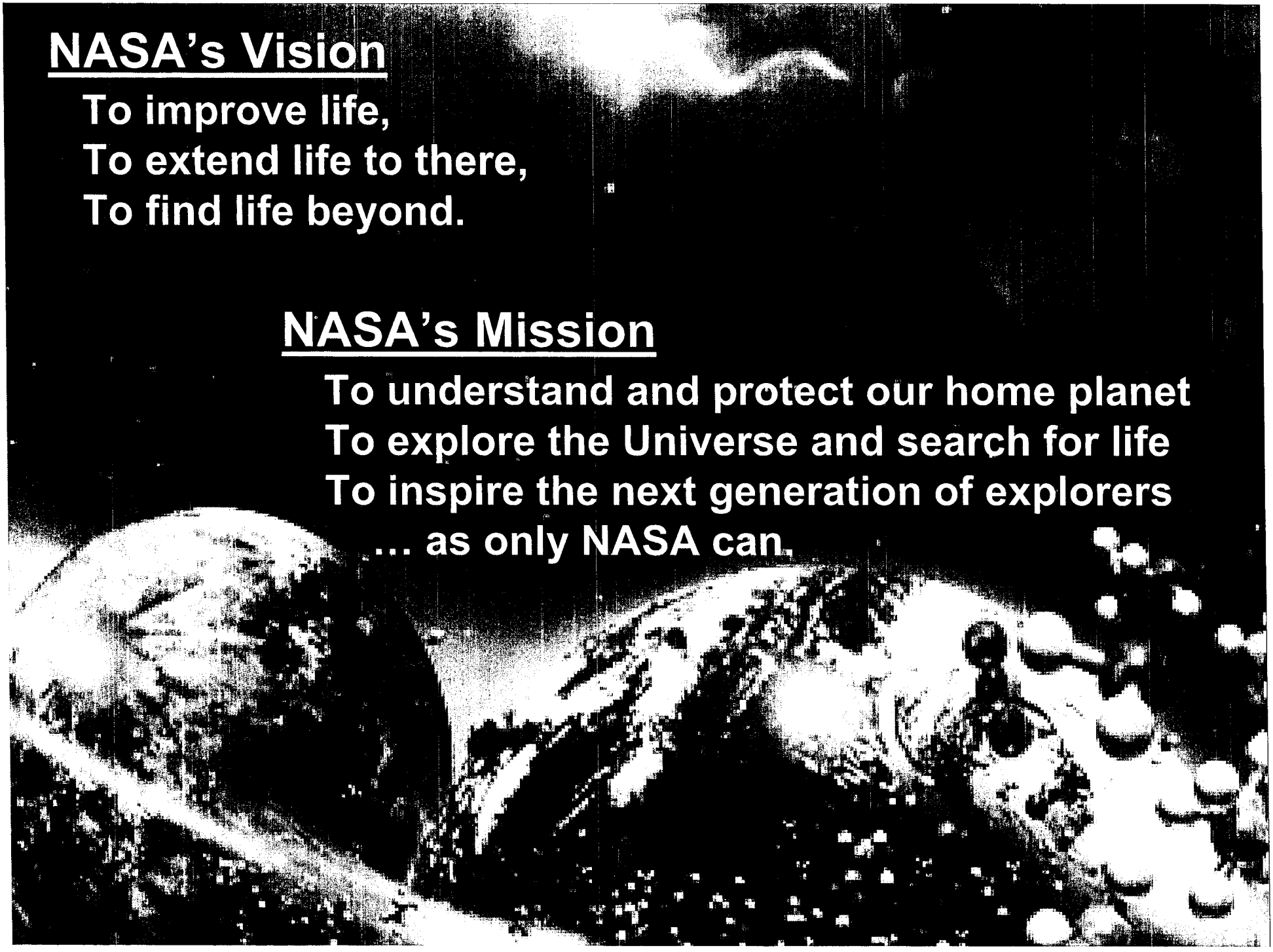
NASA Simulation Activities Supporting the Columbia Accident Investigation and Space Shuttle Return to Flight

Dr. Woodrow Whitlow, Jr.

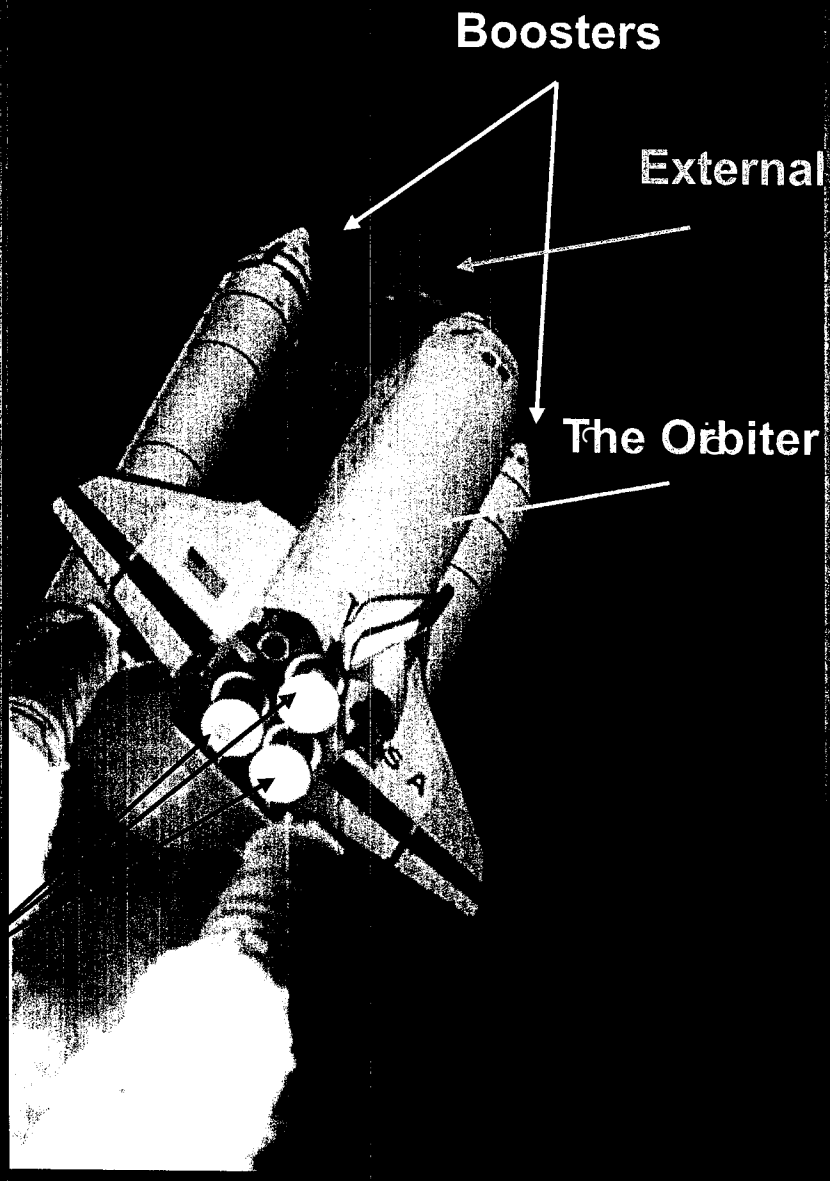
NASA Kennedy Space Center

June 28, 2004


NASA's Vision
To improve life,
To extend life to there,
To find life beyond.
NASA's Mission
To understand and protect our home planet
To explore the Universe and search for life
To inspire the next generation of explorers
... as only NASA can.

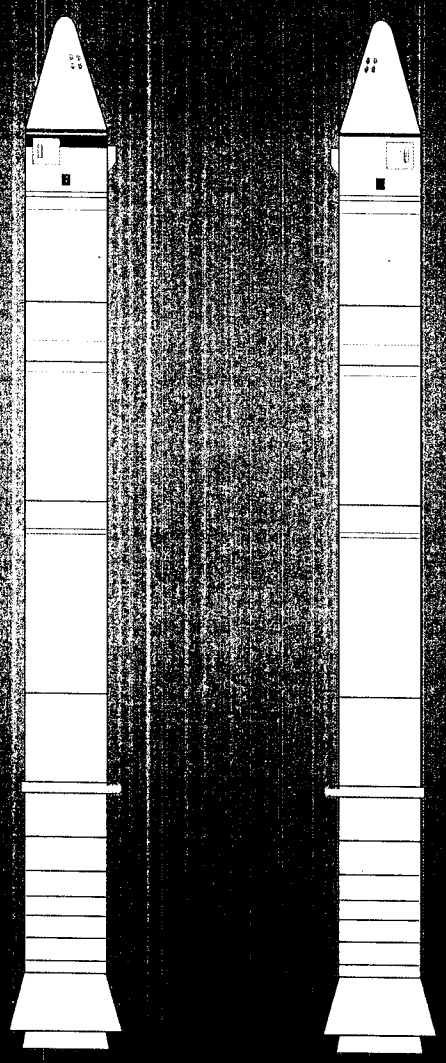

BROWN CLARK CHAWLA ANDERSON MASON
HUSBAND MCCOOL
STS 107

A Brief Overview of the Shuttle Launch System



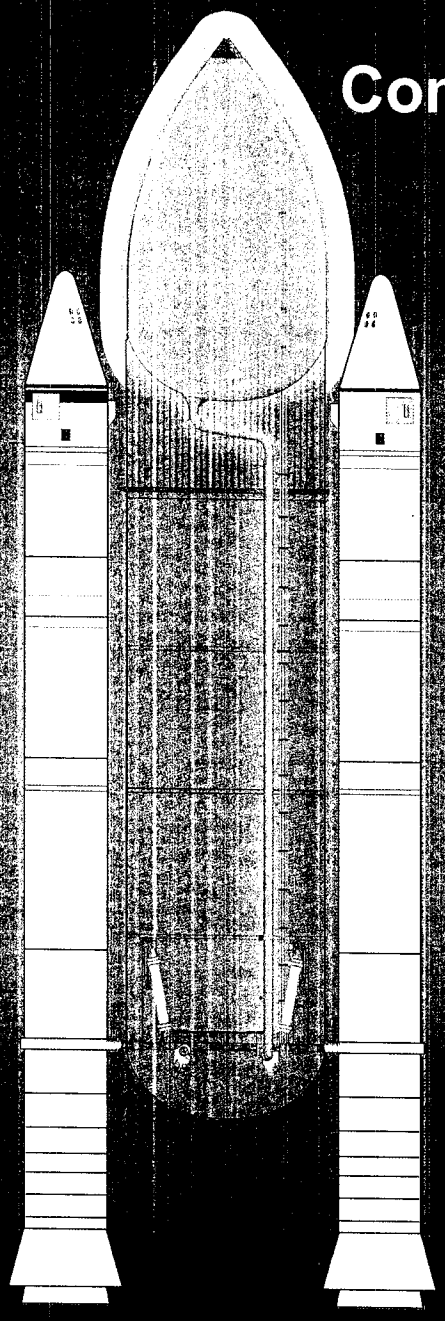
Space Shuttle
Main Engines

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



Components of the Launch Stack

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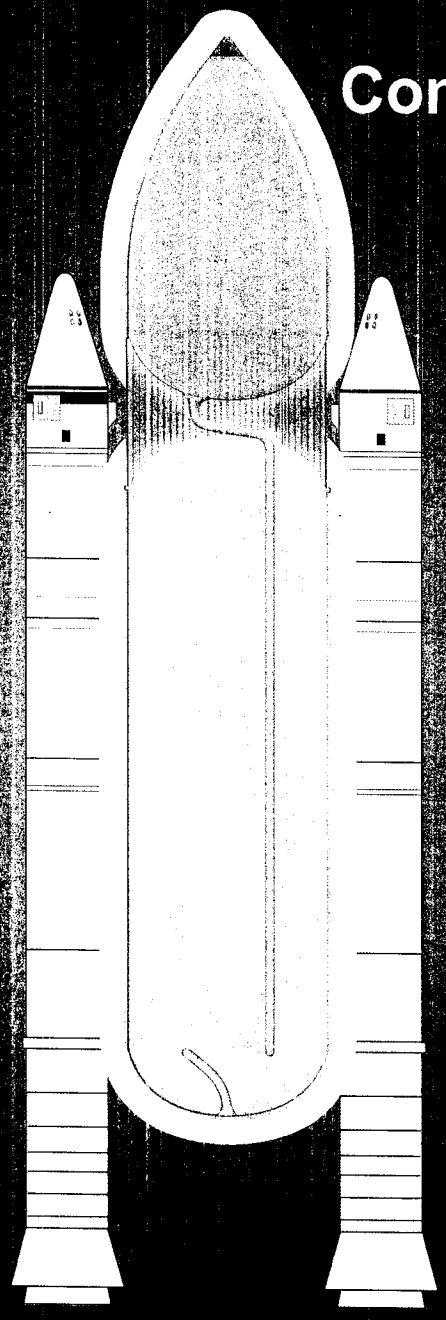
External Fuel Tank

- -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)

Components of the Launch Stack



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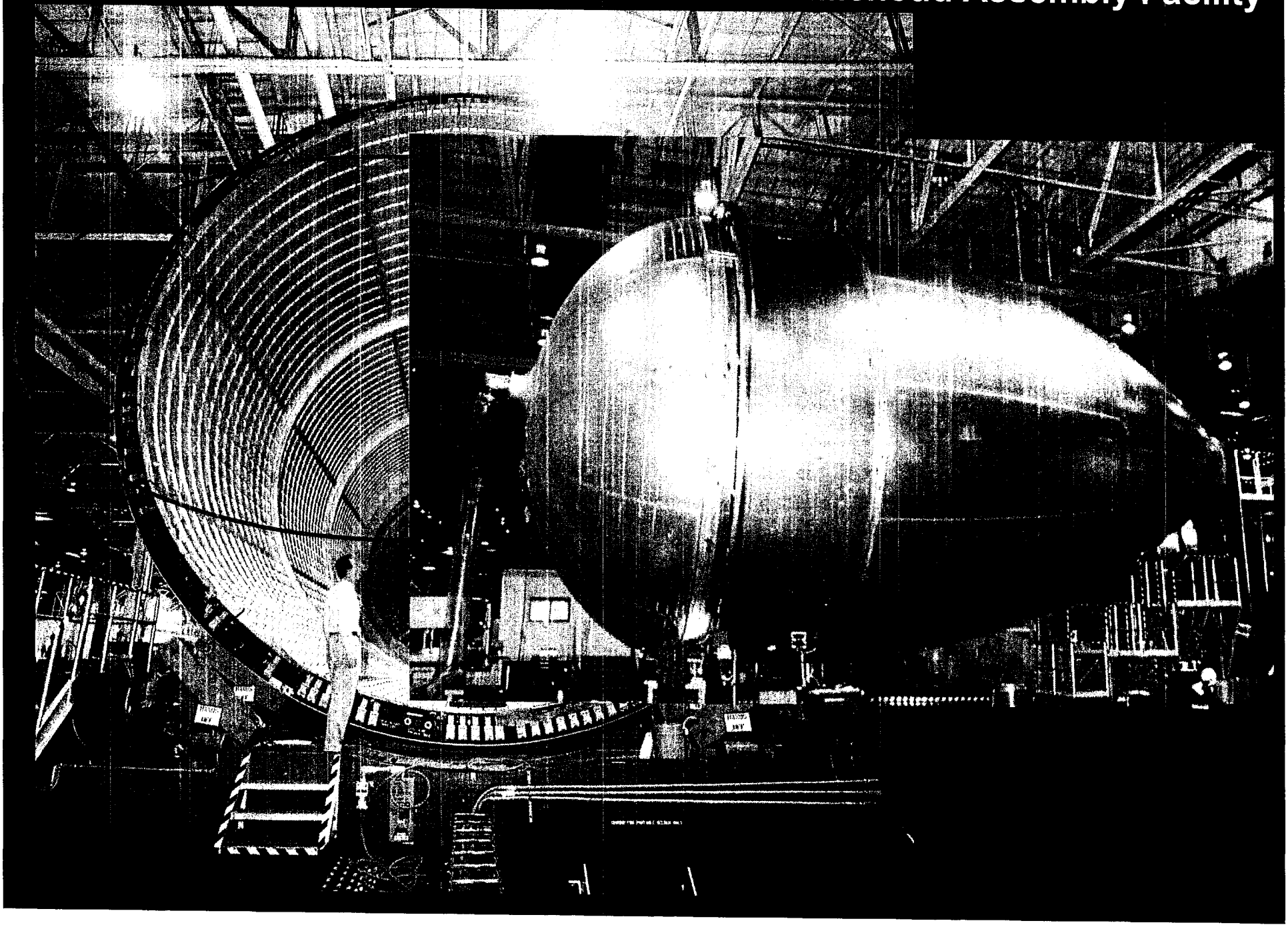
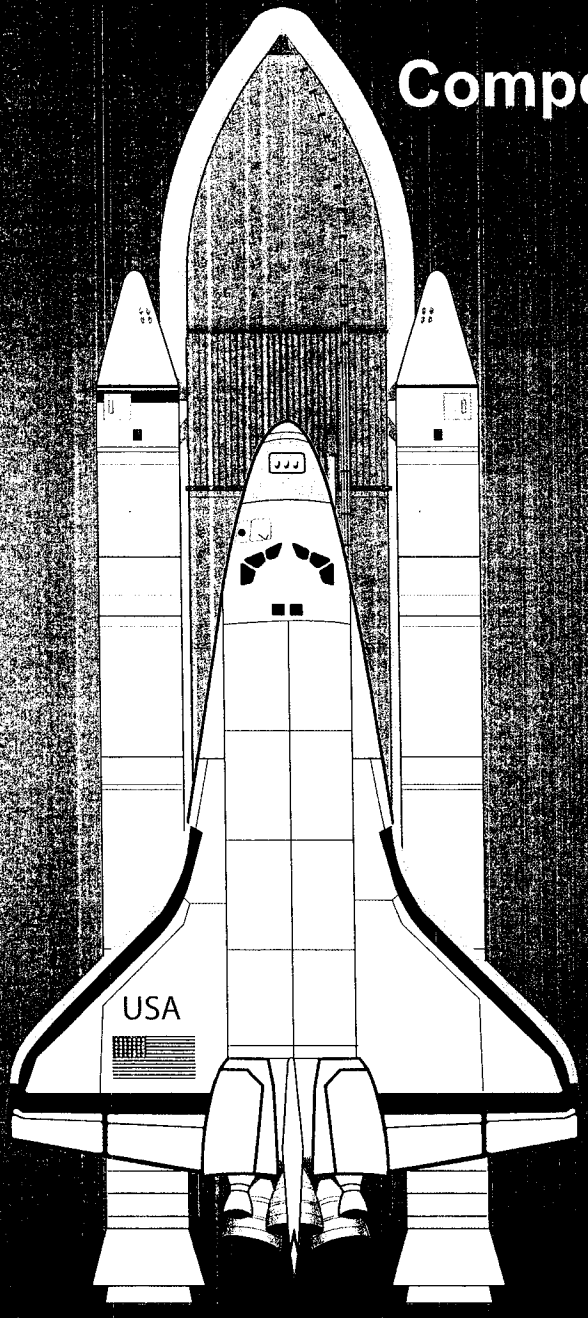
  - -Hydrogen Tank: 385,265 Gallons (238,000 pounds)

The External Tank is manufactured at NASA's Michoud Assembly Facility



Components of the Launch Stack



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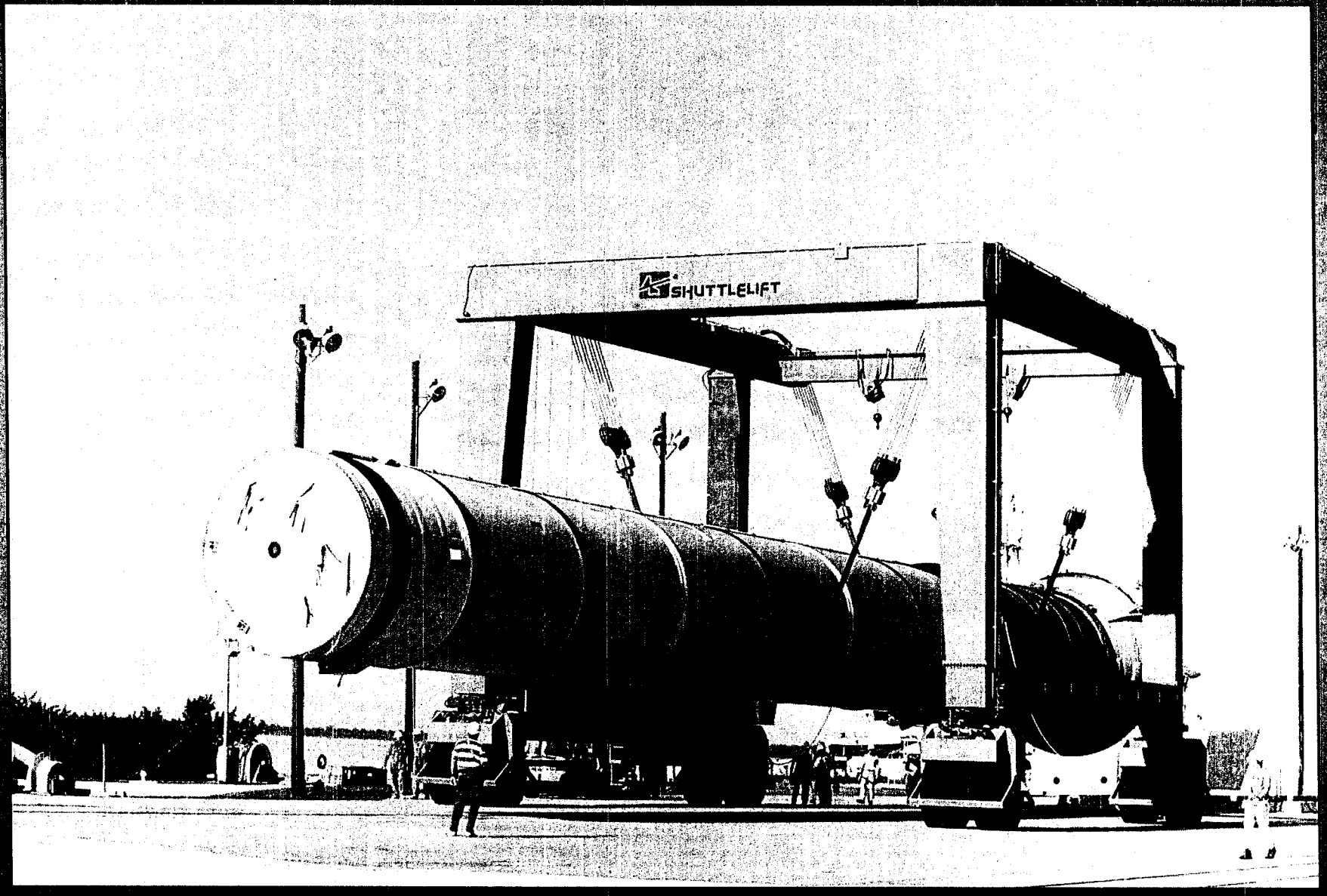
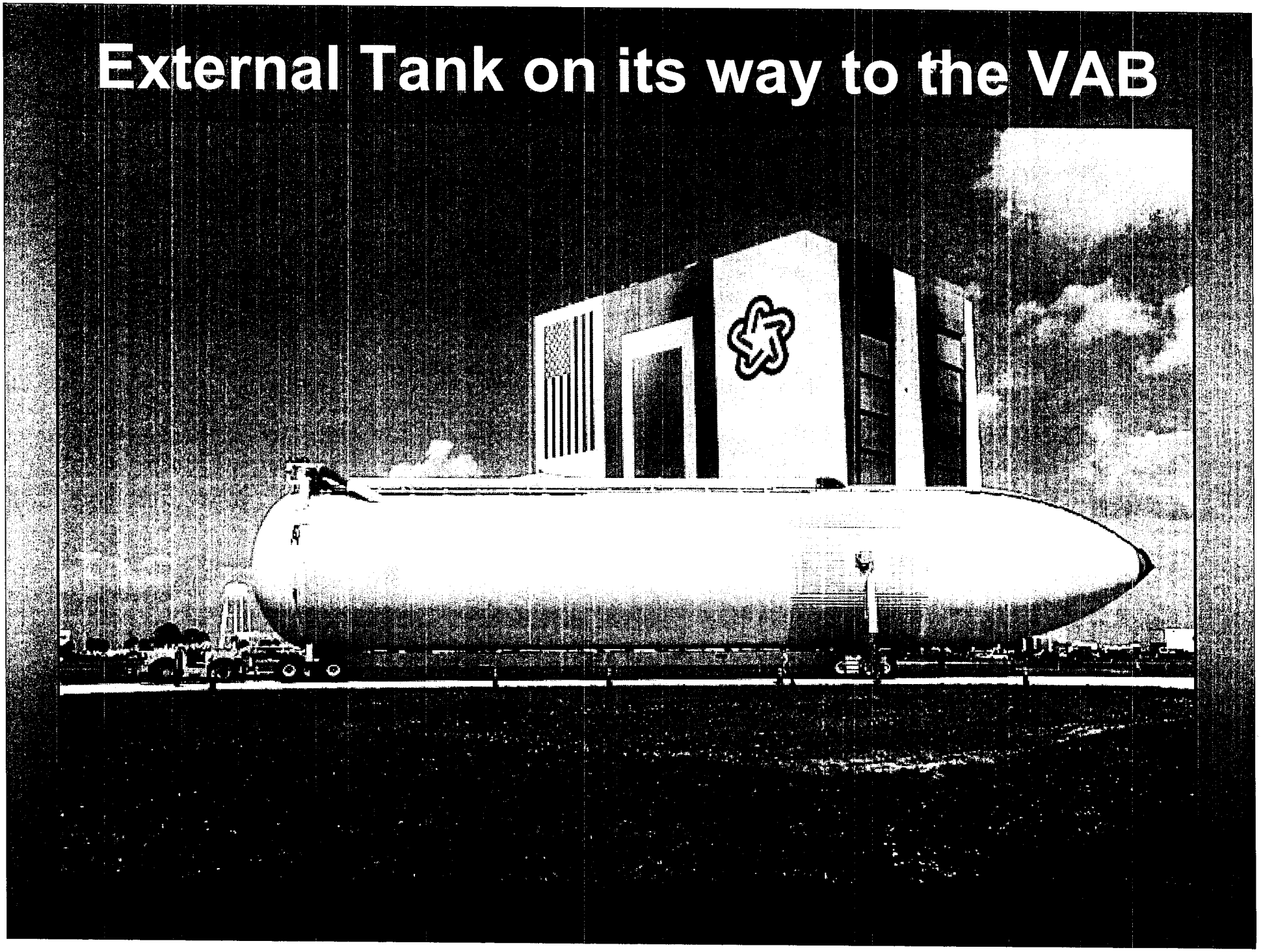
Orbiter

- -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

SRBs Are Recovered after Splashdown



External Tank on its way to the VAB

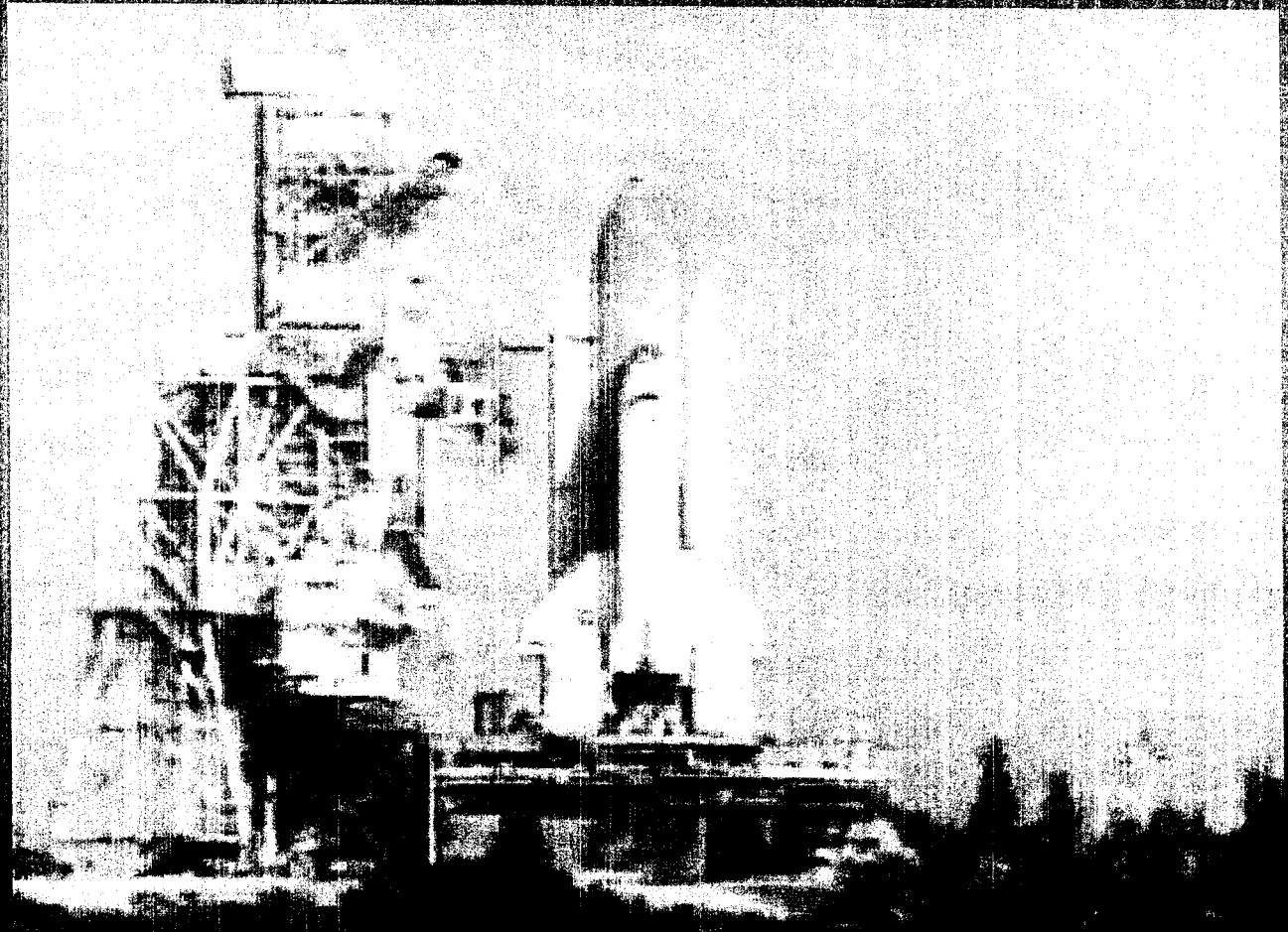



Orbiter Discovery
4
Discovery
United States

- 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

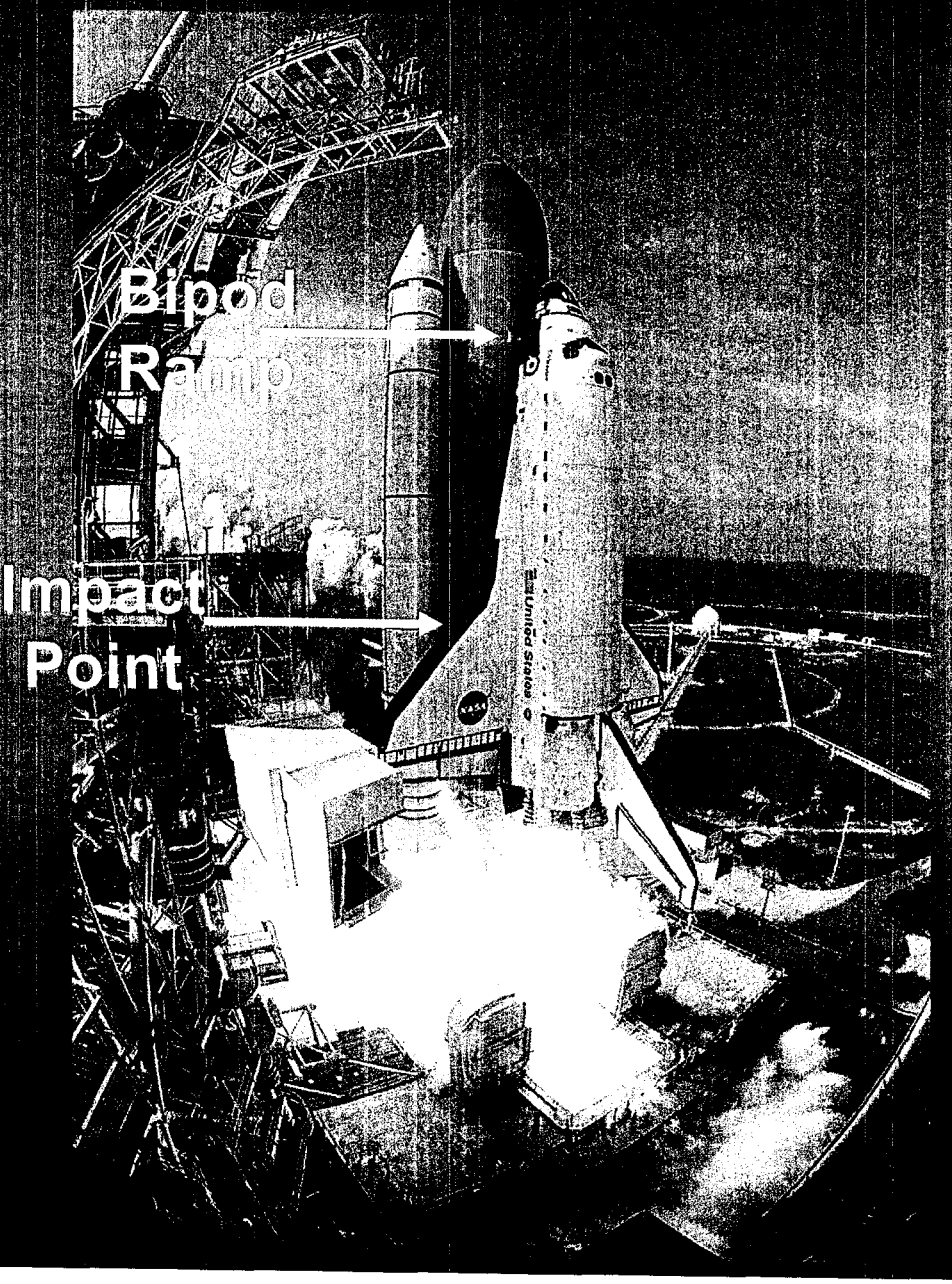
Columbia Launch, January 16, 2003



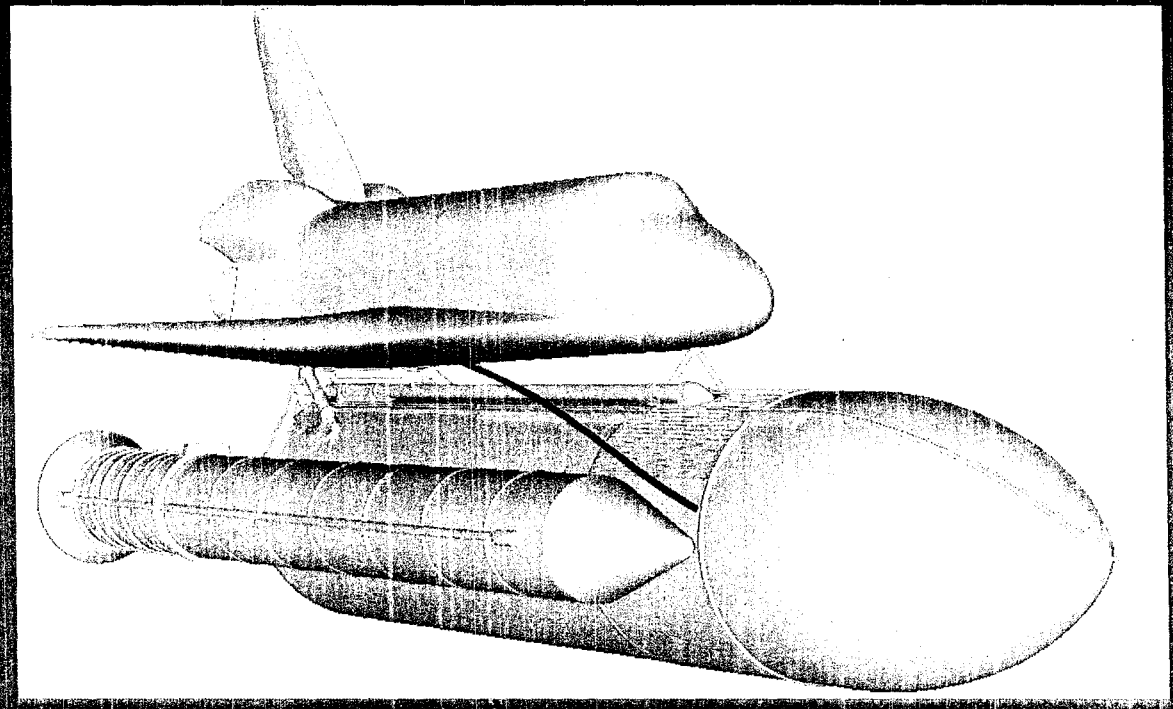
Insulating Foam Separates from Bipod Ramp and Impacts Left Wing of Columbia

Simulation of Aerodynamic Pressures

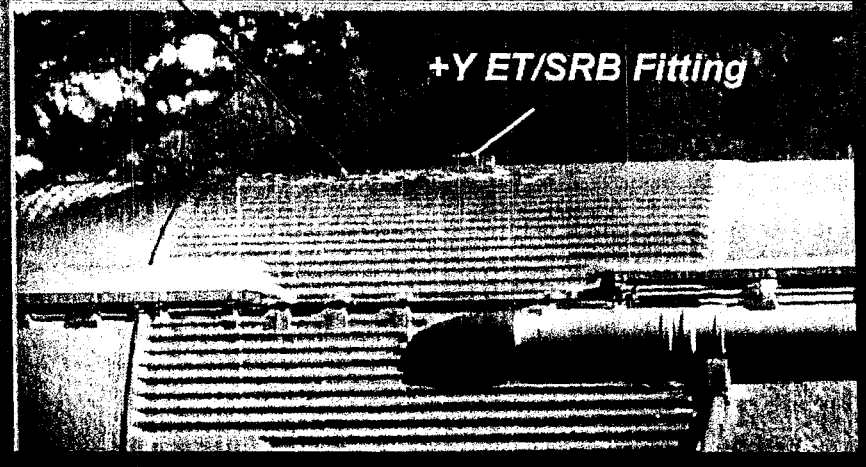
Launch of Space Shuttle



Impact Environment

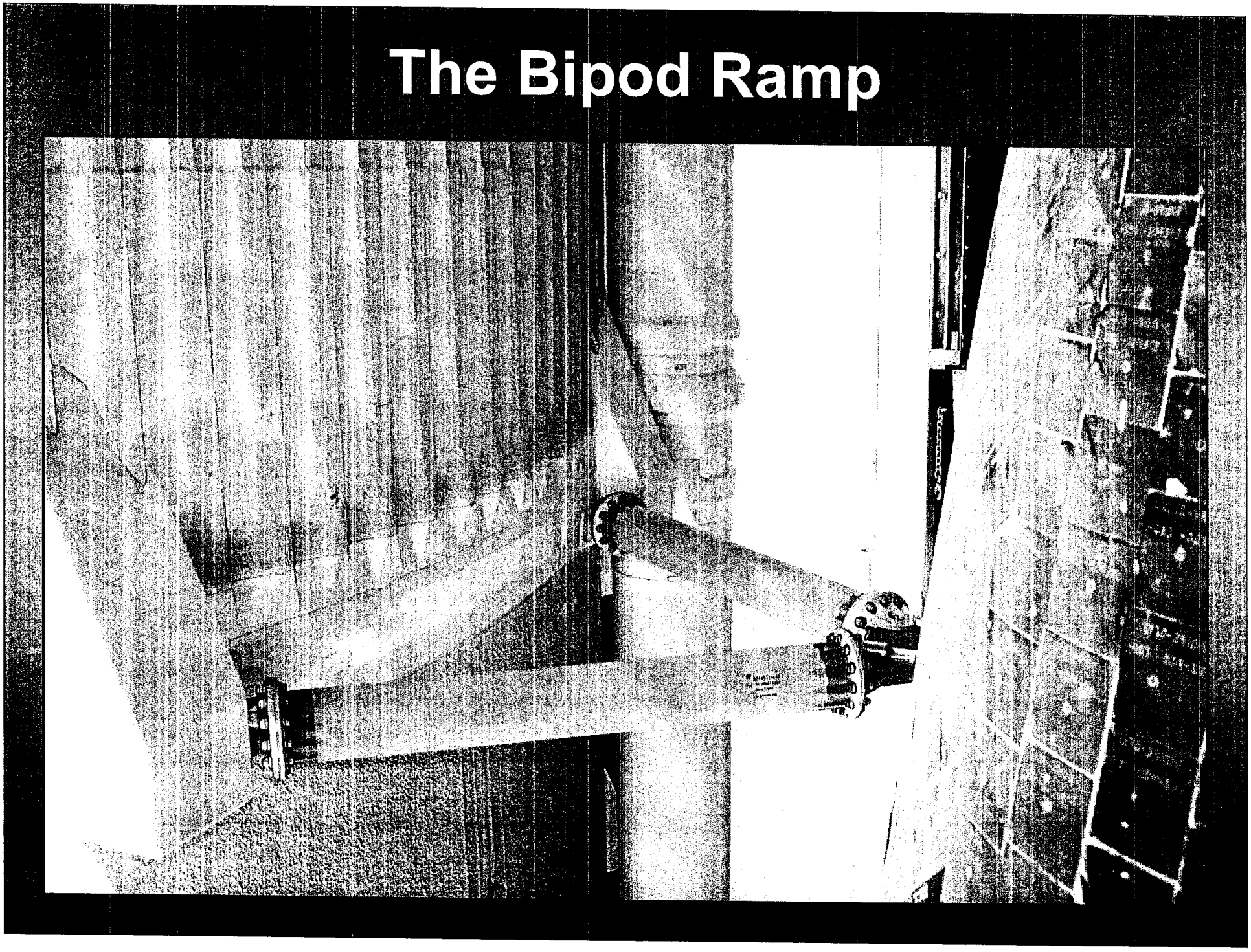


Debris Source

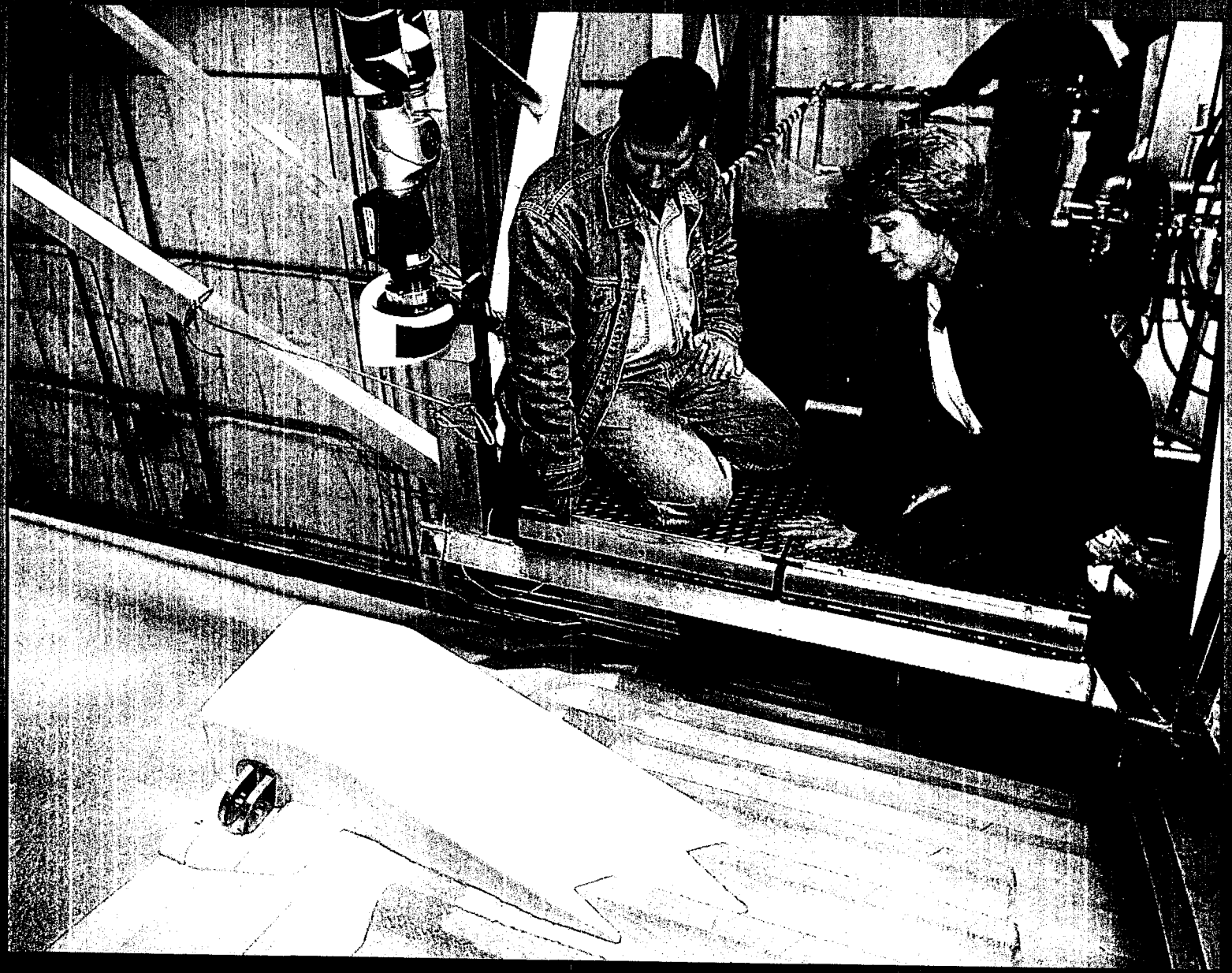


Damage Assessment

The Bipod Ramp

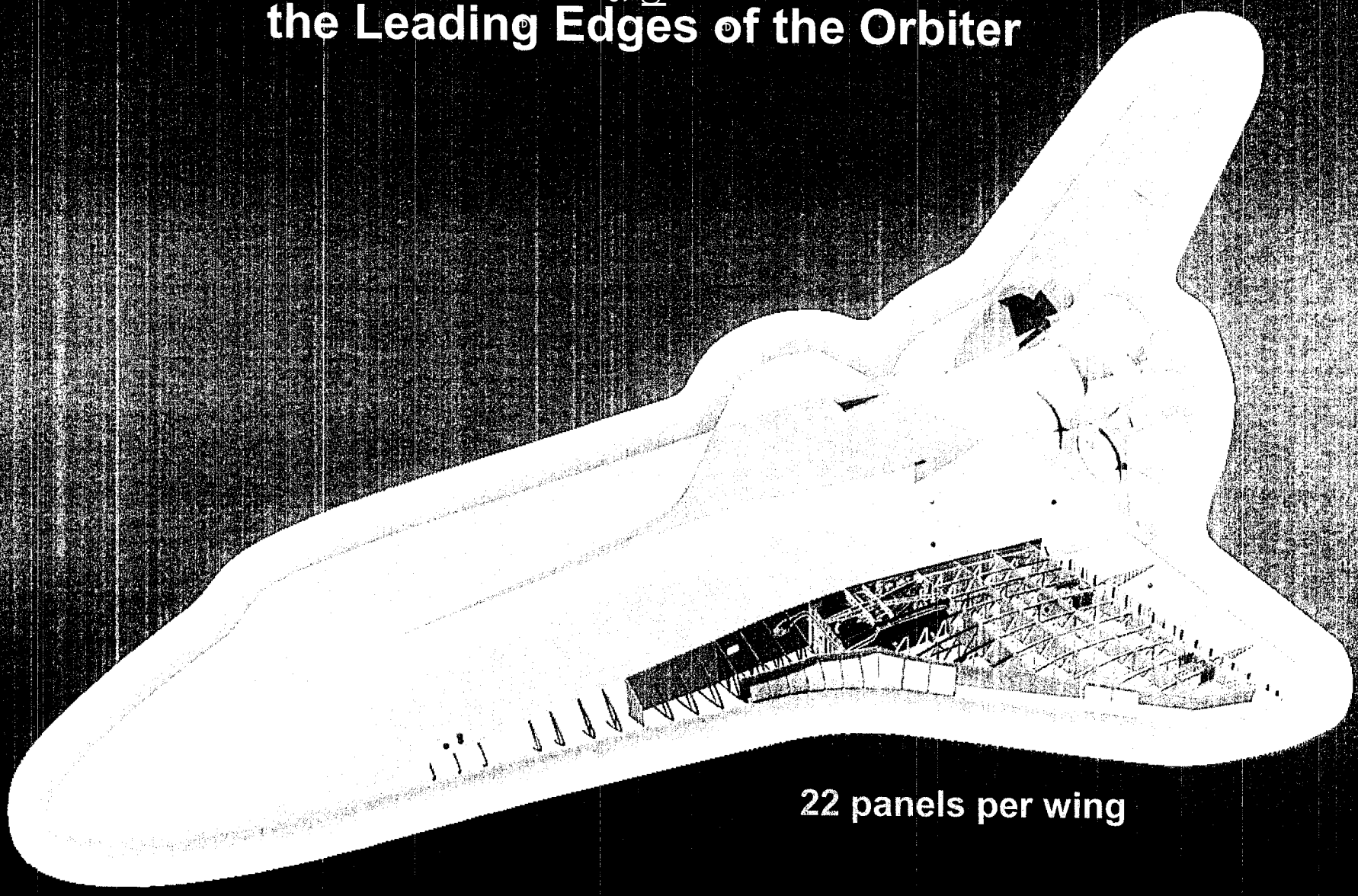


The Bipod Ramp



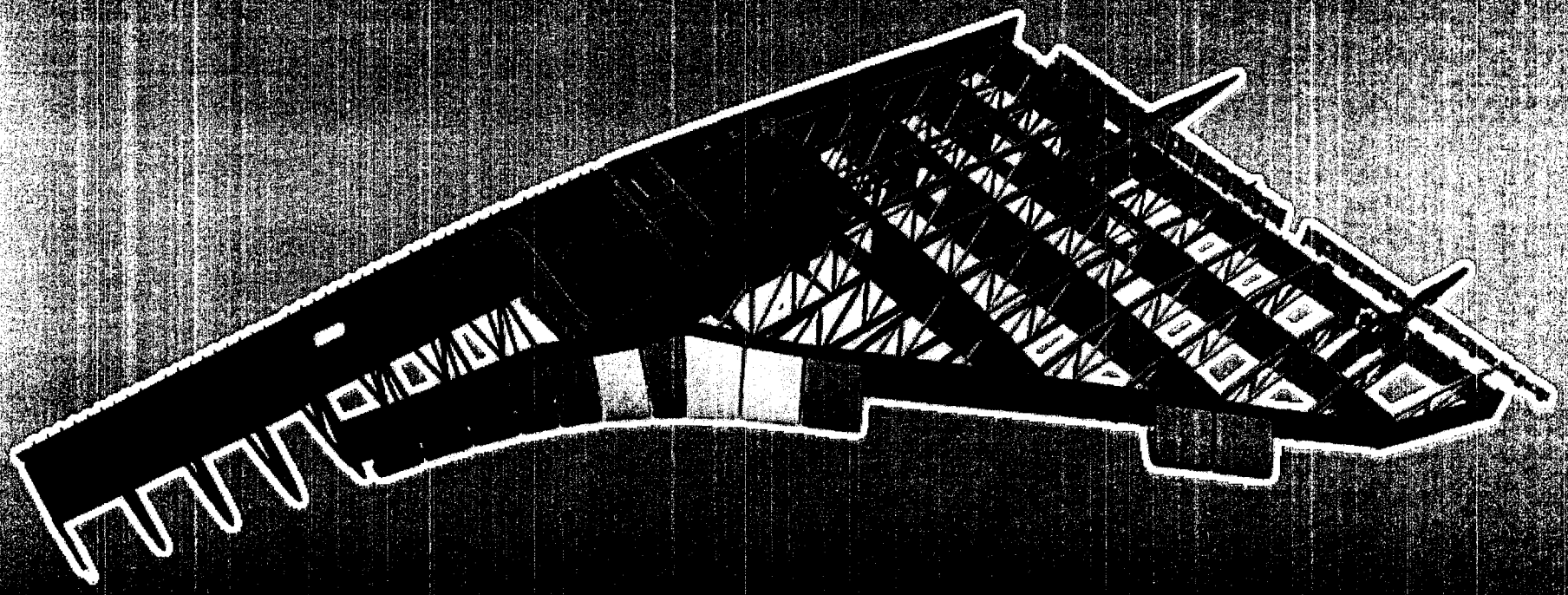
The Orbiter Leading Edges

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

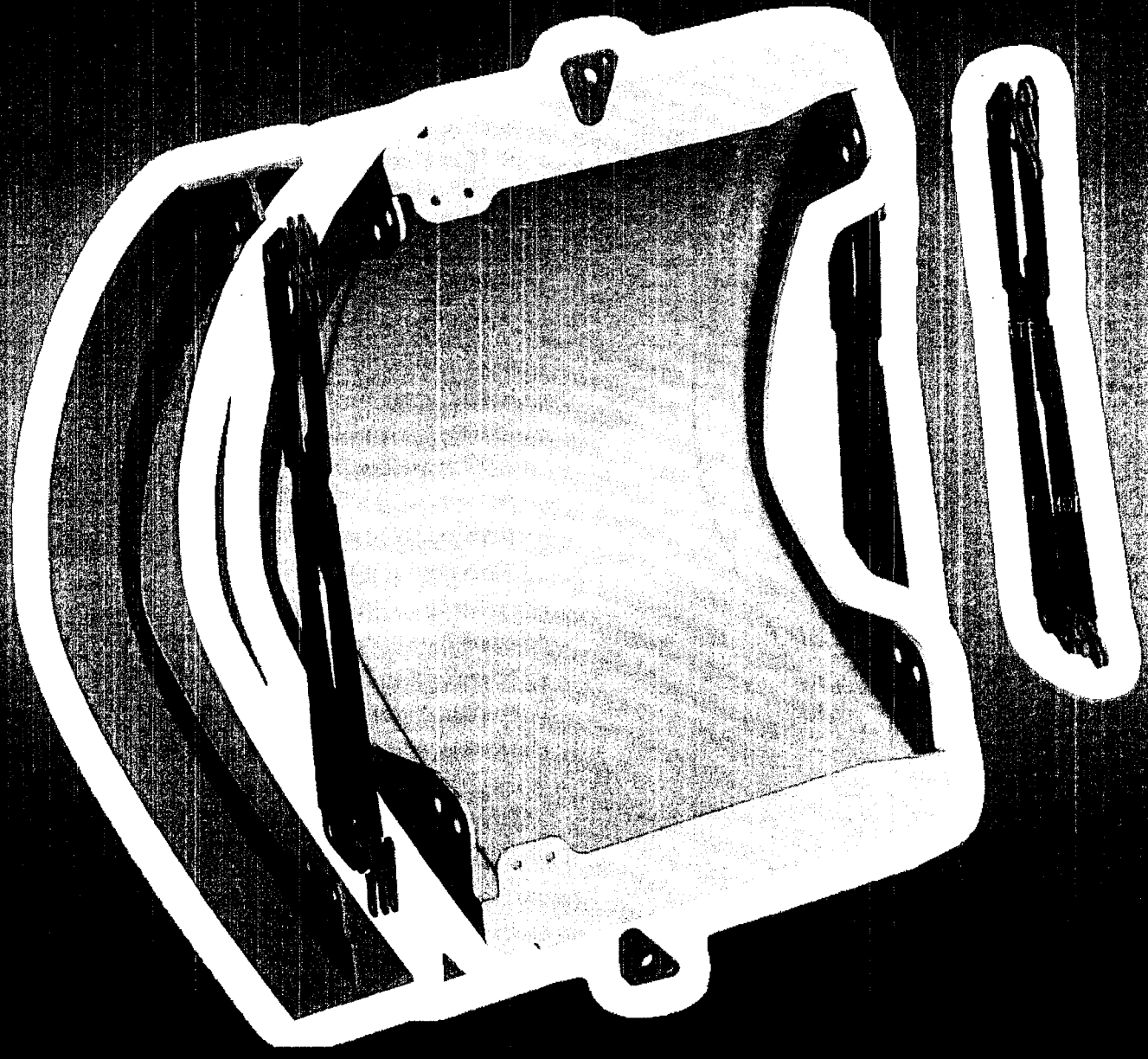


22 panels per wing

RCC Panels 6, 8 & 9 of Specific Interest



RCC T-Seals Seal the Gap Between Panels



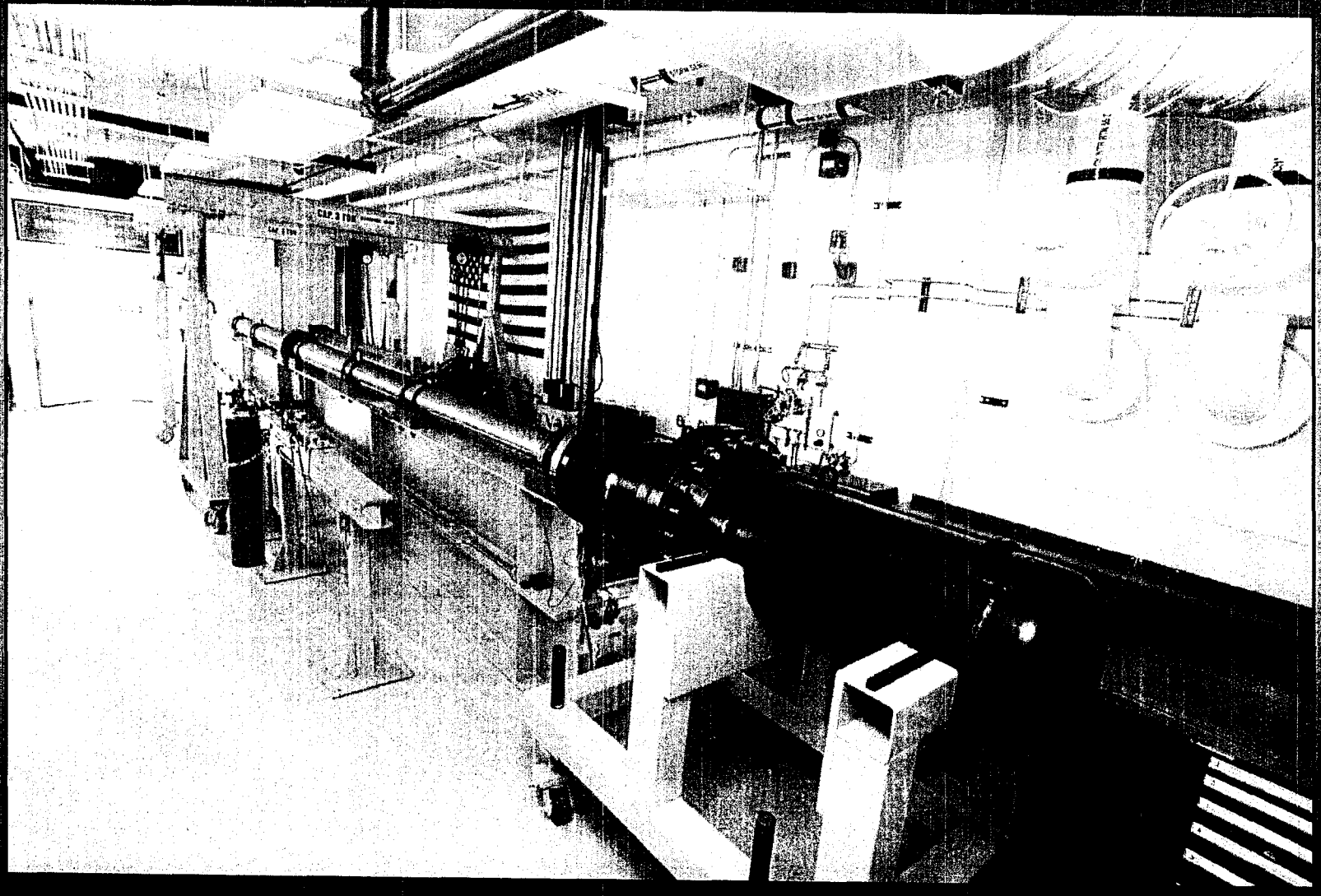
Ballistic Impact Research Efforts on the Accident Investigation

at NASA Glenn Research Center

- Impact testing to characterize External Tank foam and reinforced carbon-carbon leading edge material
- Develop impact analysis capability to predict such impact events
- Support Full Scale Impact Test in San Antonio TX

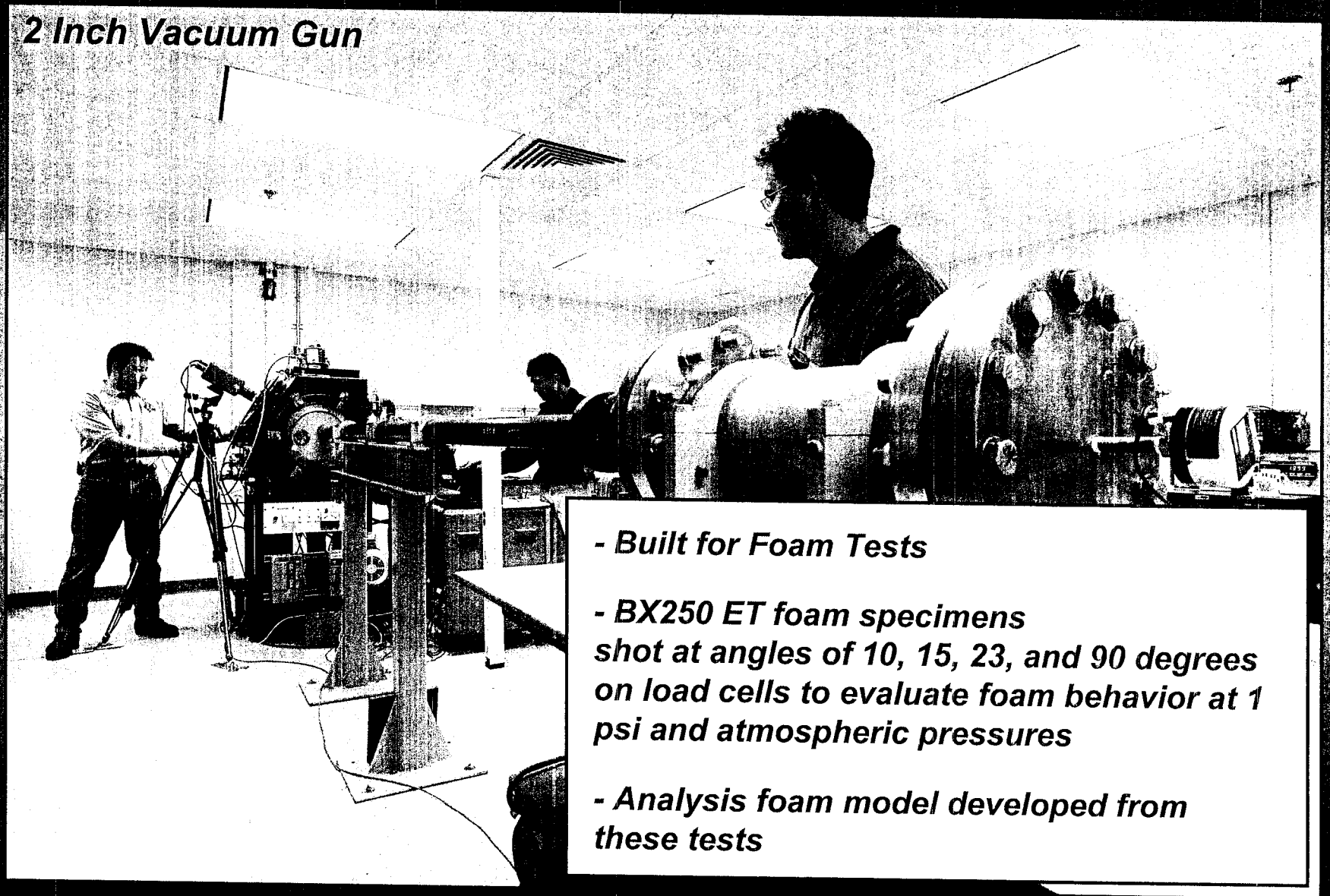
BX-250 External Tank Foam Characterization

The NASA Glenn Ballistic Impact Lab Assisted in the Columbia Accident Investigation



1/16 – 16 inch barrels

Ballistic Research Supporting the Accident Investigation



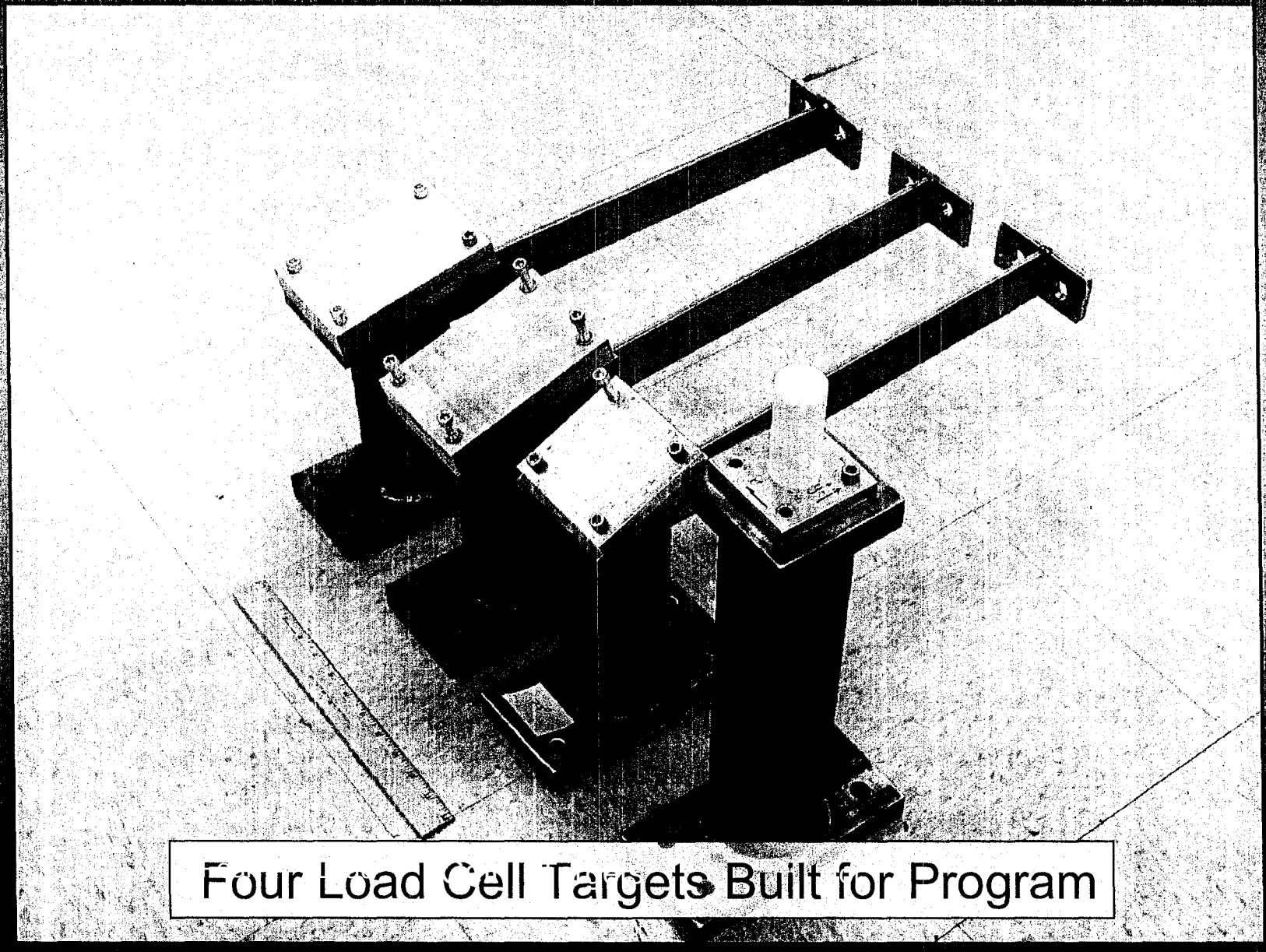
- *Built for Foam Tests*

- *BX250 ET foam specimens shot at angles of 10, 15, 23, and 90 degrees on load cells to evaluate foam behavior at 1 psi and atmospheric pressures*

- *Analysis foam model developed from these tests*

Ballistic Research Supporting the Accident Investigation

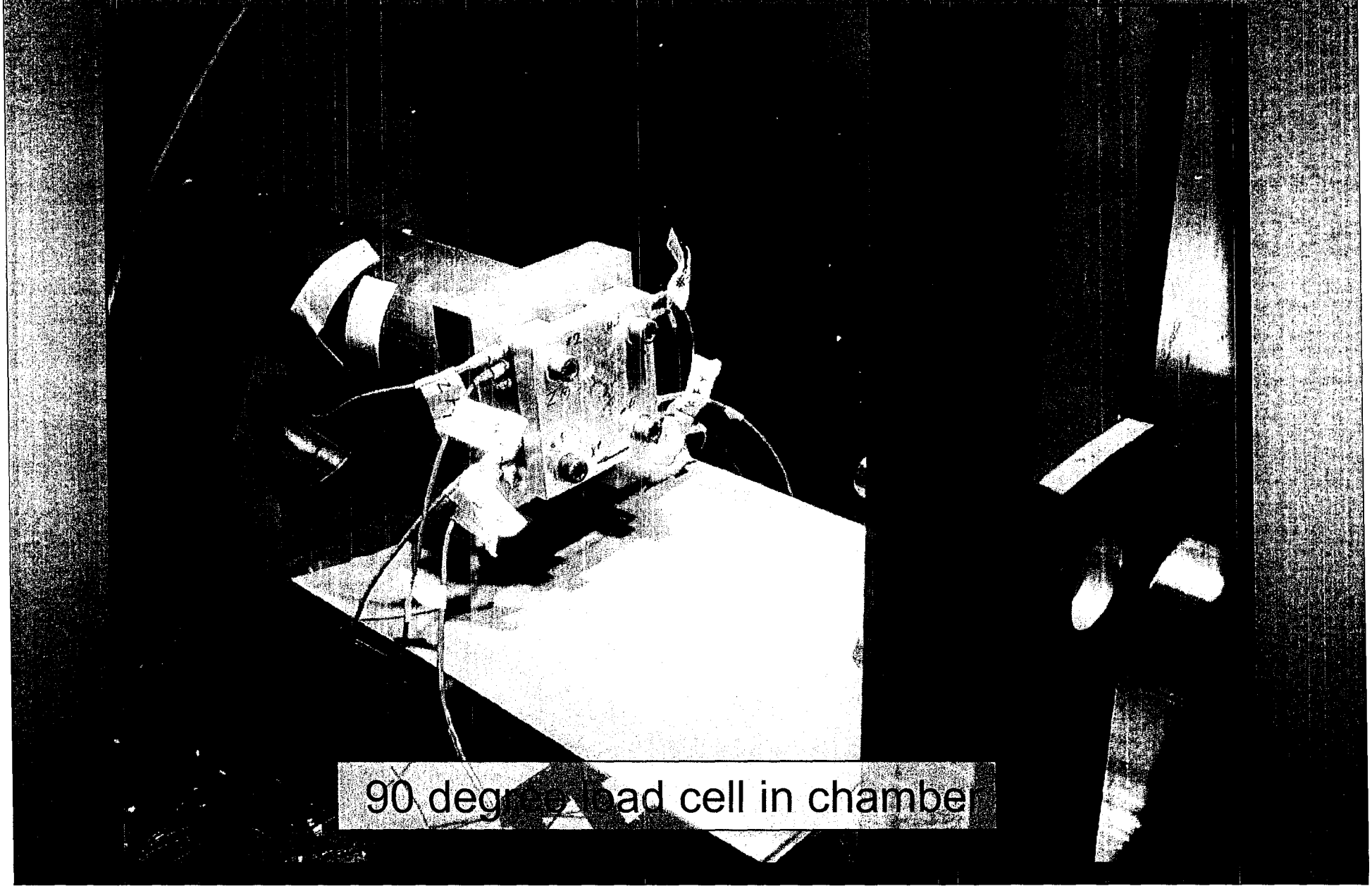
BX-250 External Tank Foam Characterization



Four Load Cell Targets Built for Program

Ballistic Research Supporting the Accident Investigation

BX-250 External Tank Foam Characterization



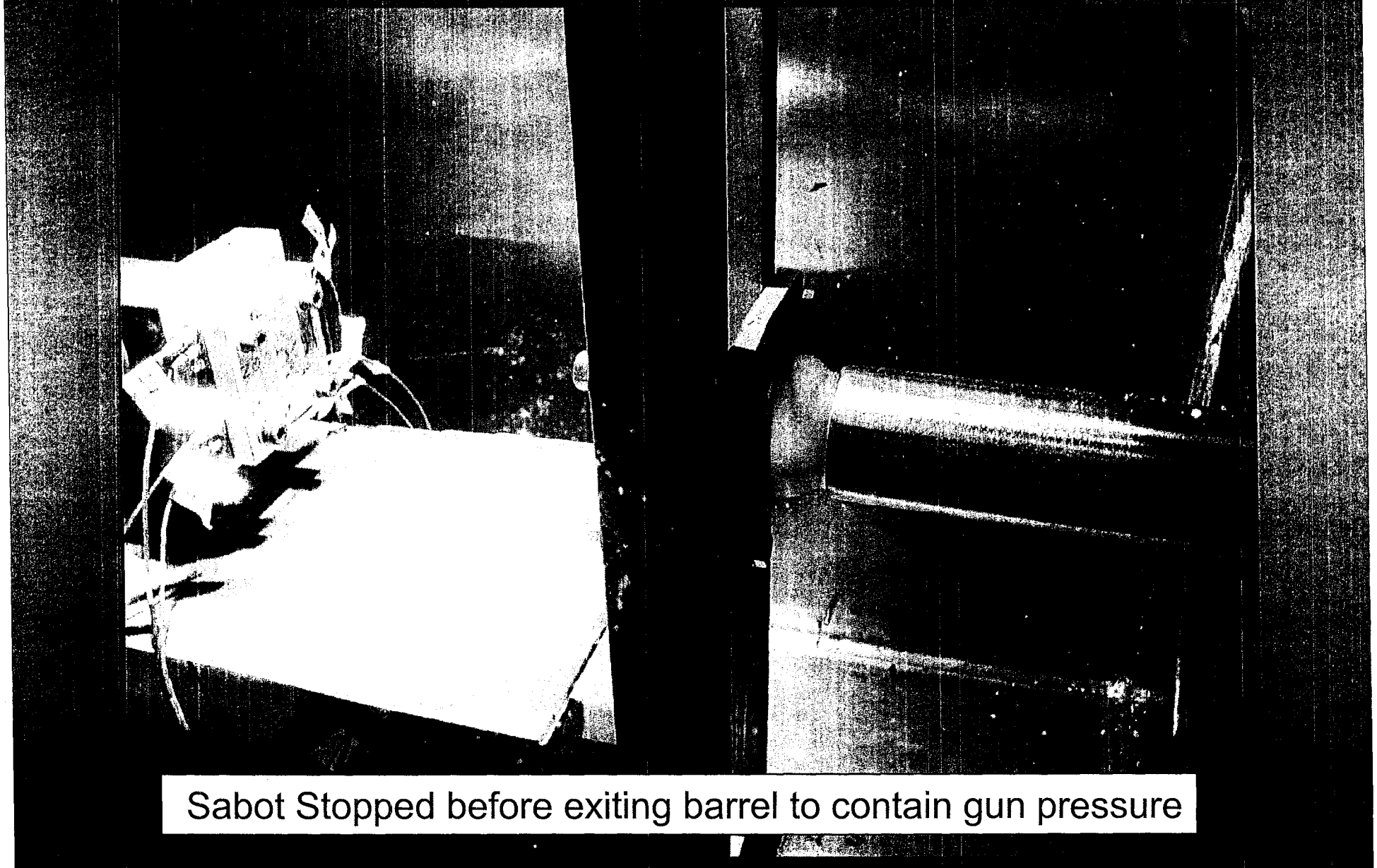
Ballistic Research Supporting the Accident Investigation

BX-250 External Tank Foam Characterization

Sabot and foam projectile in shooting configuration. O-rings contain pressure in gun.

Ballistic Research Supporting the Accident Investigation

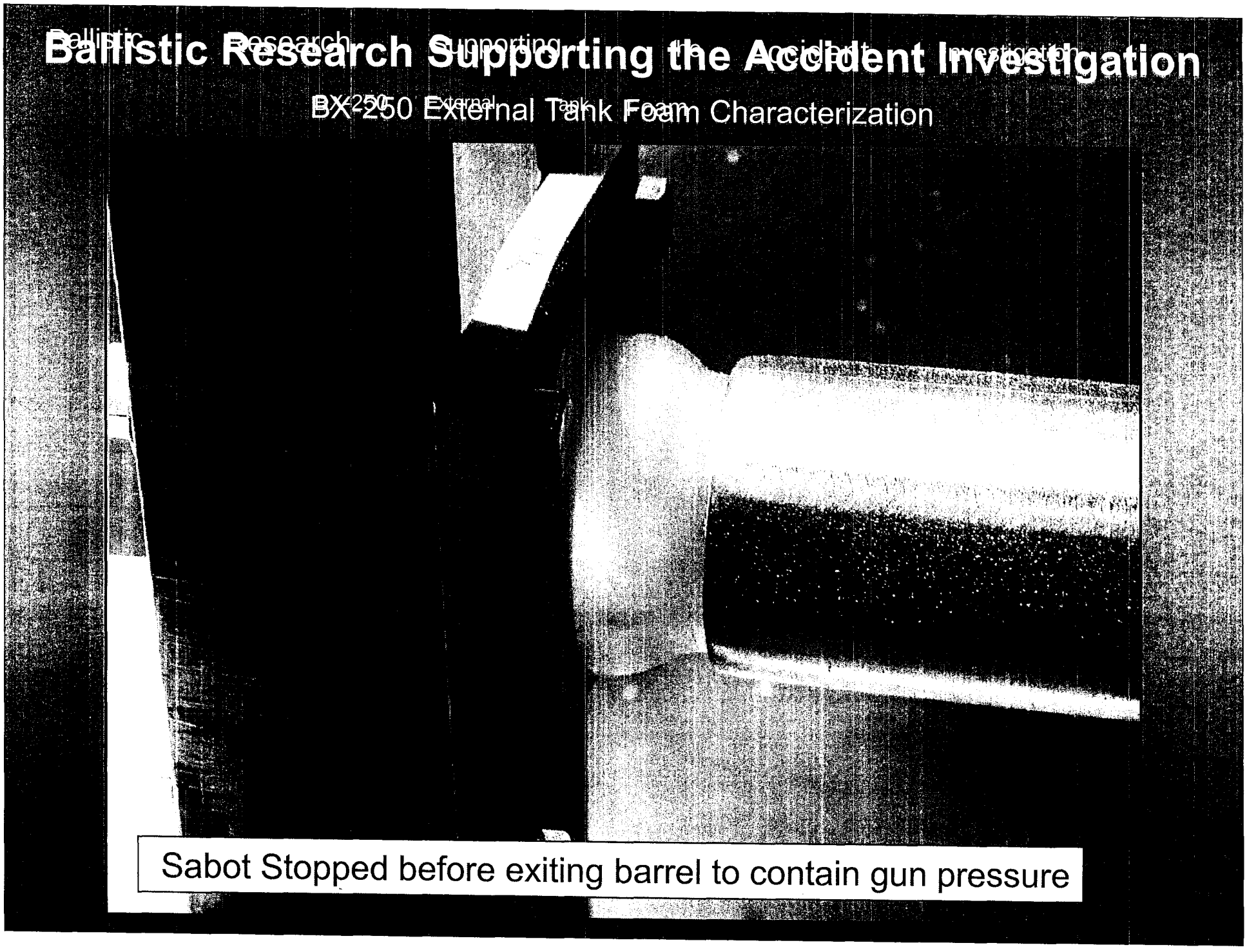
BX-250 External Tank Foam Characterization



Sabot Stopped before exiting barrel to contain gun pressure

Ballistic Research Supporting the Accident Investigation

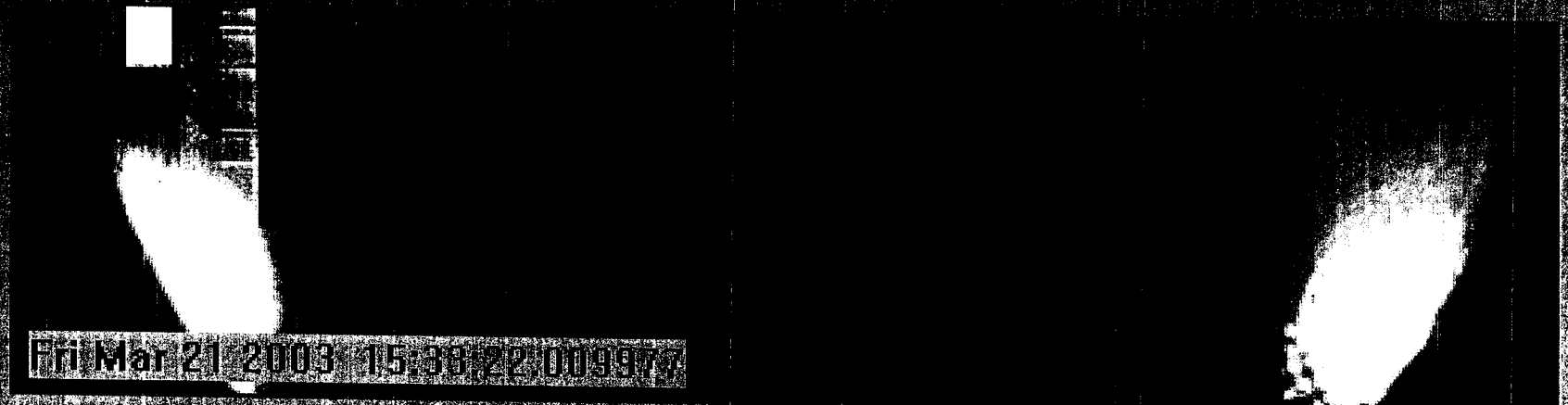
BX-250 External Tank Foam Characterization



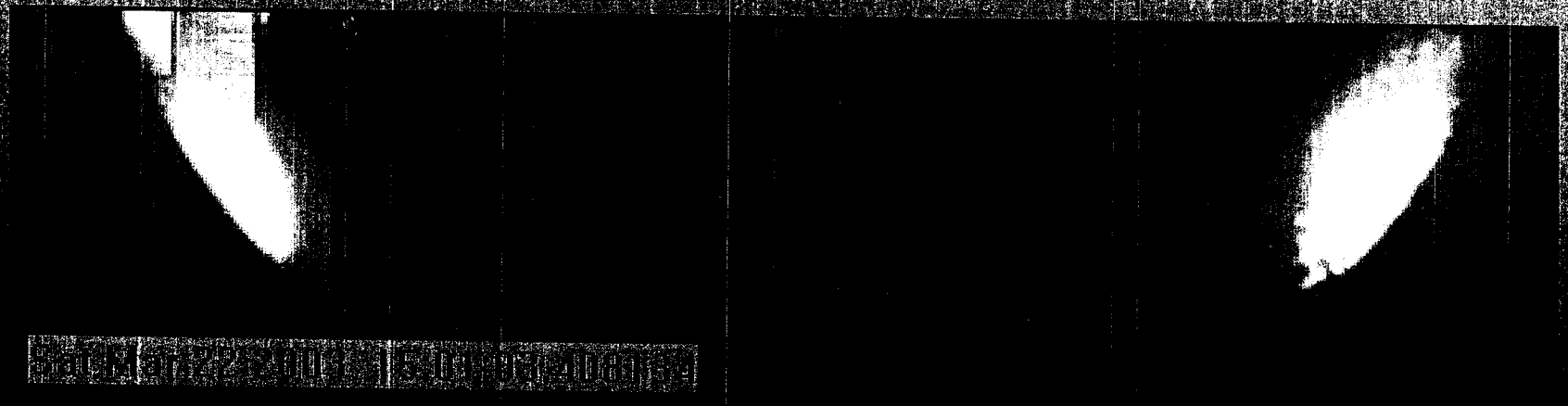
Ballistic Research Supporting the Accident Investigation

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

BX-250 External Tank Foam Characterization

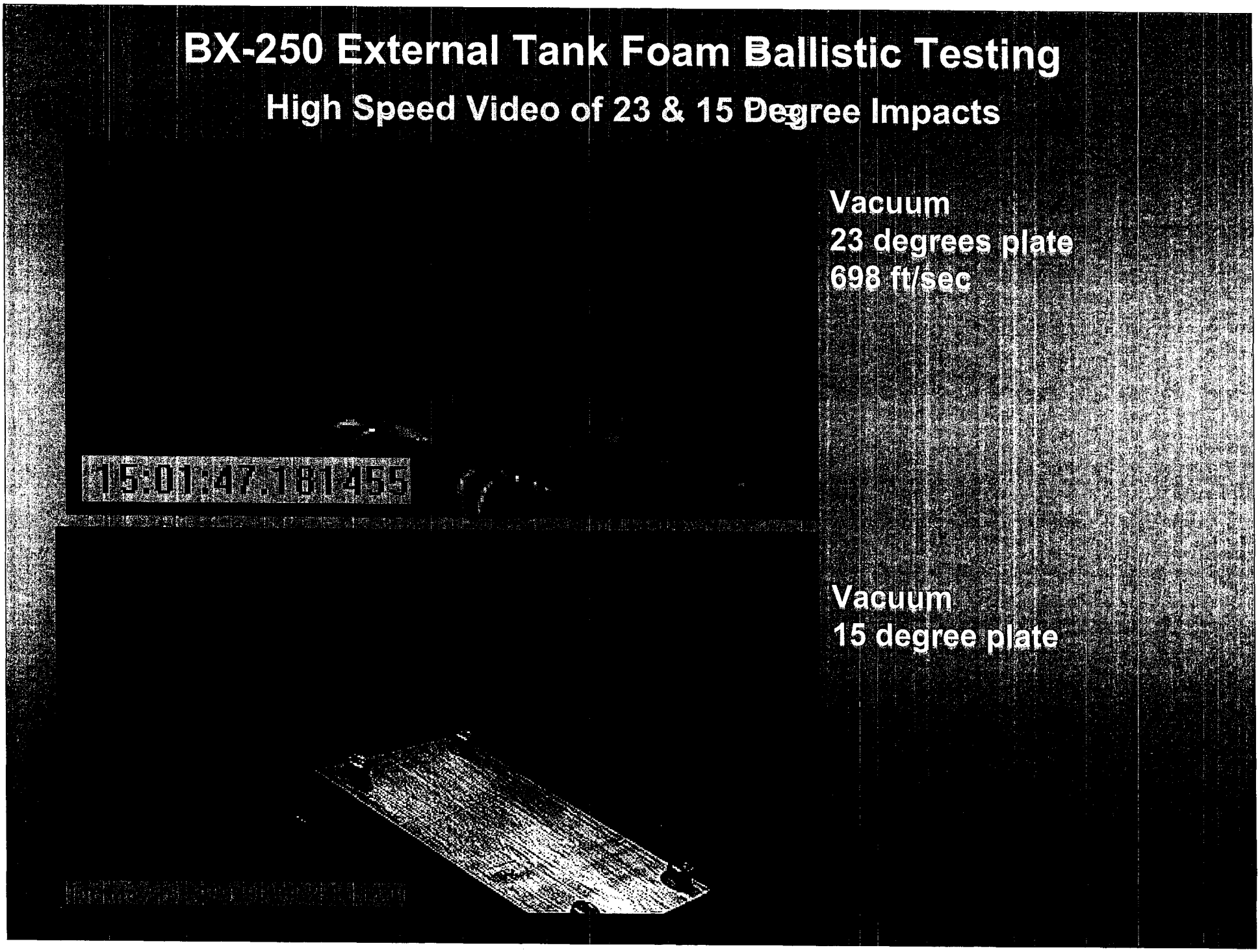
High Speed Video of 90 Degree Impacts

No Vacuum
708 ft/sec

Vacuum
693 ft/sec

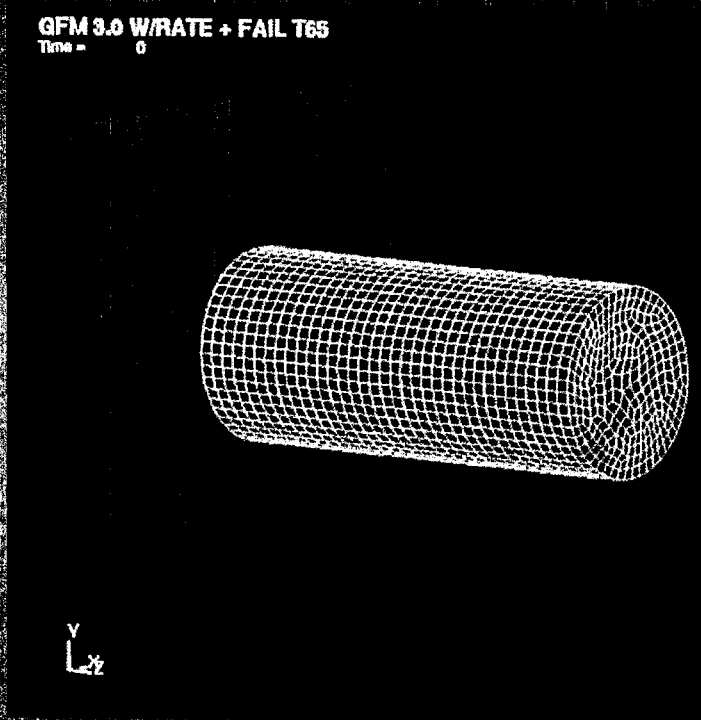
BX-250 External Tank Foam Ballistic Testing

High Speed Video of 23 & 15 Degree Impacts



Ballistic Research Supporting the Accident Investigation

Dyna - explicit finite element impact analysis

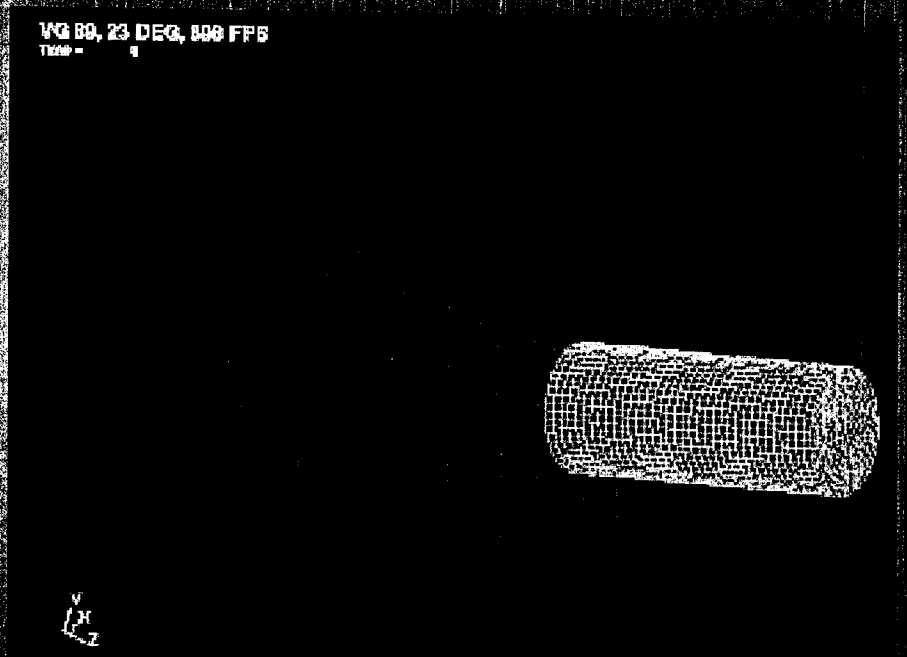


Dyna Predicts 90 Degree Foam Impact on Load Cell

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

Ballistic Research Supporting the Accident Investigation

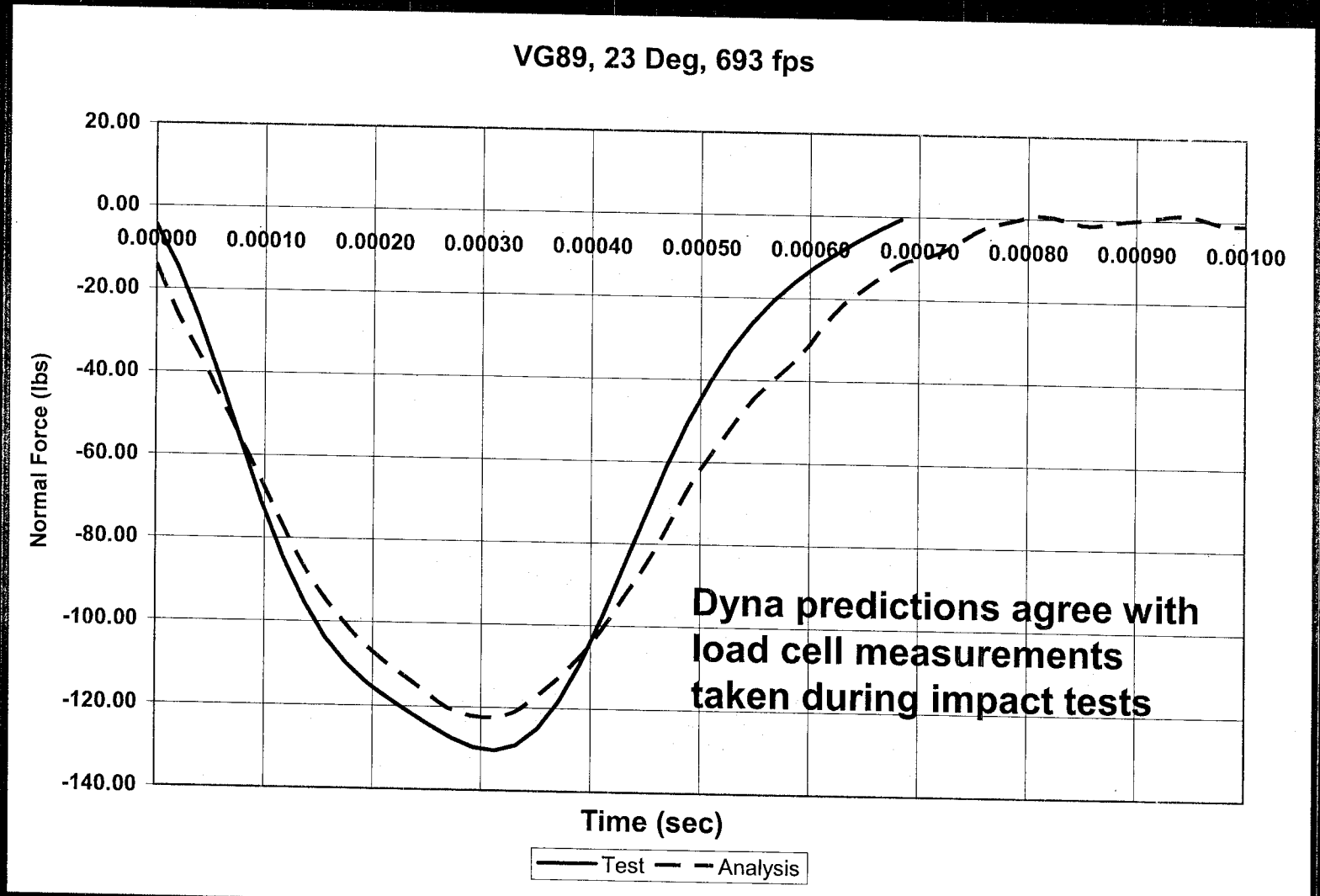
Dyna - explicit finite element impact analysis



Dyna Predicts 23 Degree Foam Impact on Load Cell

Ballistic Research Supporting the Accident Investigation

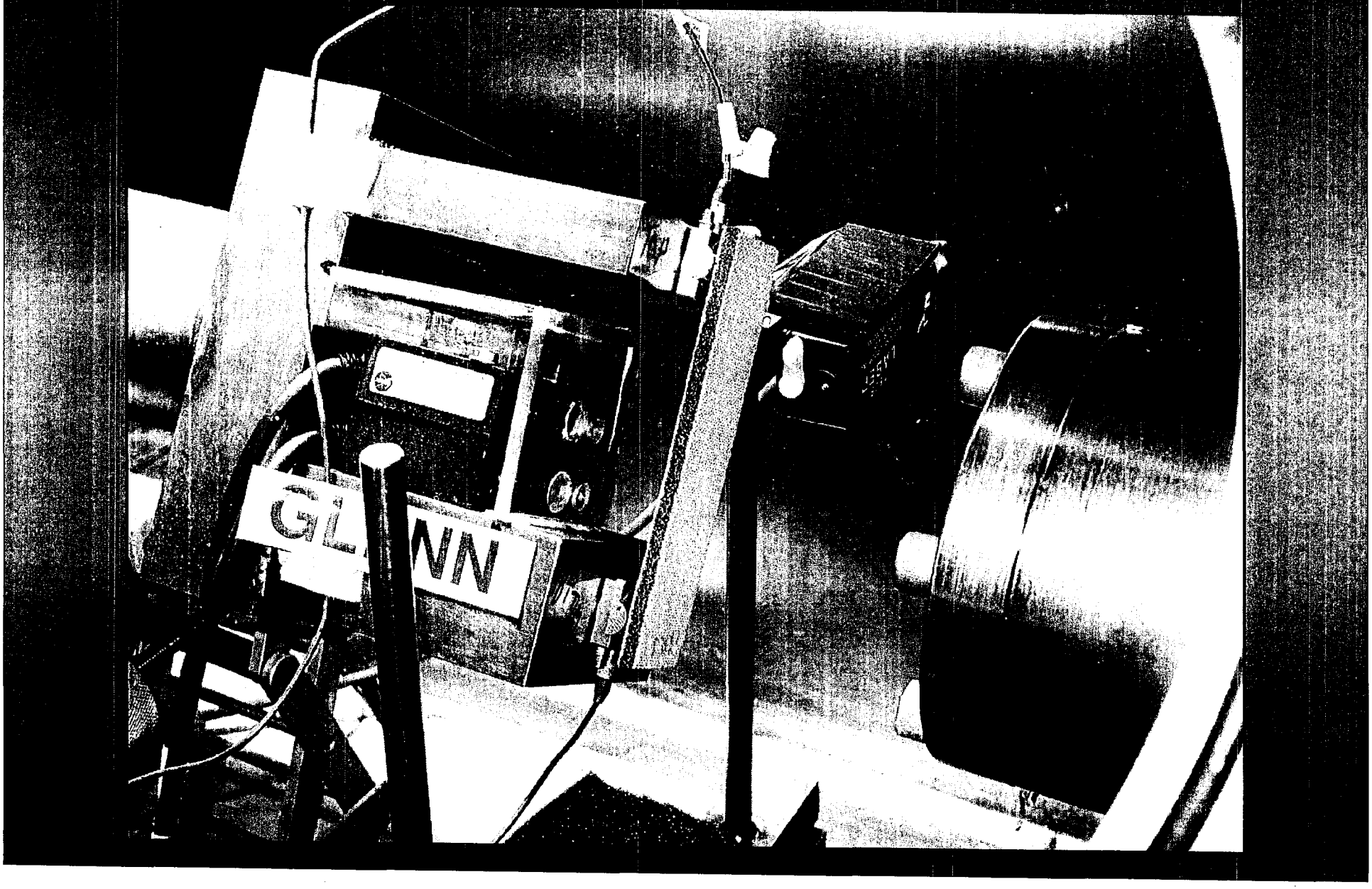
Dyna - explicit finite element impact analysis



Reinforced Carbon-Carbon Characterization

Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



Ballistic Research Supporting the Accident Investigation

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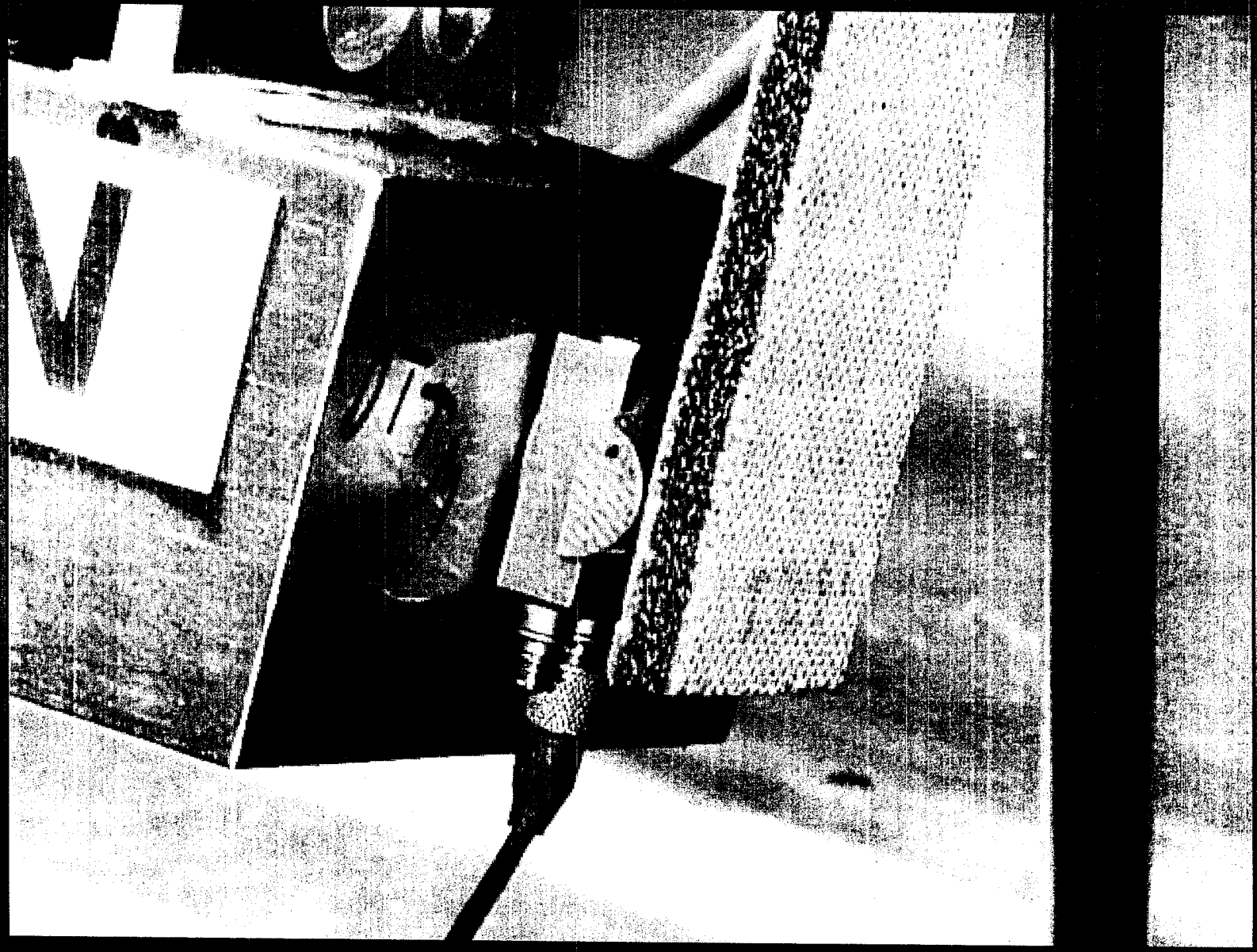

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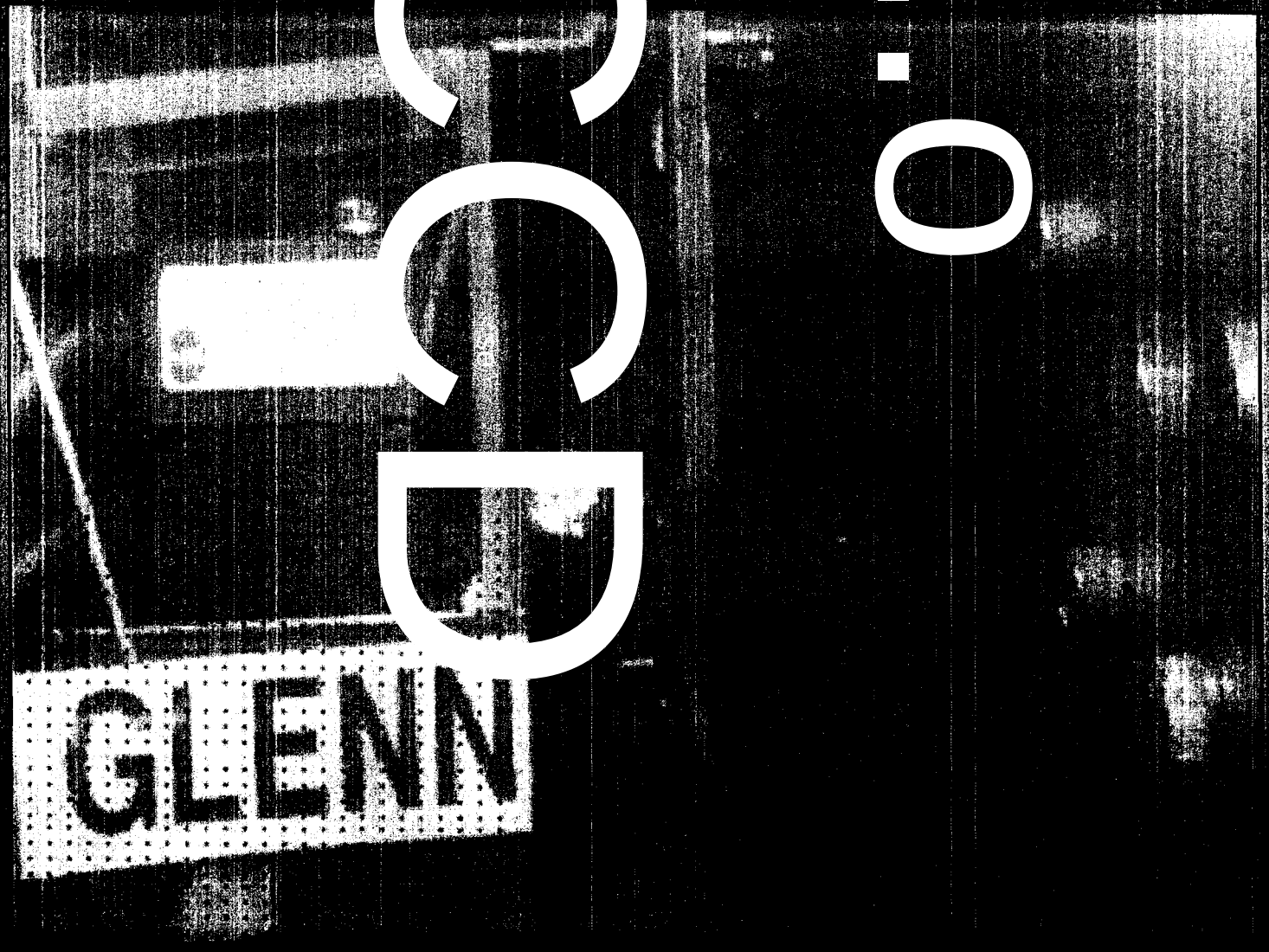


RCC Coupon Shows No Damage After 397 ft/sec Foam Impact

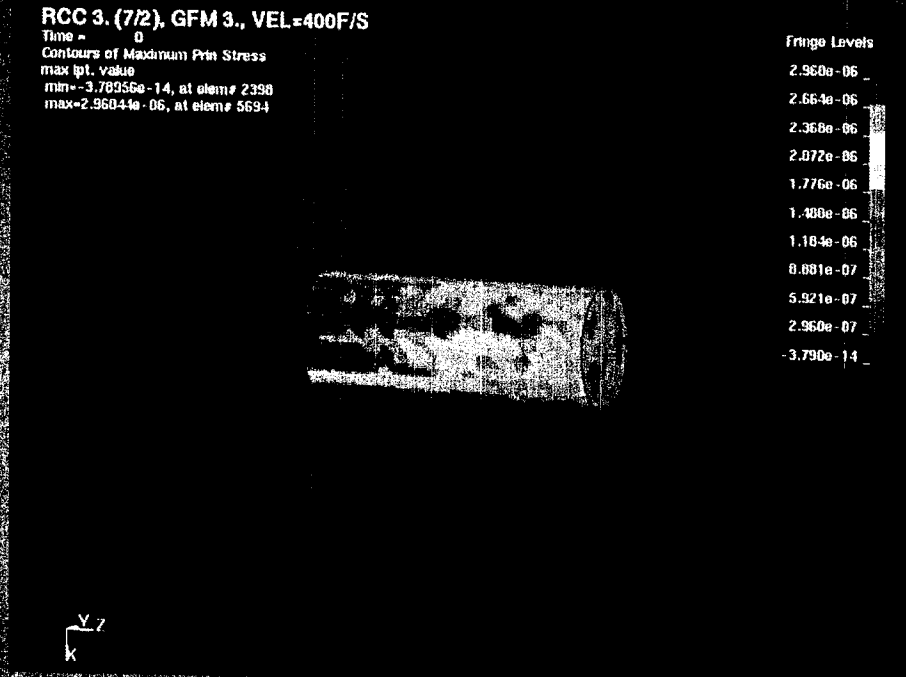
Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons

Foam Fractures RCC coupon in half at 695 ft/sec

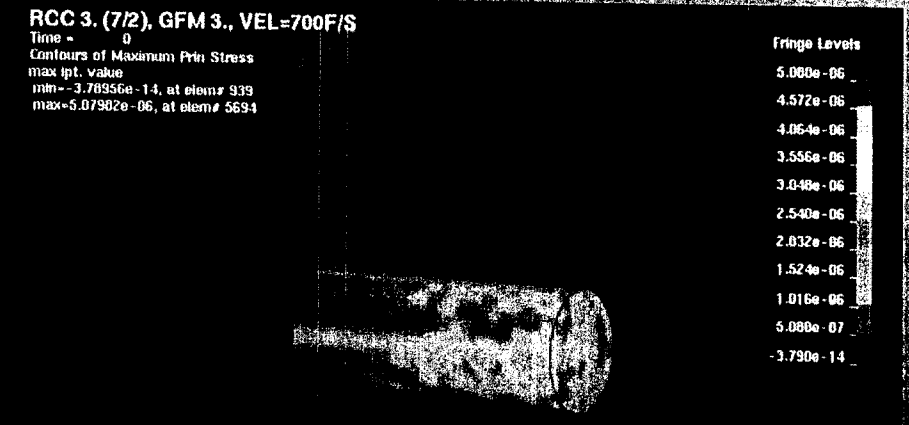
Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



400 ft/second Impact

700 ft/second Impact



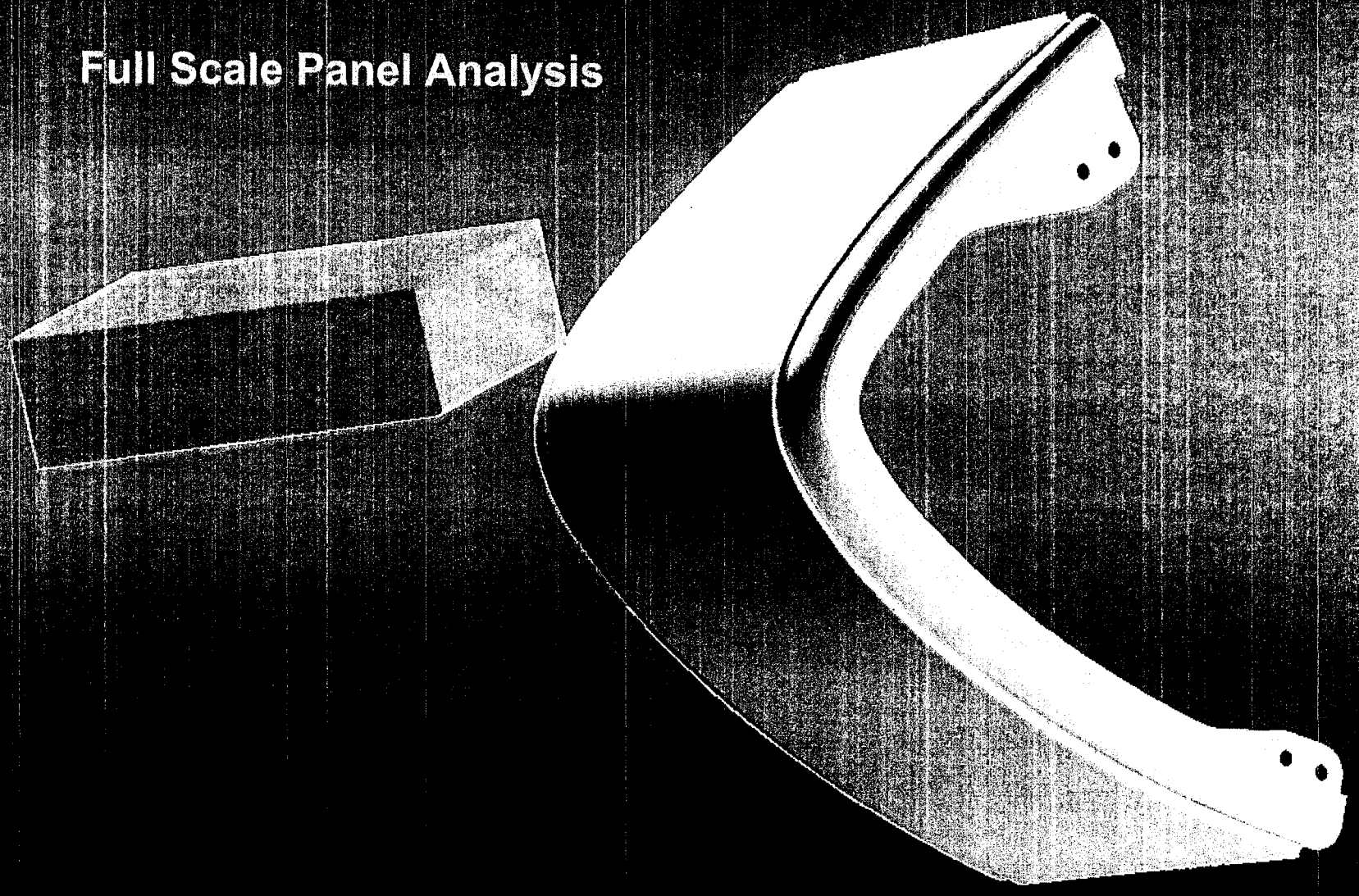
Current RCC Model Predicts these tests well

Full Scale Impact Analysis with LS Dyna

Ballistic Research Supporting the Accident Investigation

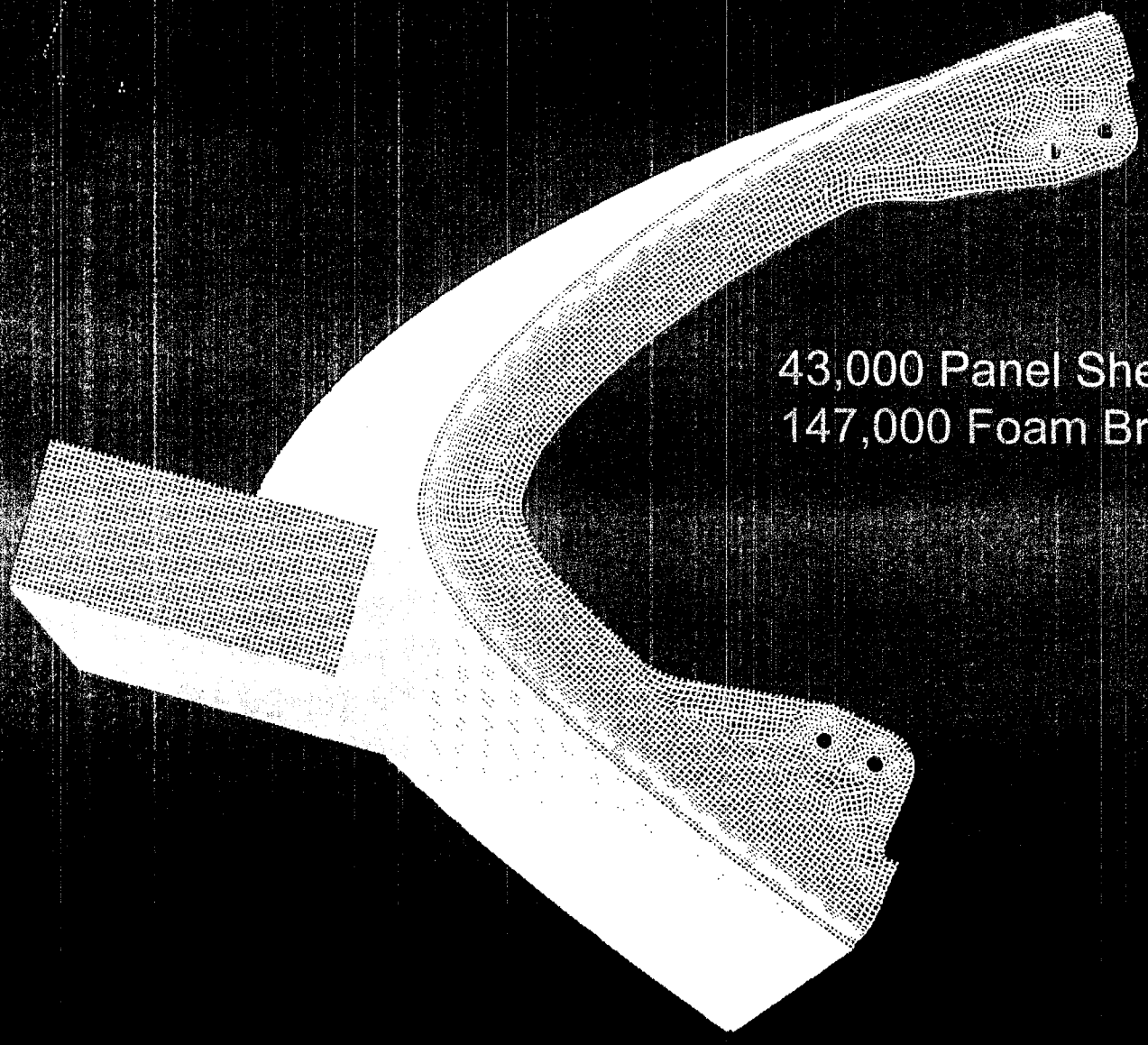
Dyna - explicit finite element impact analysis

Full Scale Panel Analysis



Ballistic Research Supporting the Accident Investigation

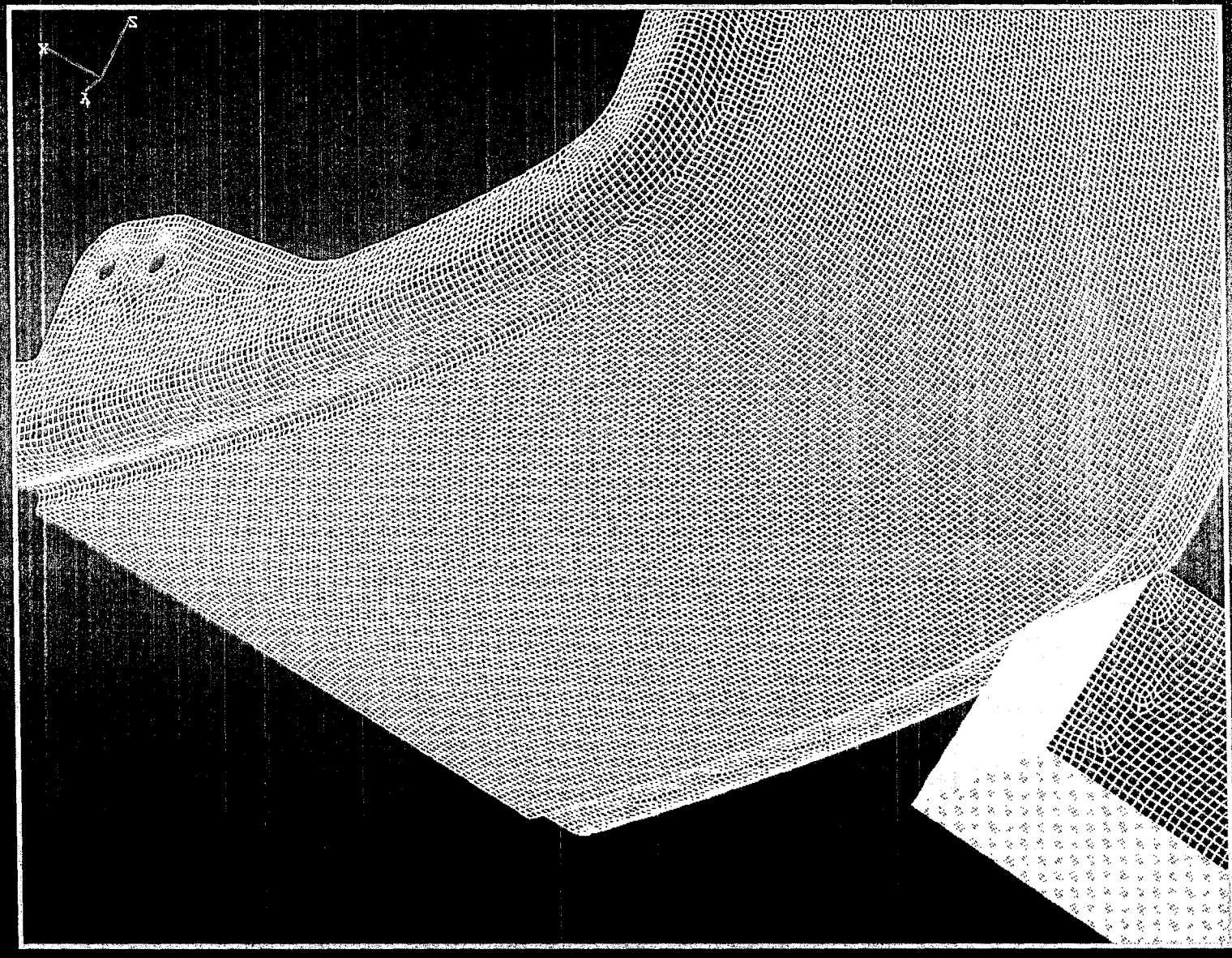
Dyna - explicit finite element impact analysis



43,000 Panel Shell Elements
147,000 Foam Brick Elements

Ballistic Research Supporting the Accident Investigation

Dyna - explicit finite element impact analysis



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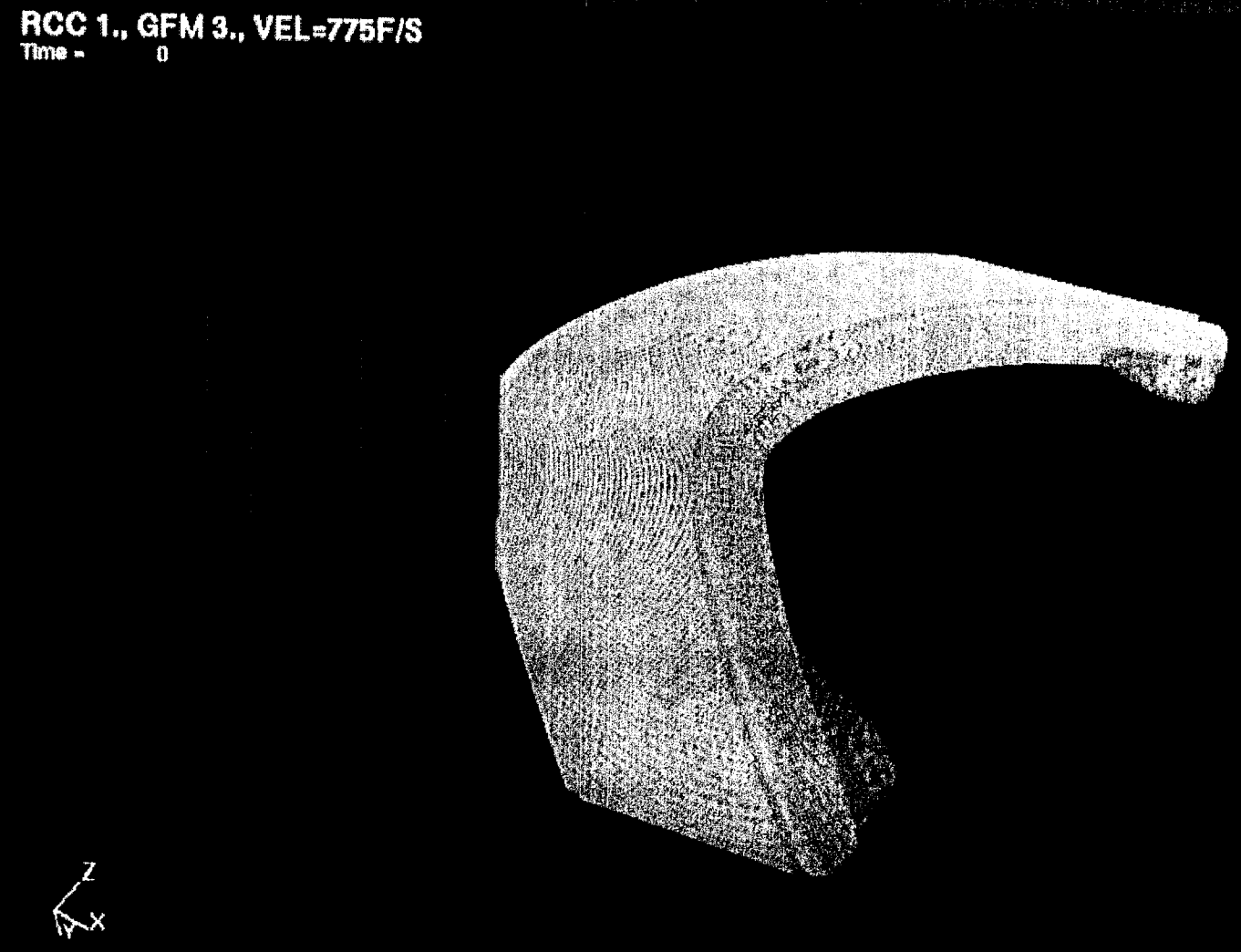
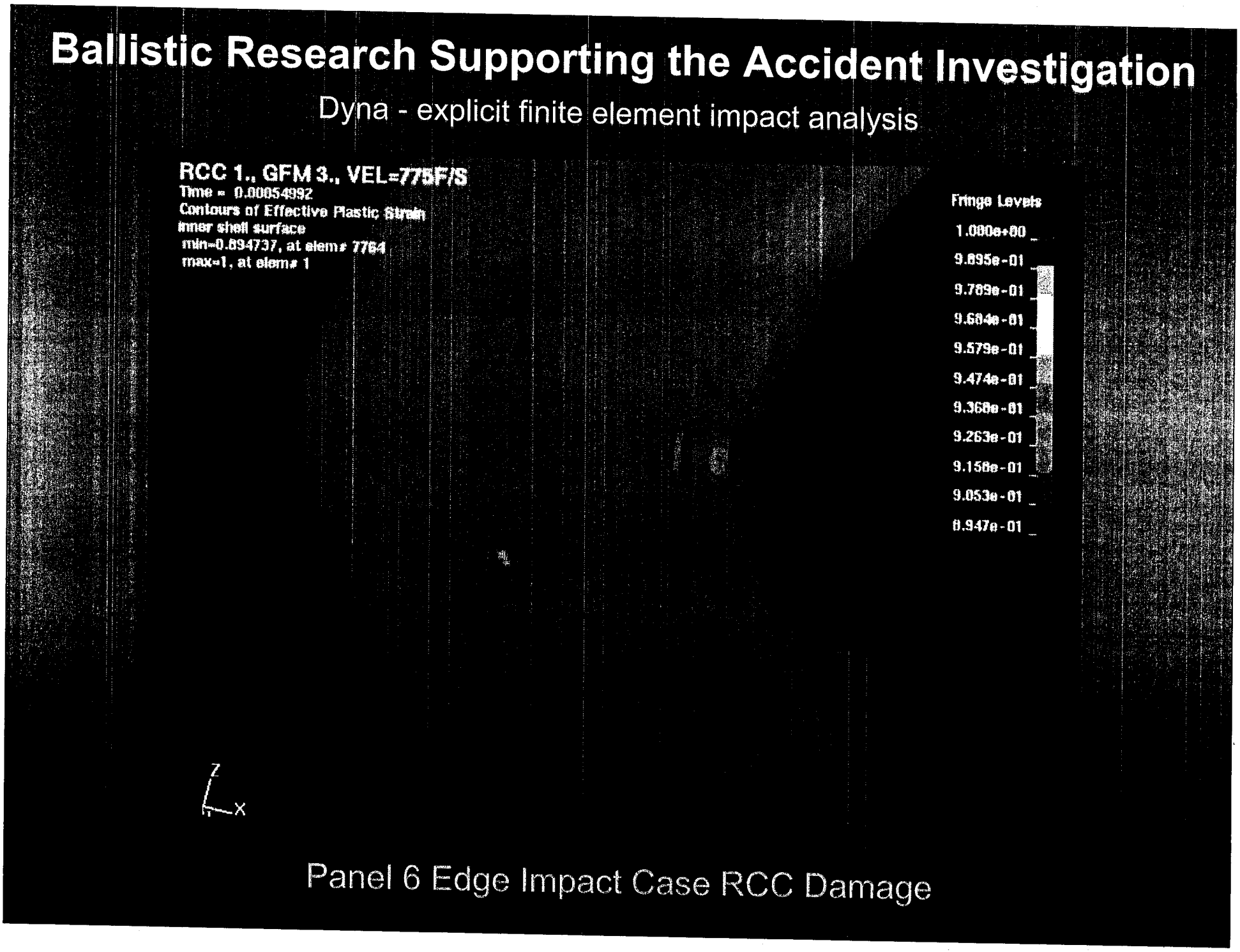


Panel 6 Edge Impact Case

Ballistic Research Supporting the Accident Investigation

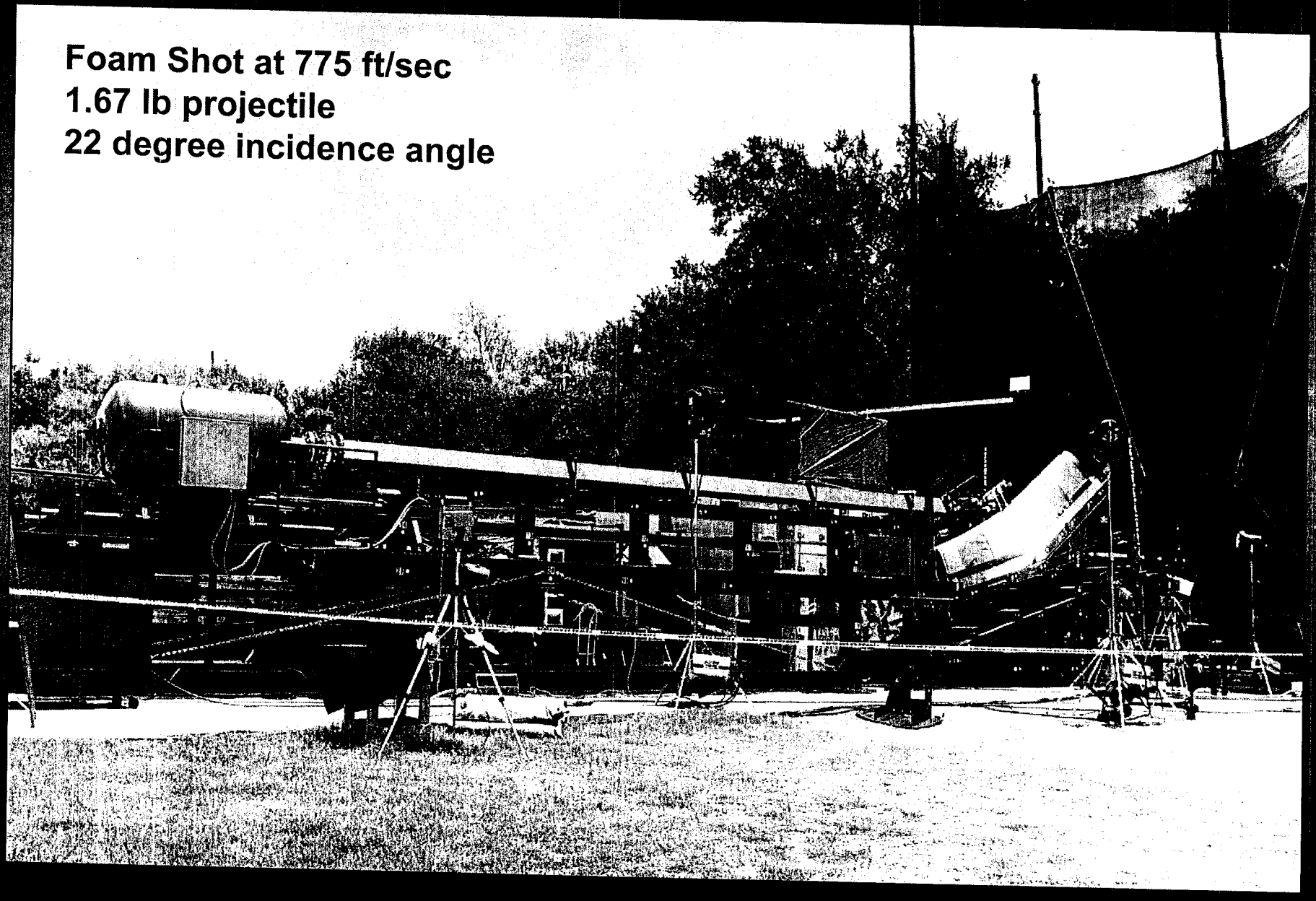
Dyna - explicit finite element impact analysis



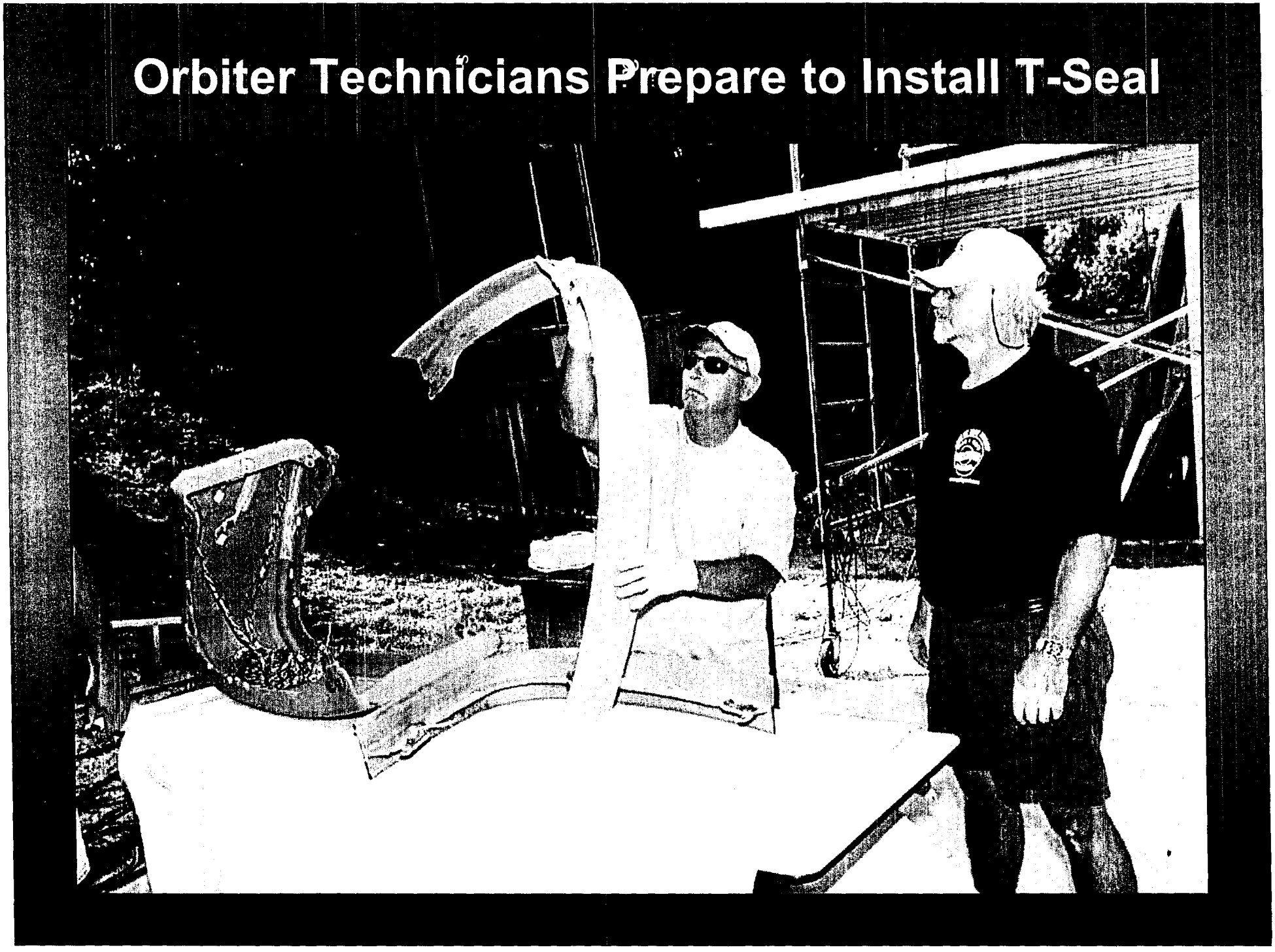
Panel 6 Edge Impact Case RCC Damage

Orbiter Leading Edge Full Scale Tests

Tests conducted at Southwest Research Institute



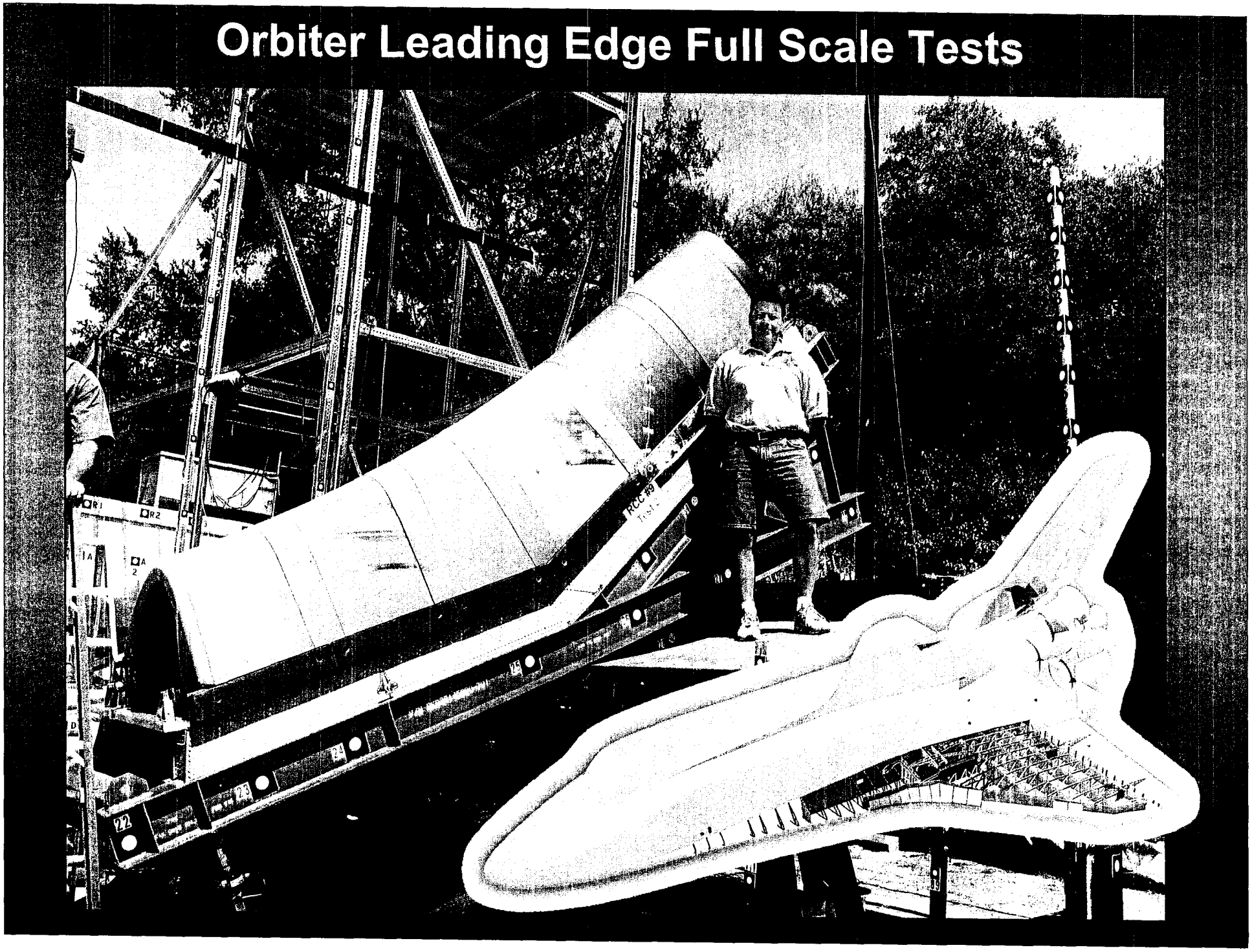
Orbiter Technicians Prepare to Install T-Seal



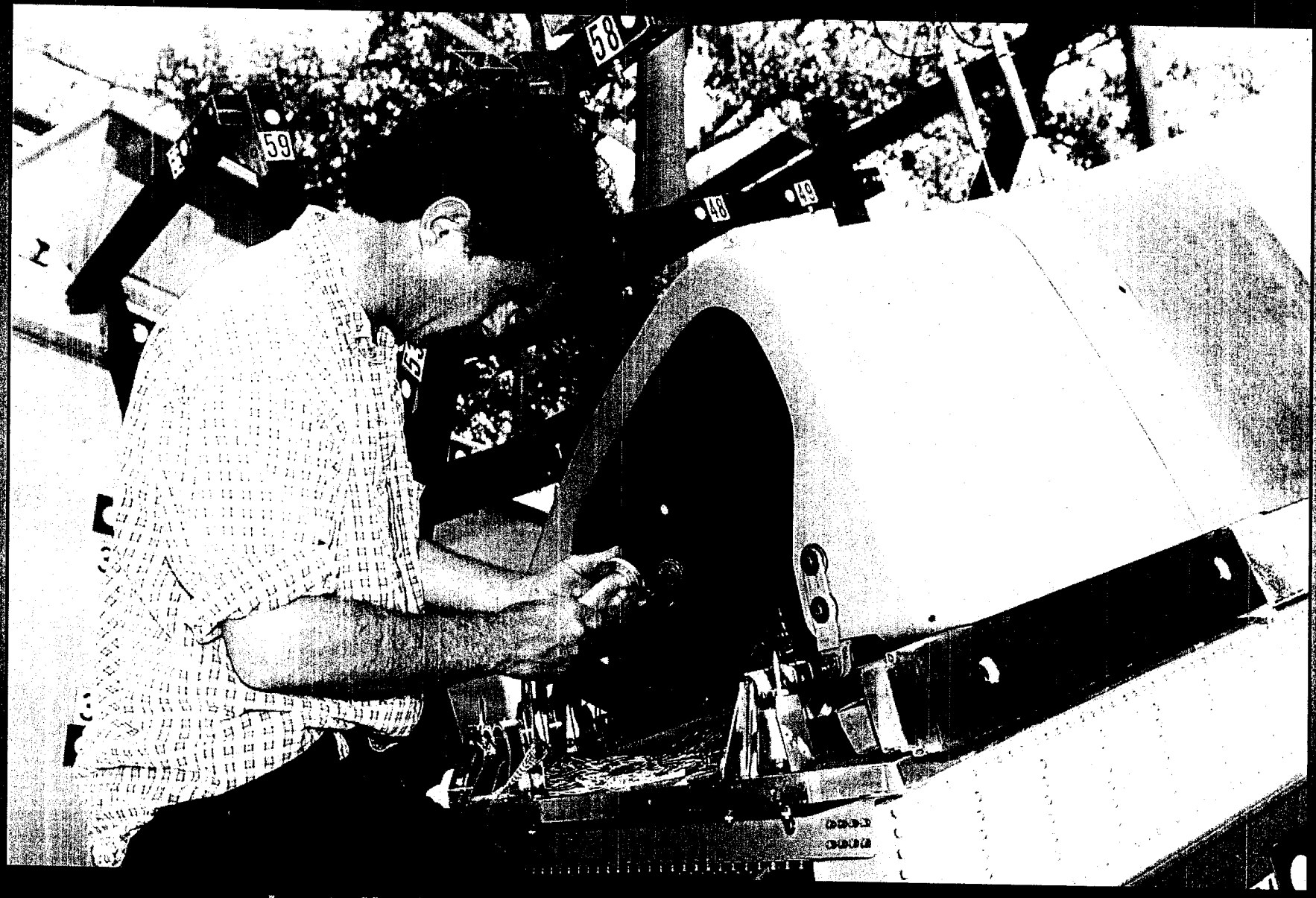
Orbiter Technicians Install T-Seal

Orbiter Technicians Check Steps and Gaps on Leading Edge

Orbiter Leading Edge Full Scale Tests

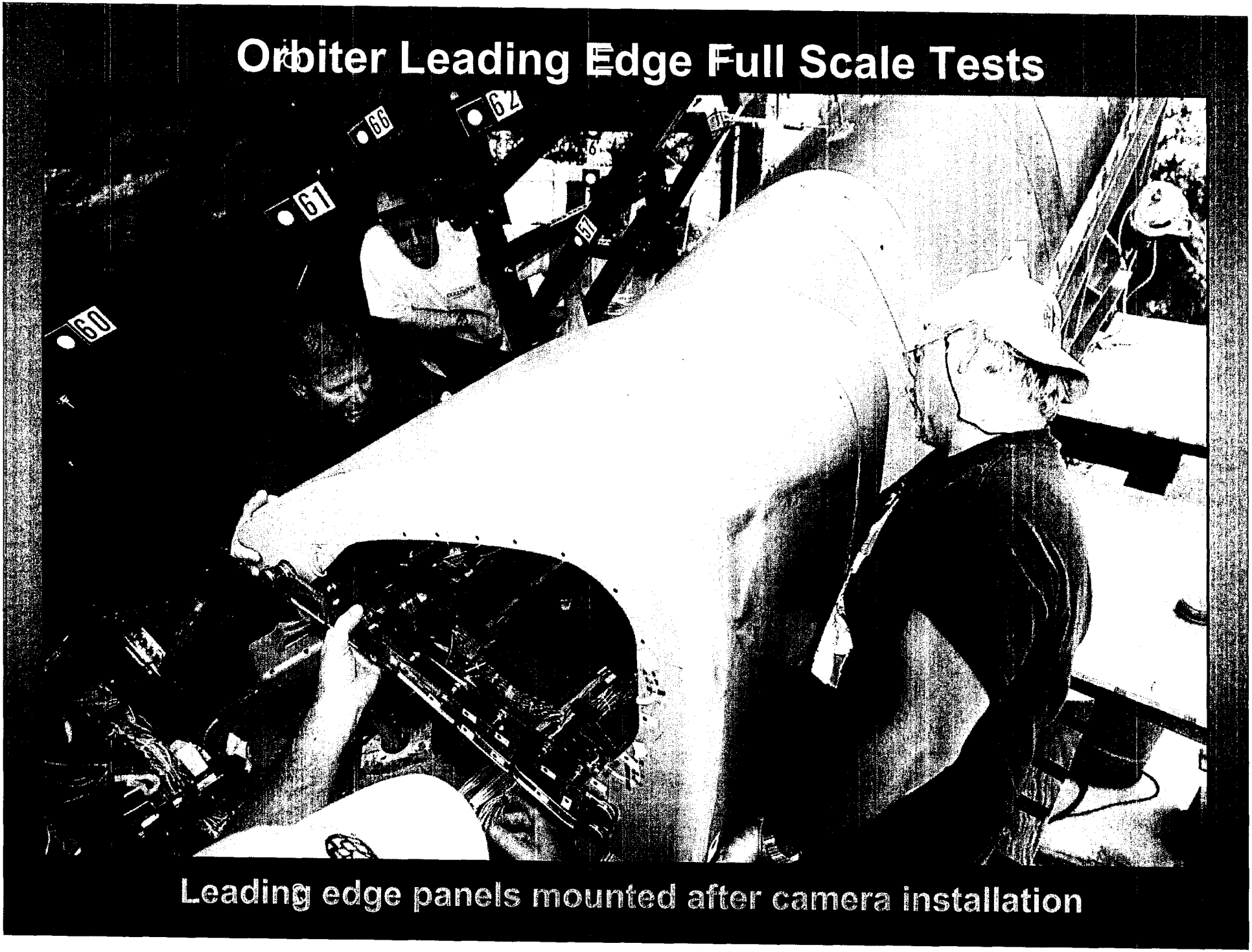


Orbiter Leading Edge Full Scale Tests



Installation of internal high speed cameras

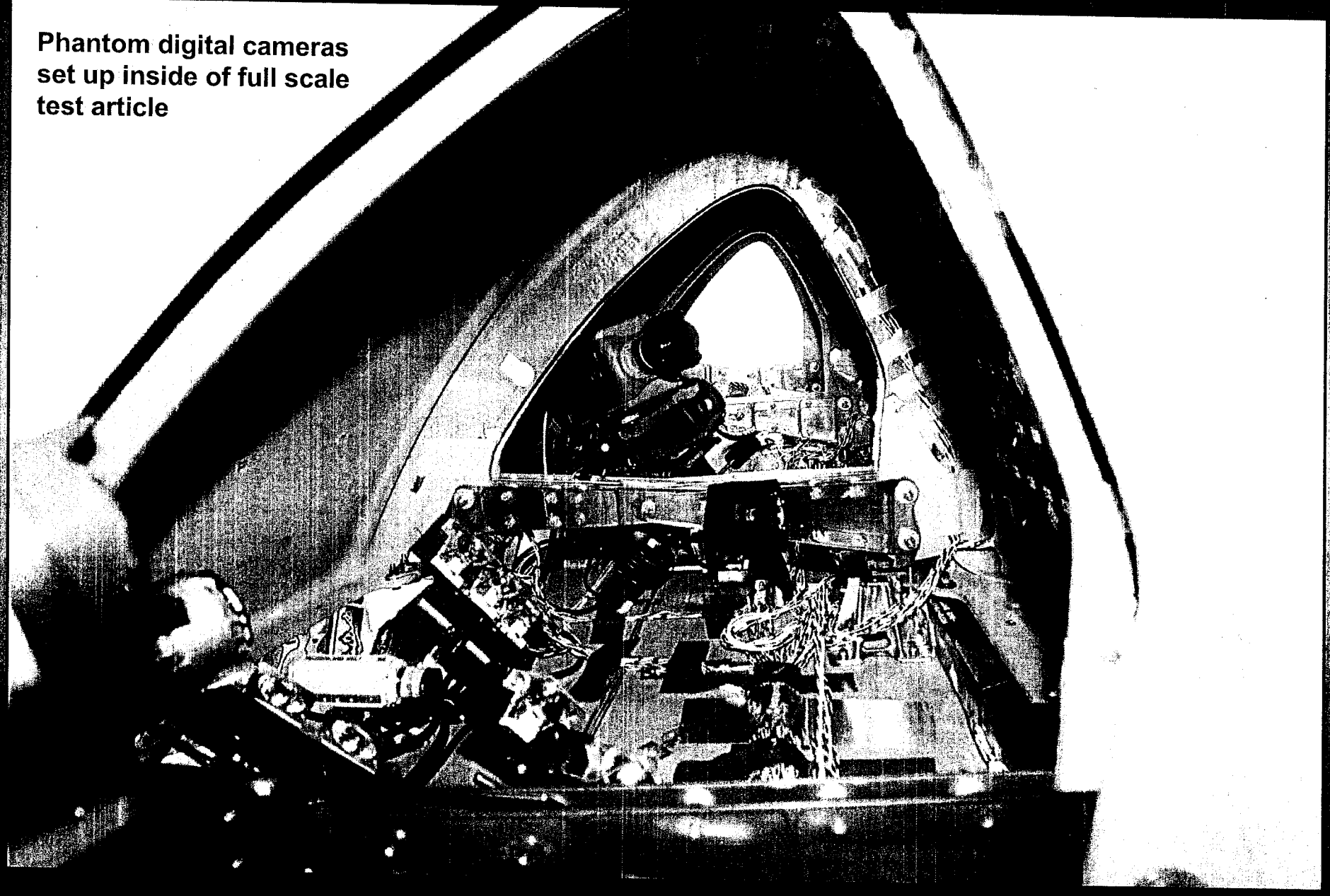
Orbiter Leading Edge Full Scale Tests



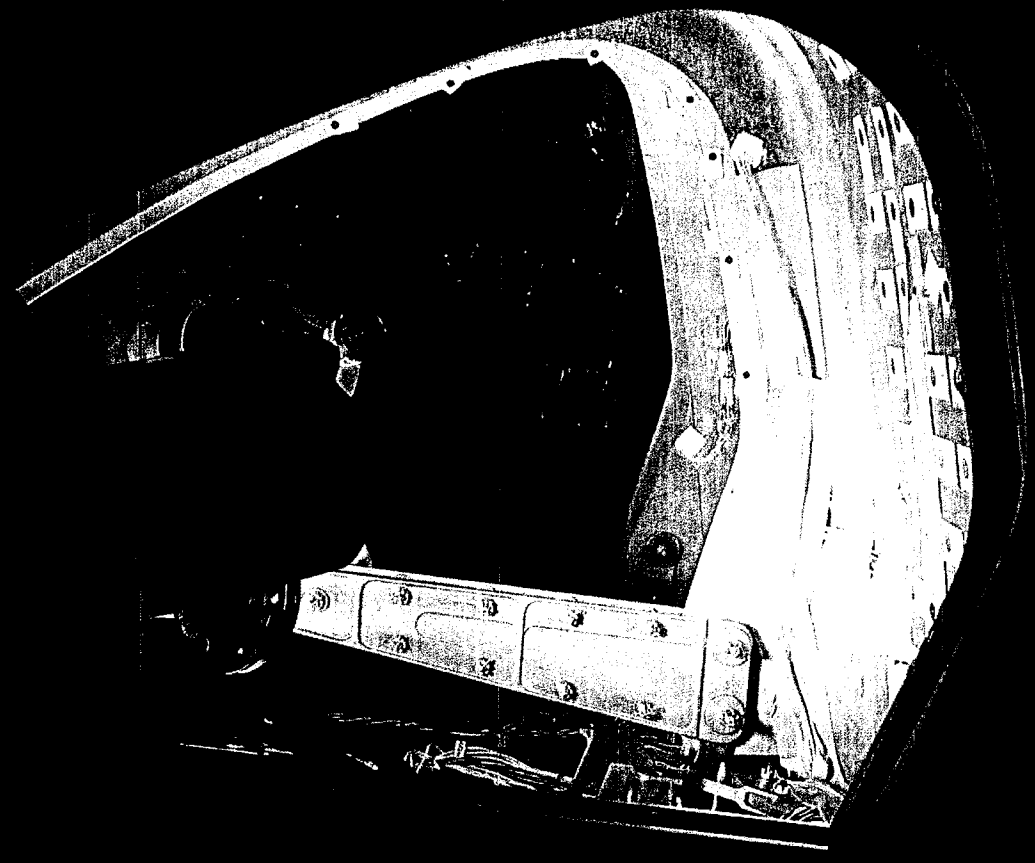
Leading edge panels mounted after camera installation

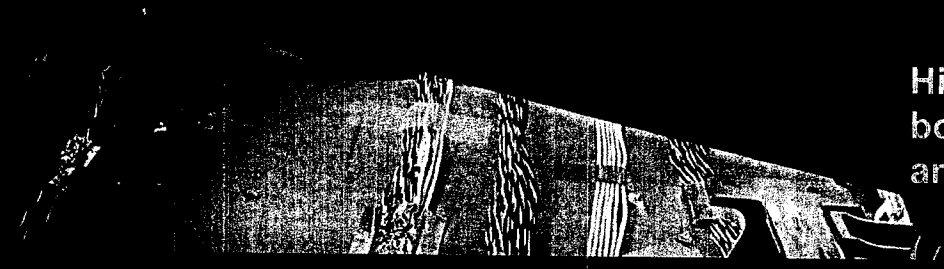
Orbiter Leading Edge Full Scale Tests

Phantom digital cameras set up inside of full scale test article



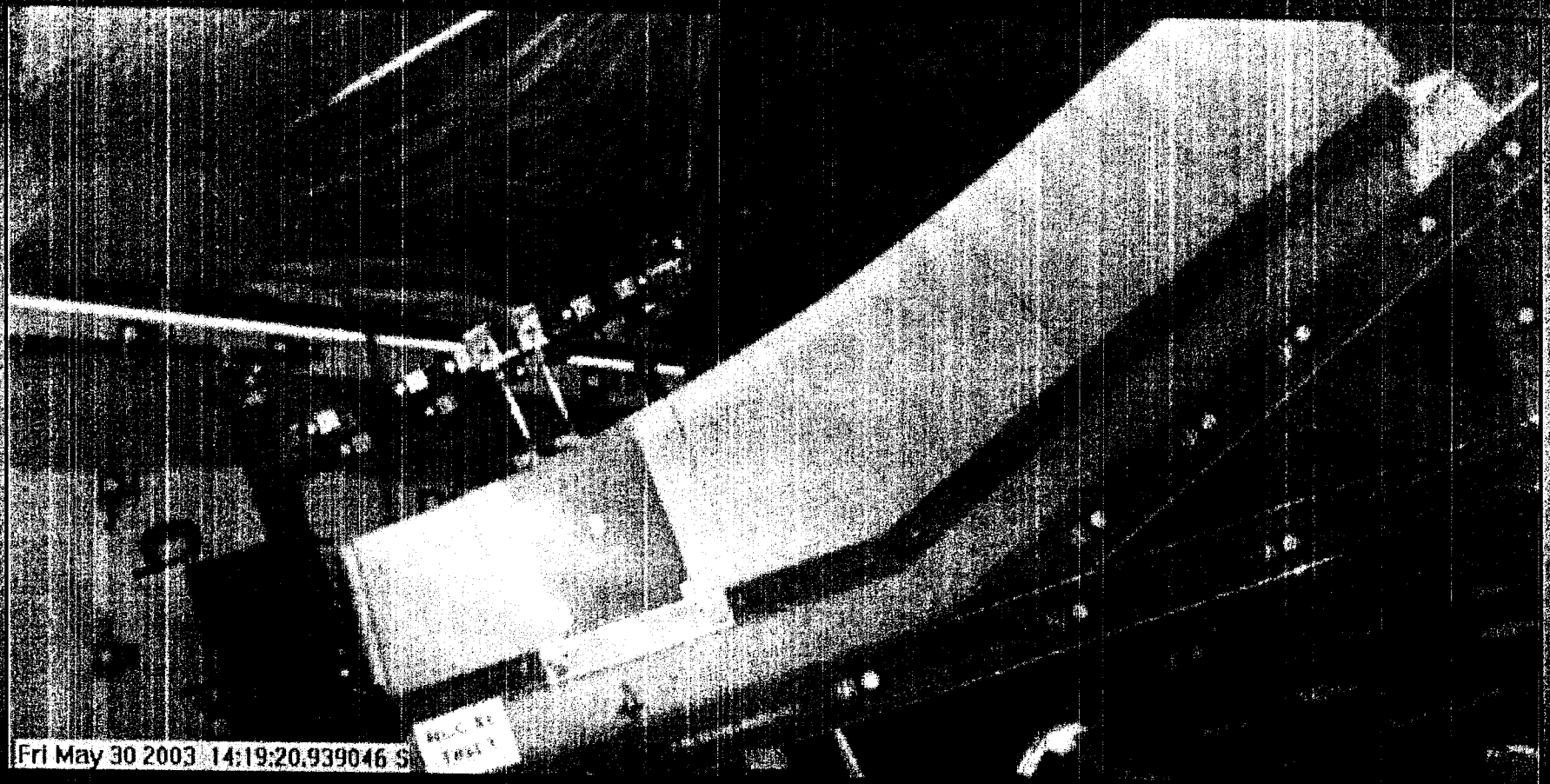
Orbiter Leading Edge Full Scale Tests





High intensity lights required both in and outside of test article

Orbiter Leading Edge Full Scale Tests



External View of RCC Panel 6 Test

Orbiter Leading Edge Full Scale Tests

External View of RCC Panel 6 Test

Pre-Test Simulation Results: Influence of Plastic Failure Strain

LS-DYNA predicted structural deformation and damage at 1.7 ms

Yield = 6000 psi
Failure strain = 0.0015

Baseline
Yield = 6000 psi
Failure strain = 0.003

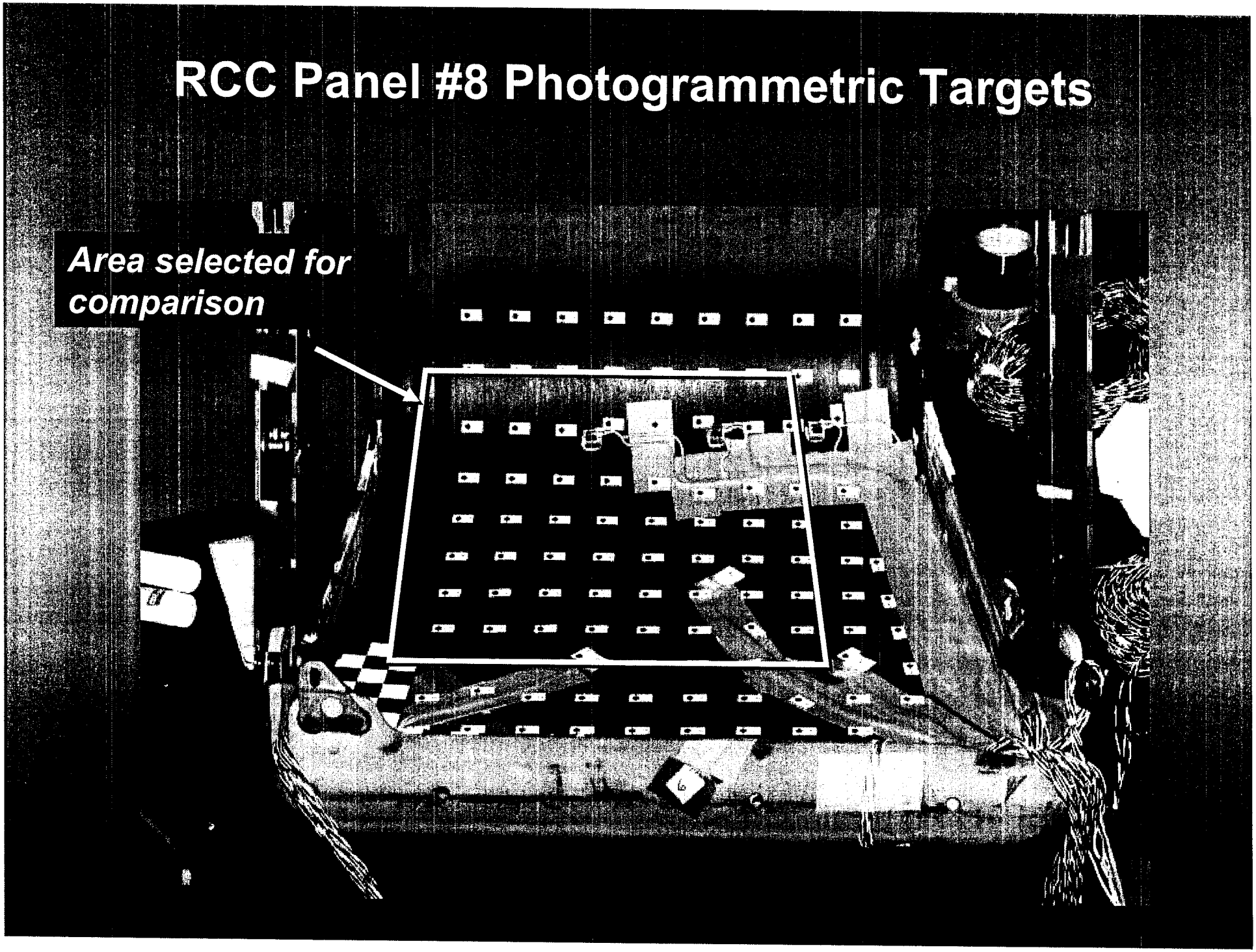
Yield = 6000 psi
Failure strain = 0.006

Failure

Plastic strain

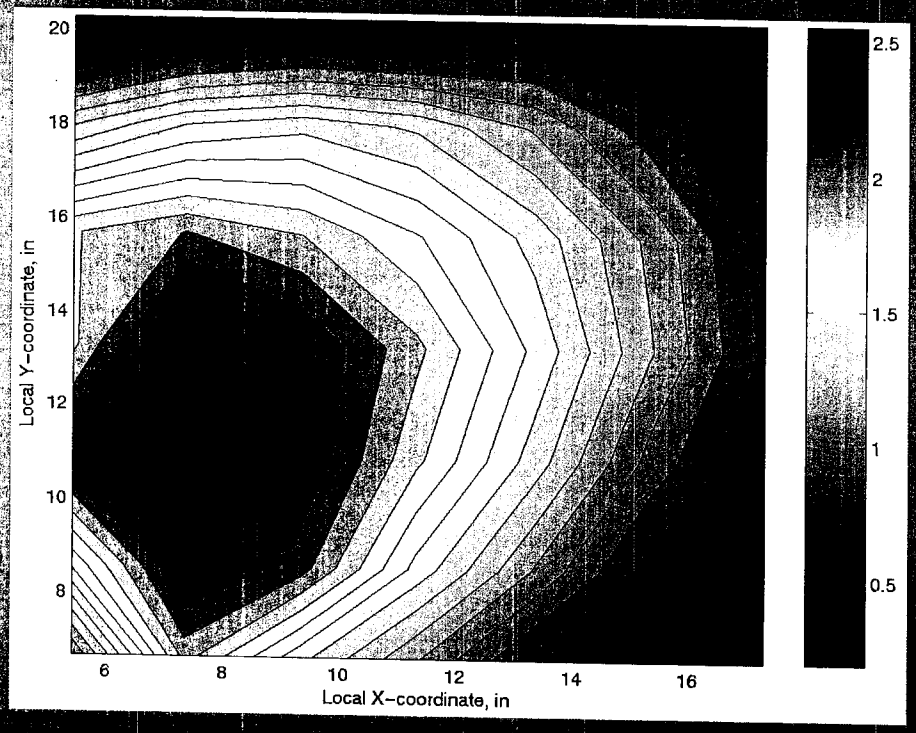
0.0

RCC Panel #8 Photogrammetric Targets



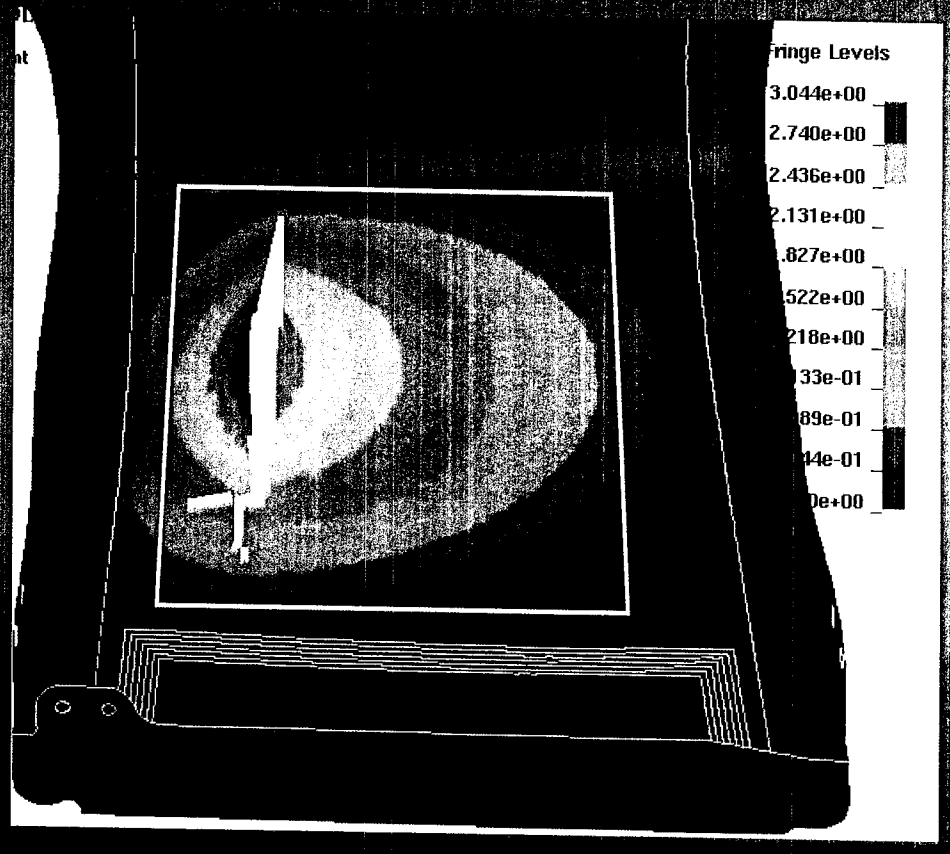
Comparison of Measured vs Predicted Displacement For SwRI Panel 8 Test at ~ 2.8 ms after Impact

Measured



Resultant displacement (in.)
From photogrammetry
(not-to-scale, see white square on right)

Predicted



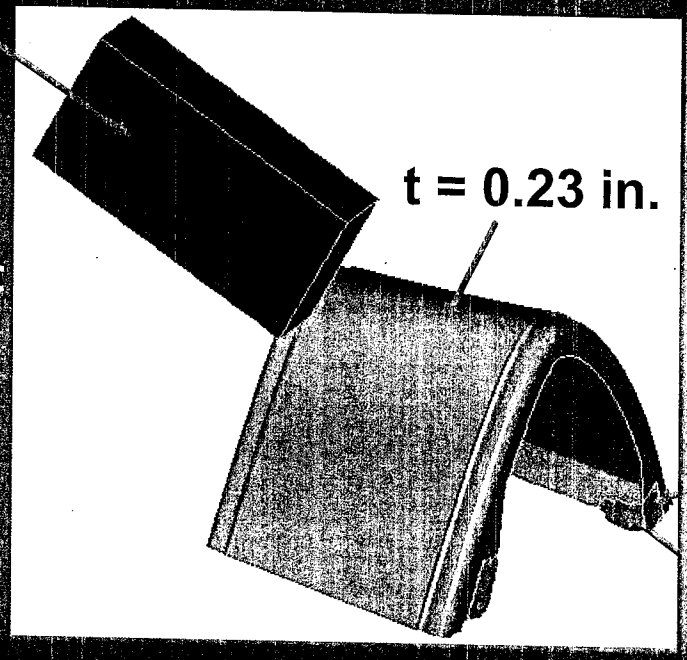
LS-Dyna model
(rear inside view)

RCC Model Development: Corner Impact Scenario

v = 9,300 in/s

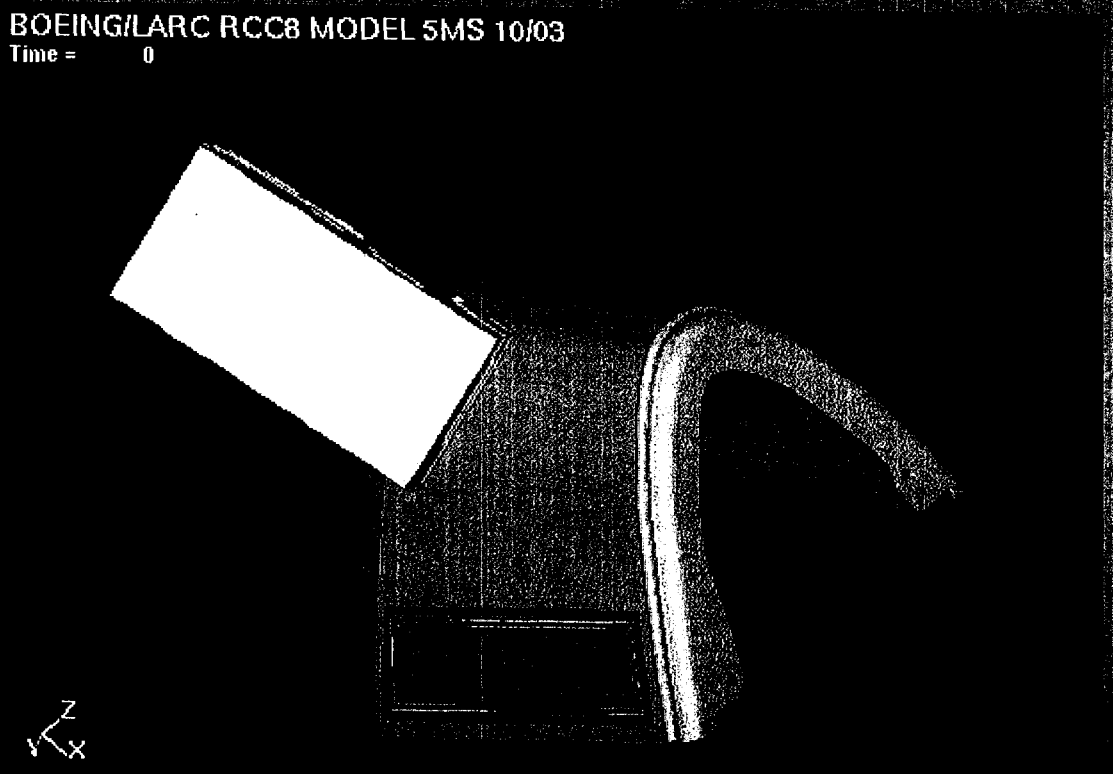
Modeling Details:

- Fully constrained at bolt holes
- Foam properties from experiment
- RCC – Bi-linear with failure
- Initial time step = 7×10^{-7} seconds
- ~15 minutes CPU/millisecond
- Coefficient of friction = 0.1

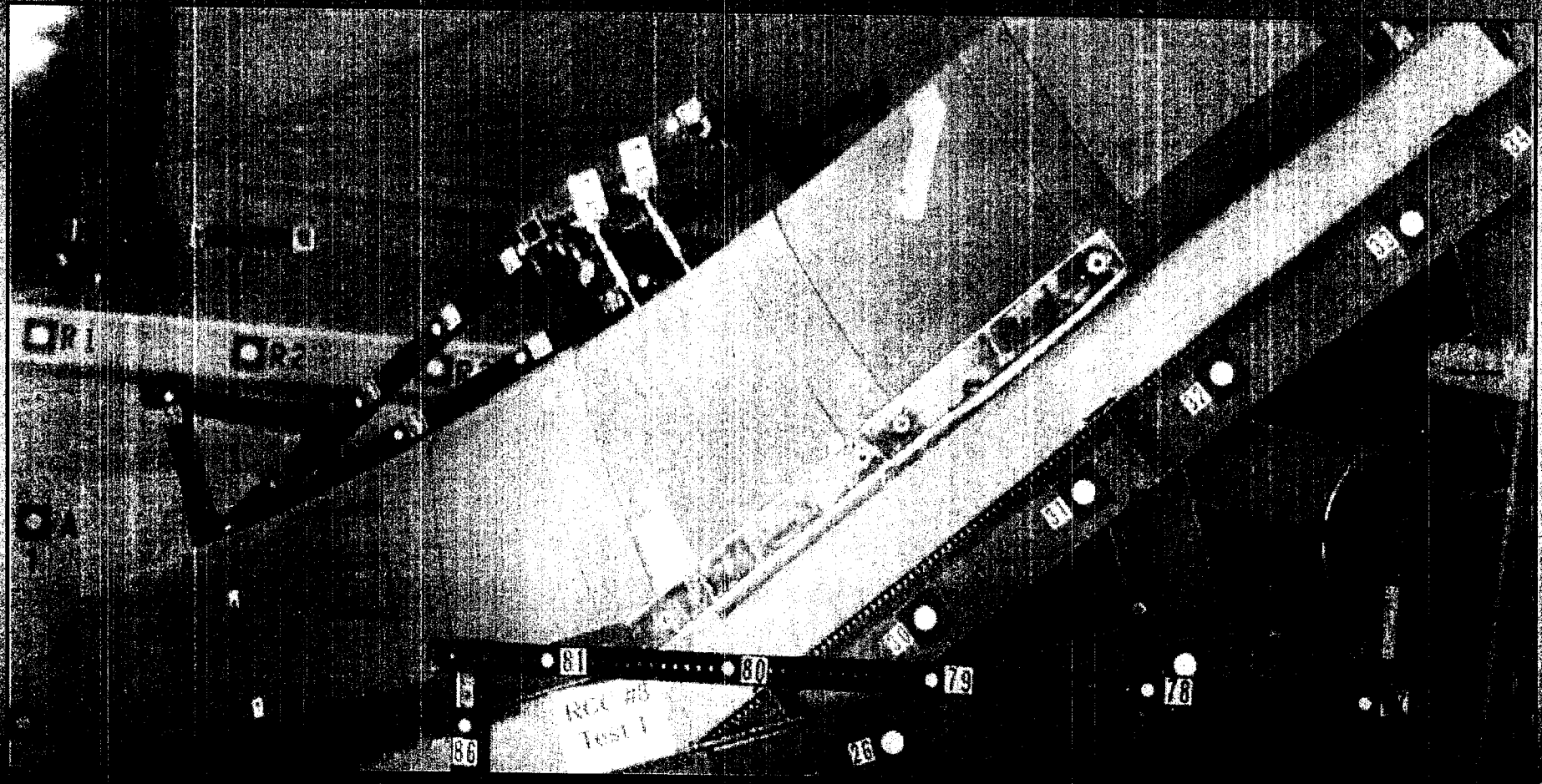


	RCC	Impactor
Density, lb s^2/ $in.^4$	1.47×10^{-3}	3×10^{-6}
Weight, lb.	22.36	1.67
Nominal length, in.	0.3	0.4
Elements	19,073 shells	23,142 solids

Foam Impact Prediction



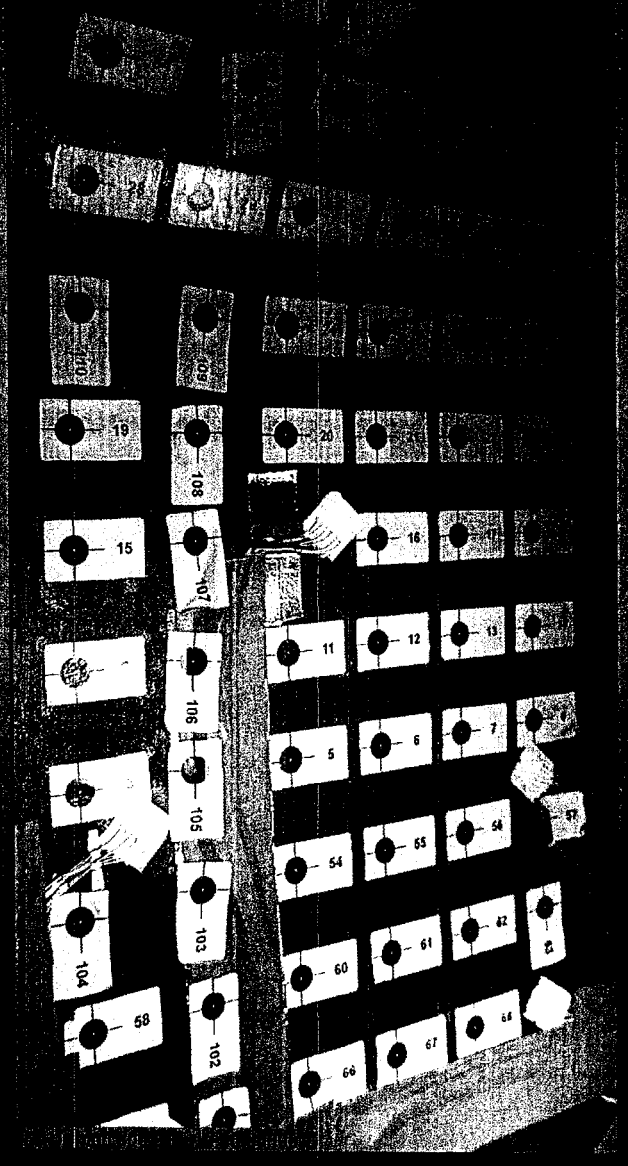
Orbiter Leading Edge Full Scale Tests



External View of RCC Panel 8 Test

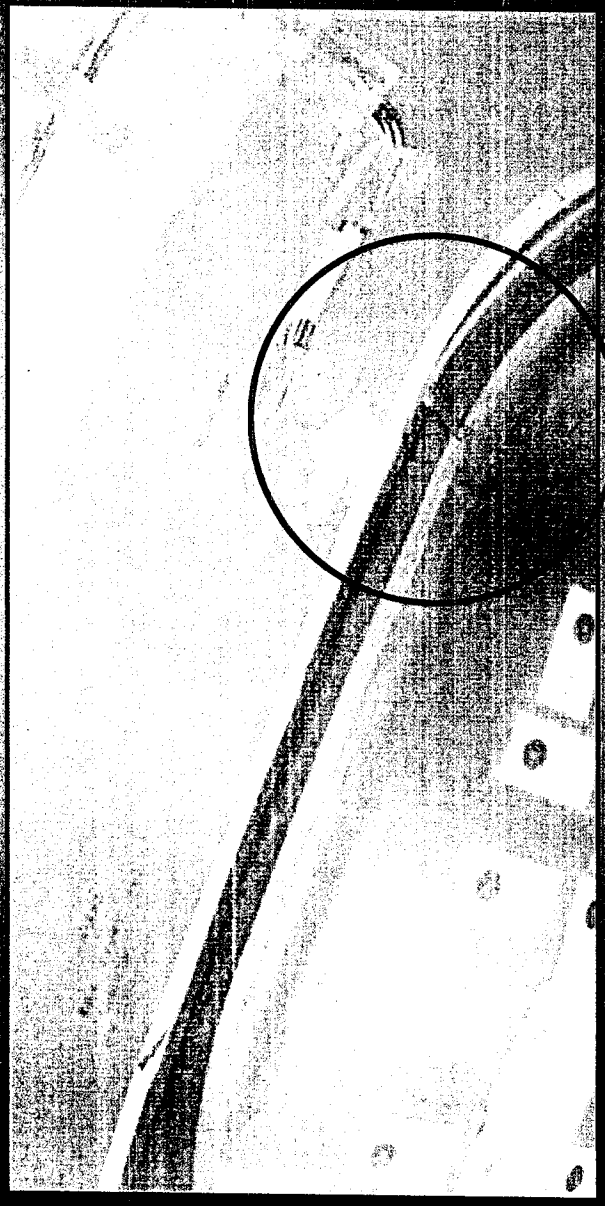
Foam Impact Testing

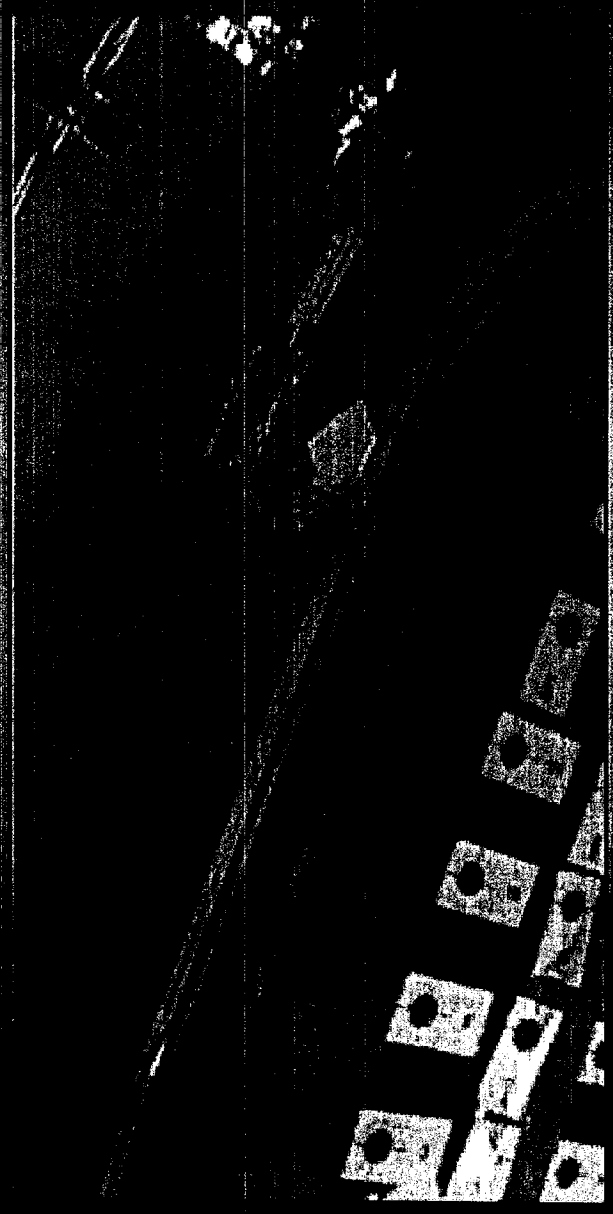
Orbiter Leading Edge Full Scale Tests



Internal View of RCC Panel 6 Test

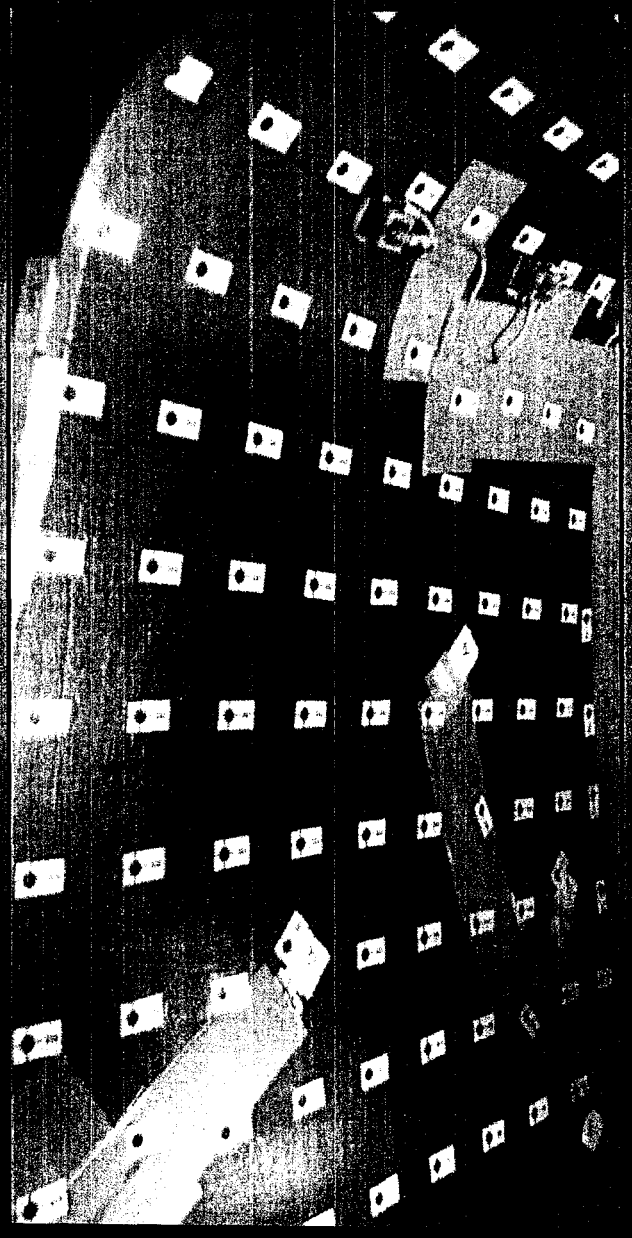
Orbiter Leading Edge Full Scale Tests





Internal View of RCC Panel 6 Test shows crack form in rib

Orbiter Leading Edge Full Scale Tests

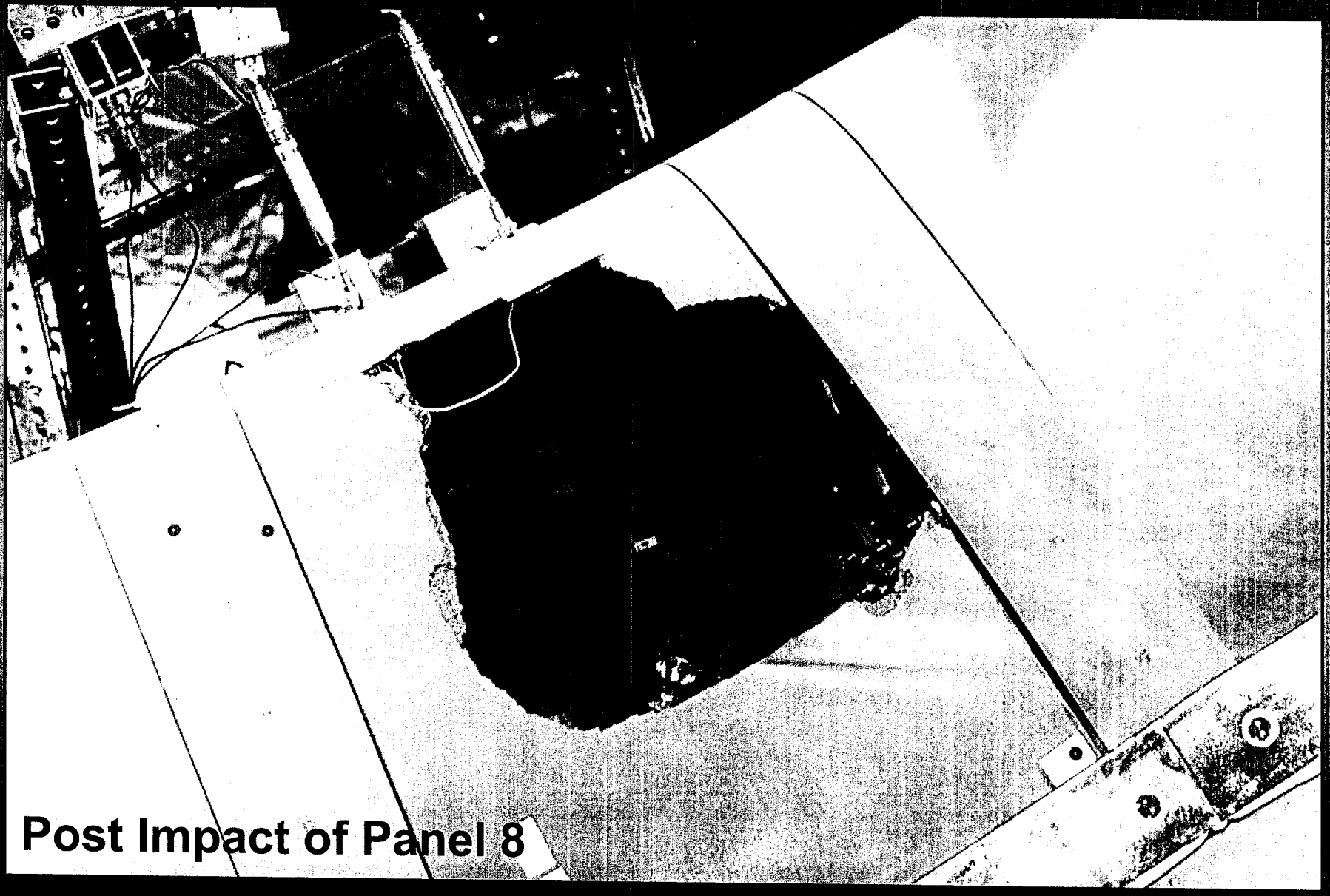


Internal View of
RCC Panel 8 Test

Orbiter Leading Edge Full Scale Tests

Post Impact of Panel 8

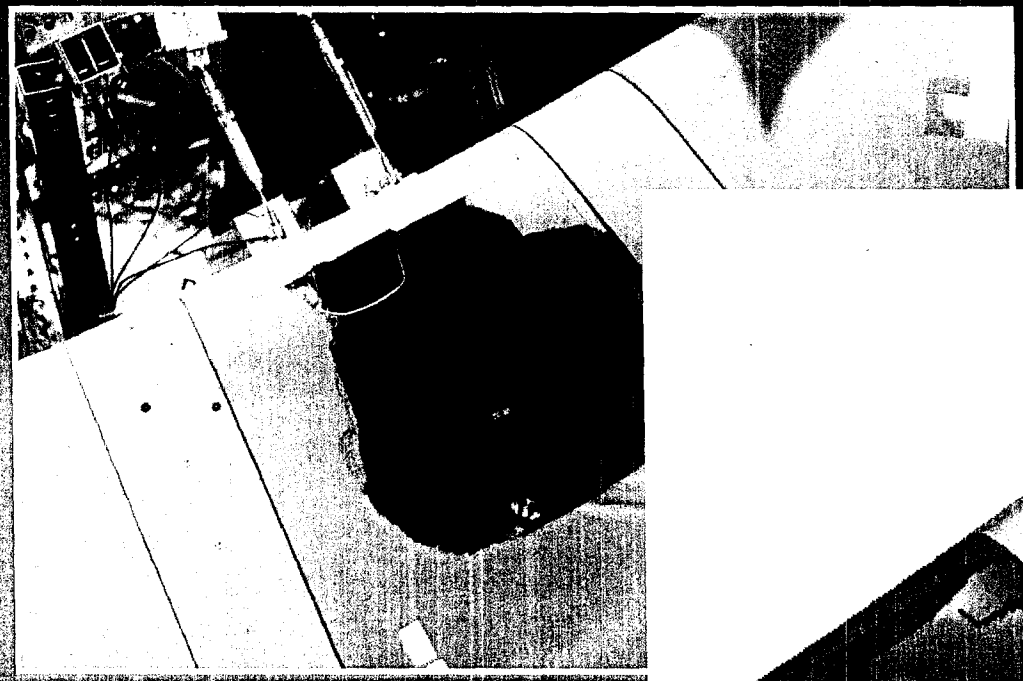
Orbiter Leading Edge Full Scale Tests



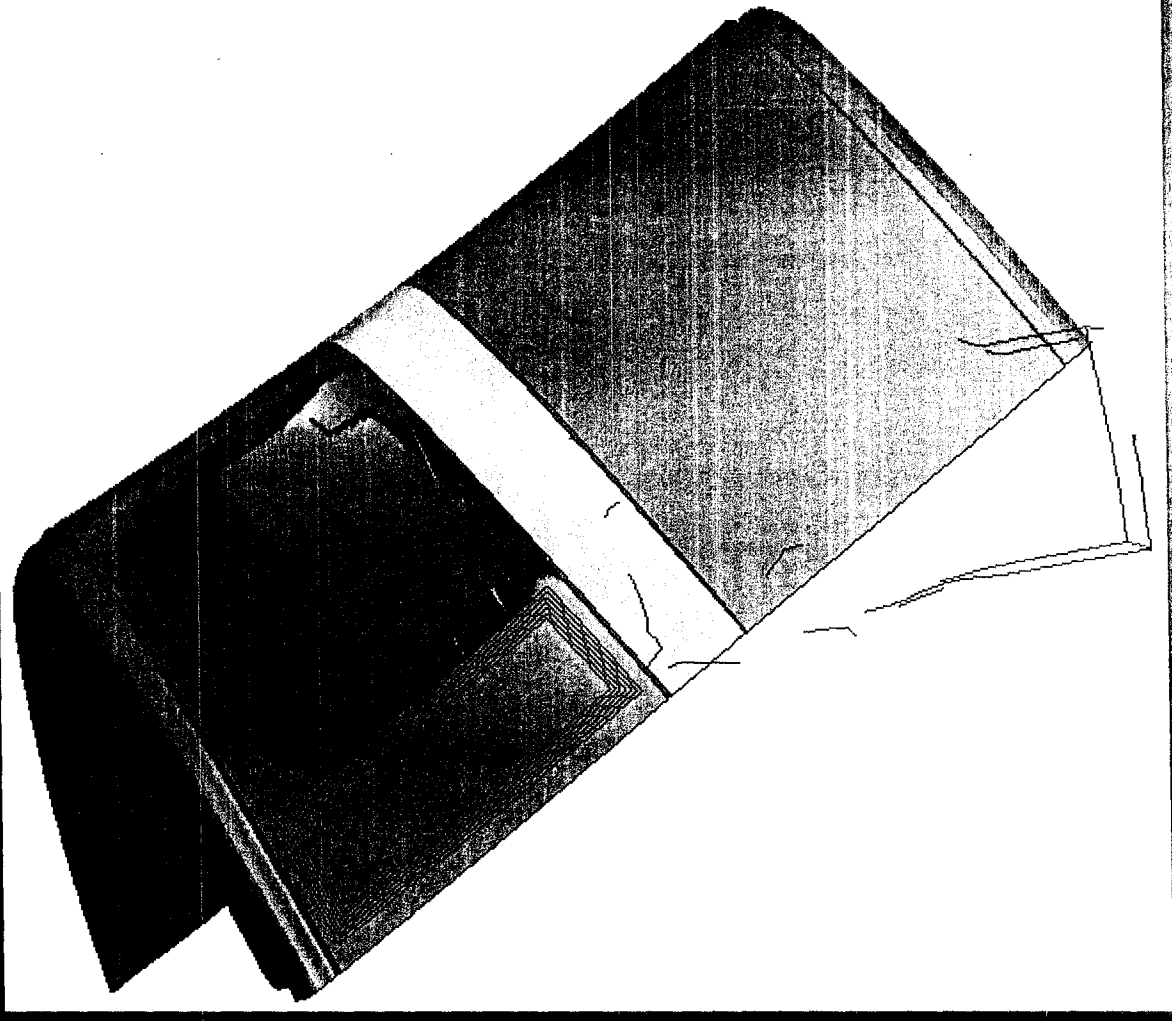
Post Impact of Panel 8

Analysis Supporting Full Scale Tests

Dyna – explicit finite element impact analysis

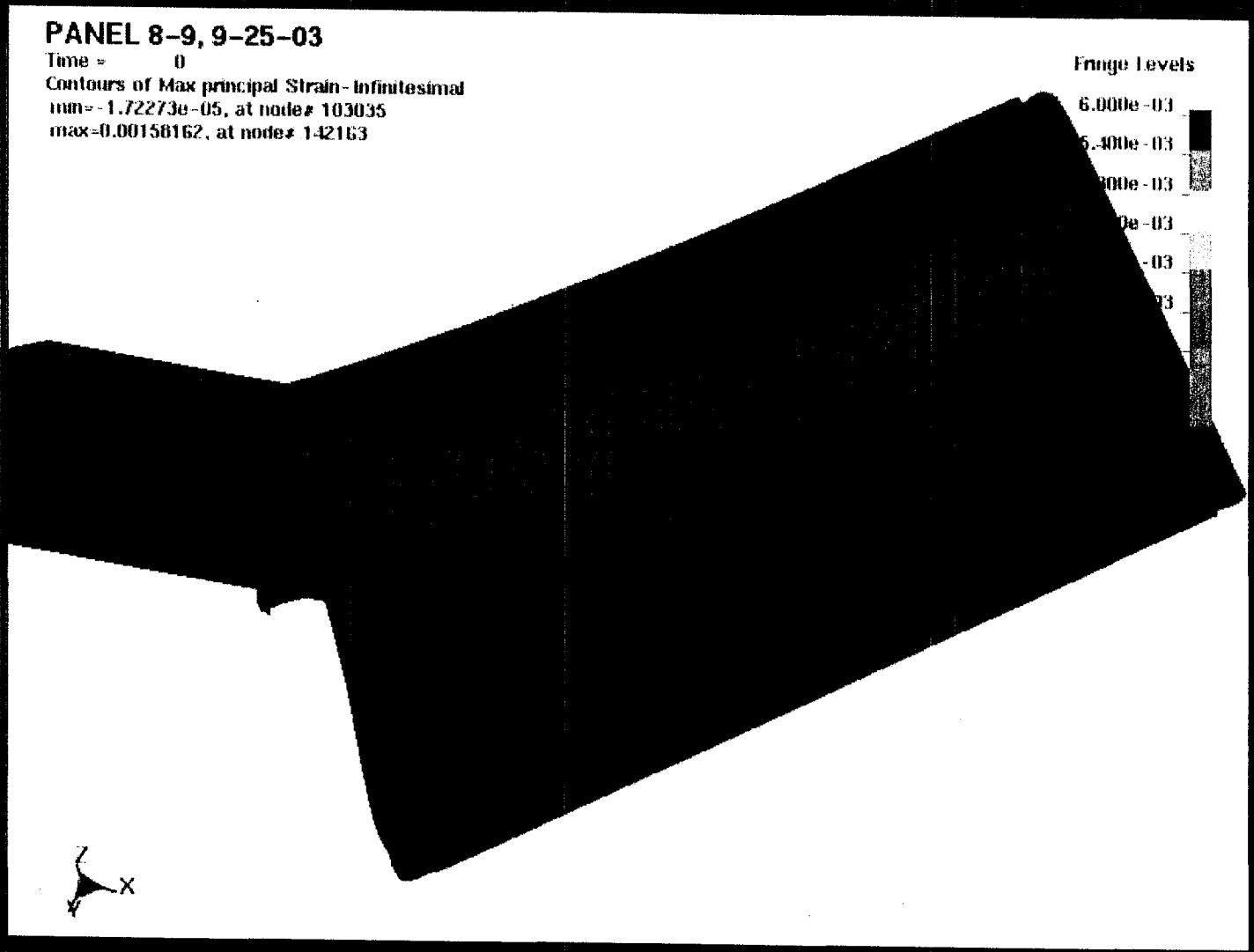


Latest Dyna Predictions Correlate with Panel 9 Test



Analysis Supporting Full Scale Tests

Dyna – explicit finite element impact analysis

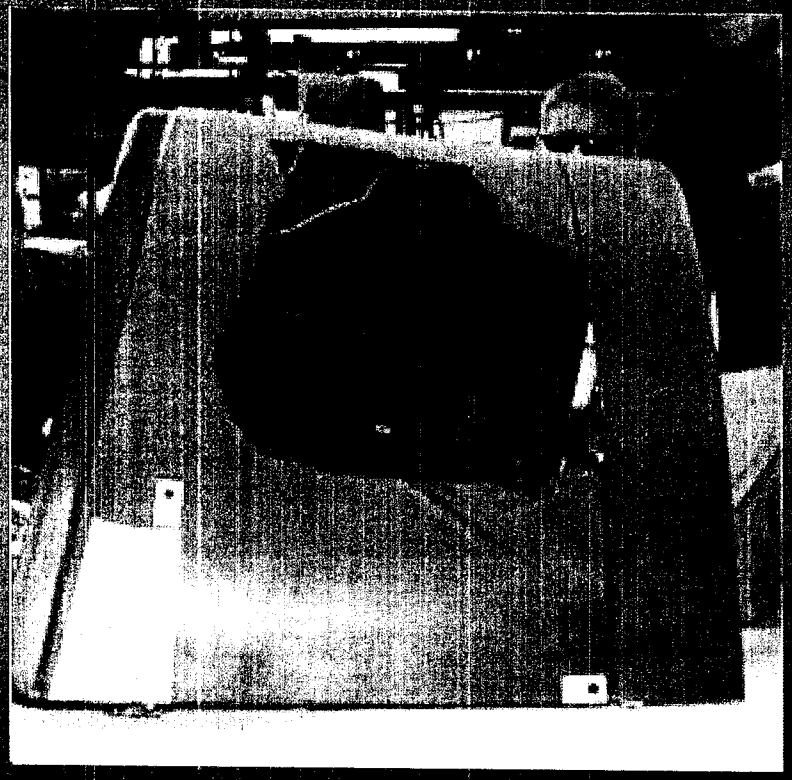


Latest Dyna Predictions Correlate with Panel 9 Test

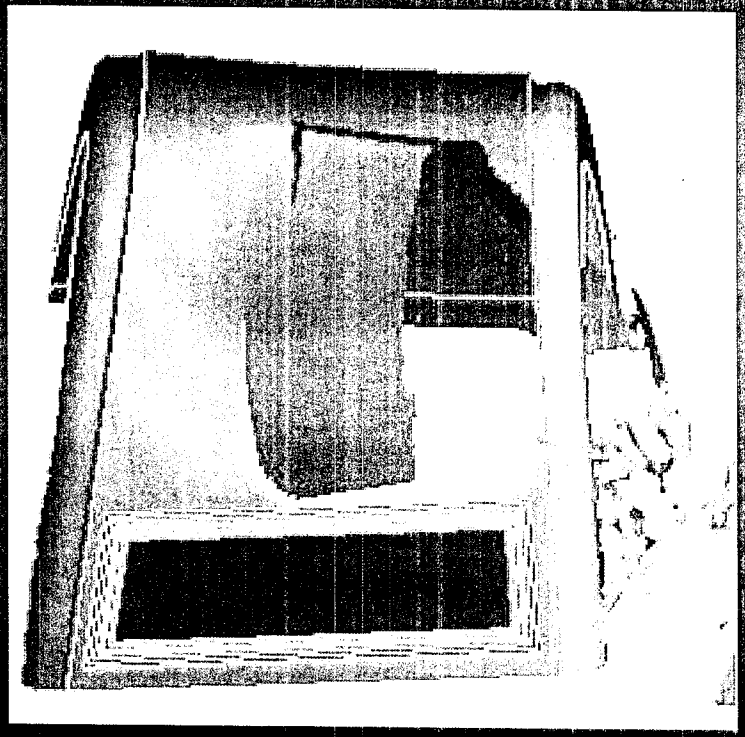
Orbiter Leading Edge Full Scale Tests

Barrel View of RCC Panel 8 Test

Comparison of Damage: SwRI Panel 8 Test

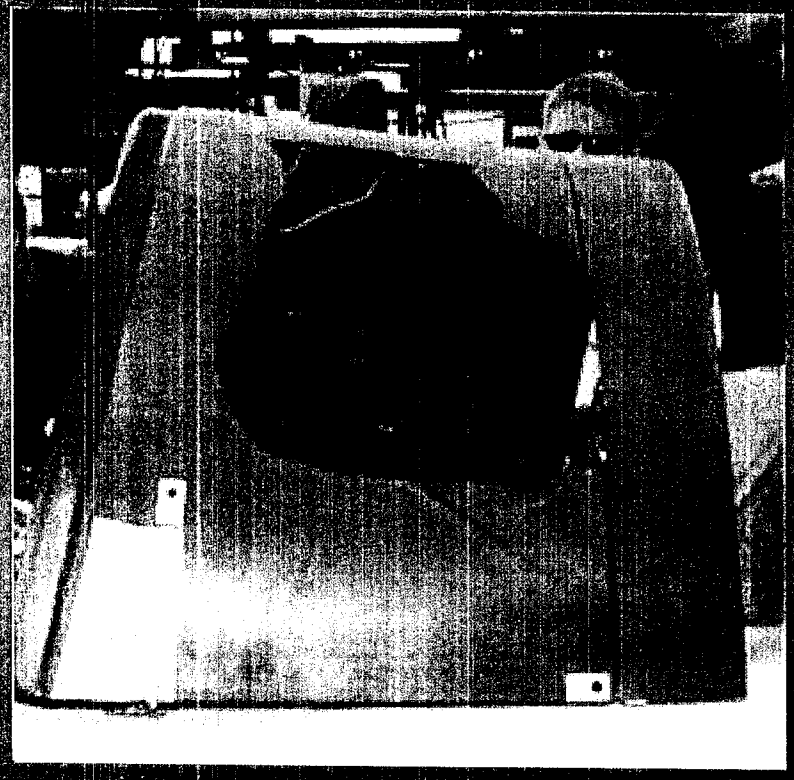


Panel 8, post-test

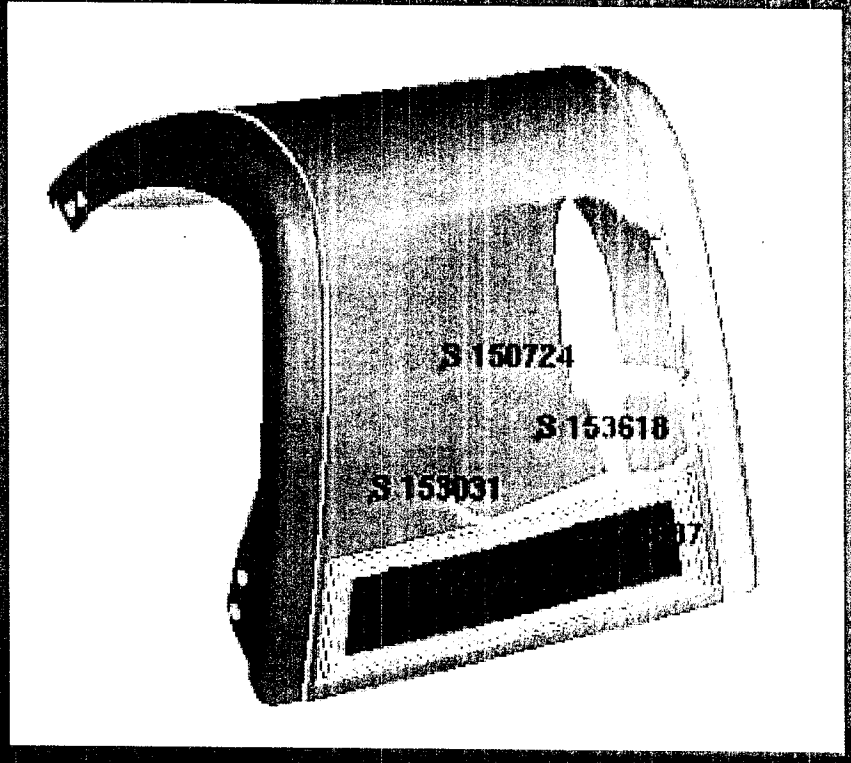


LS-Dyna model at 6 ms
(showing damage progressing)

Comparison of Damage: SwRI Panel 8 Test

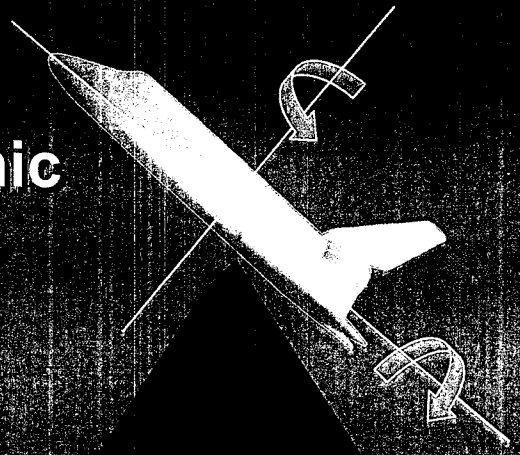


Panel 8, post-test



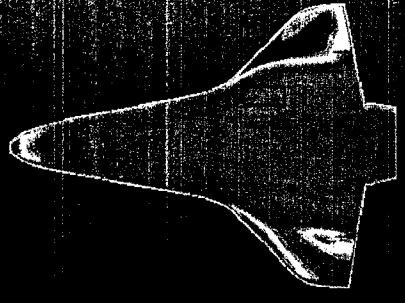
LS-Dyna model at 4 ms
(numbered elements correspond
to locations of strain gages 1 - 5)

Aerothermodynamics



Aerodynamic deltas

Main landing gear (MLG) wheel well temperature deltas



Motivation

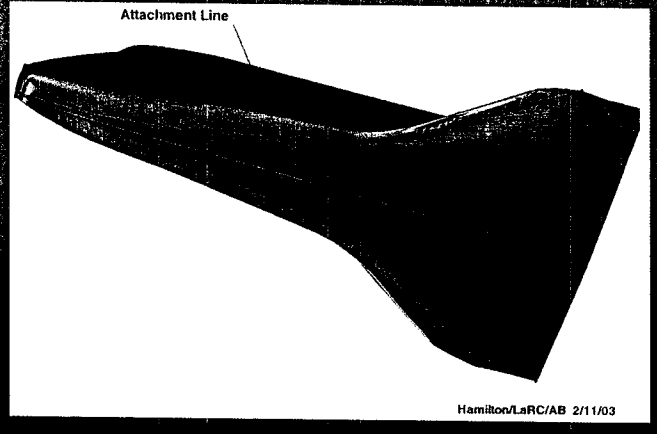
Address failure scenarios involving wing leading edge and acreage thermal protection system (TPS) tile damage

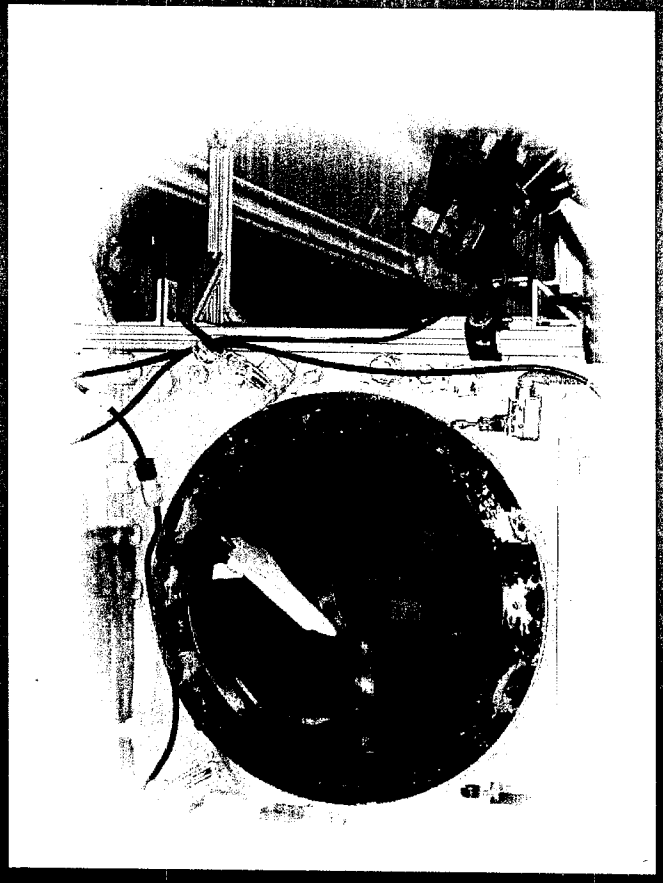
Left side fuselage bondline temperature deltas

Aerodynamics

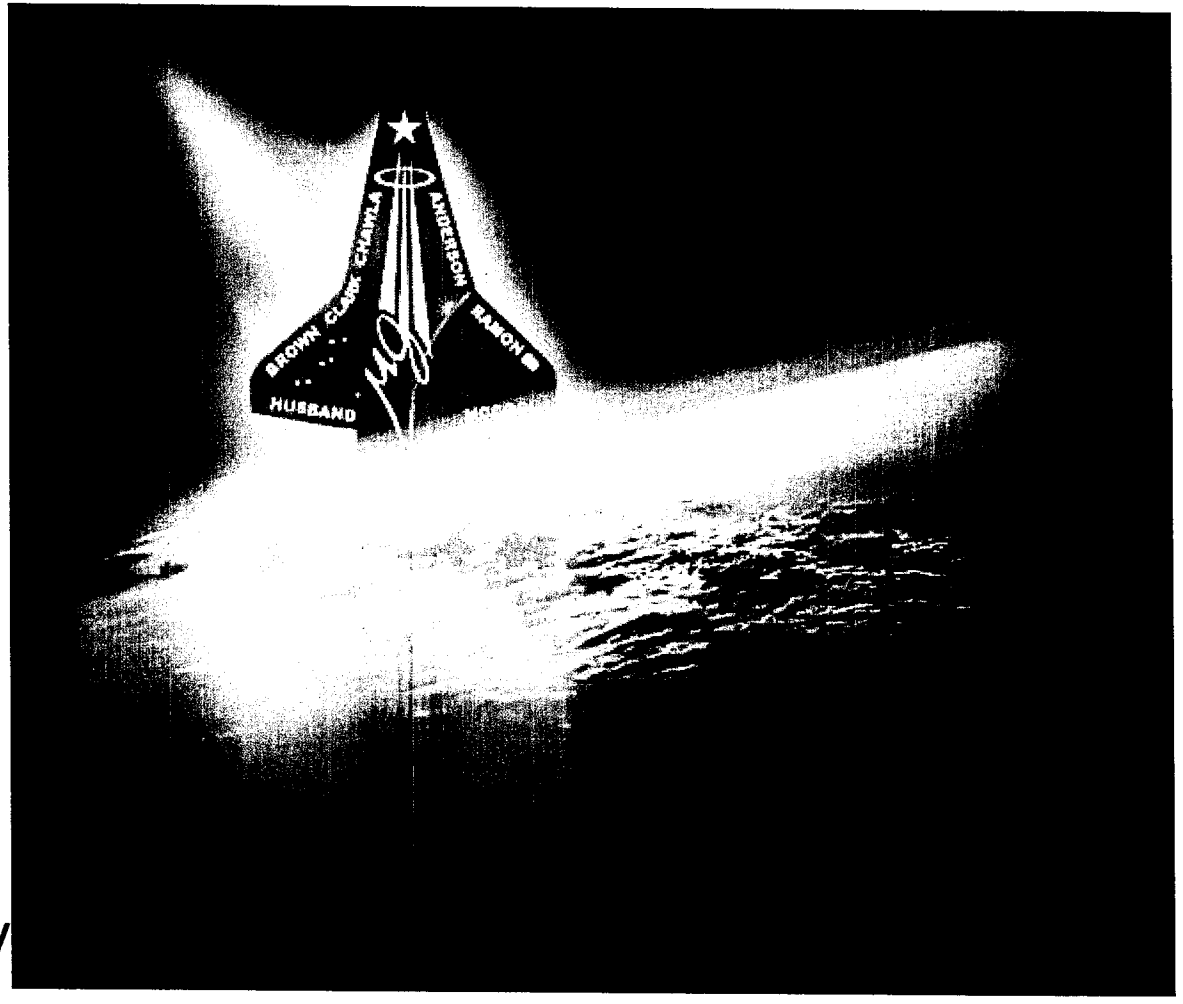
Objective:

Replicate what might have happened based on damage scenarios and aerodynamic data.





Remembering *Columbia STS-107*



www.nasa.gov

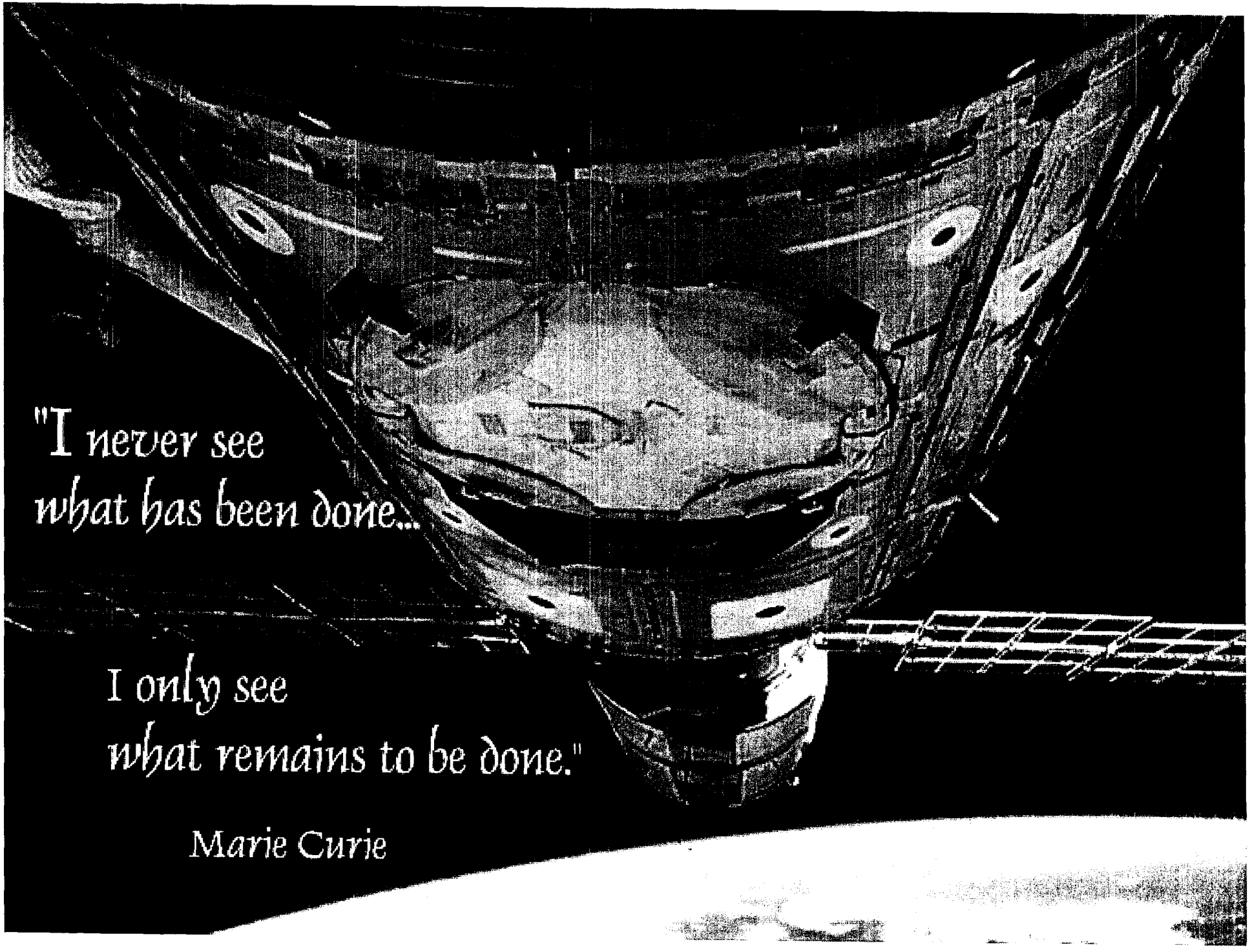
www.nasa.gov/columbia

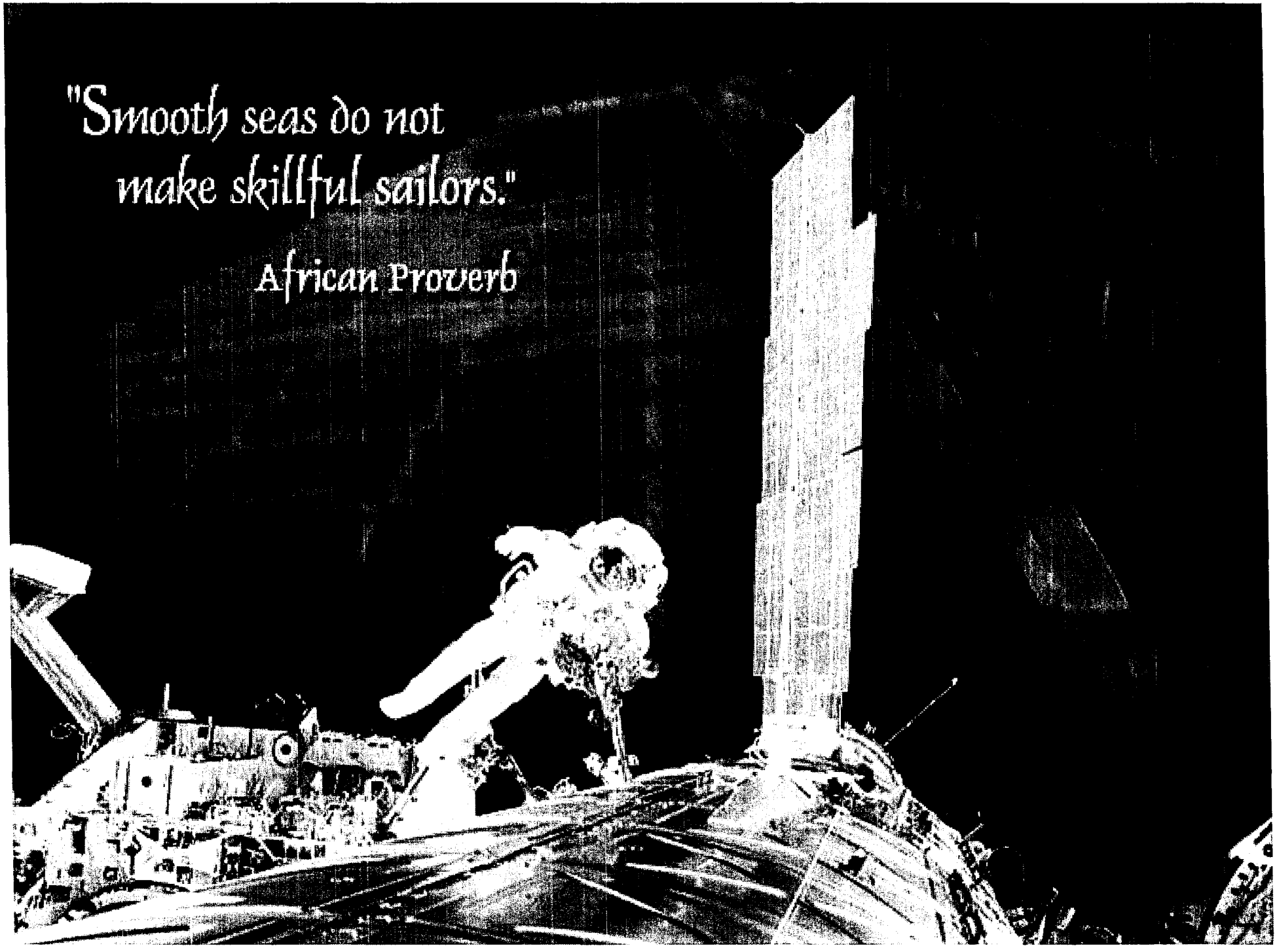
"No pessimist ever
discovered the secrets
of the stars...

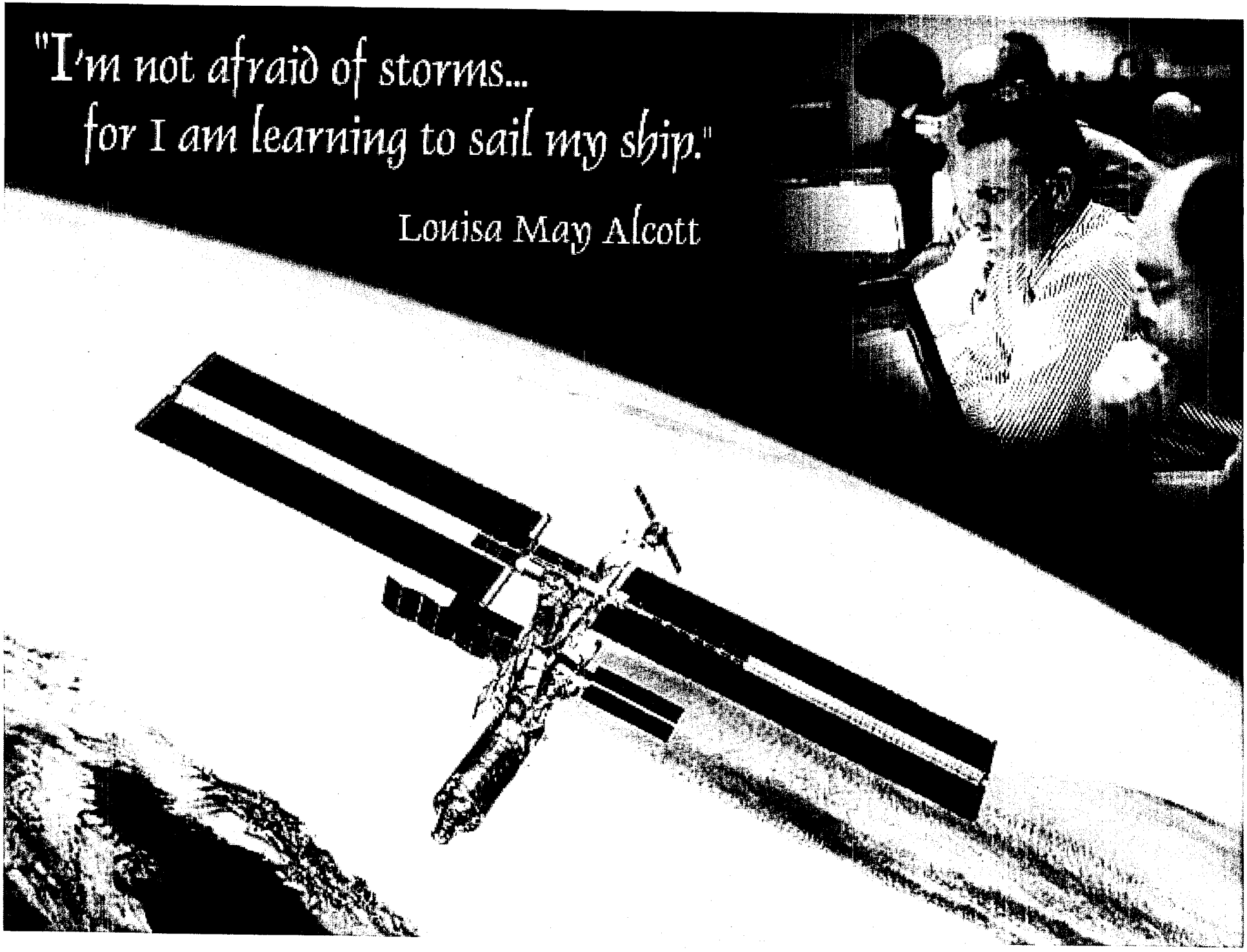
or sailed to an
uncharted land...

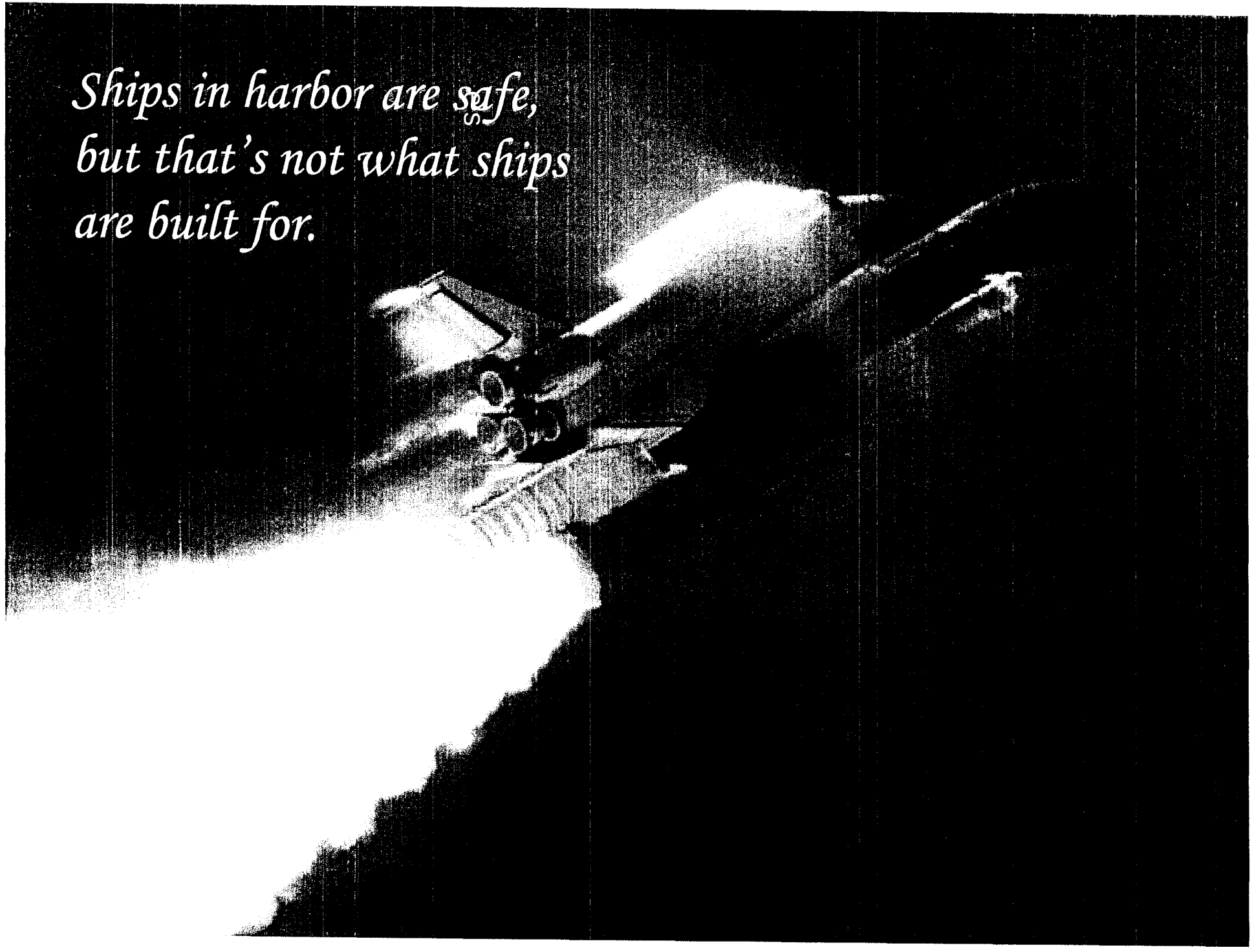
or opened a new
heaven to
the human spirit."

Helen Keller


"I never see
what has been done...
I only see
what remains to be done."
Marie Curie


"Smooth seas do not
make skillful sailors."
African Proverb


"I'm not afraid of storms...
for I am learning to sail my ship."
Louisa May Alcott


Ships in harbor are safe,
but that's not what ships
are built for.