Nondestructive Testing of Fracture and Failure Critical Components

Ed Generazio

Agency NDE Specialist
Research and Technology Directorate
National Aeronautics and Space Administration
Langley Research Center, Hampton, VA

NDE Program Manager
Safety and Mission Assurance Office
National Aeronautics and Space Administration Headquarters, Washington, DC

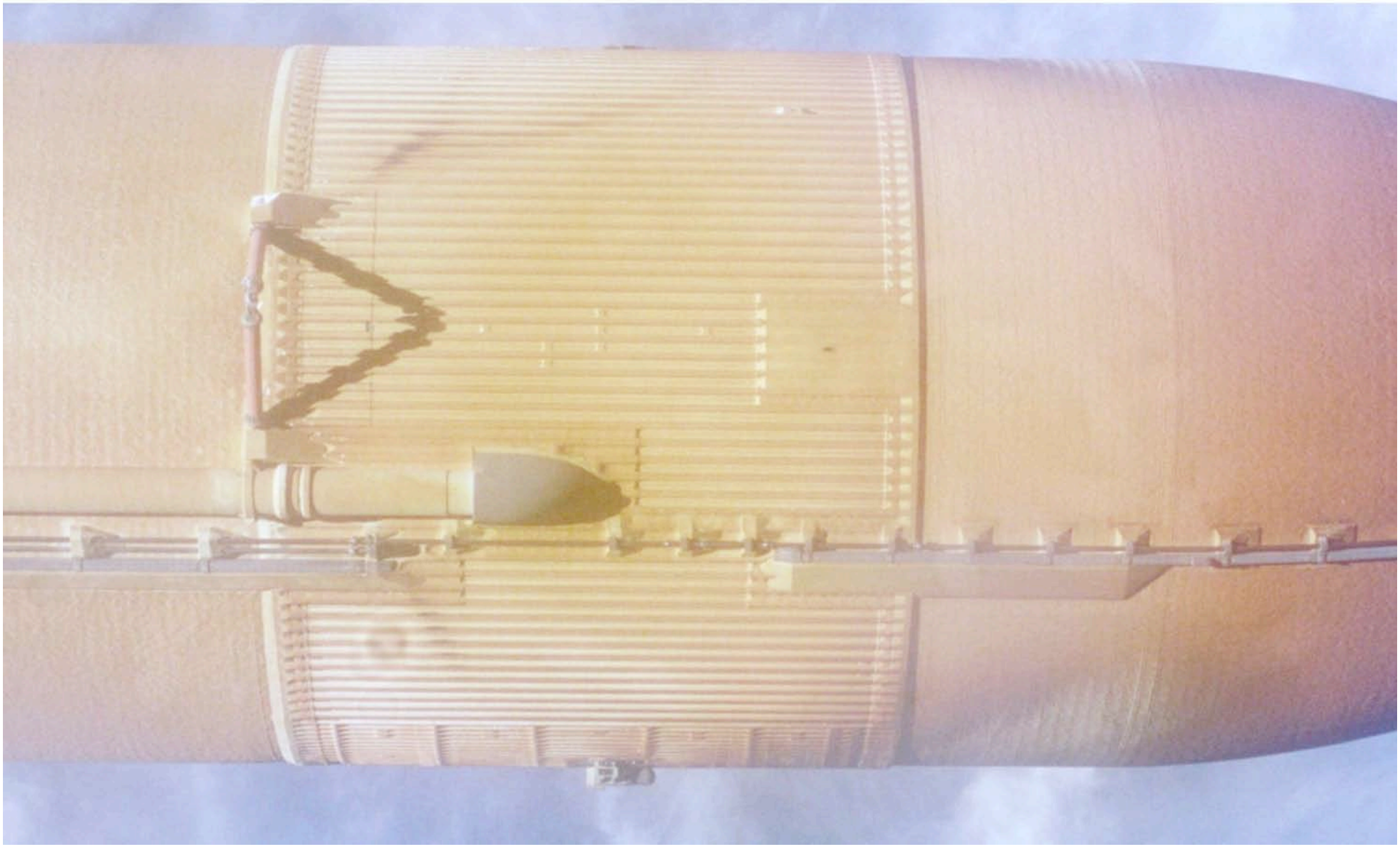
50th Annual Air Transportation Association (ATA) Non-Destructive Testing (NT) Forum
Hyatt Regency Hotel, Orlando International Airport
Orlando, Florida
August 27 - 30, 2007

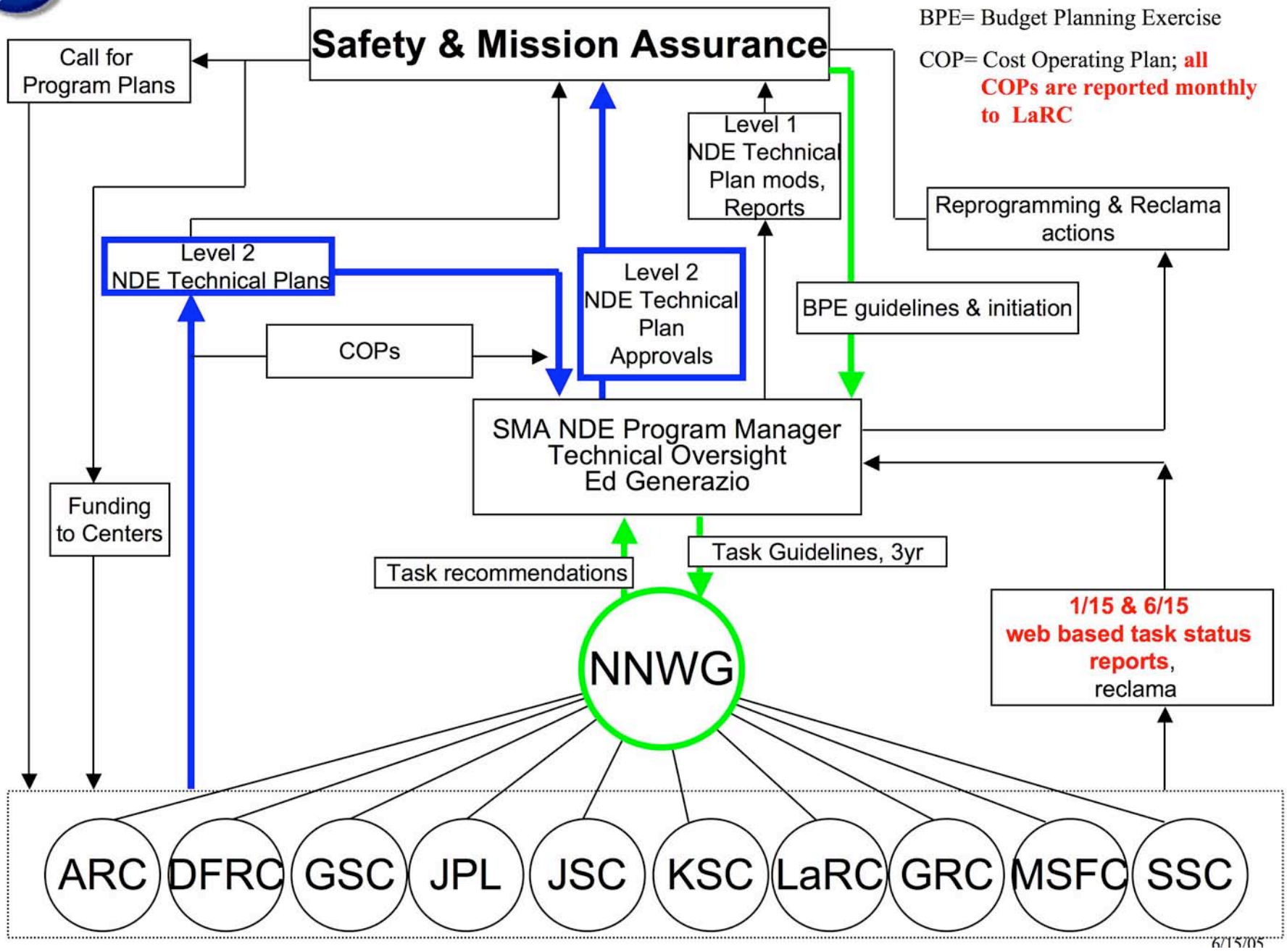
OUTLINE

- Columbia Mishap
- NASA NDE Team & Agency NDE Program
- Space Transportation System Inspection (Advanced NDI)
- On-Orbit NDT (Inspectors in Space)
- NASA Core NDT Standards
- Looking Toward the Future
- Summary

- Launch Movie
- Debris Strike Movie
- Foam Impact on RCC – Outside View
- Foam Impact on RCC – Inside View

External Tank TPS



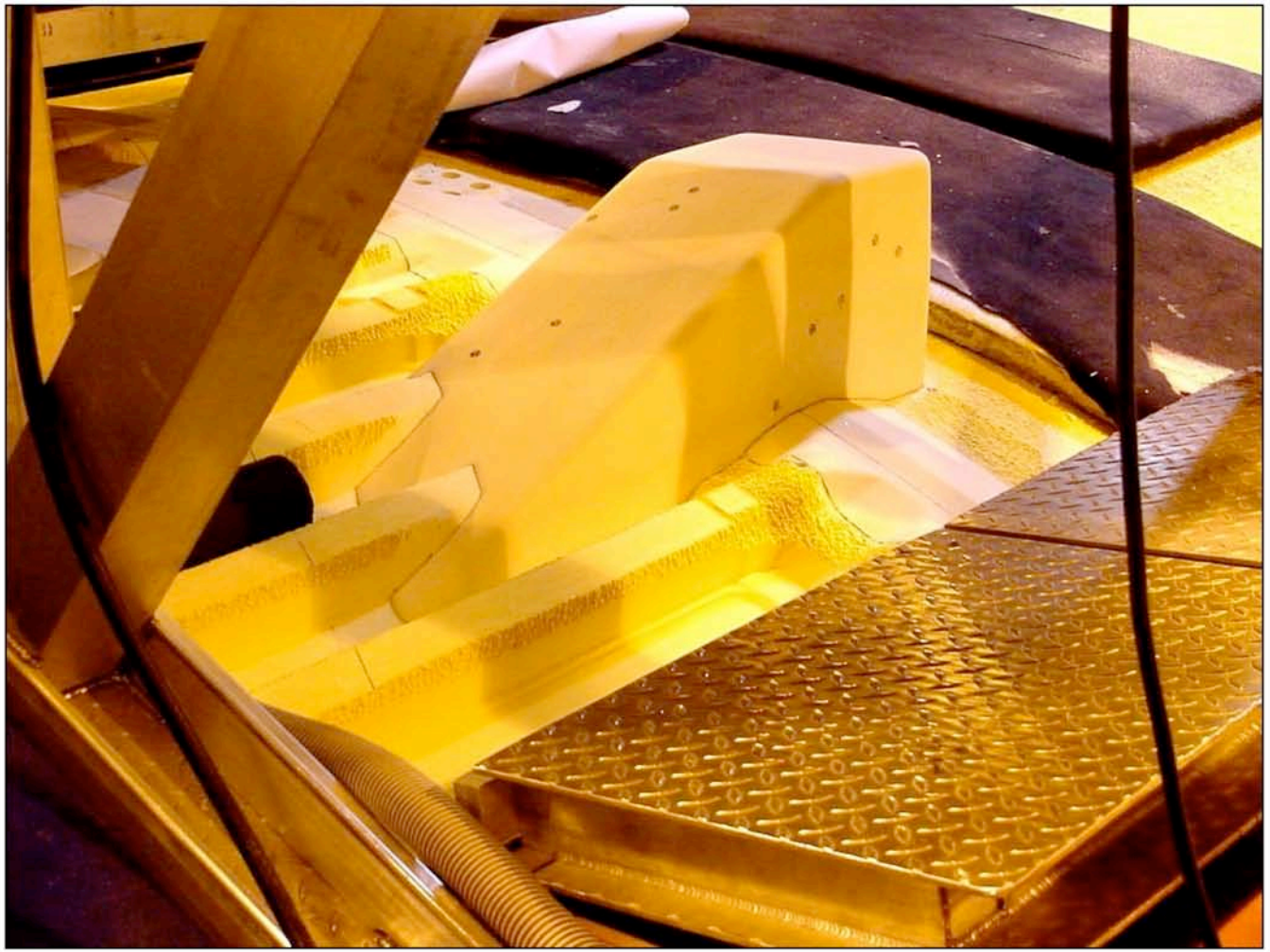

Safety & Mission Assurance
BPE= Budget Planning Exercise
COP= Cost Operating Plan; all COPs are reported monthly to LaRC
Call for Program Plans
Level 1 NDE Technical Plan mods, Reports
Reprogramming & Reclama actions
Level 2 NDE Technical Plans
Level 2 NDE Technical Plan Approvals
BPE guidelines & initiation
COPs
SMA NDE Program Manager Technical Oversight Ed Generazio
Funding to Centers
Task recommendations
Task Guidelines, 3yr
1/15 & 6/15 web based task status reports, reclama
NNWG
ARC
DFRC
GSC
JPL
JSC
KSC
LaRC
GRC
MSFC
SSC

Agency NDE Program

- Physical Brittle Matrix Composites Standards for validating inspection systems.
- Scanning materials characterization System applied to impact and oxidation damaged Orbiter RCC Leading Edge.
- Enhanced Micro-focus X-ray Tomography for applications to Orbiter RCC, CEV seals, and metallic sandwich foams.
- NDE Capability Assessment (thermal, ultrasonic, eddy current, x-ray tomography, backscatter X-ray, for characterization of impact and oxidation damaged Orbiter RCC Leading Edge.
- NDE Capability Assessment of Laser Vibrometer for global damage characterization in structures
- NDE Capability Assessment of Air Coupled Ultrasonics for bond evaluation of satellite systems (mirror segments, etc.)
- NDE Capability Assessment of Time Domain Reflectometry for Wiring Intergity (Vibration test-bed included: bend radii, sharp corner, oversized clamp, clamp missing rubber, exposed conductor, fraying, missing clamp, chaffing.
- NDE Capabilities Assessment of Electric Field Imaging for wire integrity.
- NDE Standard Guide (WK8211) and Practices *[Acoustic Emissons (WK12759), Thermal (WK12737), Shearography (WK12796), Radiography (13191), Ultrasonics (11990)]* for Composites
- NDE Technology Assessment (Acoustic Emission and Thermography) supporting 40" OMS COPV test.
- NDE Technology Assessment for COPVs, and 100 aged Physical COPV Standards for characterizing COPV age and state of stress rupture.
- Advanced NDE Technology for High Performance COPV
- Eddy Current On-Orbit Inspection System and Physical Standards for and Intravehicular activity (IVA) characterization of micrometeoroid damaged to Space Station skin panels.
- NDE Capabilities Assessment of thermography, backscatter x-ray, and millimeter wave, terahertz inspection technology for corrosion under paint, primer, and RTV Silicon (Obiter configuration), Tile Bond, Gap Filler Impregnation Level, FRSI, and SRB, supporting International Space Station (ISS), Constellation (Cx), Launch Services (LSP), Space Shuttle (SSP) Programs, and aging Ground Support Equipment (GSE).
- NDE Technology for ET close-outs and crushed foam at KSC, including: 3rd hardpoint, Orbiter Jack Panel and Umbilical Pyro Bolt, and Upper and Lower SRB Attach Points.
- NDE Technology for Orbiter Tile Bond Verification
- Computational Simulations of On-Orbit Solar Heating Thermography for TPS integrity
- Standard Methods for Generating Cork, Foam, and Carbon Fiber Physical Standards for NDE capability assessments for CLV, ET, RSRM, SRB, and Ares I Programs
- Health Monitoring identification of load and active areas of load distribution during COPV burst testing for SSP.
- Materials Engineering Properties at millimeter wavelengths for NDE systems calibrations applied to ET TPS inspections.
- NDE Capability Assessment of Limited Angle Reverse Geometry X-ray Laminography for Double Wall (12' apart) ET SOFI inspection, RCC, and Orbiter TPS Tile.

Terahertz NDE

A View of the SOFI Closeout Region

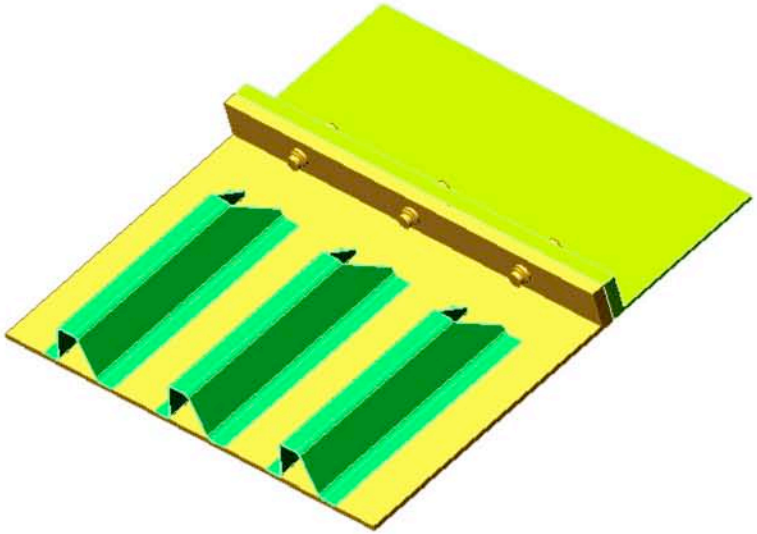


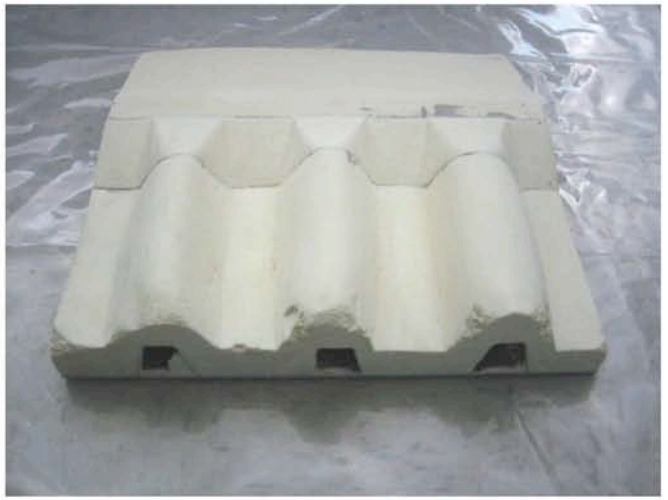
External Tank SOFI closeout region

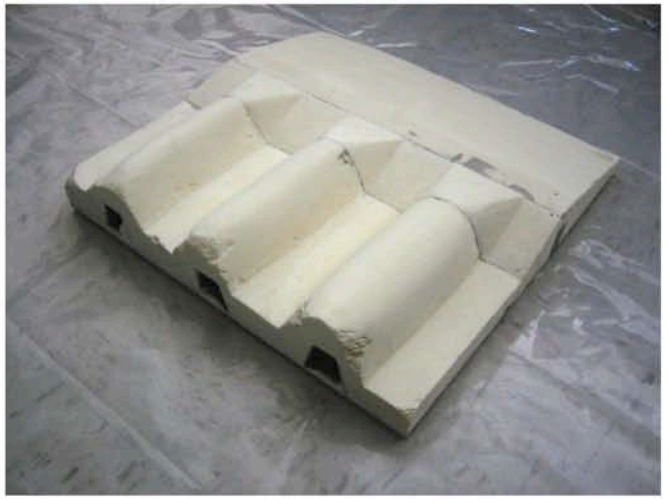
Bipod Joint Structure Under SOFI

NDE mockup of bipod joint with SOFI removed.

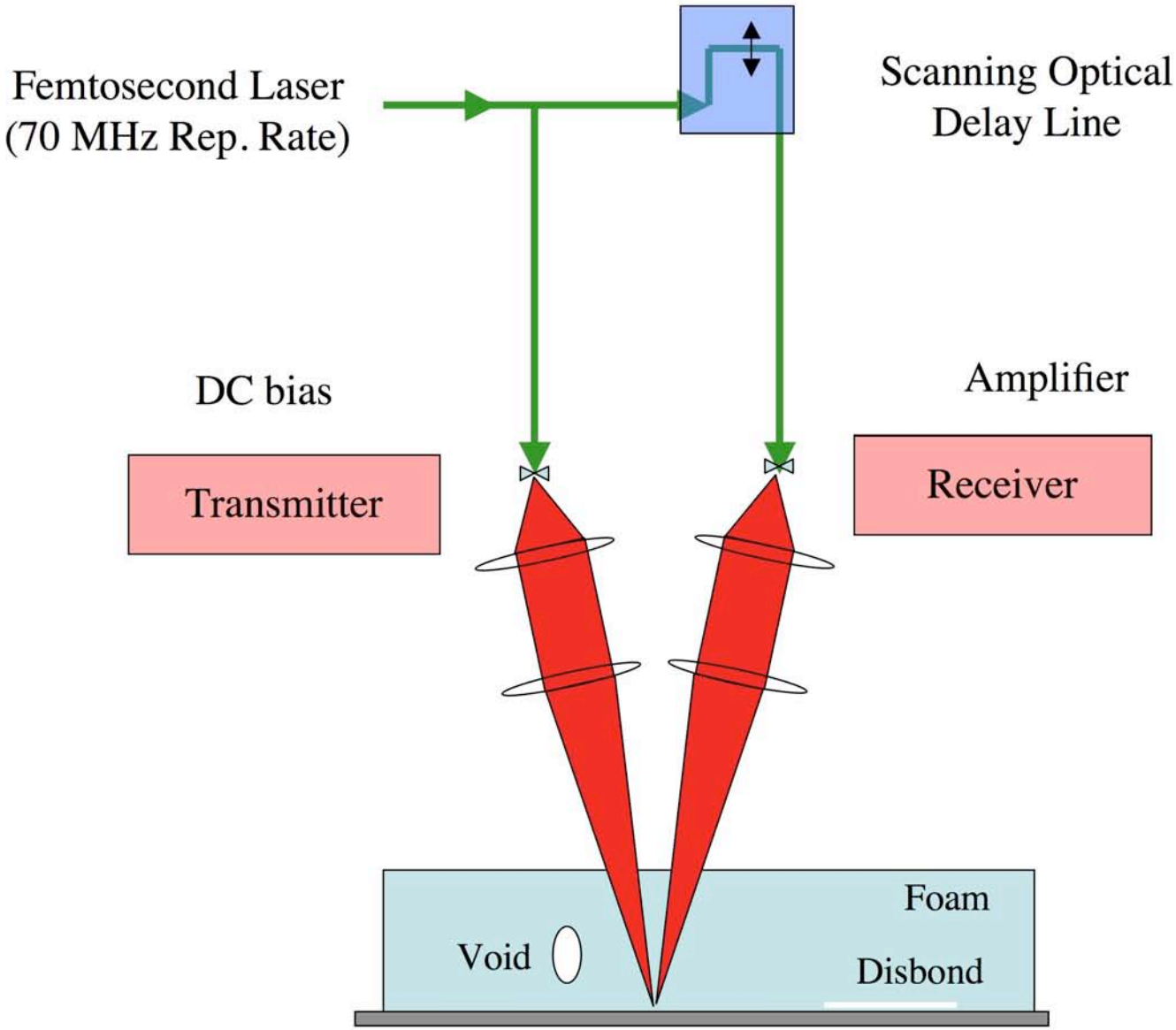
Probability of Detection (POD) Foam Panel Model



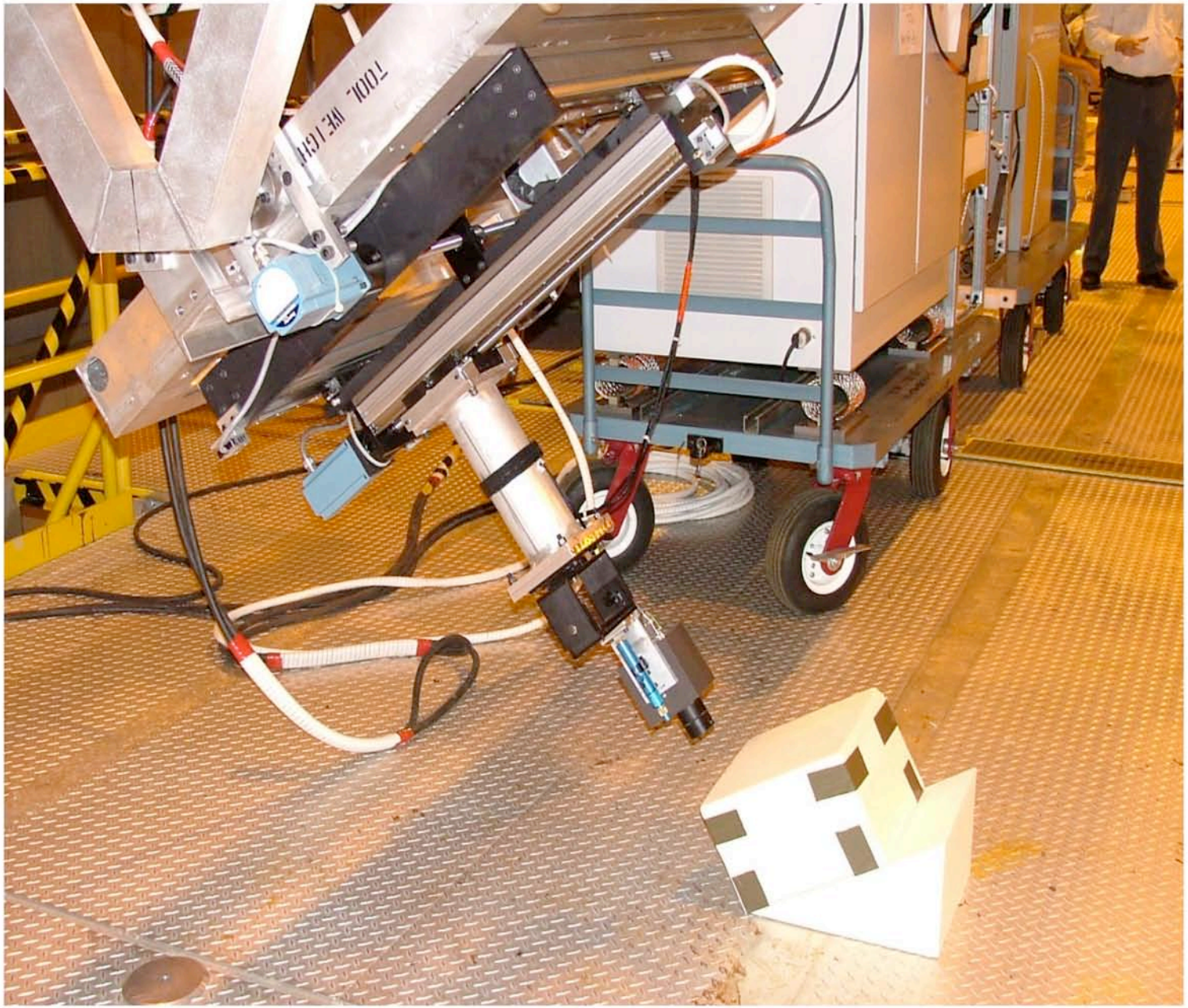




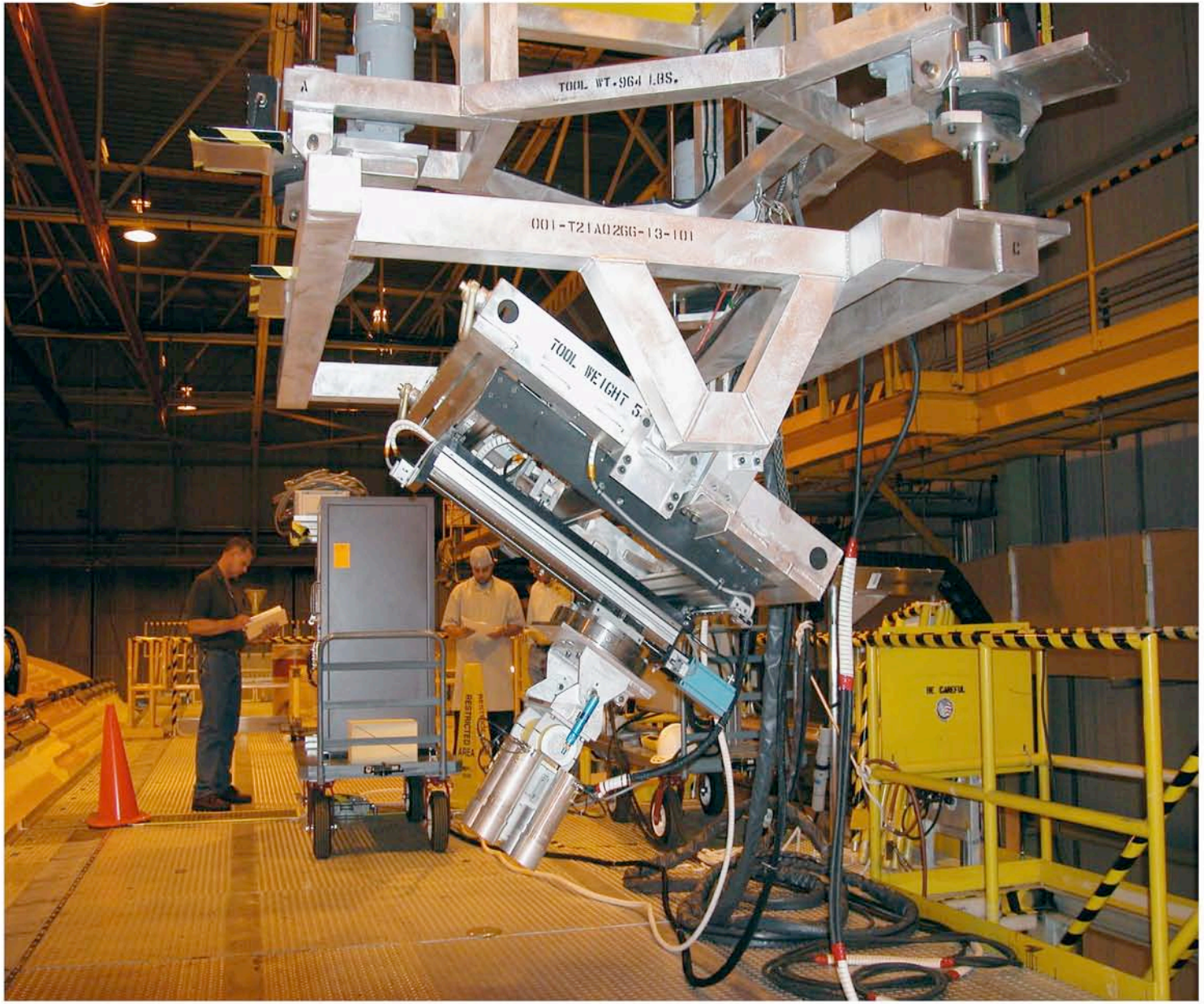
Time Domain Terahertz System



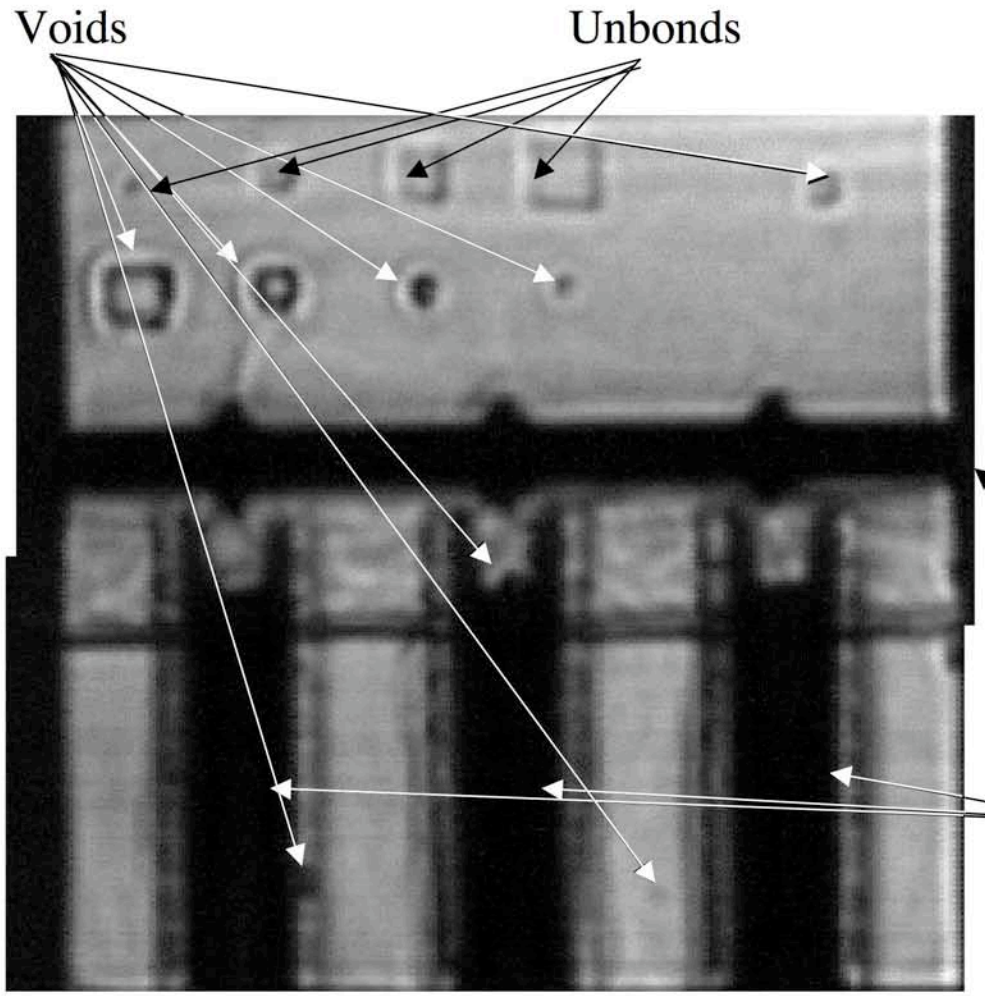
Terahertz SOFI Inspection System



Backscatter X-Ray SOFI Inspection System



Terahertz imaging of SOFI with flaws



Terahertz image of flaws in a test panel with complex geometry. This figure was made with LaRC's new T-ray system.

Flange joint under 2" of SOFI

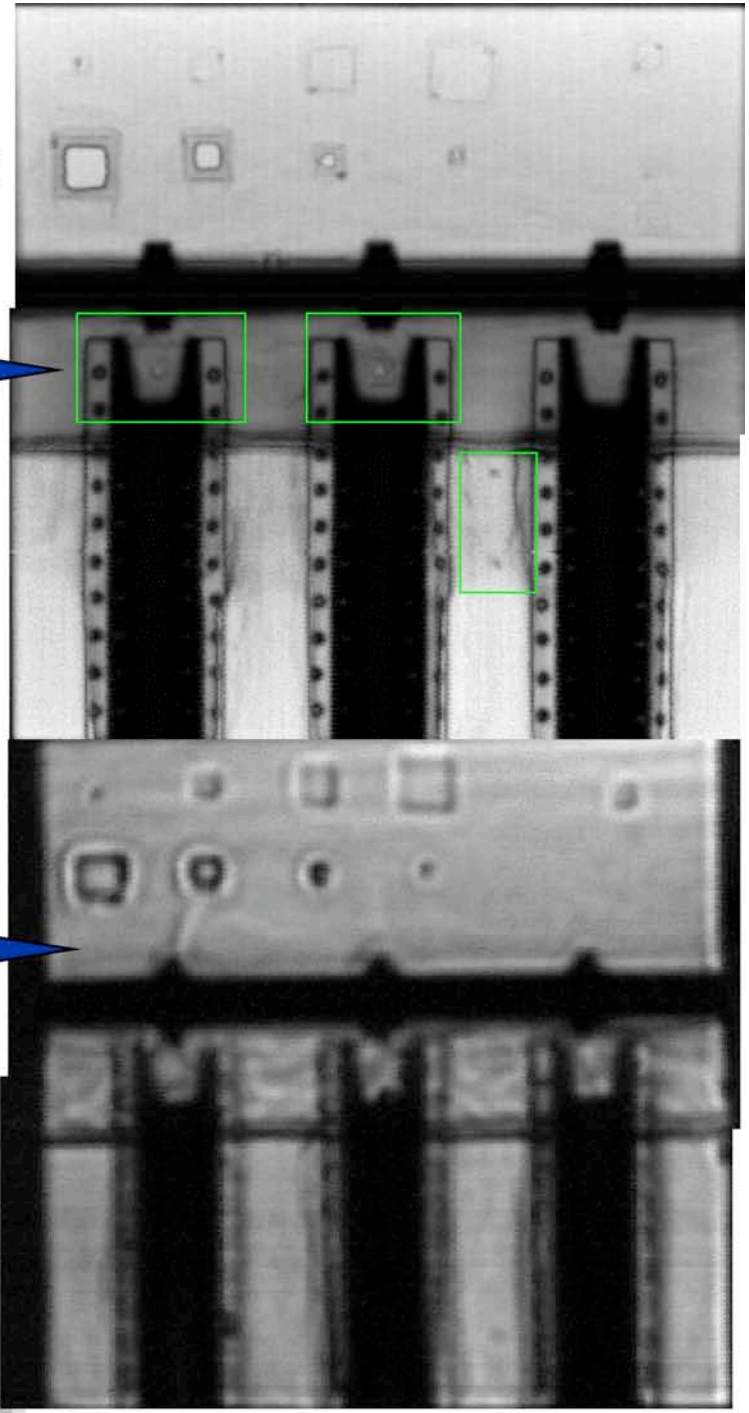
Stiffeners under 2" of SOFI

NASA Technology Readiness Level (TRL)

Terahertz NDE

On-line, TBD	Actual system flight proven through success mission operations	9
July 2005	Actual system completed & flight qualified through test & demo (ground or flight)	8
	System prototype demo in an air/space environment	7
POD 11/03	System/subsystem validation model or prototype demo in relevant environment (ground or space)	6
T-Ray at MAF 8/03	Component and/or breadboard validation in relevant environment	5
Modified T-Ray at LaRC 7/03	Component and/or breadboard validation in laboratory environment	4
	Analytical & experimental critical function and/or characteristic proof-of-concept	3
SOFI @ Picometrix 3/03	Technology concept and/or application formulated	2
2/03	Basic principles observed & reported	1

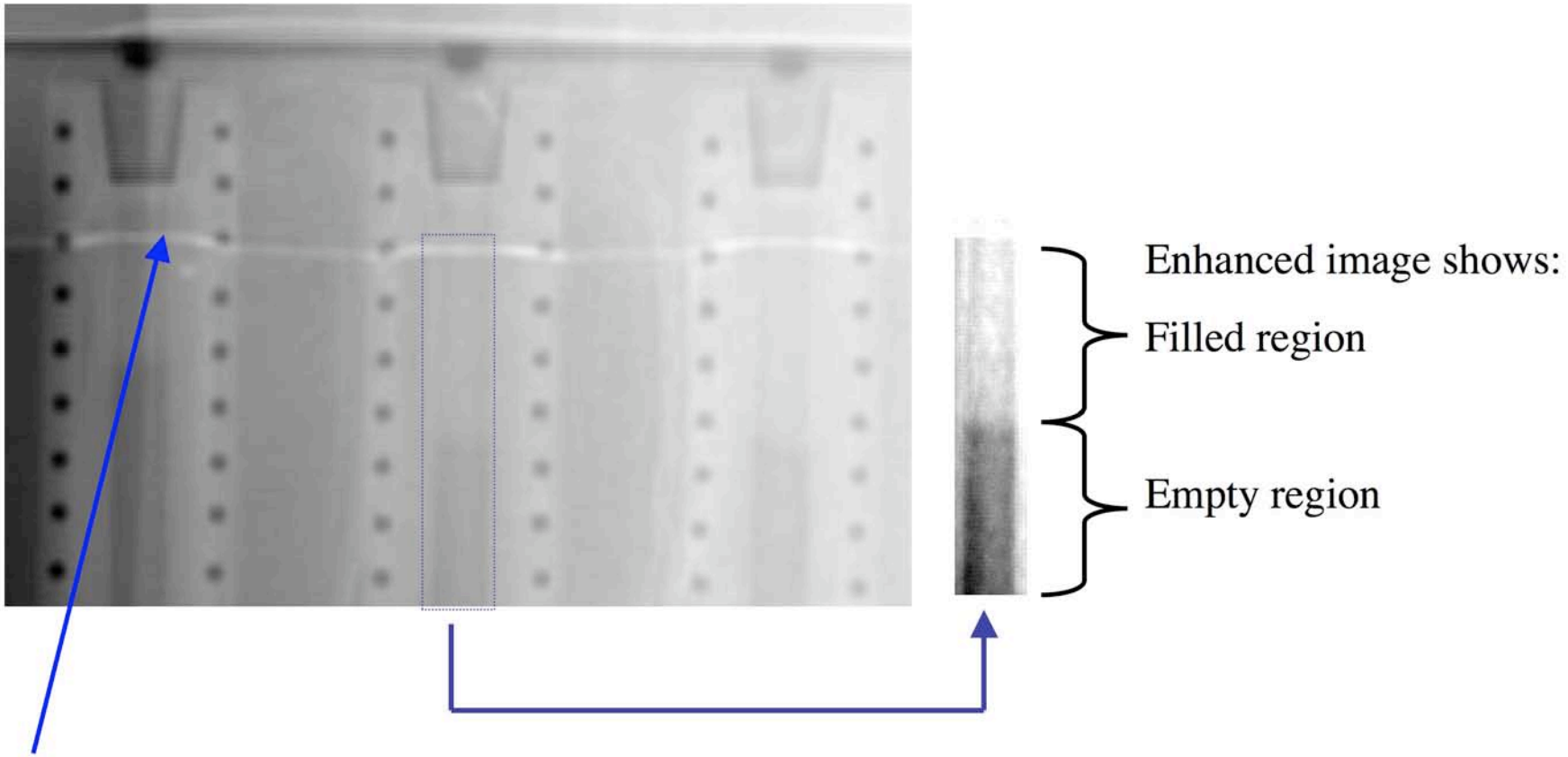
Development Spectrum



File: Technology Readiness Level ERG 7/2/97

Backscatter X-ray

SOFI Backscatter X-ray



- Backscatter X-ray results, 2” of SOFI

Non-Destructive Evaluation (NDE) for TPS

(March 2005)

Certification Status: Micro-focus x-ray will be certified for engineering evaluations on stringer closeouts in April 2005. THZ and BSX will be certified for inspection of LH2 stringer closeouts and PAL ramps in August 2005.

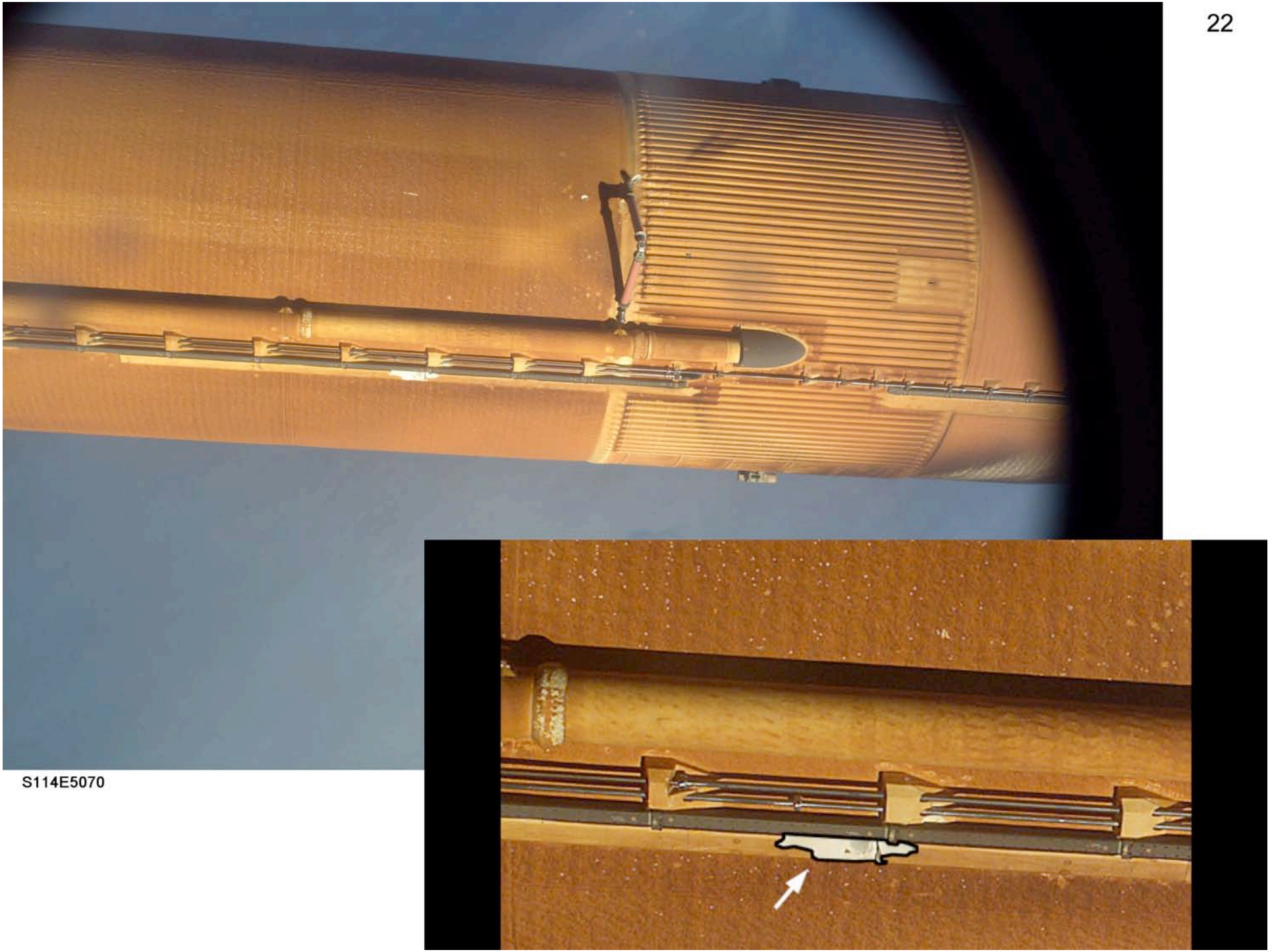
(August 2005)

Certification Status: Micro-focus x-ray, THZ and BSX will be certified for engineering evaluations on stringer closeouts in August 2005. THZ and BSX will be certified for inspection of LH2 stringer closeouts and PAL ramps in December 2005

(August 2007)

Still establishing THZ and BSX inspection system capabilities.

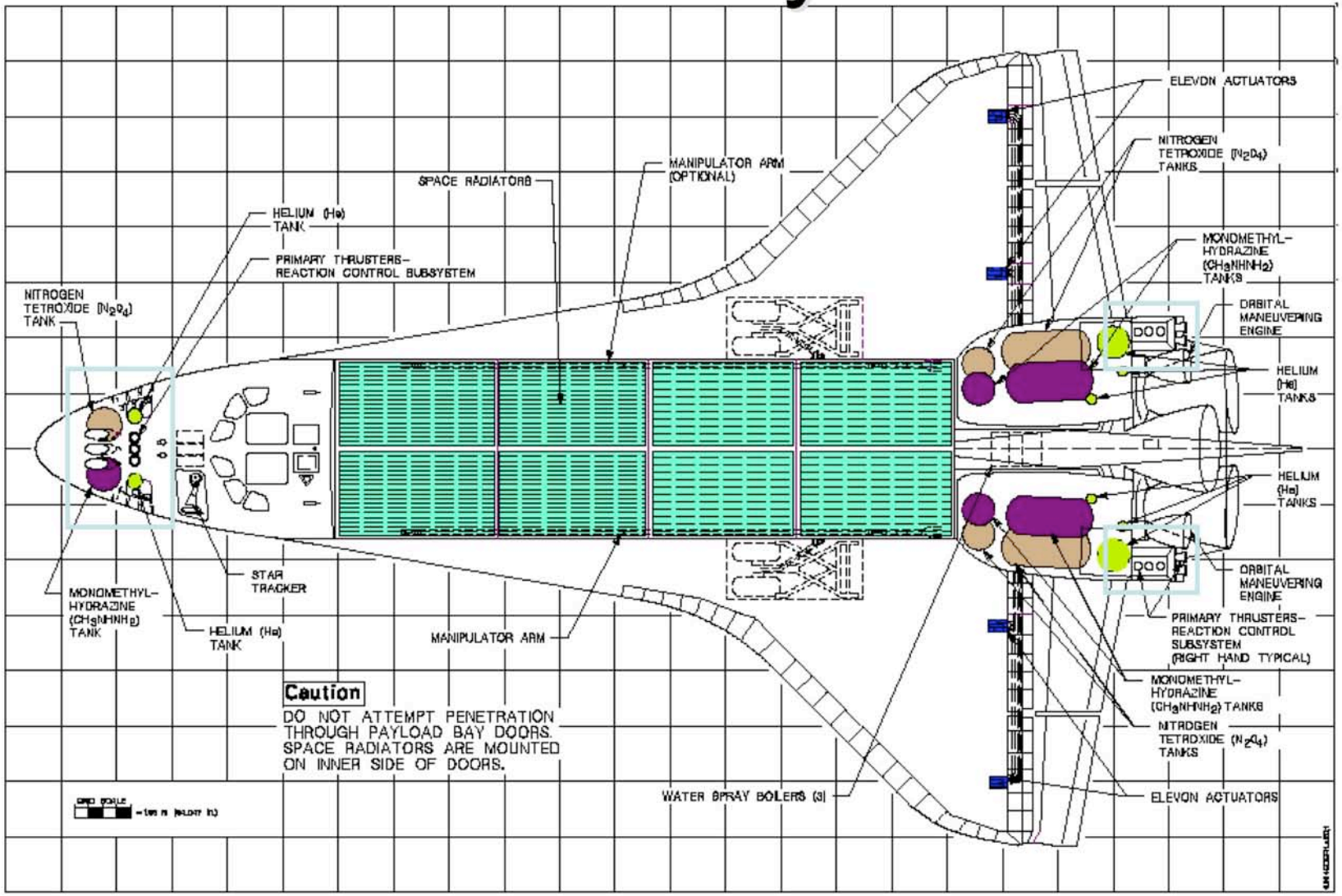
“We have no hard inspection requirements at this time, that is the Project office and/or Fracture control board have not explicitly stated what size we must find. We have been working toward the self imposed 50% design ultimate critical defect size at a 90/95 level as a point to demonstrate capability.” NDI



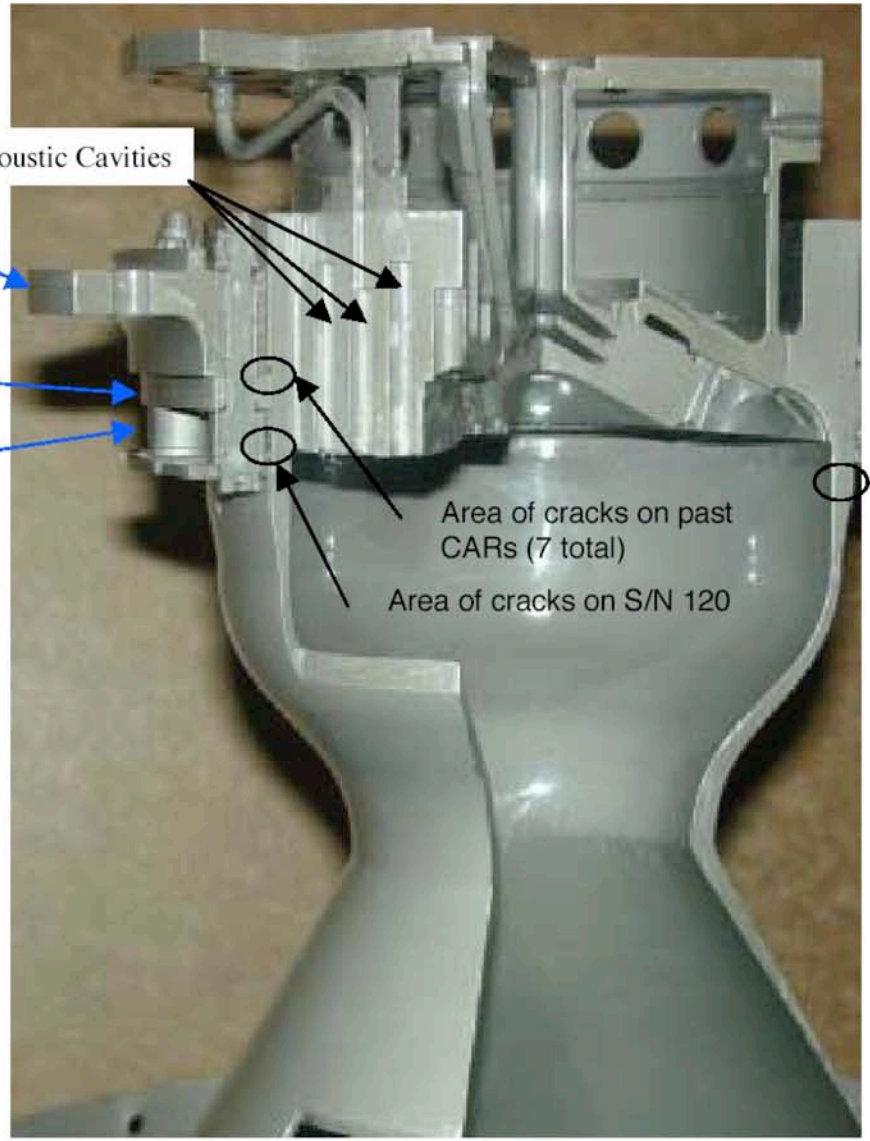
S114E5070

Primary Reaction Control System Thrusters

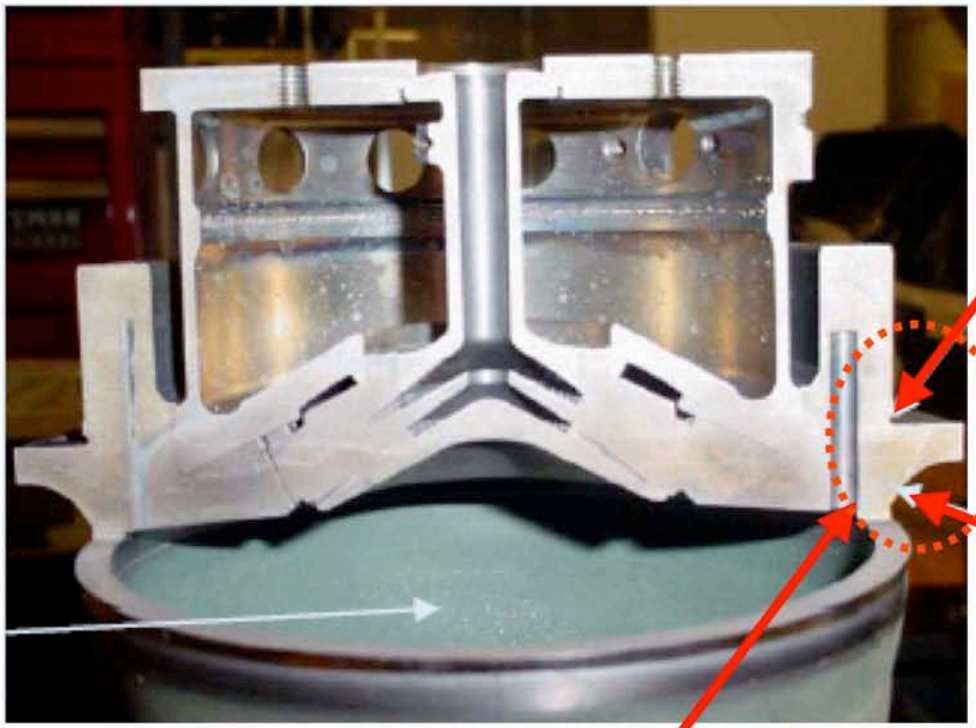
PRCS Layout

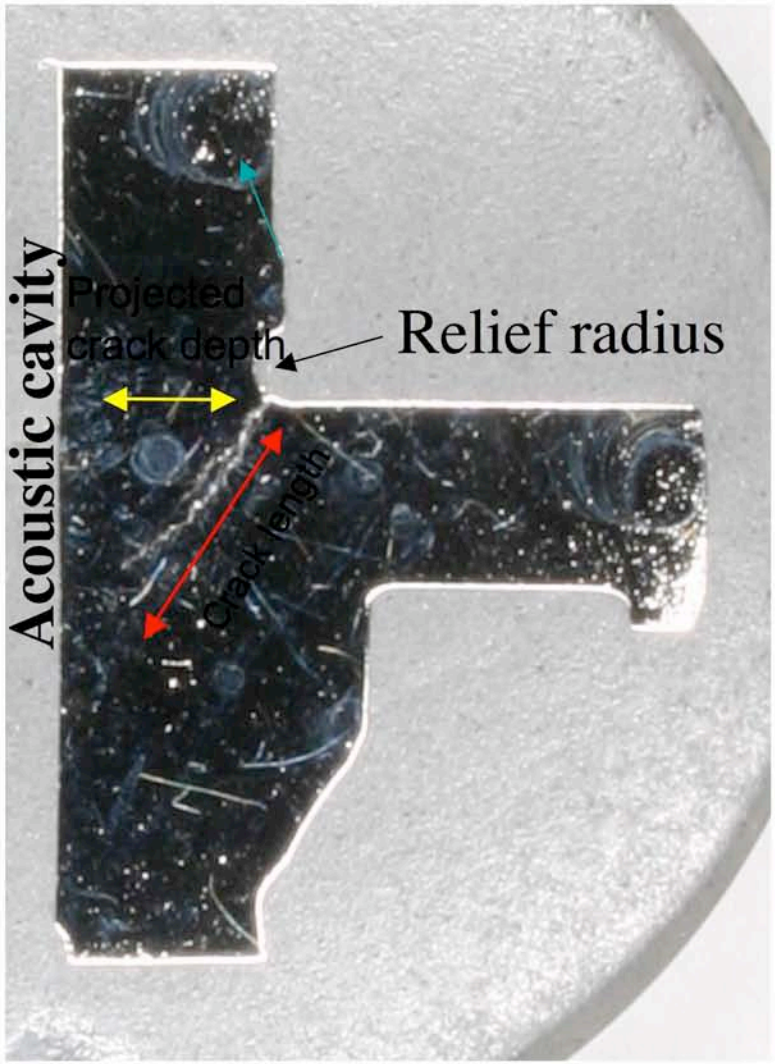

FRCS (14)
ARCS (24)
ELEVON ACTUATORS
NITROGEN TETROXIDE (N_2O_4) TANKS
MANIPULATOR ARM (OPTIONAL)
SPACE RADIATORS
HELIUM (He) TANK
PRIMARY THRUSTERS-REACTION CONTROL SUBSYSTEM
MONOMETHYL-HYDRAZINE (CH_3NHNH_2) TANKS
NITROGEN TETROXIDE (N_2O_4) TANK
ORBITAL MANEUVERING ENGINE
HELIUM (He) TANKS
HELIUM (He) TANKS
STAR TRACKER
ORBITAL MANEUVERING ENGINE
MONOMETHYL-HYDRAZINE (CH_3NHNH_2) TANK
HELIUM (He) TANK
MANIPULATOR ARM
PRIMARY THRUSTERS-REACTION CONTROL SUBSYSTEM (RIGHT HAND TYPICAL)
MONOMETHYL-HYDRAZINE (CH_3NHNH_2) TANKS
NITROGEN TETROXIDE (N_2O_4) TANKS
Caution
DO NOT ATTEMPT PENETRATION THROUGH PAYLOAD BAY DOORS. SPACE RADIATORS ARE MOUNTED ON INNER SIDE OF DOORS.
WATER SPRAY BOILERS (3)
ELEVON ACTUATORS

THRUSTER CRACKS



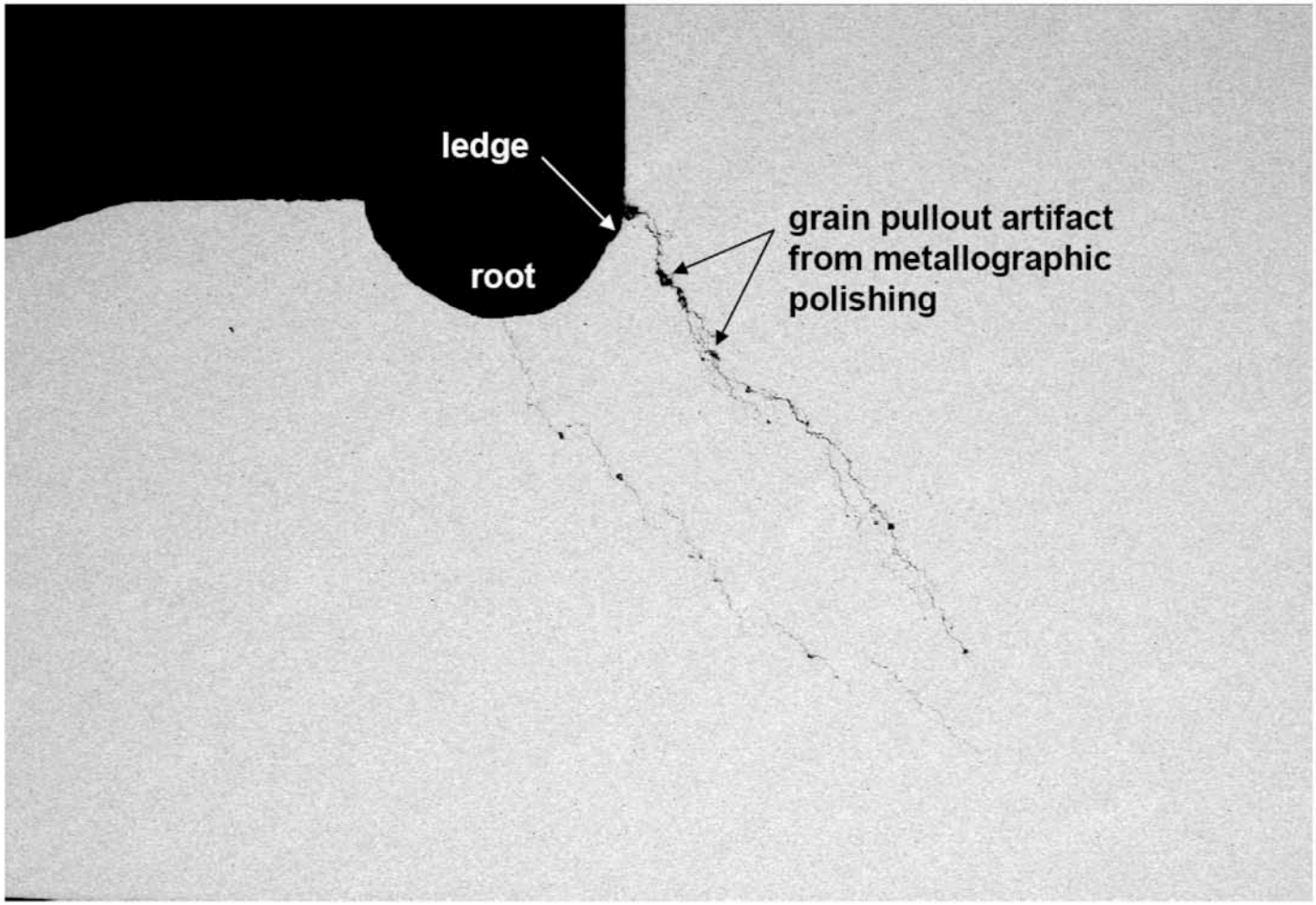
RCS Injector: Cut Away



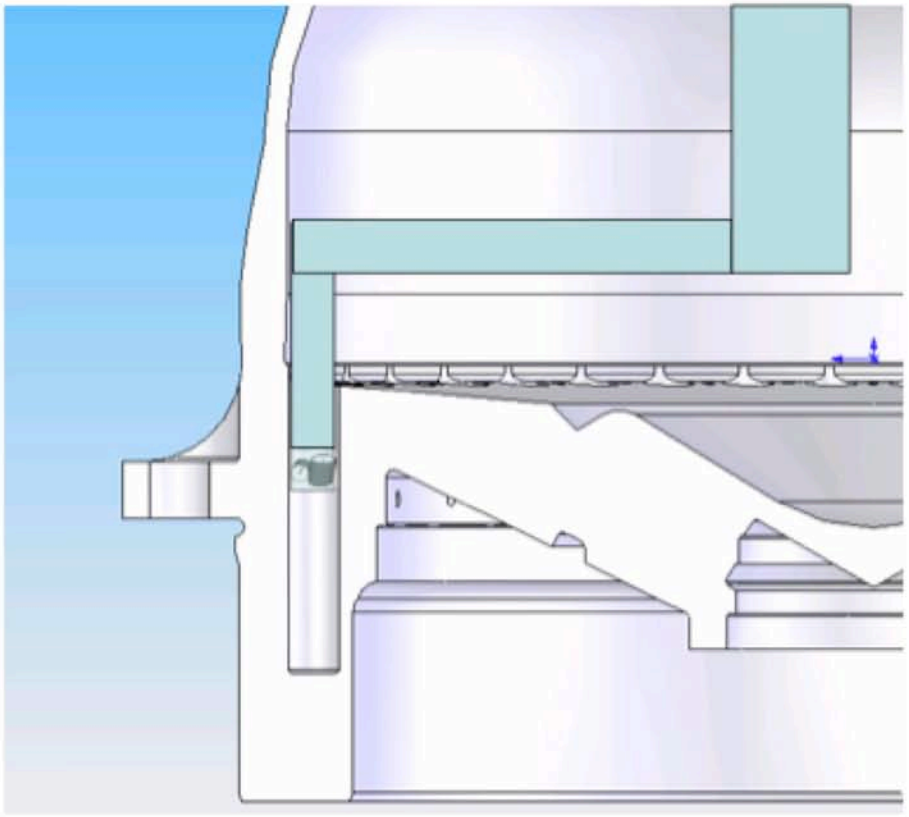


Metallographic Cross-Section Crack Measurements

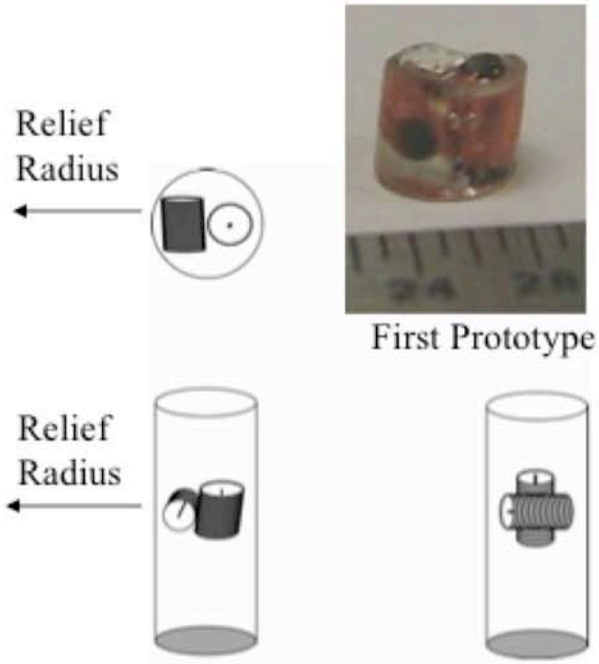
Multiple Cracks were Observed in Some Polished Sections



Orientation of Orthogonal EC Coils Inside Acoustic Cavity for Relief Radius Crack Detection



Thruster Cut-away



Projection Drawing

Corrosion Under Tile

Corrosion Under Tile

- **Corrosion under tile SIP 10/2002**
- **The Tile/SIP came off with the RTV and koropon attached to it.**
- **There was a corrosion spot in the middle of the bare aluminum area and it was cleaned up leaving us with what is seen in the third attachment.**
- **There was no path from the SIP perimeter.**

Composite over-wrapped Pressure Vessels

Composite Overwrapped Pressure Vessels

COPV

COPV failed test article

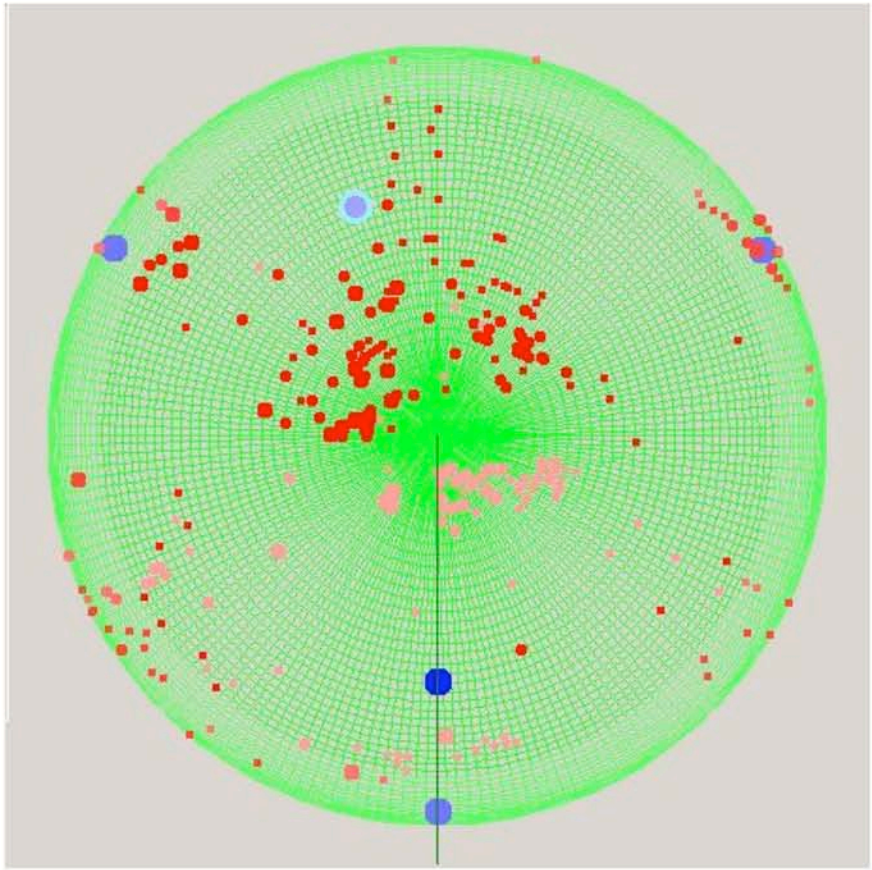
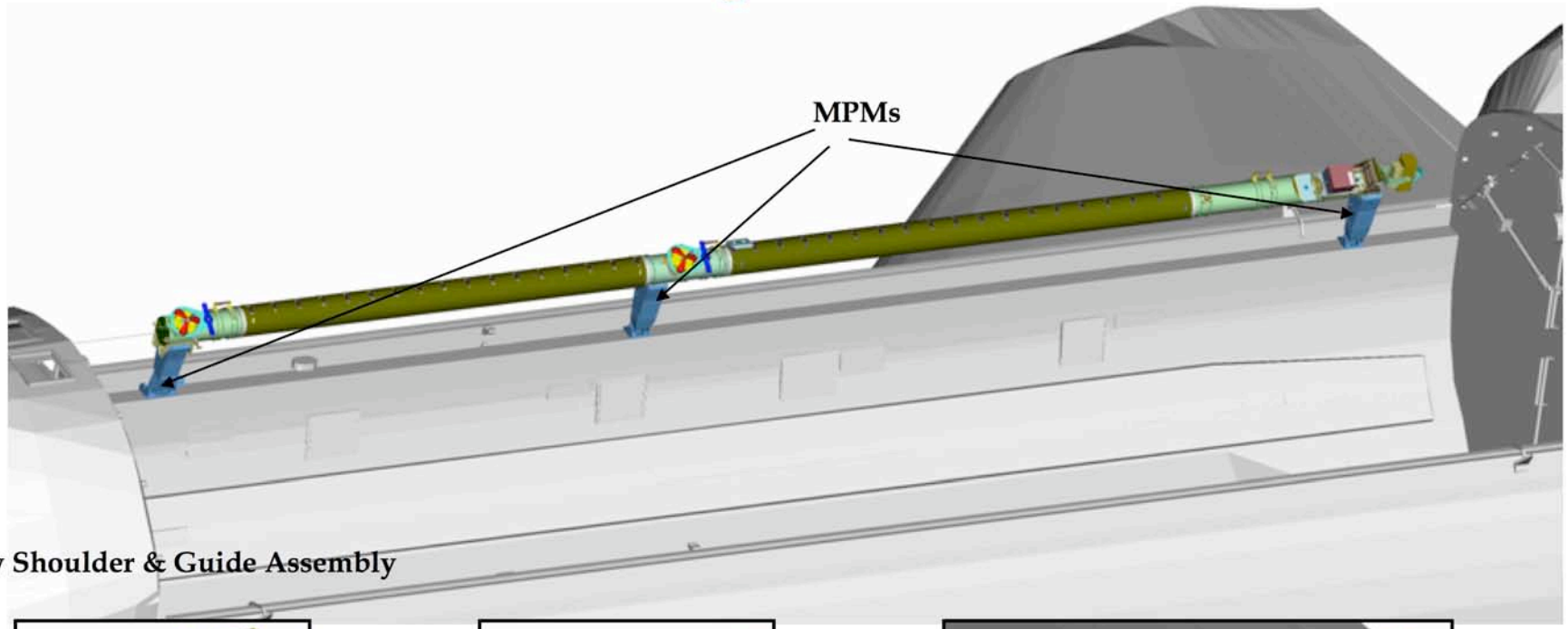
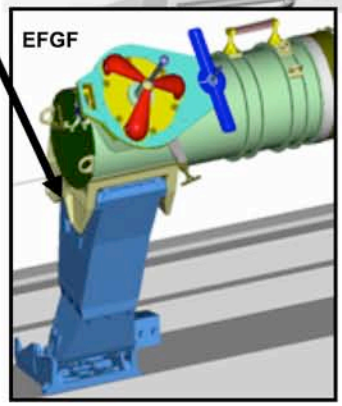


Figure 1. Schematic of Centaur COPV test article showing a cluster of AE events located at the top prior to failure. Blue dots are the location of the AE transducers. Red dots are the location of the AE events.

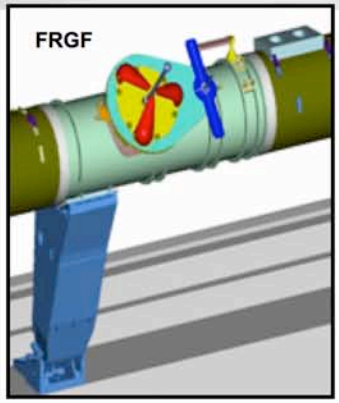
On-Orbit NDE of RCC

Background:

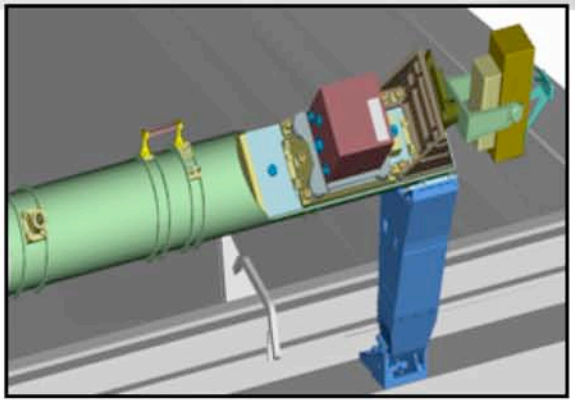




Shoulder Transition

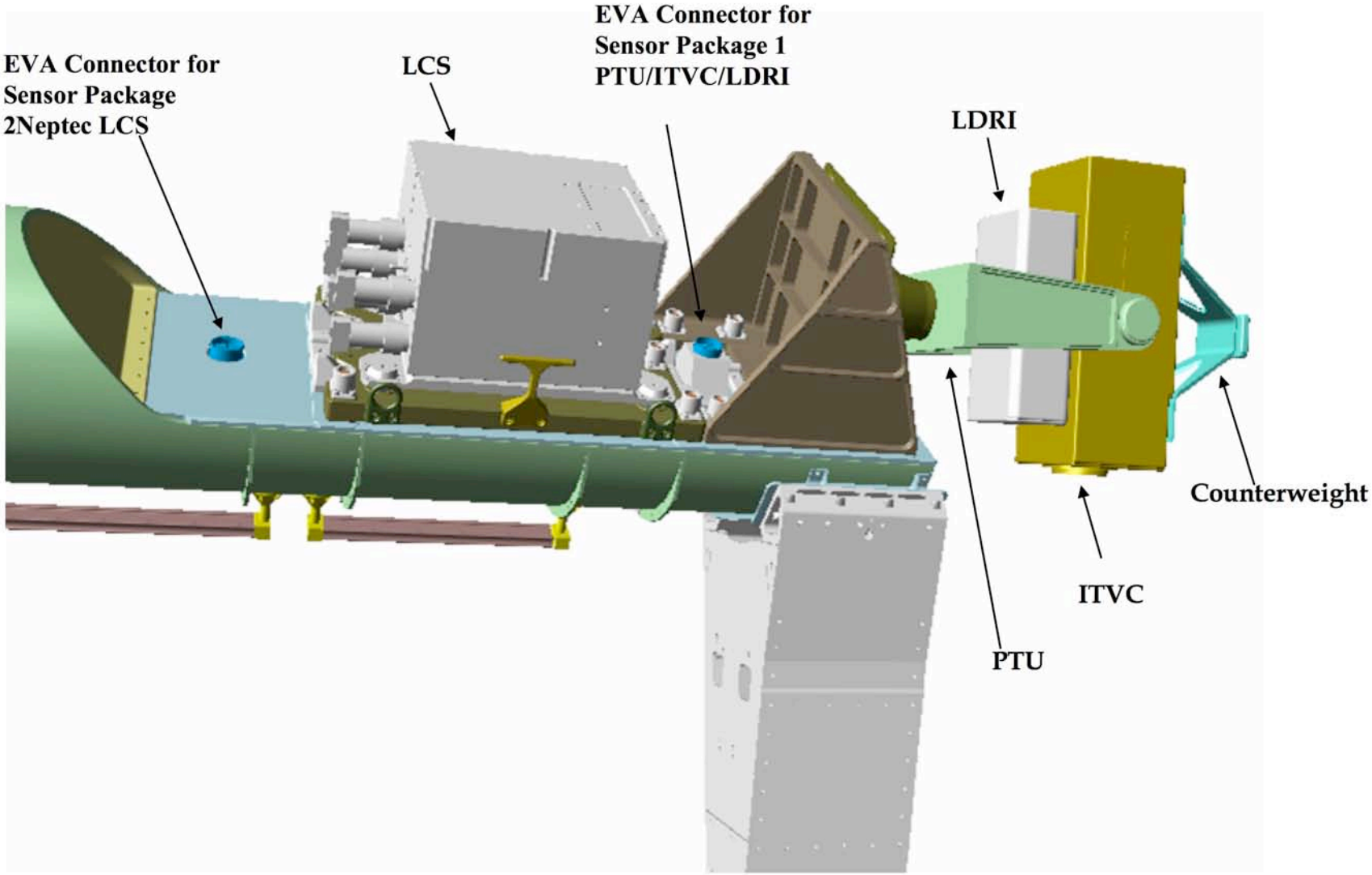


Elbow Transition



Wrist Transitions +Sensors

Background: Integrated Sensor Inspection System

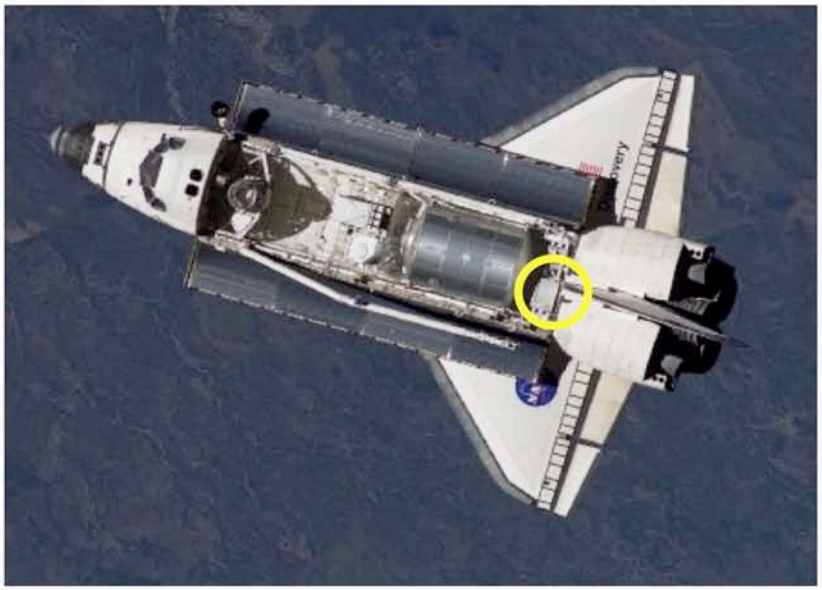


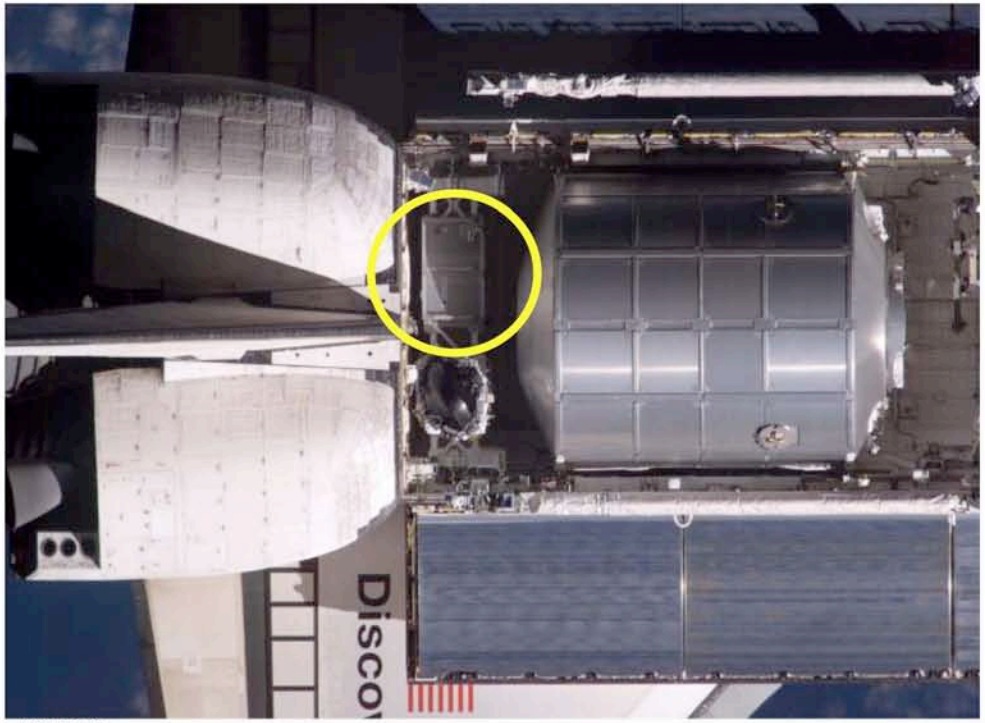
Boom Installed in OV-103

Inspectors in Space


NOWAK LINDSEY STEWART KELLY

Test Samples In Payload Bay





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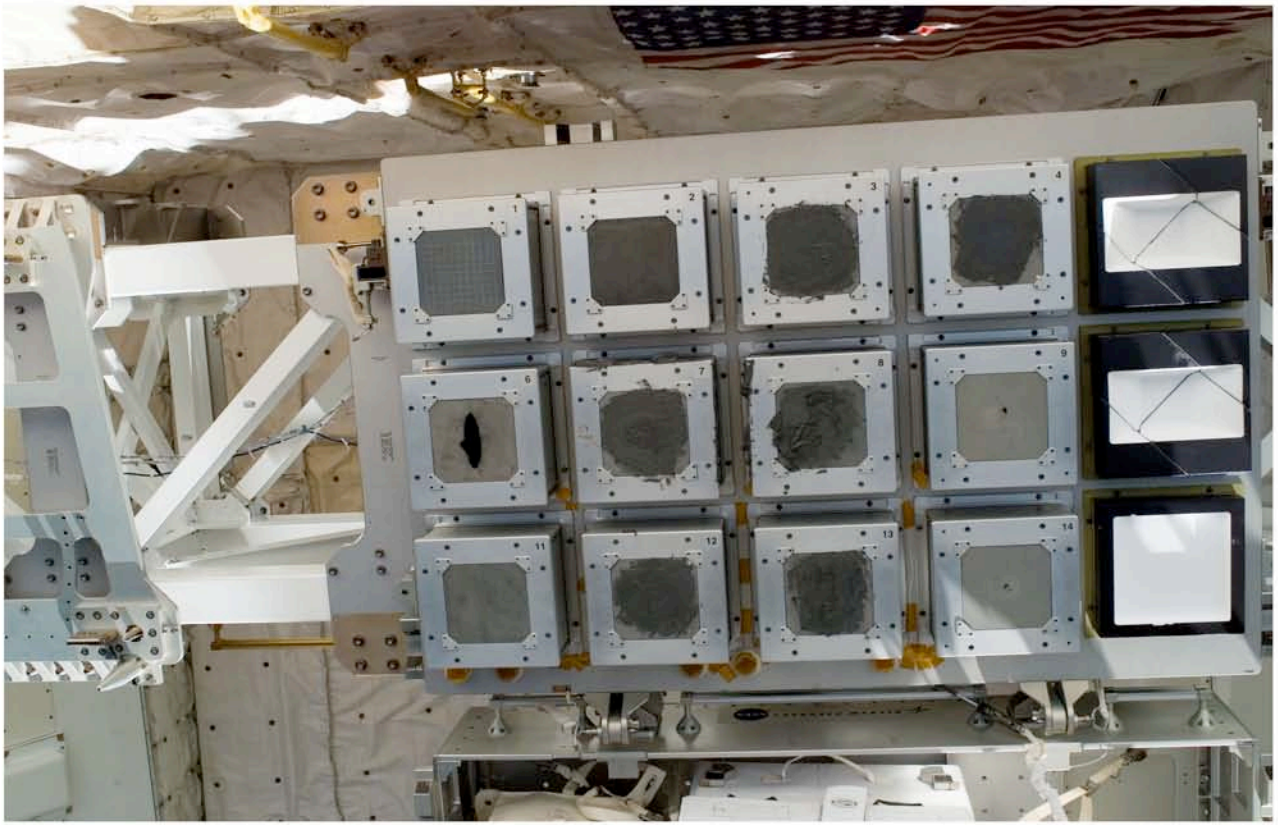

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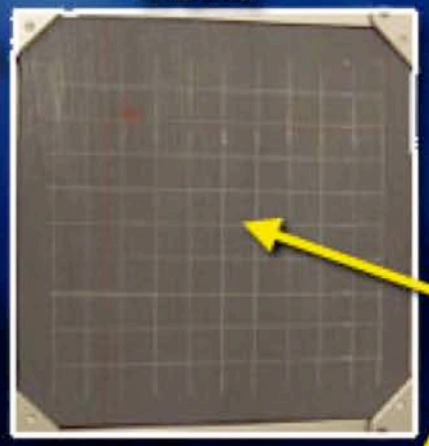
Inspection In a Relevant Environment

- Inspection Process Movie
- Thermal Data Movie

Reinforced Carbon-Carbon Samples 1 & 2
Infrared camera image

front



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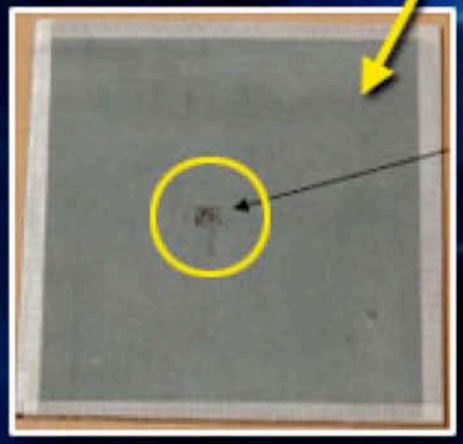
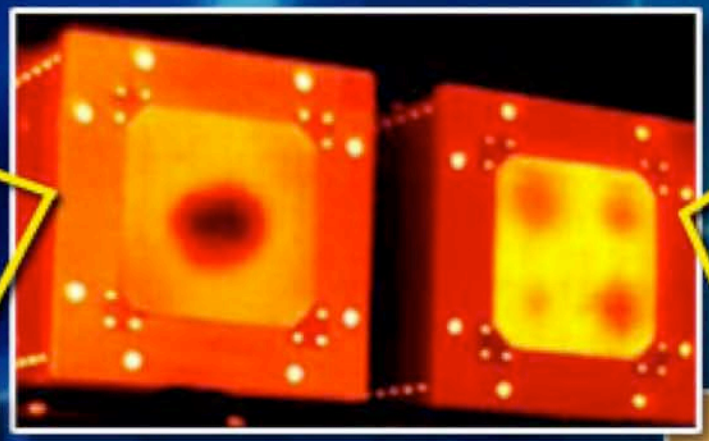
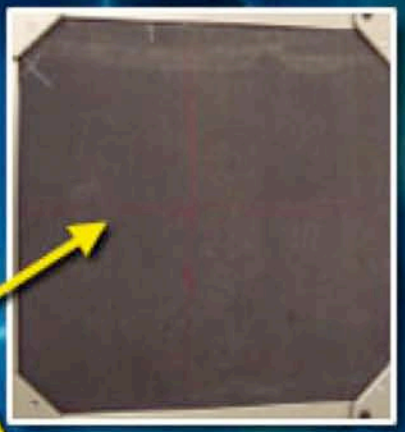




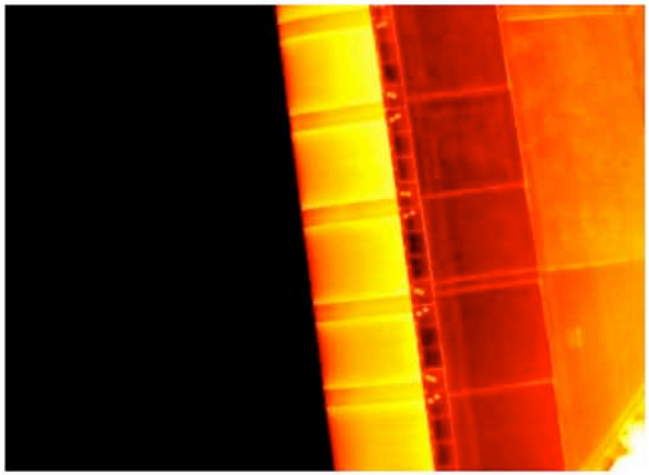
front

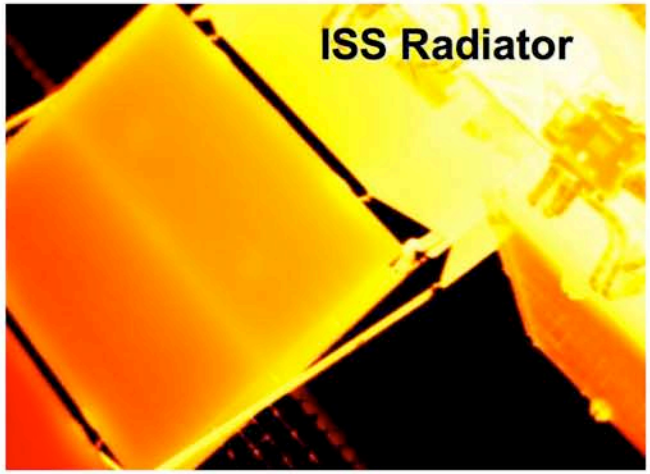


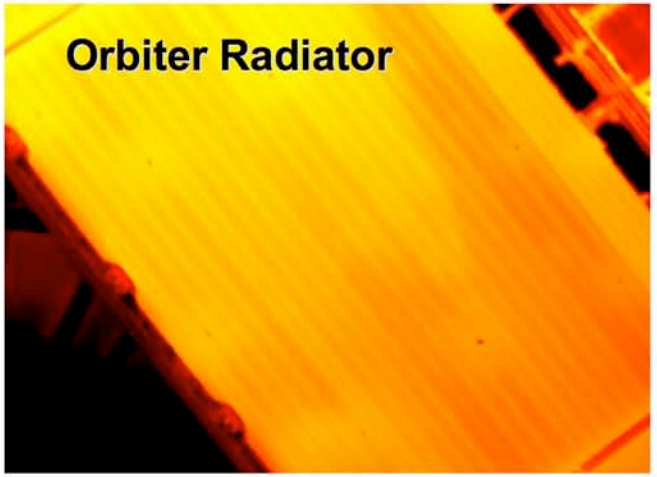
back

STS-121 Additional IR Data

Wing Leading Edge







NASA Standards

NASA-STD-5009, "Nondestructive Evaluation Requirements for Fracture Critical Metallic Components"

NASA-STD-5014, "NDE Implementation Handbook for Fracture Control Programs"

NASA-STD-5013, "NASA-STD-5013, "NDE Requirements for Fracture Critical Composite Components"

NASA-STD-XXXX, "NDE Requirements for Failure Critical Fitness-for Service Components", (e.g., non-structural systems like foam, RCC, etc)

NASA Standards

NASA-STD-5009, "Nondestructive Evaluation Requirements for Fracture Critical Metallic Components"

- **Additional critical issues that are now addressed specific applicability**
- **NDE planning for life cycle planning**
- **Document and configuration control**
- **Record retention**
- **Procurement requirements**
- **Demonstrating probability of detection (POD) and establishing NDE capability (accepts Mil-HDBK-1823* when validated by test)**
- **Requirements for acceptance criteria**
- **Organizational responsibilities**
- **Use of similarity**
- **Physical standards**

MIL-HDBK-1823 - "Nondestructive Evaluation System Reliability Assessment", 1999

NASA Standards

NASA-STD-5014, "NDE Implementation Handbook for Fracture Control Programs"

- **Being drafted**
- **Application to Special NDE Inspector Certification**

NASA-STD-5013, "NASA-STD-5013, "NDE Requirements for Fracture Critical Composite Components"

- **Initial draft, but has a long way to go**
- **Supporting ASTM "Standard Guide for NDT of Polymer Matrix Composites Used in Aerospace Applications", and 5 ASTM Standard Practices documents for composites covering thermography, shearography, radiology/radioscopy, acoustic emissions, and ultrasonics.**

NASA-STD-XXXX, "NDE Requirements for Failure Critical Fitness-for Service Components", (e.g., non-structural systems like foam, RCC, etc)

- **Not started**

CEV Crew Exploration Vehicle

The Contractor shall perform 100% non-destructive inspection of all critical components. If the standards listed above are not applicable to specific components, then the contractor shall develop and deliver acceptable (approved by NASA) standard practices and physical standards for non-destructive inspection of components. The Contractor shall develop a Nondestructive Evaluation Plan for Component Acceptance and Life Cycle Maintenance to verify the integrity of delivered components and for the maintenance of components throughout the system's life cycle. The Nondestructive Evaluation Plan for Component Acceptance and Life Cycle Maintenance shall include, as a minimum, elements addressing inspection personnel qualification, inspection processes, qualifying inspection procedures, inspection technologies, records, nondestructive inspection for raw materials acceptance, in-process nondestructive inspection for assembly, acceptance, and final test, critical components list linked to the fracture control plan, and nondestructive inspection for life cycle maintenance. The Nondestructive Evaluation Plan for Component Acceptance and Life Cycle Maintenance shall have configuration control linked to engineering design drawings, critical components lists, and risk analysis documents. Non-critical components shall be subjected to State-of-the-Art non-destructive evaluation practices and requirements. All inspection processes, procedures, data collected, and results shall be made available.

Probability of Detection (POD)

"I'm too much of a knucklehead to know this stuff"

"Oh boy, confidence limits. I hate these."

"They don't use 90/50 they use 90/95."

"I should have used 90/50"

"I defer my answer to the statistician"

"I'm not a statistician."

"90/50 POD means that there is a 50% chance that the true POD is greater than 90% at that flaw size?" Responses: "No.", and "Yes." , rest of world gives blank stares.

"Confusion over 'common definitions' continues to be an issue…"

"We have been using 29 out of 29 clandestinely for years"

Probability of Detection (POD)

- A core issue here is that the NDE personnel, nationwide, have differentt levels of understanding of statistics, and have delegated basic NDE POD statistical analysis to the statisticians.
- NDE community should not blindly accept statistical results, but rather challenge the statistical results.
- When NDE personnel defer explanations on statistical confidence bounds to others, it's like saying "I don't understand the error bars of my data".
- This is not a good position.
- We all need to learn and to speak the language of the other.
- See DOEPOD presentation later in the week

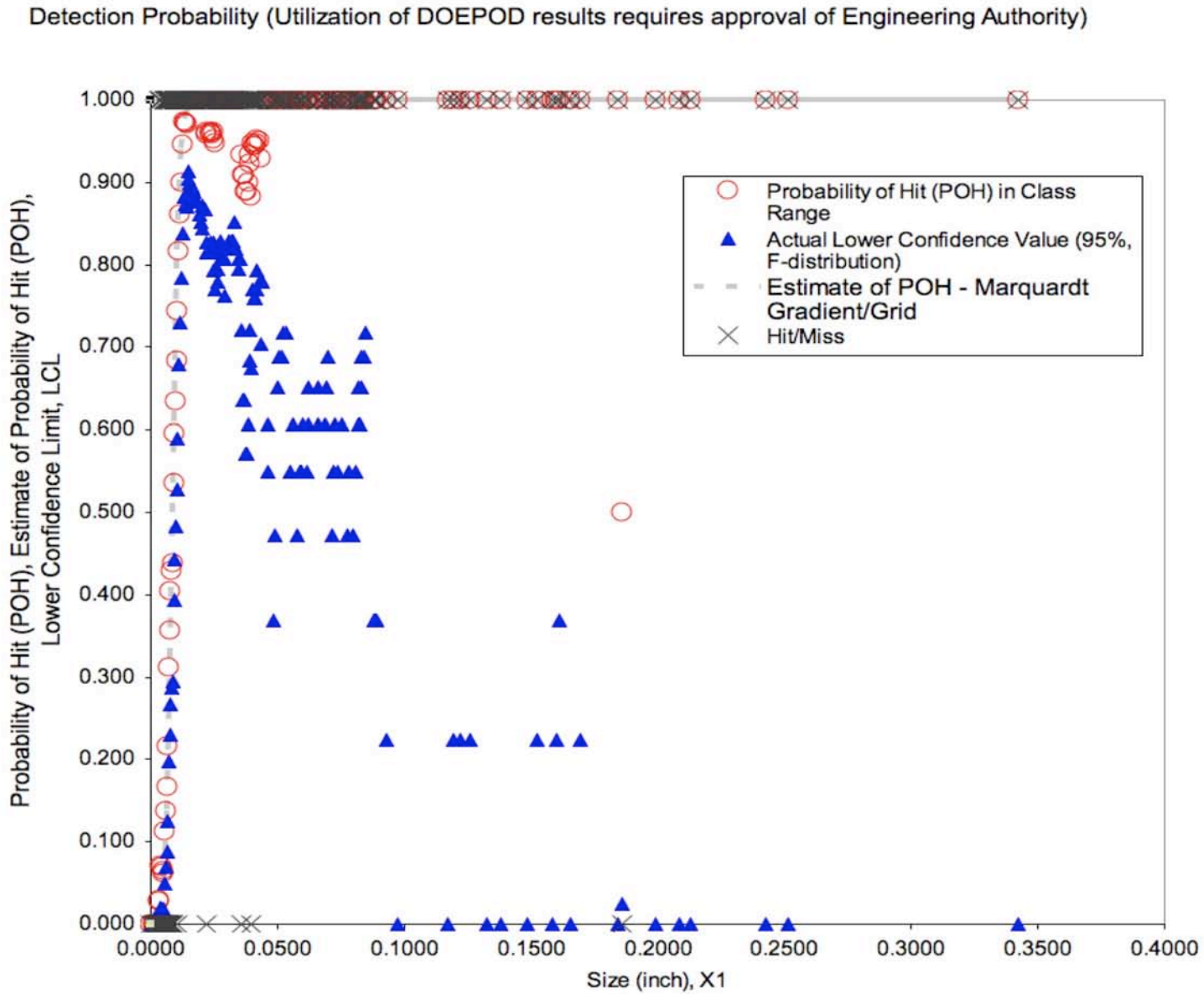
95% Confidence Level Example

$$Lower\ Confidence\ Bound,\ P_l = 0.9$$

- **There is an 95% chance that the true POD is greater than 90% at that flaw size**
- **There is a 95% chance that the inspection system reliability is greater than 90% at that flaw size**
- **90/95 POD at that flaw size**

These are all the same

Design of Experiments for Validating Probability of Detection Capability of Inspection Systems (DOEPOD)



Looking Toward the Future

KNOWN MAJOR COMPONENTS WITH ISSUES REQUIRING NDE/HEALTH MONITORING

Fuselage & Engine Structural Systems

- Thermal Protection Systems
- Insulation Blankets
- Heat Exchangers
- Fuselages
- Wings
- Tails
- Platforms
- Struts
- Debris Shields
- Docking Hardware
- Seals
- Re-entry Systems
- Windows
- Antennas
- Nose Cones
- Fuel Casings
- Fuel Tanks
- Fuel Tank Lines
- Feed Lines
- Nozzles
- Turbopumps
- Bearings
- Impellers
- Housings
- Blades

Electrical Systems

- Batteries
- Solar Arrays
- Tethers

MONITORING REQUIREMENTS AND REACTION TIMES

Micro Seconds	Seconds	Minutes	Hours
Impact Damage	Cracks	Alignment	Thermal Properties
Pressure	Debonds	Misfits	Humidity
Leaks	Composite degradation	Joints	Temperature
	Surface contamination	Stress Levels	Chemistry
	Mass loss/gain	Load Verification	Absorbtivity
	Thinning	Stiffness	Emissivity
	Delaminations	Dosimetry	Calorimetry
	Dielectric breakdown		Fatigue
			Creep
			Plasticity
			Corrosion
			Erosion

- Time frames generally overlap
- Advanced NDE technologies can address these inspection requirements

Structural Vehicle Health Monitor & On-Orbit NDE

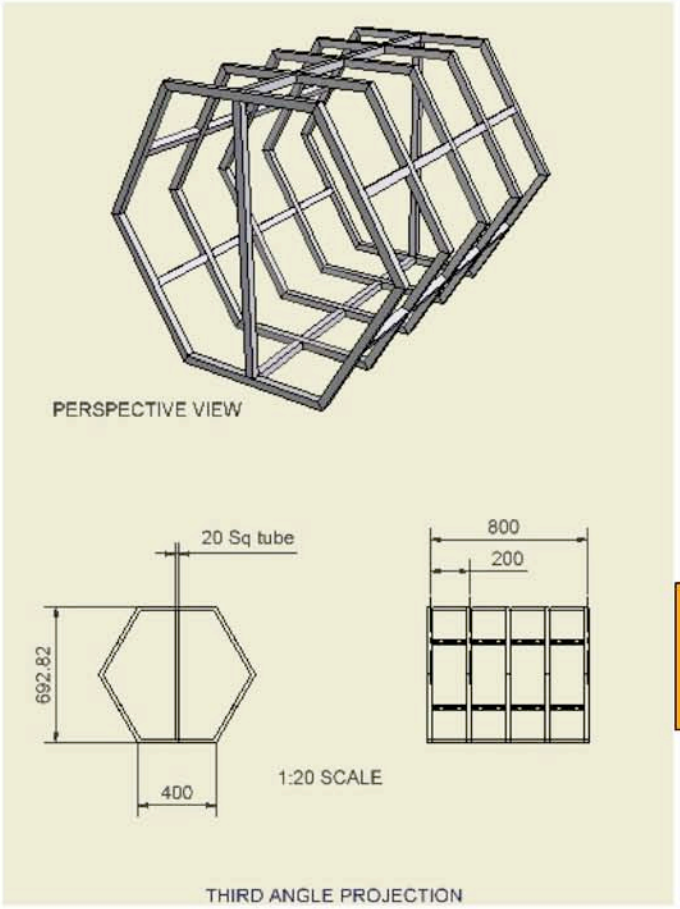
Long Term Vision

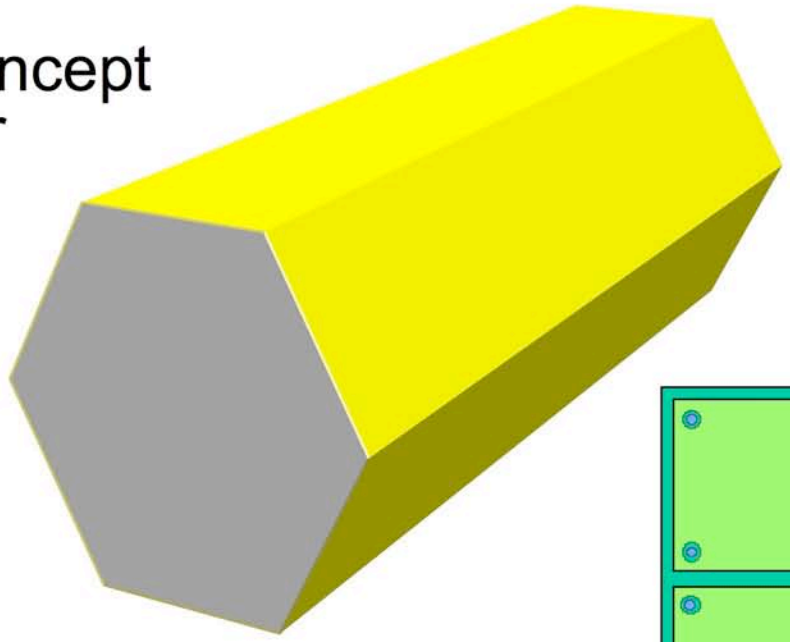
Impact Monitor

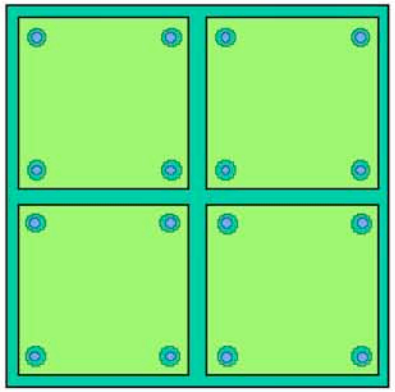
Concept Demonstrator

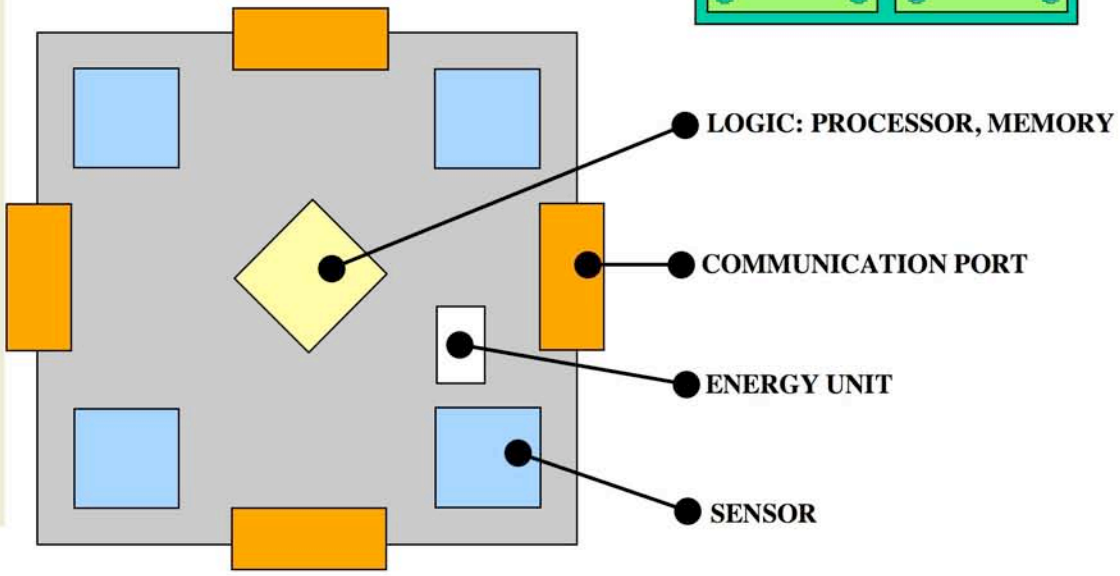
- Structural Integrated Health Monitor
- Companion Astronaut Friendly On-Orbit NDE systems (Thermal, Borescope, etc.)

Impact Monitor Concept Demonstrator



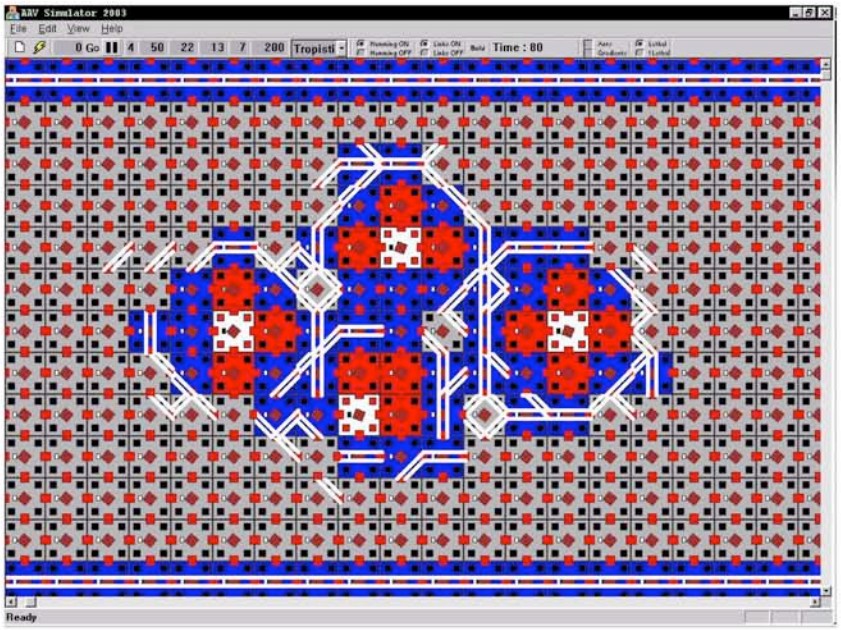


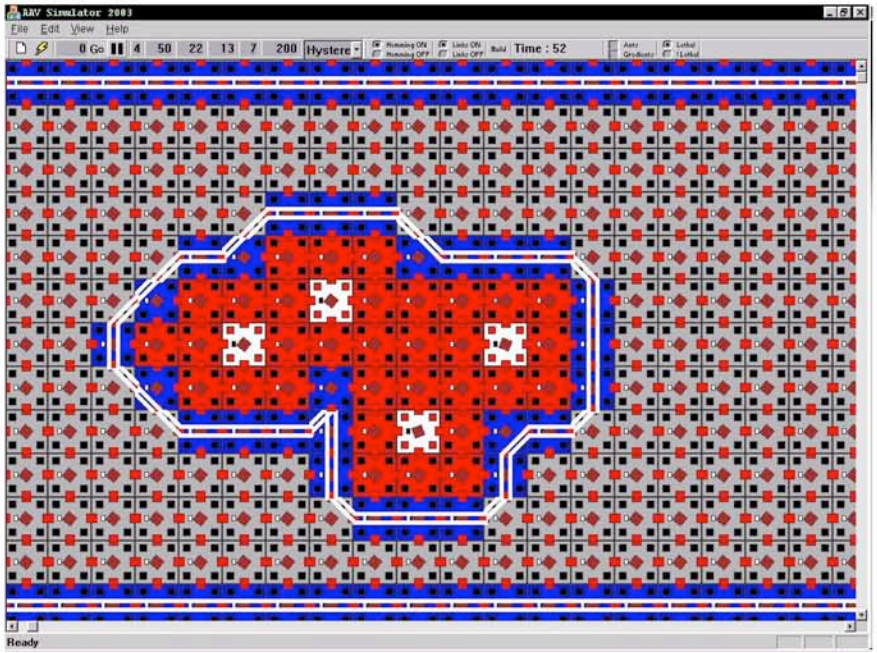


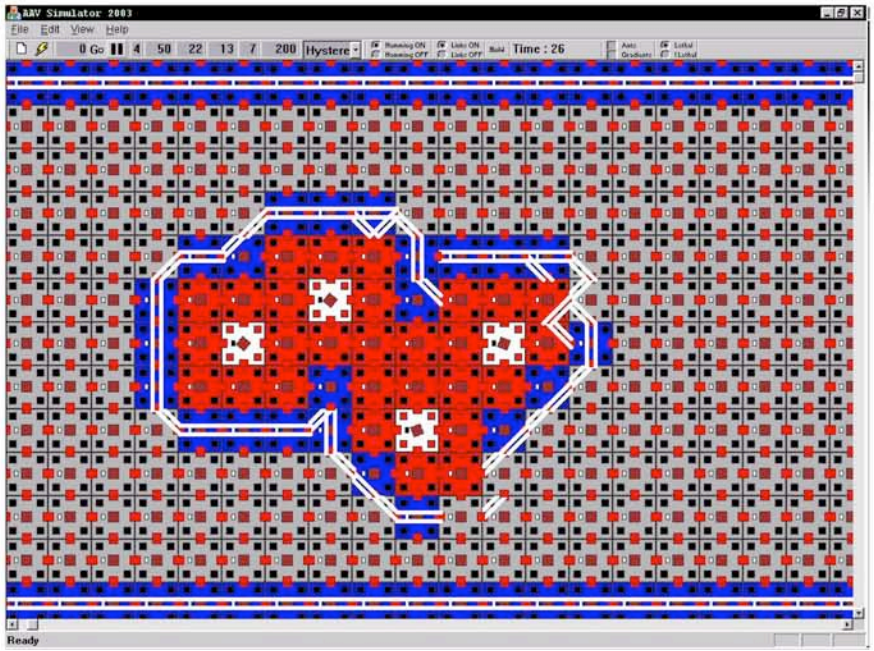


Concept Demonstrator

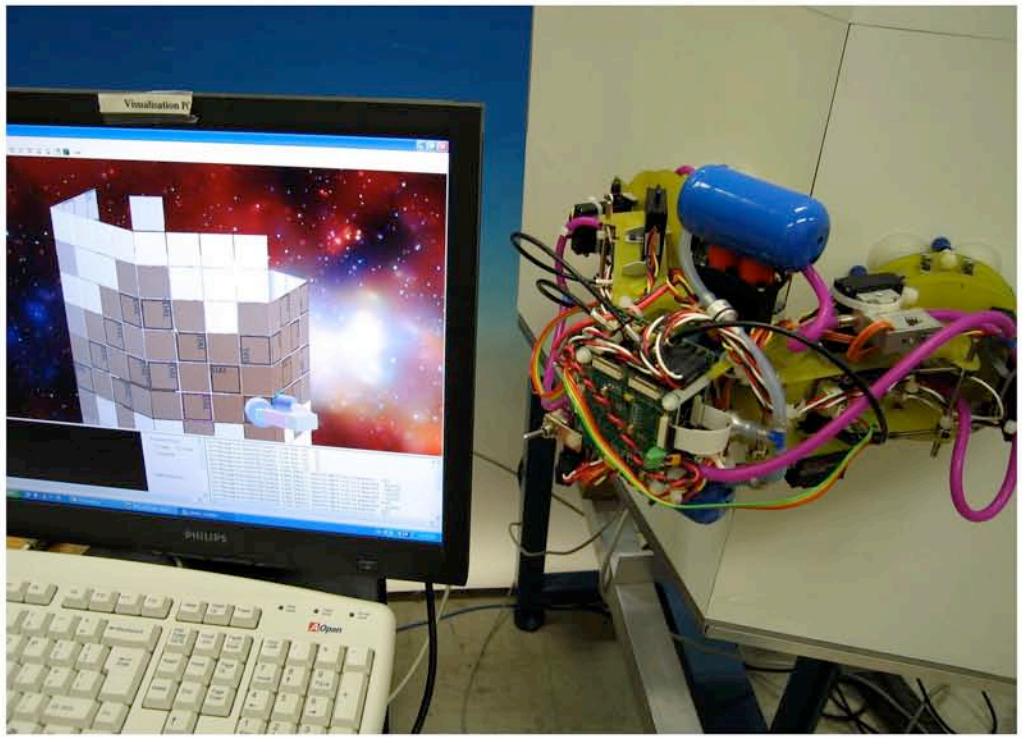
Information and knowledge about impact is maintained by reconnecting damaged communication paths







Impact Monitor Concept Demonstrator



Visualization screen (left), showing an animation of the NDI robot in its actual position on the CD structure (right).

Summary

- **Discussed the Columbia Mishap and NDI activities for added mission assurance**
- **Covered projects of the NASA NDE Team & Agency NDE Program**
- **Approaches for Space Transportation System unique inspection issues**
- **Evaluated capabilities for On-Orbit NDT (Inspectors in Space)**
- **Highlighted NASA Core NDT Standards**
- **NDE/Health monitoring approach preparing for the future**