The Columbia Accident Investigation & The NASA Glenn Ballistic Impact Laboratory Contributions Supporting NASA's Return to Flight

Matthew E. Melis, NASA Glenn Research Center, Cleveland, Ohio

On February 1, 2003, the Space Shuttle Columbia broke apart during reentry, resulting in loss of the vehicle and its seven crewmembers. For the next several months, an extensive investigation of the accident ensued involving a nationwide team of experts from NASA, industry, and academia, spanning dozens of technical disciplines. The Columbia Accident Investigation Board (CAIB), a group of experts assembled to conduct an investigation independent of NASA, concluded in August, 2003 that the most likely cause of the loss of Columbia and its crew was a breach in the left wing leading edge Reinforced Carbon-Carbon (RCC) thermal protection system initiated by the impact of thermal insulating foam that had separated from the orbiters external fuel tank 81 seconds into the mission's launch. During reentry, this breach allowed superheated air to penetrate behind the leading edge and erode the aluminum structure of left wing, which ultimately led to the breakup of the orbiter. The findings of the CAIB were supported by ballistic impact tests, which simulated the physics of External Tank Foam impact on the RCC wing leading edge material. These tests ranged from fundamental material characterization tests to full-scale Orbiter Wing Leading Edge tests.

Following the accident investigation, NASA spent the next 18 months focused on returning the shuttle safely to flight. In order to fully evaluate all potential impact threats from the many debris sources on the Space Shuttle during ascent, NASA instituted a significant impact testing program. The results from these tests led to the validation of high-fidelity computer models, capable of predicting actual or potential Shuttle impact events, were used in the certification of STS-114, NASA's Return to Flight Mission, as safe to fly.

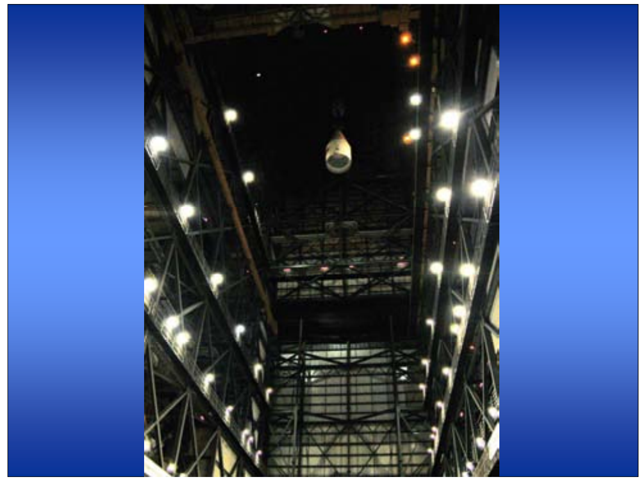
This presentation will provide a look into the inner workings of the Space Shuttle and a behind the scenes perspective on the impact analysis and testing done for the Columbia Accident Investigation and NASA's Return to Flight programs. In addition, highlights from recent Shuttle missions are presented.

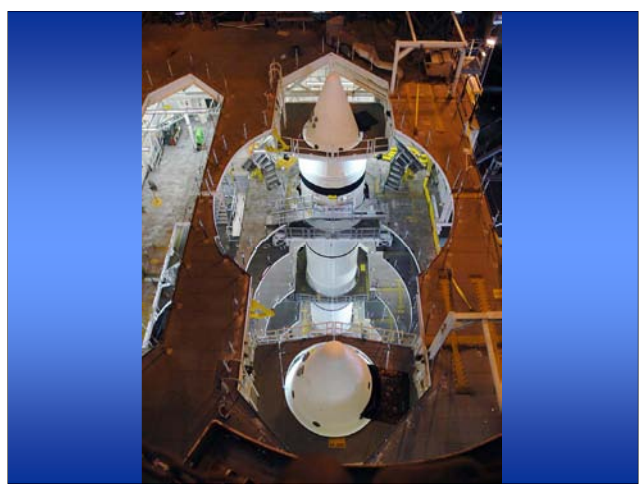
The Columbia Accident Investigation
&
The NASA Glenn Ballistic Impact Laboratory
Contributions Supporting
NASA's Return to Flight

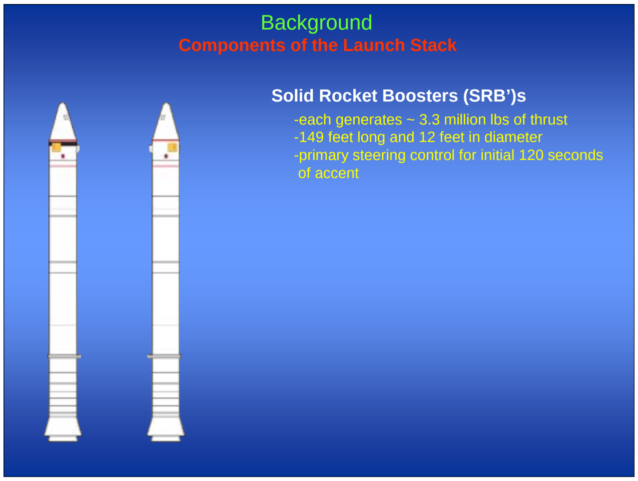
Matt Melis
NASA Glenn Research Center
Cleveland Ohio

Background
Components of the Launch Stack

Solid Rocket Boosters (SRB')s
-each generates ~ 3.3 million lbs of thrust
-149 feet long and 12 feet in diameter
-primary steering control for initial 120 seconds of accent



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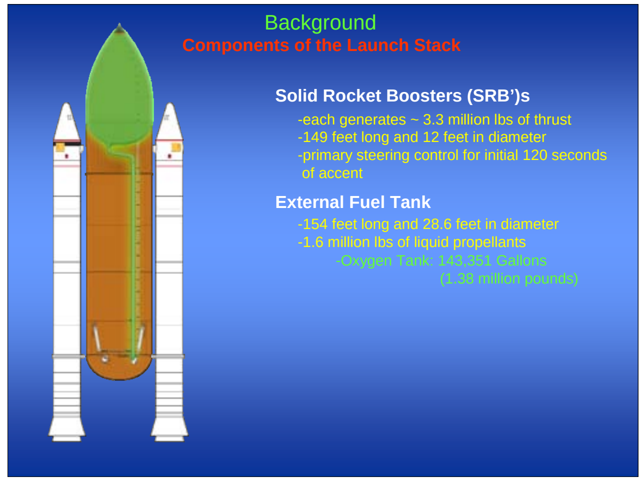
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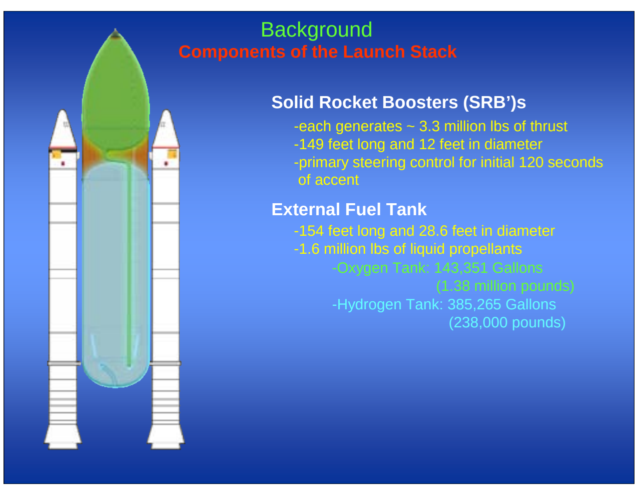
-154 feet long and 28.6 feet in diameter
-1.6 million lbs of liquid propellants
-Oxygen Tank: 143,351 Gallons
(1.38 million pounds)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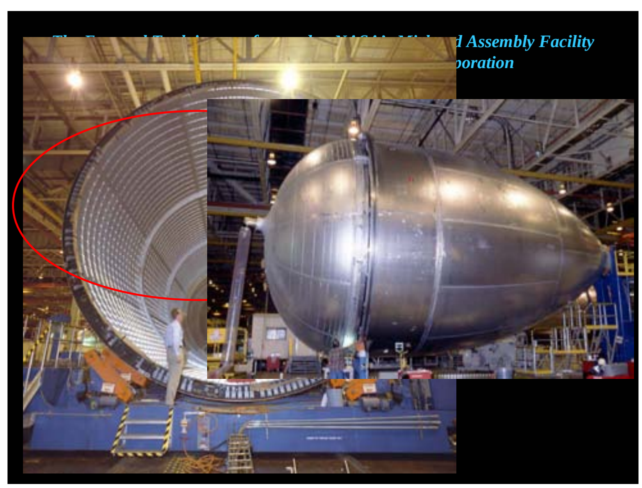
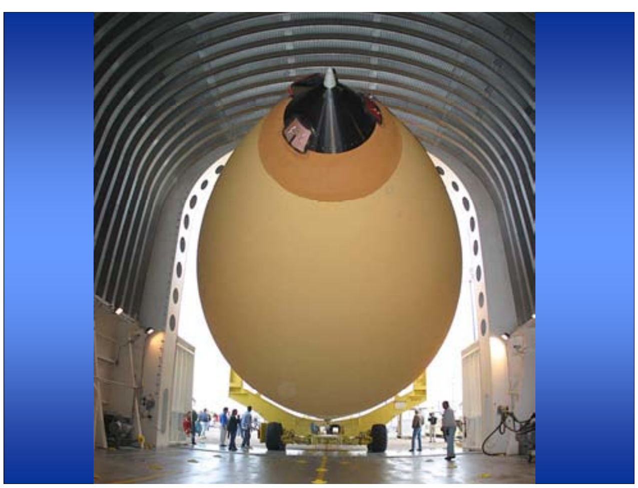
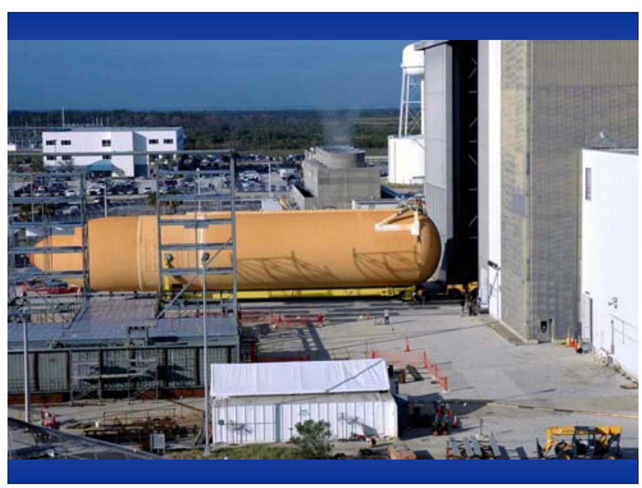
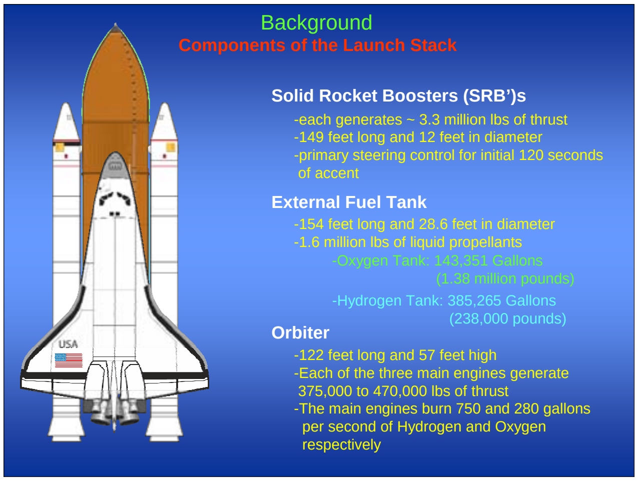
-Hydrogen Tank: 385,265 Gallons
(238,000 pounds)


Assembly Facility




NASA




Background
Components of the Launch Stack
USA
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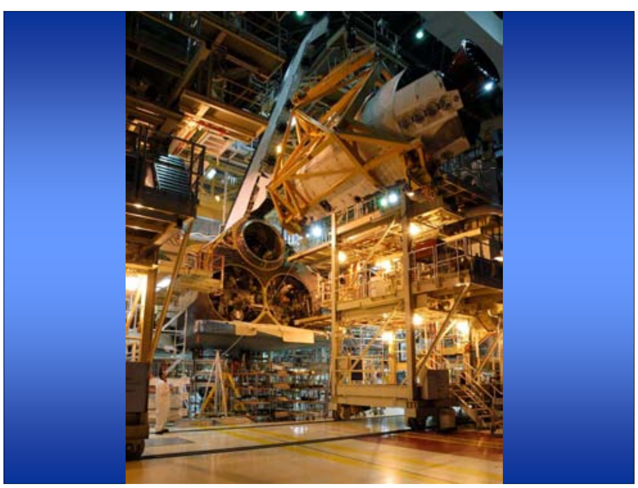
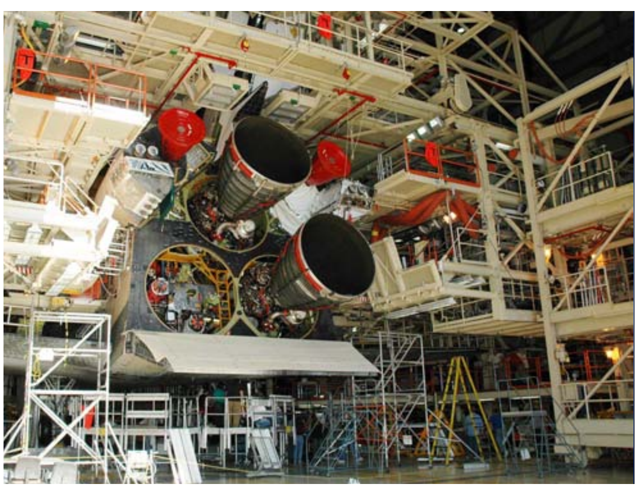
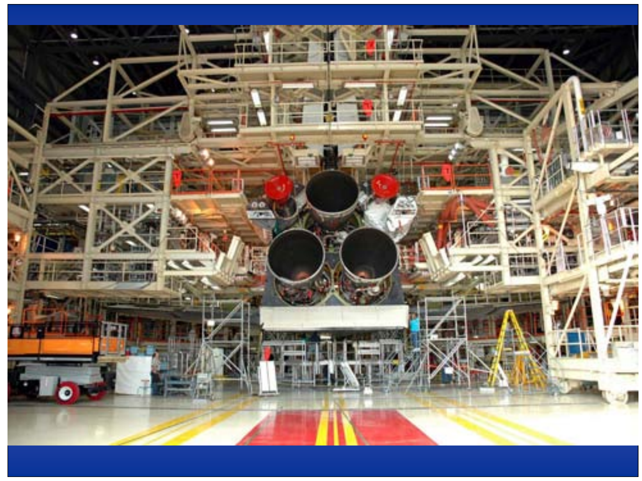
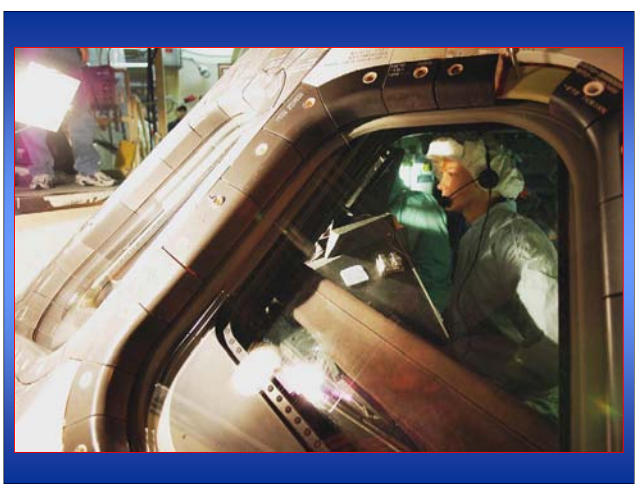
-Oxygen Tank: 143,351 Gallons (1.38 million pounds)
-Hydrogen Tank: 385,265 Gallons (238,000 pounds)
Orbiter
-122 feet long and 57 feet high
-Each of the three main engines generate 375,000 to 470,000 lbs of thrust
-The main engines burn 750 and 280 gallons per second of Hydrogen and Oxygen respectively







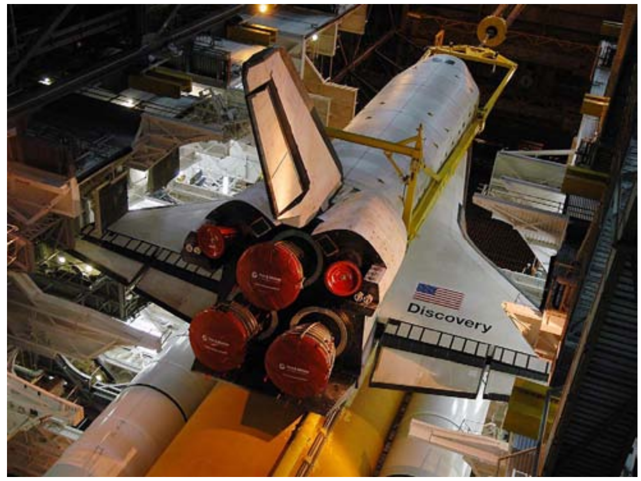






Discovery


Discovery


NASA
Discovery


Discovery

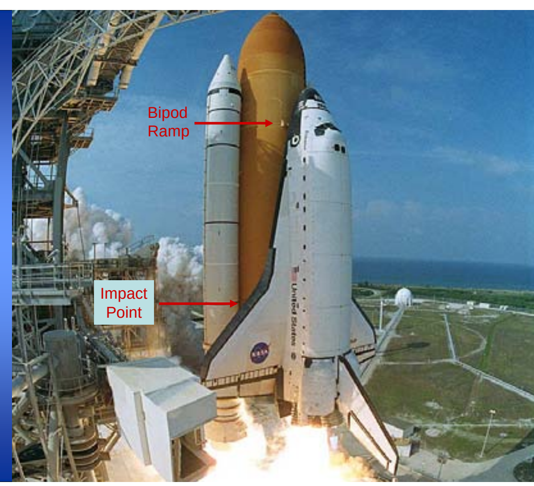
The Columbia Accident

On January 16 2003, Columbia's leading edge was impacted by a piece of foam suspected to have separated from the external tank bipod ramp at 81 seconds into its launch.

Columbia was traveling at Mach 2.46, at an altitude of 65,860 feet. The foam was calculated to have hit the orbiter at 700 – 800 feet per second

Insulating Foam Separates from Bipod Ramp and Impacts Left Wing of Columbia

Insulating Foam Separates from Bipod Ramp and Impacts Left Wing of Columbia

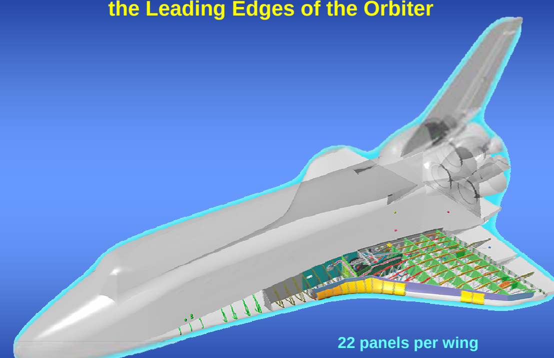


The Bipod Ramp

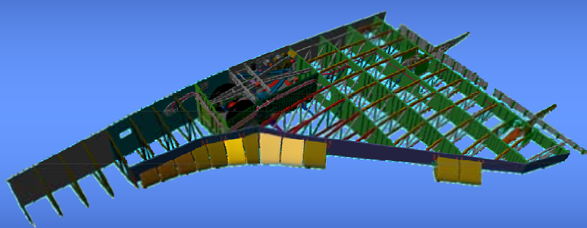
The Bipod Ramp

The Orbiter Leading Edges

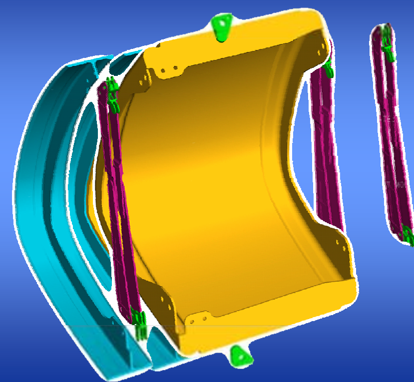
Reinforced Carbon-Carbon (RCC) Panels Protect the Leading Edges of the Orbiter



RCC Panels 6, 8 & 9 of Specific Interest



RCC T-Seals Seal the Gap Between Panels



Leading Edge Panel Used for Full Scale Tests

The Reconstruction Effort

The Debris Field

The Debris Hanger

The Debris Hanger

The Debris Hanger

Reconstructing the Left Wing Leading Edges

Reconstructing the Left Wing Leading Edges

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Reconstructing the Left Wing Leading Edges


Reconstructing the Left Wing Leading Edges
United States


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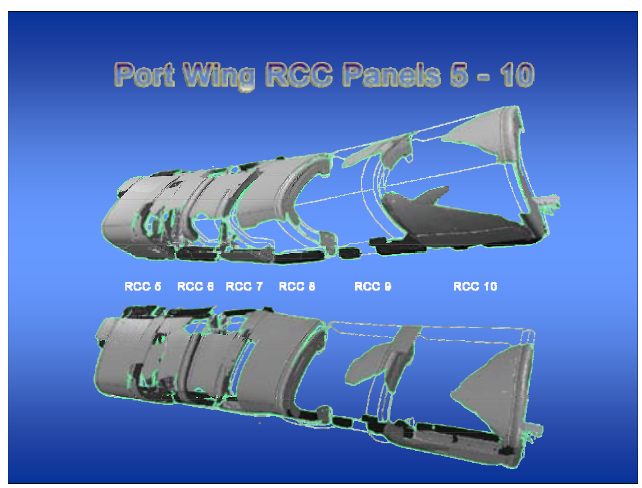

Port Wing RCC Panels 5 - 10
RCC 5
RCC 6
RCC 7
RCC 8
RCC 9
RCC 10

The NASA Glenn Ballistic Impact Lab

The NASA Glenn Ballistic Impact Lab

Small Vacuum Gun

The NASA Glenn Ballistic Impact Lab

Large Vacuum Gun

The NASA Glenn Ballistic Impact Lab

Particle Vacuum Gun

BX-250 External Tank Foam Characterization

Ballistic Research Supporting the Accident Investigation

BX-250 External Tank Foam Characterization

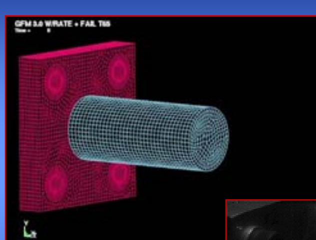
High Speed Video of 90 Degree Impacts

No Vacuum
708 ft/sec

Vacuum
693 ft/sec

Ballistic Research Supporting the Accident Investigation

Dyna - explicit finite element impact analysis

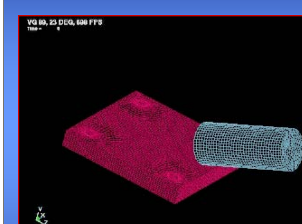


Dyna Predicts 90 Degree Foam Impact on Load Cell

Dyna is an industry standard commercial finite element analysis code typically used to model impact events

Ballistic Research Supporting the Accident Investigation

Dyna - explicit finite element impact analysis

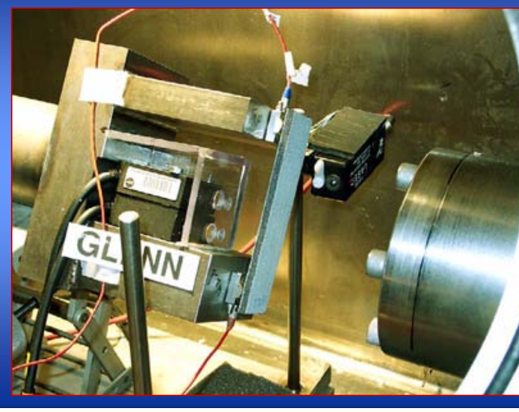


Dyna Predicts 23 Degree Foam Impact on Load Cell

Reinforced Carbon-Carbon Characterization

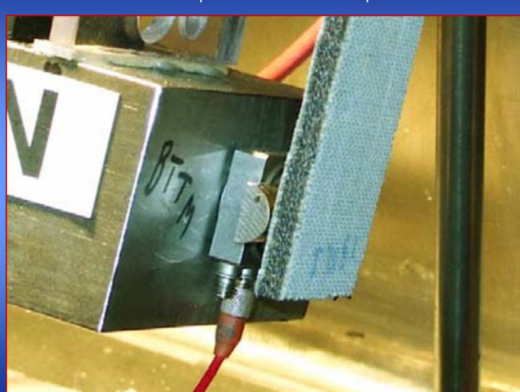
Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons

RCC Coupon Shows No Damage After 397 ft/sec Foam Impact

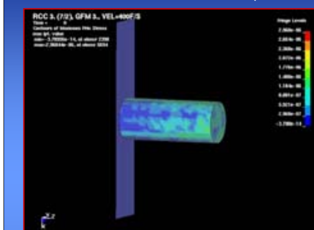
Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons

Foam Fractures RCC coupon in half at 695 ft/sec

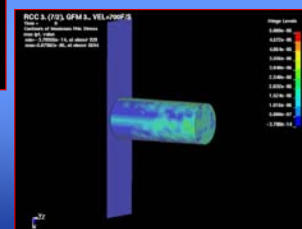
Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



400 ft/second Impact

700 ft/second Impact



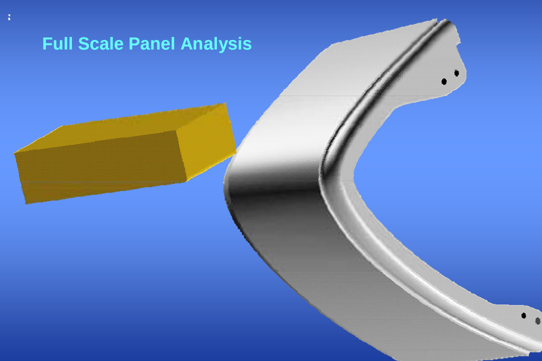
Current RCC Model Predicts these tests well

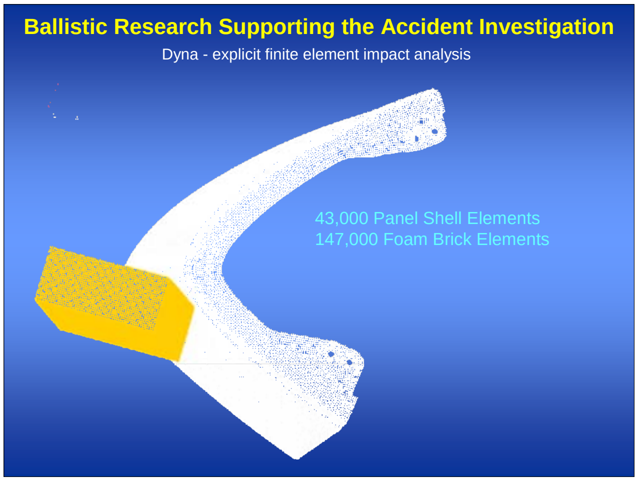
Full Scale Impact Analysis with LS Dyna

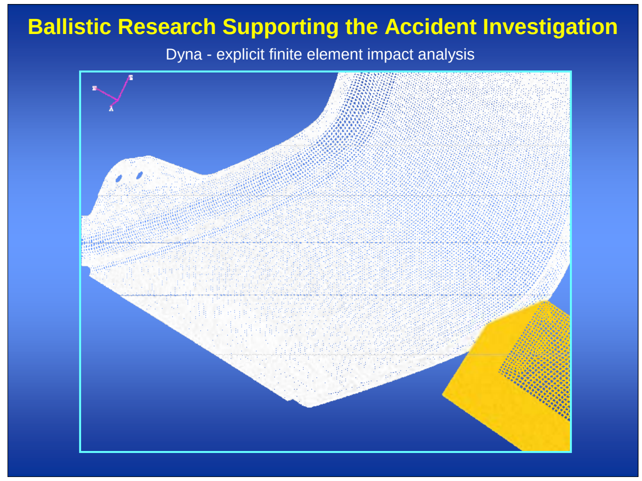
Ballistic Research Supporting the Accident Investigation

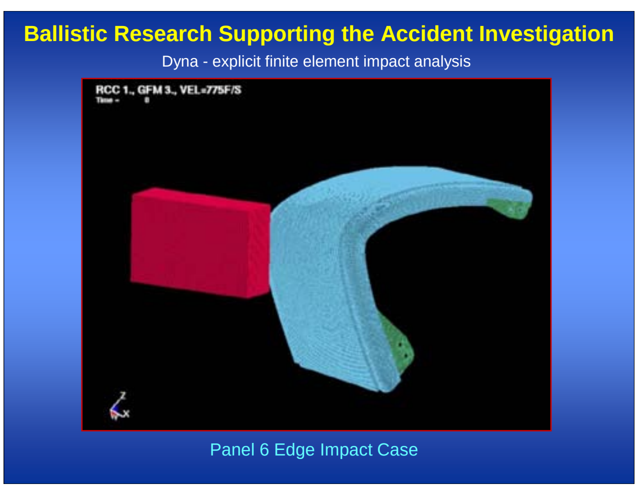
Dyna - explicit finite element impact analysis

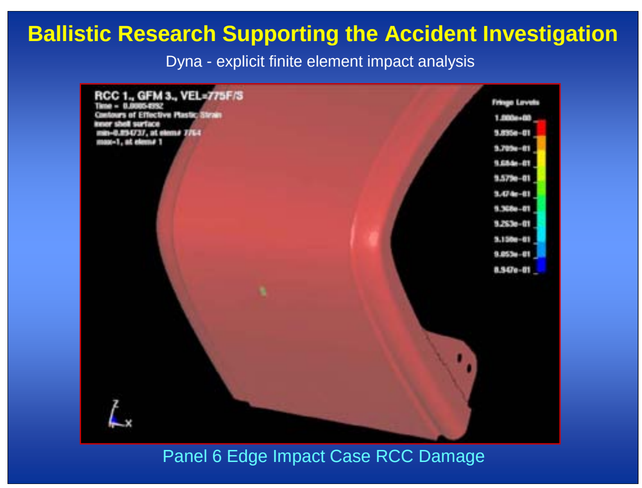
Full Scale Panel Analysis




Ballistic Research Supporting the Accident Investigation
Dyna - explicit finite element impact analysis
43,000 Panel Shell Elements
147,000 Foam Brick Elements


Ballistic Research Supporting the Accident Investigation
Dyna - explicit finite element impact analysis


Ballistic Research Supporting the Accident Investigation
Dyna - explicit finite element impact analysis
RCC 1., GFM 3., VEL=775F/S
Panel 6 Edge Impact Case


Ballistic Research Supporting the Accident Investigation
Dyna - explicit finite element impact analysis
RCC 1., GFM 3., VEL=775F/S
Panel 6 Edge Impact Case RCC Damage

Orbiter Leading Edge Full Scale Tests

Tests conducted at Southwest Research Institute

Orbiter Leading Edge Full Scale Tests

Orbiter Leading Edge Full Scale Tests

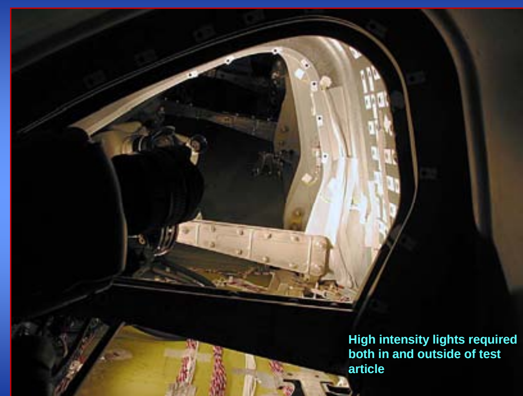
Installation of internal high speed cameras

Orbiter Leading Edge Full Scale Tests

Leading edge panels mounted after camera installation

Orbiter Leading Edge Full Scale Tests

Orbiter Leading Edge Full Scale Tests



Orbiter Leading Edge Full Scale Tests

Orbiter Leading Edge Full Scale Tests

External View of RCC Panel 8 Test

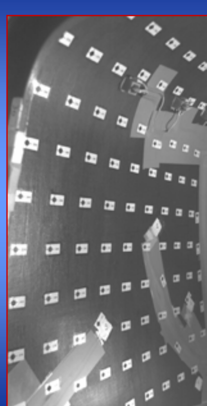
Orbiter Leading Edge Full Scale Tests

Barrel View of RCC Panel 8 Test

Orbiter Leading Edge Full Scale Tests

External View of RCC Panel 8 Test

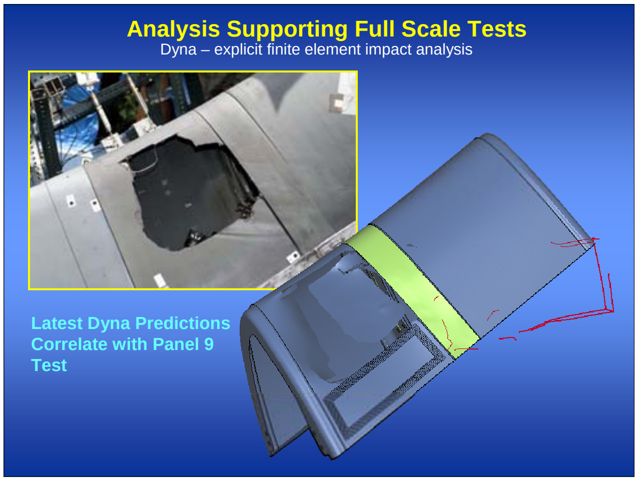
Orbiter Leading Edge Full Scale Tests

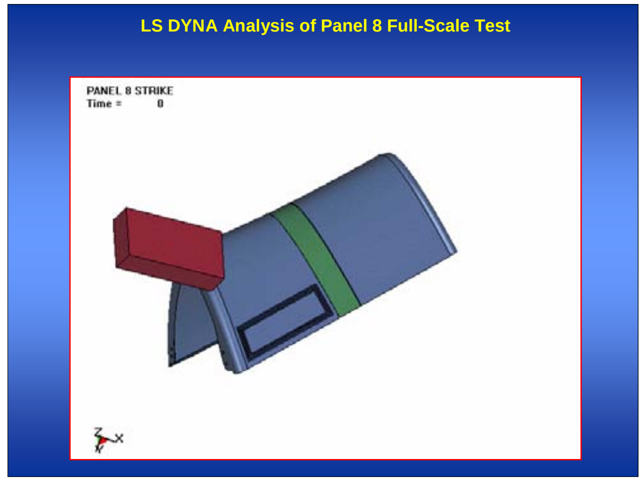


Internal View of RCC Panel 8 Test

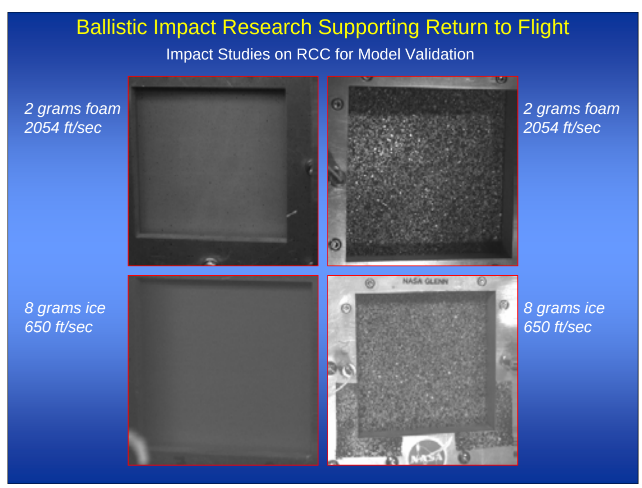
Orbiter Leading Edge Full Scale Tests

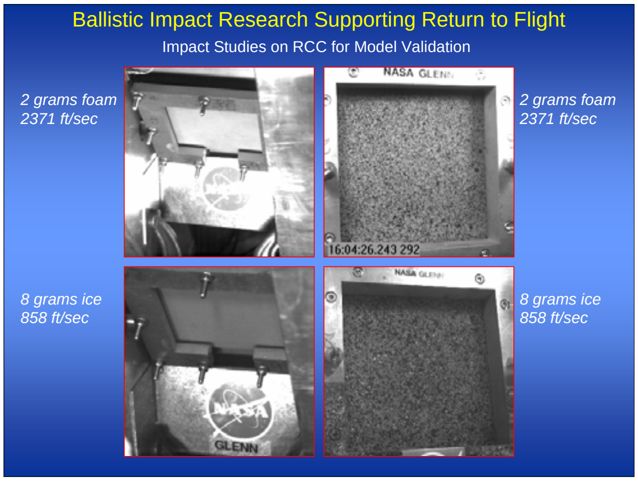
Post Impact of Panel 8


Analysis Supporting Full Scale Tests
Dyna – explicit finite element impact analysis
Latest Dyna Predictions Correlate with Panel 9 Test

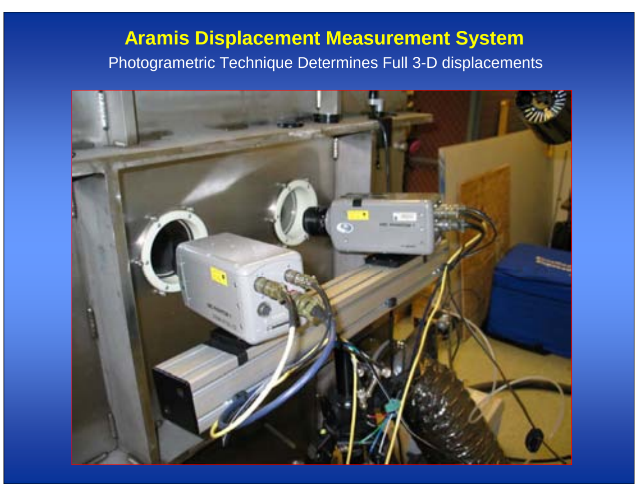

LS DYNA Analysis of Panel 8 Full-Scale Test
PANEL 8 STRIKE
Time = 0

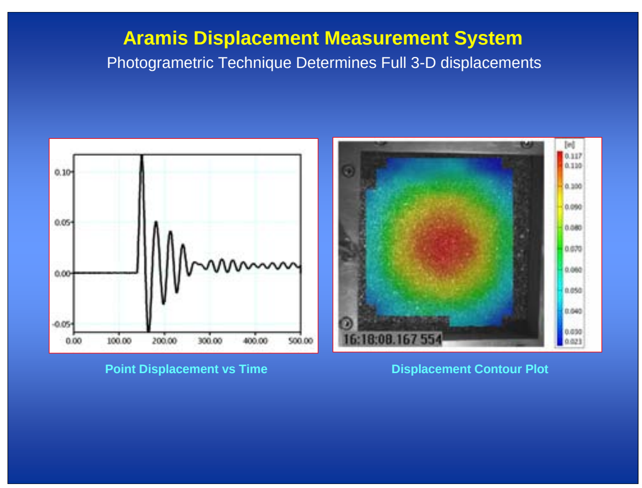

Return to Flight


Ballistic Impact Research Supporting Return to Flight
Impact Studies on RCC for Model Validation
2 grams foam 2054 ft/sec
2 grams foam 2054 ft/sec
8 grams ice 650 ft/sec
8 grams ice 650 ft/sec


Ballistic Impact Research Supporting Return to Flight
Impact Studies on RCC for Model Validation
2 grams foam
2371 ft/sec
2 grams foam
2371 ft/sec
16:04:26.243 292
8 grams ice
858 ft/sec
8 grams ice
858 ft/sec
GLENN

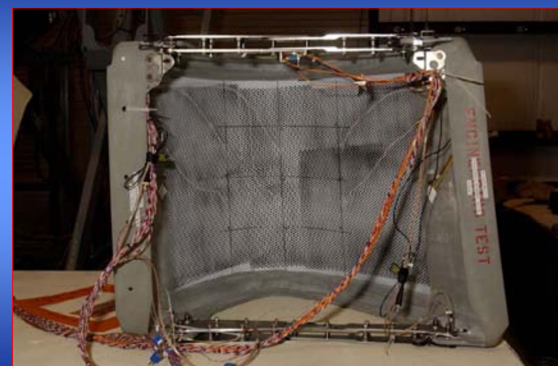

Ballistic Impact Research Supporting Return to Flight
Impact Studies on RCC for Model Validation
15:12:10.174 055 S


Aramis Displacement Measurement System
Photogrametric Technique Determines Full 3-D displacements

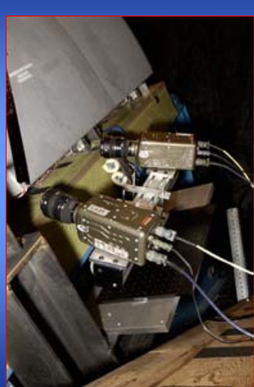

Aramis Displacement Measurement System
Photogrametric Technique Determines Full 3-D displacements
16:18:08.167 554
Point Displacement vs Time
Displacement Contour Plot

Aramis Adapted to Full-Scale Wing Leading Edge Tests

Aramis Adapted to Full-Scale Wing Leading Edge Tests

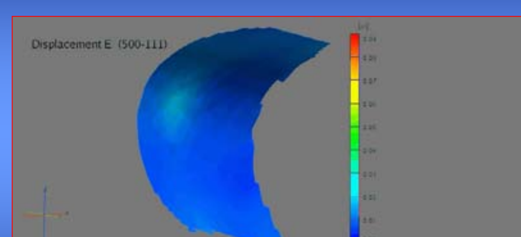


Full-Scale Leading Edge Test Setup with Aramis at SwRI



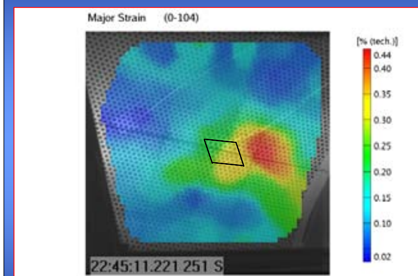
Aramis Data Validates LS DYNA Analysis Predictions

Full Field Displacements of Wing Leading Edge Impact Test



Aramis Data Validates LS DYNA Analysis Predictions

Principle Strain Comparison to Bonded Gauges



Aramis Indicated 2100-2700 Microstrain

Gauge Indicated 2100 Microstrain

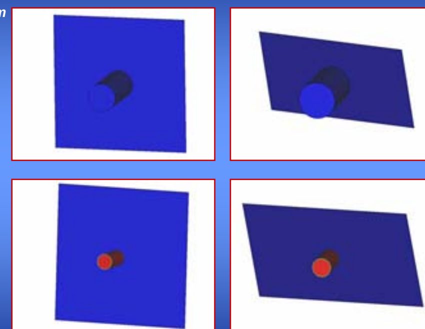
Note Much Higher Amplitude 2" From Gauge

Ballistic Impact Research Supporting Return to Flight

Impact Studies on RCC for Model Validation

2 grams foam 2054 ft/sec

2 grams foam 2371 ft/sec

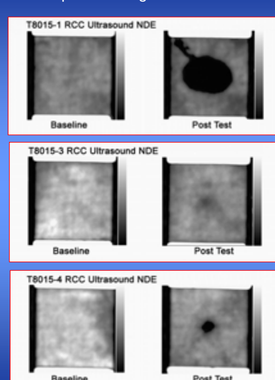


8 grams ice 650 ft/sec

8 grams ice 858 ft/sec

Ballistic Impact Research Supporting Return to Flight

NDE Performed Pre and Post Impact Testing



Ballistic Impact Research Supporting Return to Flight

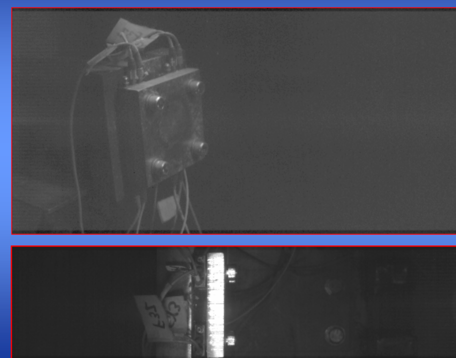
Post Impact Specimens Tested in JSC Arcjet

Efforts Supporting the Return to Flight

RT 455 ablator impact at approximately 300 ft/sec

Efforts Supporting the Return to Flight

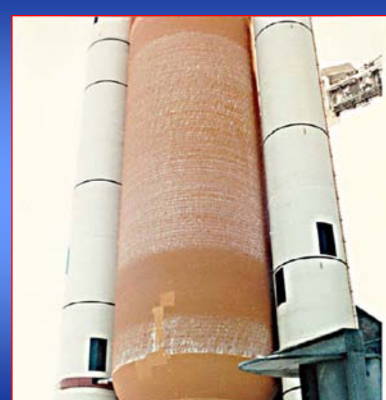
NCFI foam impact at approximately 800 ft/sec



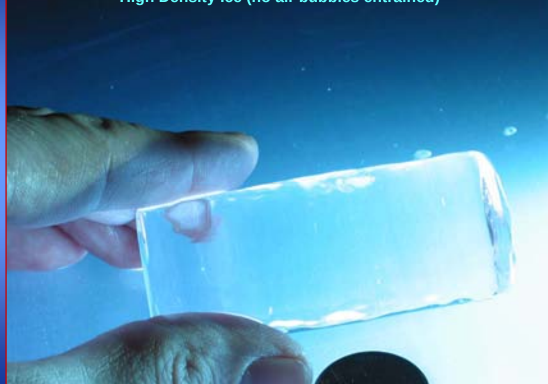
Efforts Supporting the Return to Flight

Tile Gap Filler Material Impact Testing

Ice Formations on External Tank

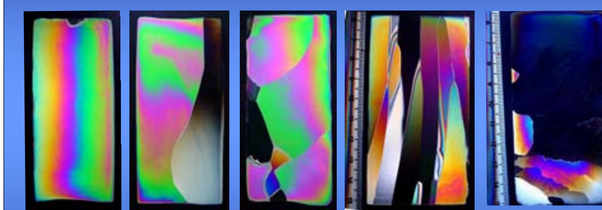


Ice Research Supporting the Return to Flight


High Density Ice (no air bubbles entrained)

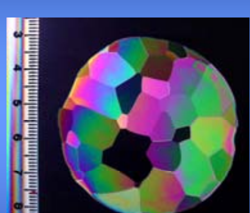
Ice Research Supporting the Return to Flight

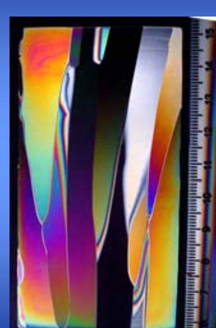
Identification of Ice Microstructure



Ice Research Supporting the Return to Flight

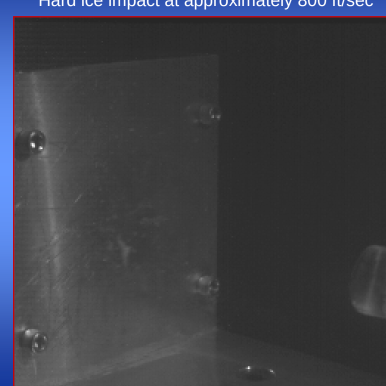
Identification of Ice Microstructure


Transverse thin section


Longitudinal thin section

Impact Testing of Ice

Hard ice impact at approximately 800 ft/sec

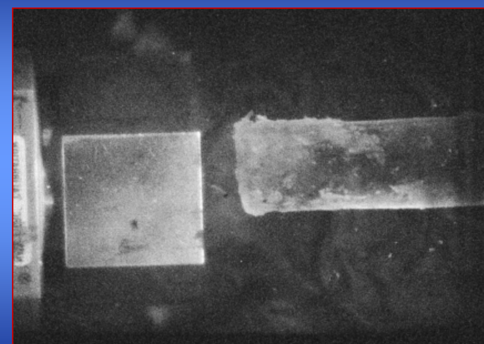


Hadland Camera Captures Fracture Wave Propagation

700 ft per second ice impact 280,000 frames per second

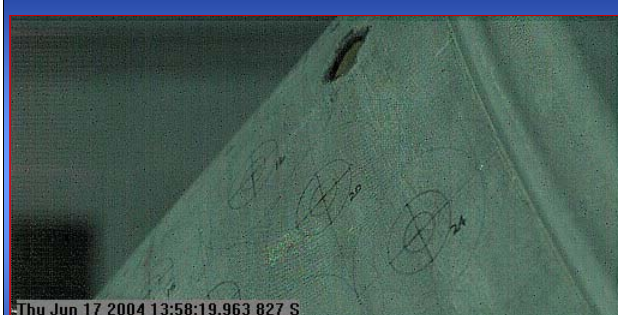
Cordin Camera Captures Fracture Wave Propagation

600 ft per second ice impact at 480,000 frames per second



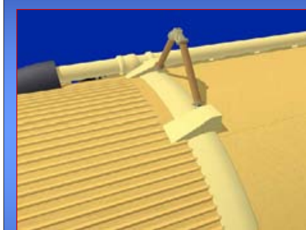
Panel 17R Ice Impact Tests at SwRI

Panel 17R Ice Impact Tests at SwRI

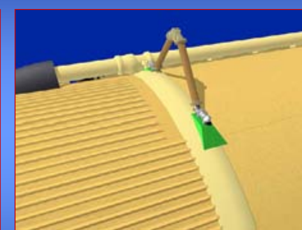


External Tank Impact Testing

Redesign of the External Tank Bipod Ramp



Old Design



New Design

Ballistic Impact Research Supporting Return to Flight

External Tank Impact Test Article with Acreage Foam

Efforts Supporting the Return to Flight

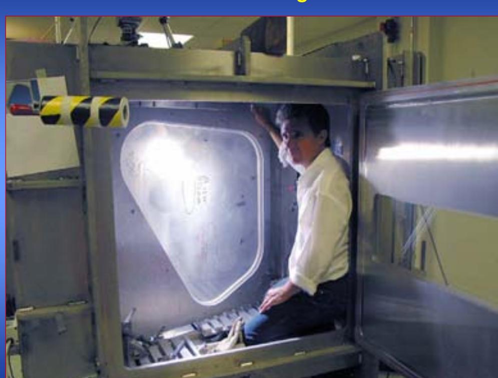
External Tank Foam on Foam Impact Testing

Ballistic Impact Research Supporting Return to Flight

BX-265 Foam Impact on External Tank Intertank Panel

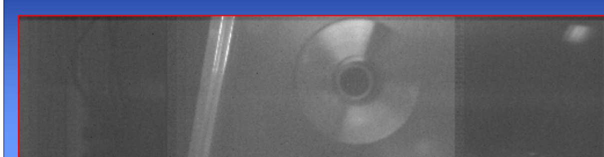
Orbiter Windows Impact Testing

Orbiter Windows Testing at NASA GRC

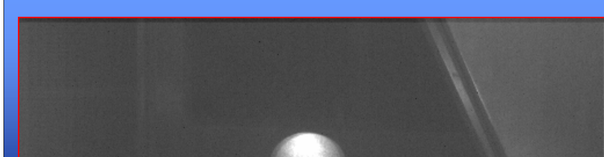


Ballistic Impact Research Supporting Return to Flight

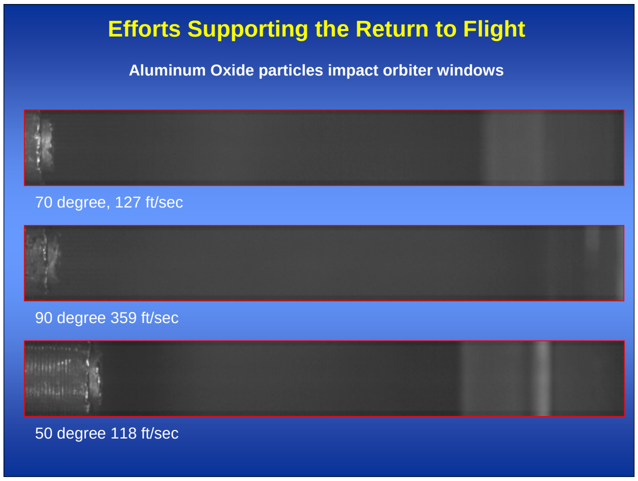
NCFI Foam Impact Test on Orbiter Window



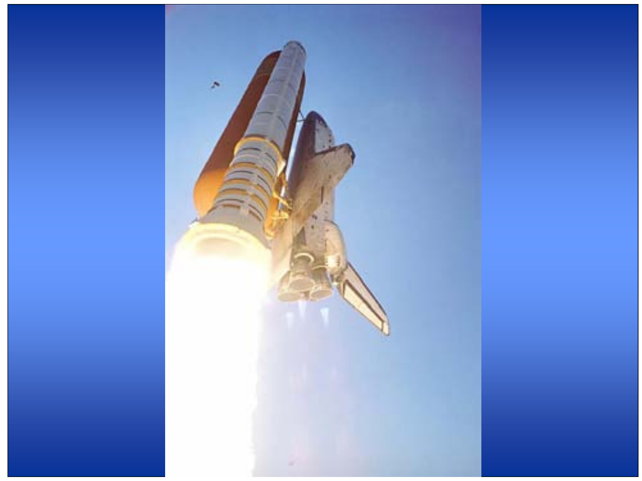
Rear View

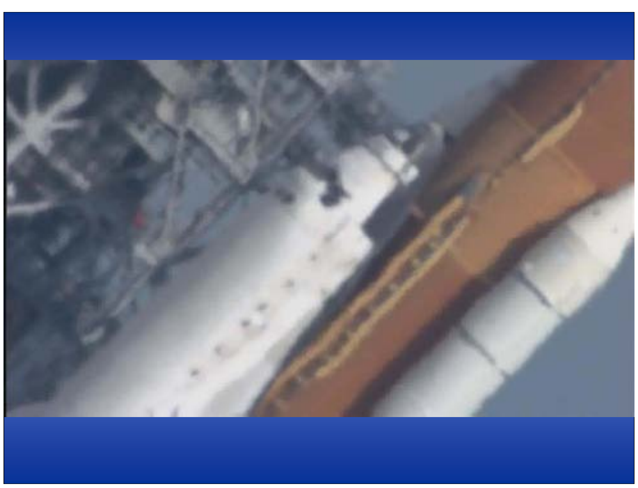


Side View

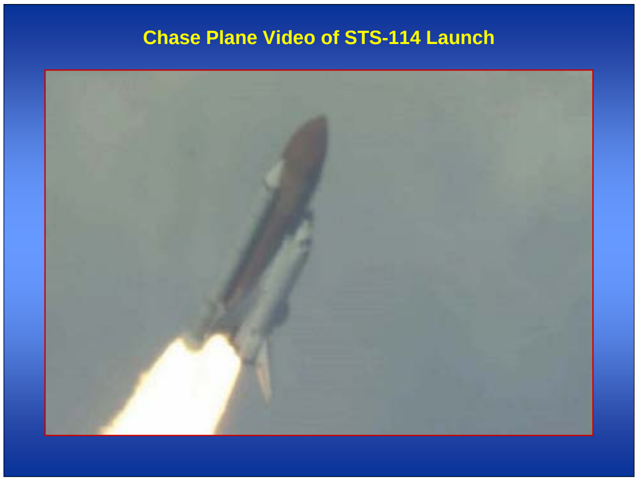

Efforts Supporting the Return to Flight
Aluminum Oxide particles impact orbiter windows
70 degree, 127 ft/sec
90 degree 359 ft/sec
50 degree 118 ft/sec


July 26, 2005
Return to Flight
The most photographed mission

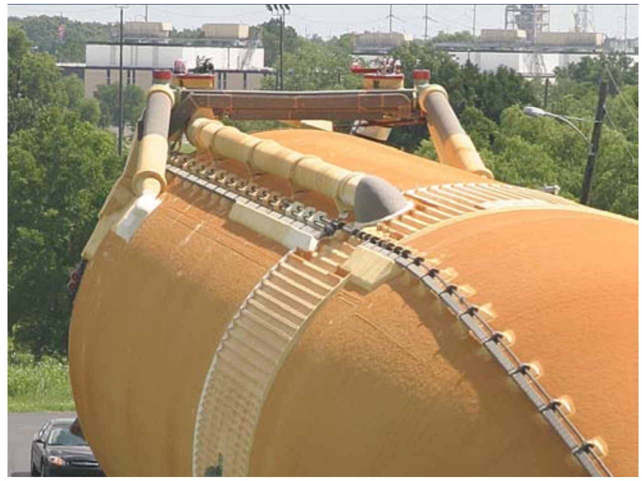




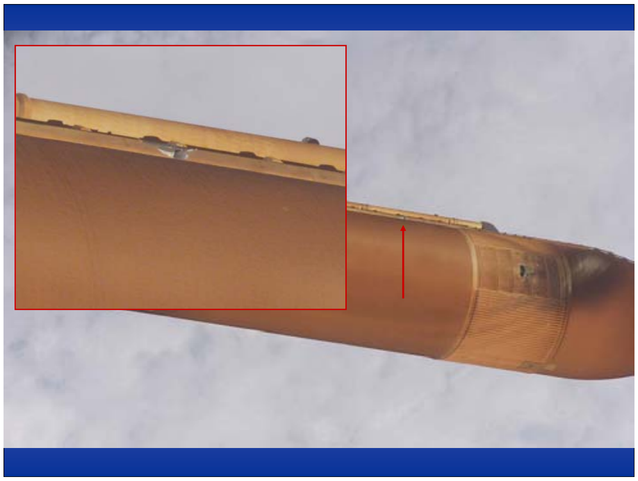

Forward and Aft SRB Cameras on STS-121


Chase Plane Video of STS-114 Launch

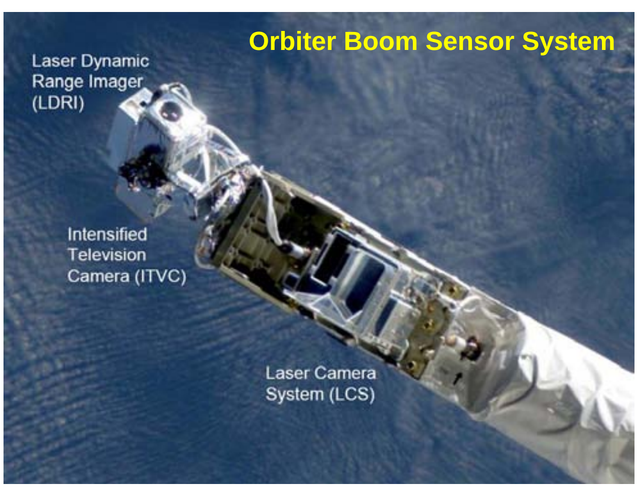

On-Board External Tank Camera

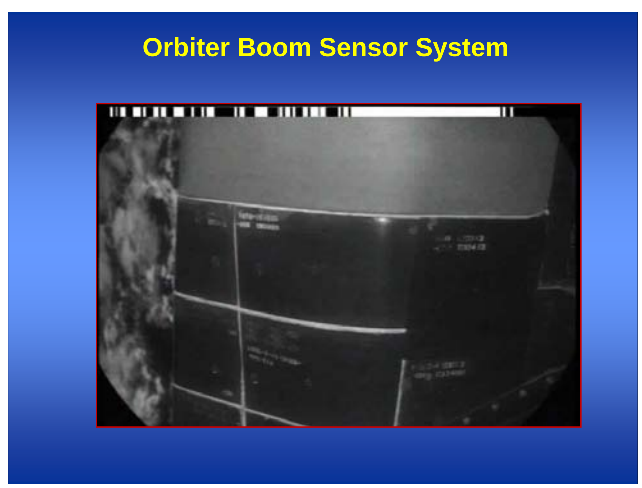


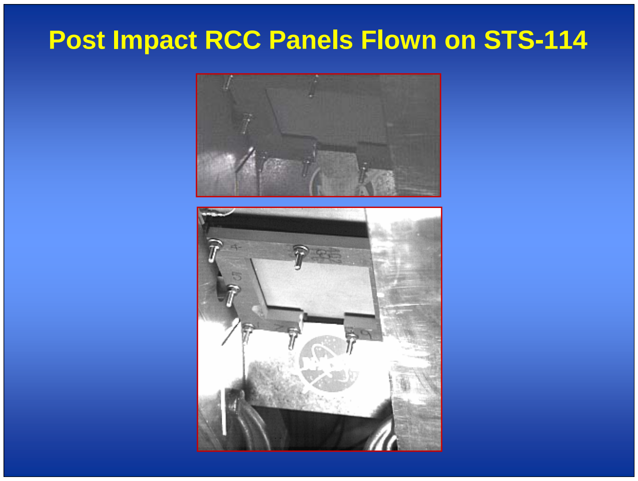

On-Board External Tank Camera
External Tank Separation
14:46:50:12

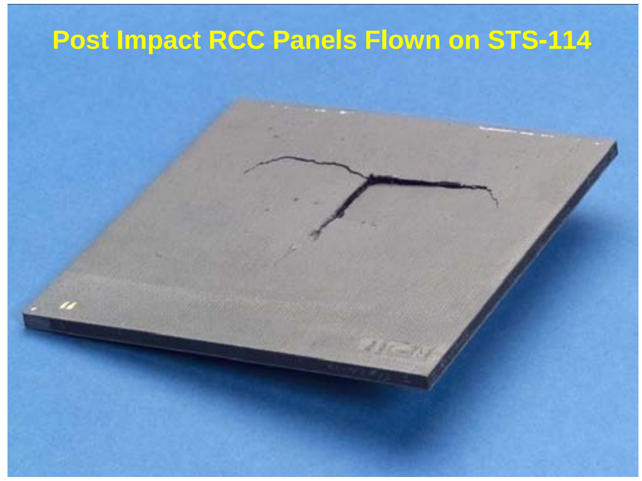


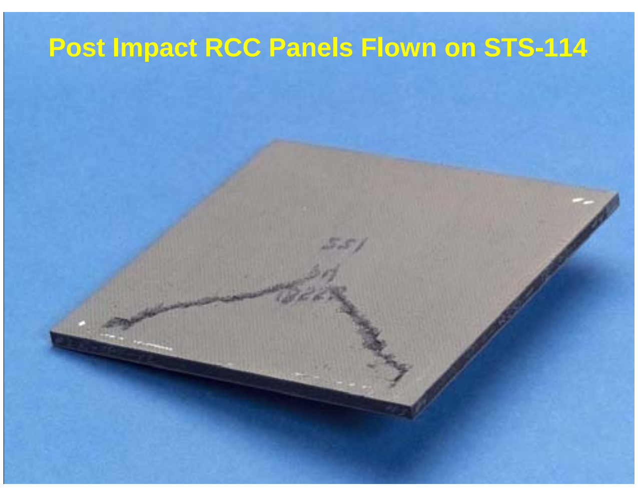

Rendezvous Pitch Manuver

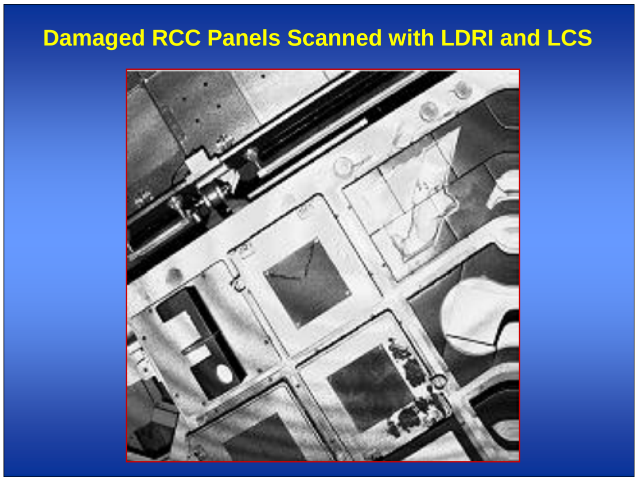

Orbiter Boom Sensor System
Laser Dynamic Range Imager (LDRI)
Intensified Television Camera (ITVC)
Laser Camera System (LCS)

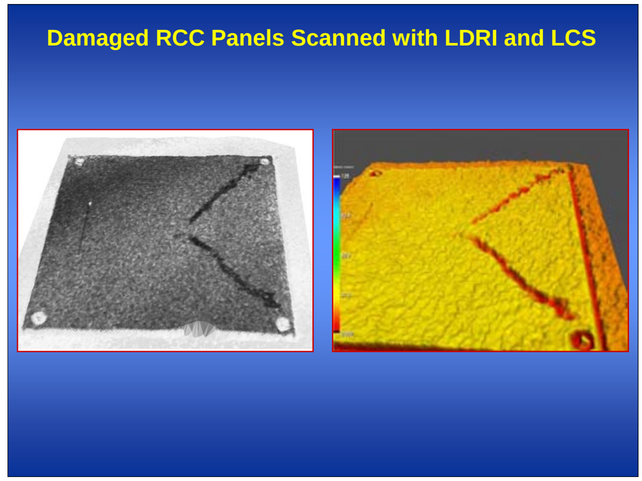

Orbiter Boom Sensor System

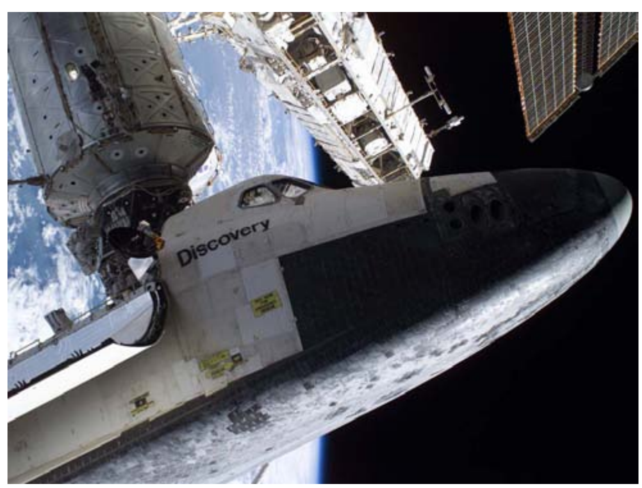

Post Impact RCC Panels Flown on STS-114


Post Impact RCC Panels Flown on STS-114


Post Impact RCC Panels Flown on STS-114


Damaged RCC Panels Scanned with LDRI and LCS

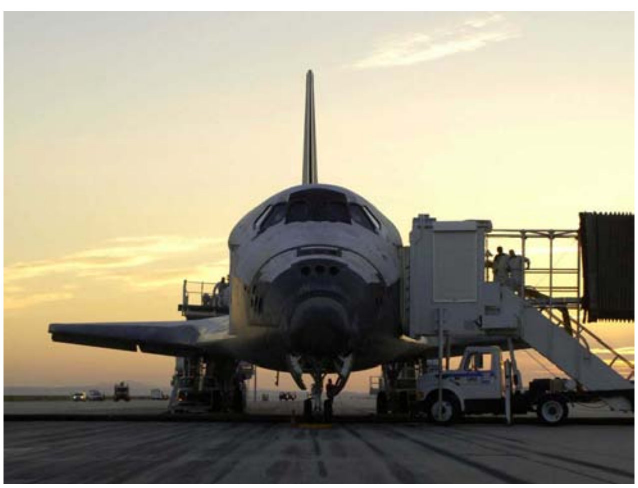

Damaged RCC Panels Scanned with LDRI and LCS


Discovery



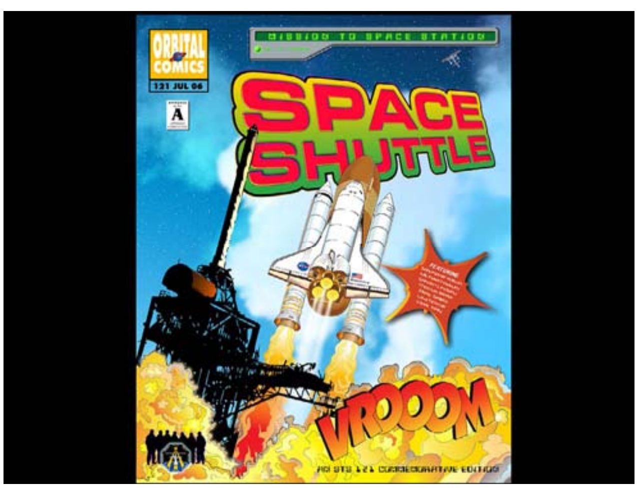

Not all work and No Play…

Discovery Returns




NASA


SILVER ANNIVERSARY
SPACE SHUTTLE
1981
2006
Serving the World for 25 Years


ORBITAL COMICS
121 JUL 06
A
MISSION TO SPACE STATION
SPACE SHUTTLE
VROOOM