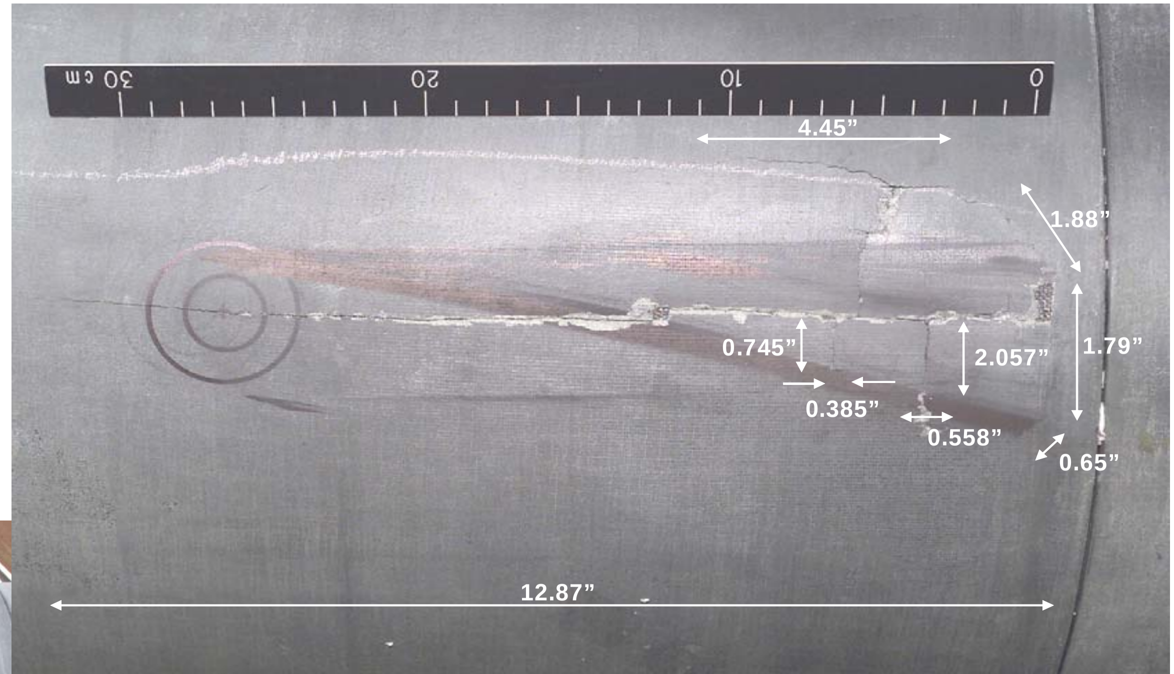
RCC panel RTF testing (panel 9)

- **Panel 9 testing provided as a "quick look" assessment of whether an RCC panel can withstand an impact by ET foam (BX 265) shed from the LH2 intertank flange area during ascent.**
  - Impact location on the panel was assessed as worst case (LS-DYNA study)
  - Impact velocities and debris masses selected represented the bounding kinetic energies for debris shed from the lower and upper flange area
  - **Three total tests were conducted**
  - Test 1: m=0.1 lbm, V=701 ft/s => K. E. = 763 ft-lbs
=> normal K. E. = 382 ft-lbs
  - Test 2: m=0.2 lbm, V=688 ft/s => K. E. = 1470 ft-lbs
=> normal K. E. = 735 ft-lbs
  - Test 3: m=0.16 lbm, V=1167 ft/s => K. E. = 3384 ft-lbs
=> normal K. E. = 1,692 ft-lbs
  - Panel 6 test K. E. = 12,351 ft-lbs => normal K. E. = 1,529 ft-lbs (crack)
  - Panel 8 test K. E. = 15,754 ft-lbs => normal K. E. = 1,843 ft-lbs (hole)

RCC panel 9, Test 3 results

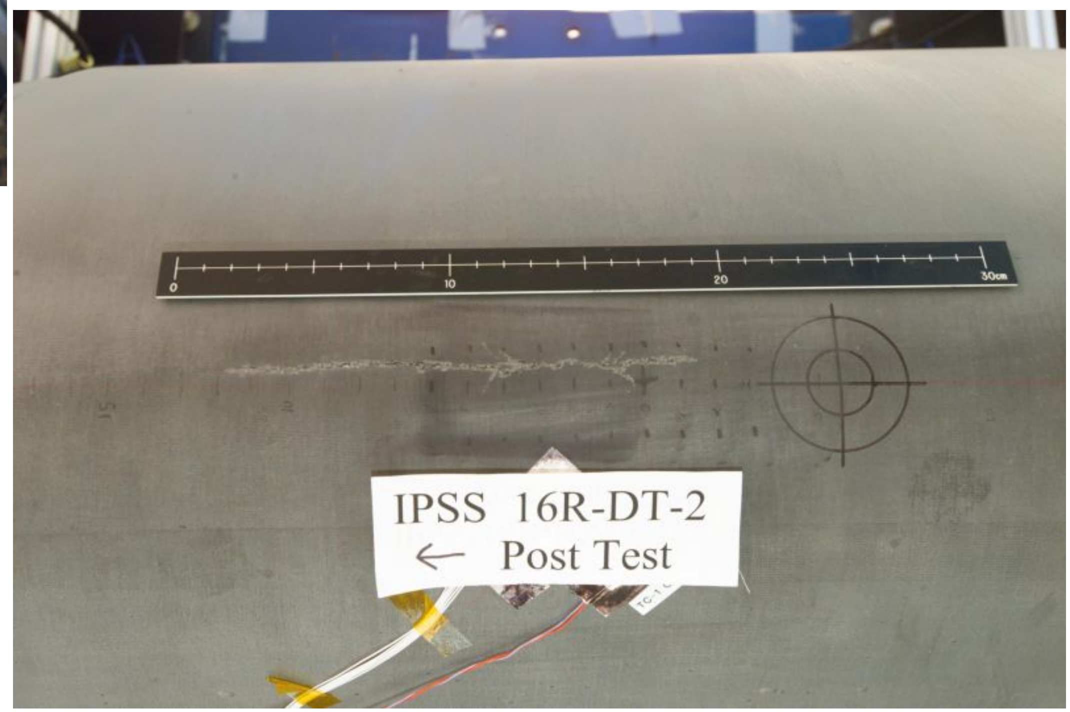
- **Impact conditions**
  - **Material: BX 265 foam**
  - **Dimensions: 2.00” x 7.00” x 9.6”**
  - **Volume: 134.4 in^3**
  - **Mass: 73.6 g (0.1623 lb.)**
  - **Launch velocity: 1167±20 ft/sec**





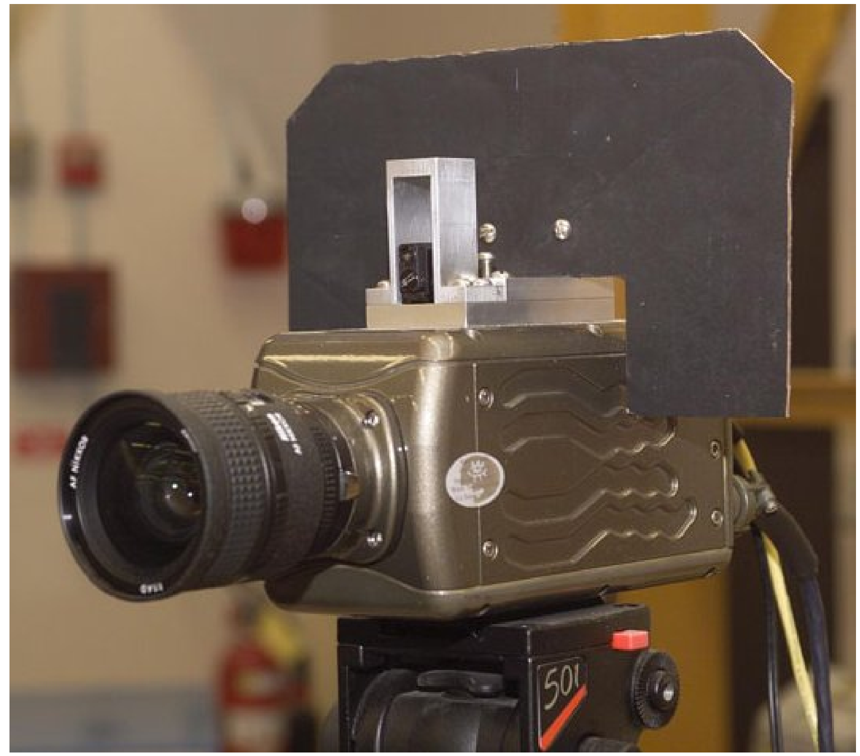
Panel 16R impact damage

- BX-265 foam impactor
  - 2”x4”x6” (0.06 lb)
  - V=1375 ft/s
  - KE=1384 ft/s
  - Angle=45 degrees
- Through thickness crack of the panel
- Damage length is 6.99”



High Speed Cameras and Lighting

- Phantom V7 cameras are used to measure the projectile velocity
- Framing rates of 5000 to 25,000
- Laser used to insure perpendicularity with the shot line
- 2 cameras are used for TPS Tile tests
- 7 cameras are used for RCC Panel tests
- 4 kW and 6 kW studio lights are used for illumination of the targets
- Up to two 6 kW and four 4 kW lights per shot (28 kW/shot)



Critical Lessons Learned

- **Presence/absence of gap fillers has a significant influence on the level of observed tile damage**
  - **Damage is smaller and more erratic where gap filler is present**
  - **Gap fillers were removed for all testing nearly from the beginning of the program**
  - **Impact location has a significant influence on the level of observed tile damage (i.e. “edge” versus “center” impact)**
  - **Test program uses bounding cases in an attempt to capture this influence through damage scatter**
- **An unanticipated “complete tile loss” failure mode was encountered**
  - **Tile failure at the interface between the tile’s densified layer and the undensified substrate**
  - **Failure threshold will be identified through execution of the as-designed test program**
  - **Testing showed that gap fillers tend to eliminate this failure mode for the conditions tested**
  - **Program is considering adding gap fillers to eliminate tile loss in critical areas**
- **Foam tests to date have demonstrated more sporadic damage than anticipated**
  - **Array tile damages are not as “clean” as previously tested single tile damage**

Critical Lessons Learned, Cont.

- HRSI (black) tiles show significantly greater resistance to foam impact damage than LRSI (white) tiles
  - Based on limited characterization testing with 12”x6”x2” (0.20 lb) BX-26 foam at 45° impact angles
- Carrier panel special configuration showed minimal damage from foam impacts at worst case conditions
  - Tested to total kinetic energy levels of 1600 – 3200 ft-lb at a 13° local impact angle, RCC Panel #6 location (worst case loading)
- MLGD special configuration showed significant damage and a potential flow path at extreme, worst-on-worst foam impact conditions
  - Total kinetic energy levels of 1600 – 3800 ft-lb at a 13.5° impact angle resulted in embedded foam, permanent deformation of the thermal barrier, and IML cracking on multiple tiles
- MLGD special configuration showed minimal damage and no potential flow path at more realistic foam impact conditions (as provided by system integration)
  - Total kinetic energy levels of 710 – 770 ft-lb at a 13° impact angle
  - Total kinetic energy levels of 940 – 1900 ft-lb at a 7.5° impact angle

Summary

- **Impact tests conducted February-July 2003 allowed the CAIB and NASA to determine the direct cause of the Shuttle Columbia disaster.**
- **Test results are communicated to the program and used in decision making for component redesign (MLGD thermal barrier, carrier panels), element debris allowables and for the development of damage models**
- **RCC panel response data (strains and accelerations) are delivered to the LS-DYNA team for use in their RCC modeling efforts**
- **Impact testing has allowed the team to safely disposition damage incurred during ascent**