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Pulse-Echo Ultrasonic Inspection System for In-Situ Nondestructive Inspection of Space Shuttle RCC Heat Shields

Dennis Roach, Phil Walkington, and Kirk Rackow

Prepared by
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Abstract

The reinforced carbon-carbon (RCC) heat shield components on the Space Shuttle's wings must withstand harsh atmospheric reentry environments where the wing leading edge can reach temperatures of 3,000°F. Potential damage includes impact damage, micro cracks, oxidation in the silicon carbide-to-carbon-carbon layers, and interlaminar disbonds. Since accumulated damage in the thick, carbon-carbon and silicon-carbide layers of the heat shields can lead to catastrophic failure of the Shuttle's heat protection system, it was essential for NASA to institute an accurate health monitoring program. NASA's goal was to obtain turnkey inspection systems that could certify the integrity of the Shuttle heat shields prior to each mission. Because of the possibility of damaging the heat shields during removal, the NDI devices must be deployed without removing the leading edge panels from the wing. Recently, NASA selected a multi-method approach for inspecting the wing leading edge which includes eddy current, thermography, and ultrasonics. The complementary superposition of these three inspection techniques produces a rigorous Orbiter certification process that can reliably detect the array of flaws expected in the Shuttle's heat shields. Sandia Labs produced an in-situ ultrasonic inspection method while NASA Langley developed the eddy current and thermographic techniques. An extensive validation process, including blind inspections monitored by NASA officials, demonstrated the ability of these inspection systems to meet the accuracy, sensitivity, and reliability requirements. This report presents the ultrasonic NDI development process and the final hardware configuration. The work included the use of flight hardware and scrap heat shield panels to discover and overcome the obstacles associated with damage detection in the RCC material. Optimum combinations of custom ultrasonic probes and data analyses were merged with the inspection procedures needed to properly survey the heat shield panels. System features were introduced to minimize the potential for human factors errors in identifying and locating the flaws. The in-situ NDI team completed the transfer of this technology to NASA and USA employees so that they can complete "Return-to-Flight" certification inspections on all Shuttle Orbiters prior to each launch.

This work was performed for the National Aeronautics and Space Administration under Work-for-Others agreement 062030623. Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Acknowledgements

This work was sponsored by the National Aeronautics and Space Administration under Work-for-Others agreement 062030623. This project was managed by Ajay Koshti at NASA-JSC. Additional project oversight was provided by Ron Allison at NASA-KSC and Alan Ling at United Space Alliance (NASA-KSC). The Shuttle in-situ NDI project was initiated by Jose Hernandez at NASA-JSC. Orbiter deployment and system certification efforts were supported by Marty Agrella and his staff at Oceaneering Space Systems. Guidance on RCC inspection issues and validation testing was provided by Dan Ryan and the NDI team at United Space Alliance along with Bob DeVries at Boeing. The test specimens used for technique development and validation were produced by Bill Sheldon at Boeing. Final validation testing was supported by Mike Tipton (SAIC) and Mary Litwinski (Boeing). The success of a program such as this depends on the support of the entire team assembled from personnel at all of the NASA facilities and their contractors. The authors would like to acknowledge the efforts put forth by the entire in-situ NDI team (recorded in this report's distribution list) to aid the overall inspection system development activities, certification tasks, and logistics for system integration into the Orbiter Processing Facility.

Pulse-Echo Ultrasonic Inspection System for In-Situ Nondestructive Inspection of Space Shuttle RCC Heat Shields

TABLE OF CONTENTS

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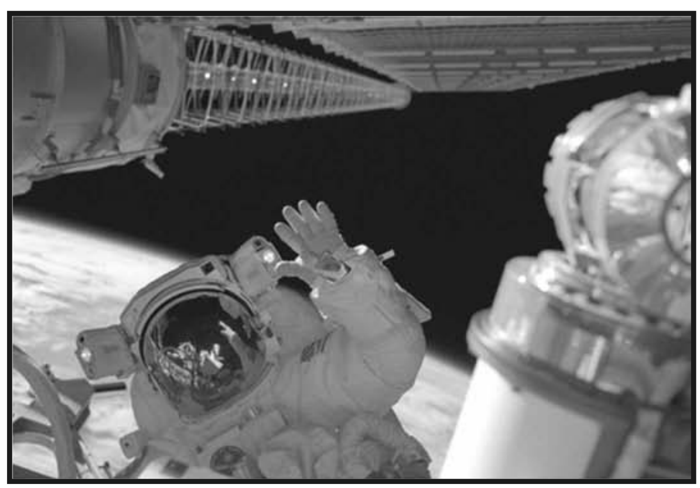
Pulse-Echo Ultrasonic Inspection System for In-Situ Nondestructive Inspection of Space Shuttle RCC Heat Shields

Configuration Information on: Technique, Hardware, Software, Design, and Performance Testing for Certification of UT Inspection System

Information for NASA Report:
NASA RCC NDE Test Report KSC-5600-7412



1.0 RCC In-Situ NDI Program Background

After the loss of OV-102 during STS-117, the Columbia Accident Investigation Board (CAIB) was formed to investigate the accident and make recommendations to increase system safety prior to return to flight (RTF). One of these recommendations was R3.3-1: *Develop and implement a comprehensive inspection plan to determine the structural integrity of all Reinforced Carbon-Carbon system components. This inspection plan should take advantage of advanced non-destructive inspection technology*. An integrated team of participants from NASA-JSC, NASA-Langley, Sandia National Laboratories, United Space Alliance (USA), Oceaneering Space Systems (OSS) and Boeing has been working since 2003 to develop and demonstrate nondestructive inspection (NDI) systems capable of performing inspection of Reinforced Carbon-Carbon (RCC) leading edges on-wing in the Orbiter Processing Facility (OPF). This report details the system development and validation of the ultrasonic testing (UT) system for detecting flaws in RCC on the Shuttle Orbiter wing leading edge panels and mating Tee Seals.

NASA Response to the *Columbia* Accident Investigation Board

NASA must Continue to Manage the Space Shuttle as a Development Vehicle:

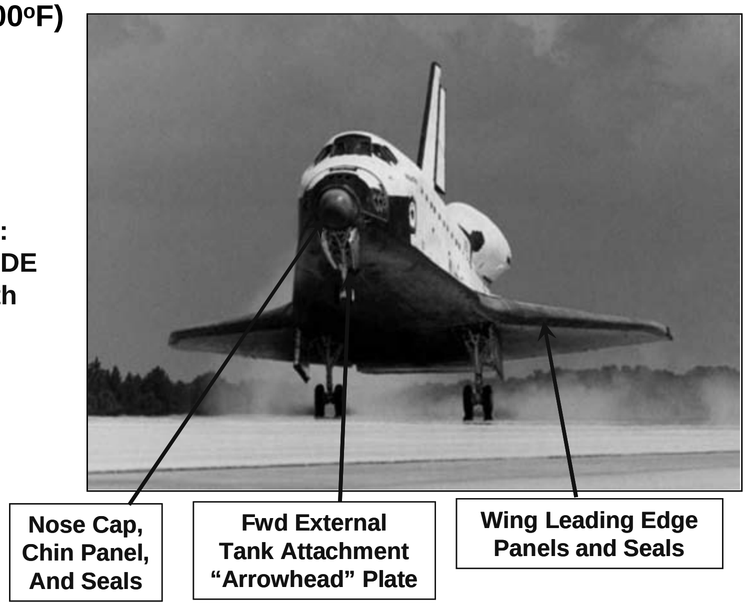
- **Be cognizant of the risks of using the Shuttle in an operational mission, and manage accordingly.**
- **Perform more testing on Space Shuttle hardware rather than relying on computer-based analysis and extrapolated experience to reduce risk - Inspection plan for recertification of Shuttle for Flights.**
- **Address aging issues through the Space Shuttle Service Life Extension, including midlife re-certification.**
- **Collaborate with high-risk industries such as nuclear power & aviation to identify and incorporate best practices.**

Leading Edge Shuttle System – Reinforced Carbon-Carbon

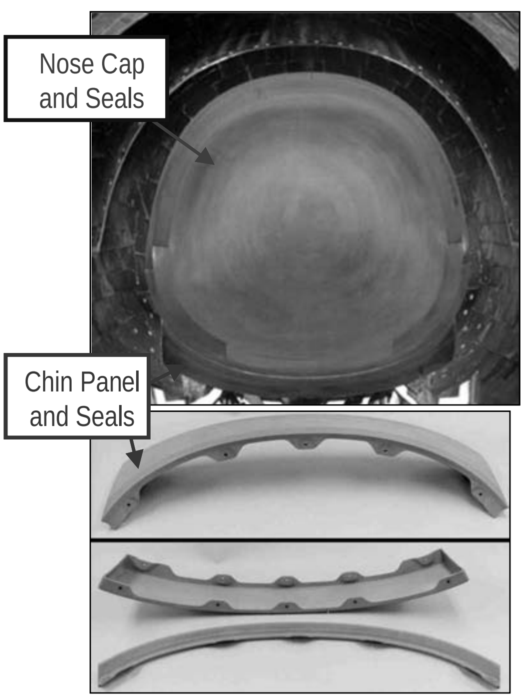
LESS/RCC Overview - Basic Requirements

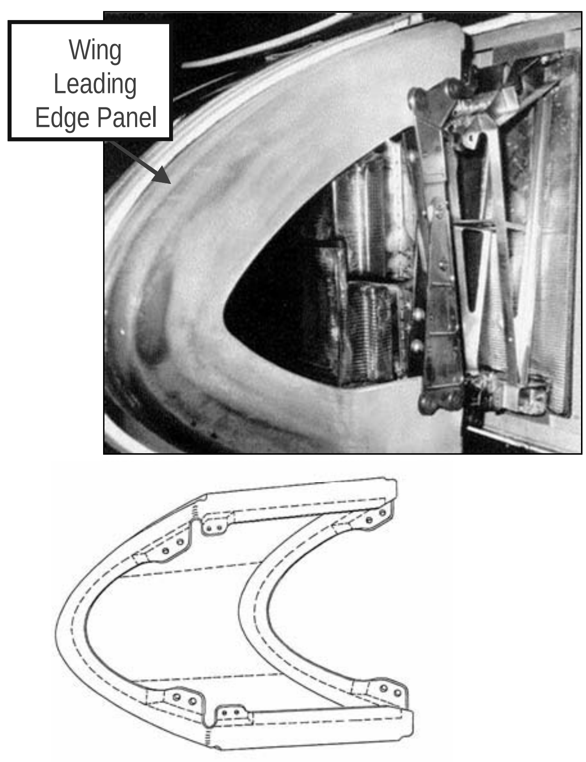
- **Thermal Protection (3200°F)**
- **Aerodynamic Shape**
- **Load Distribution**
- **Impact Resistance**

Health Monitoring Objective: Develop a comprehensive NDE program for the in-situ health monitoring of Orbiter RCC components.

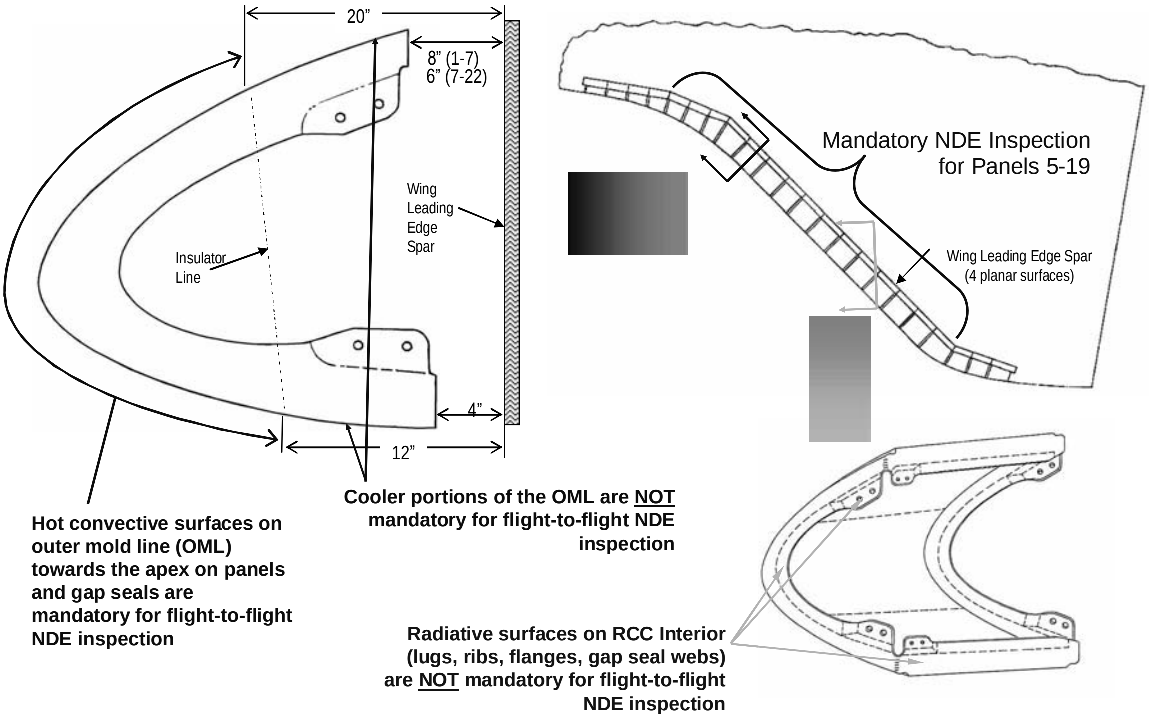


Space Shuttle Orbiter RCC Components



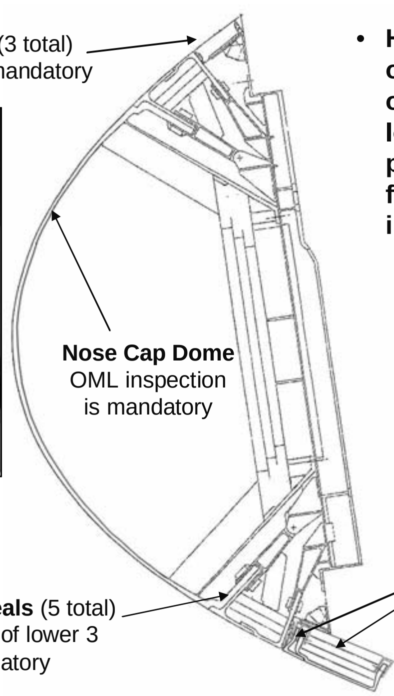


Areas To Be Inspected on Wing Leading Edge



Inspection Regions on Forward RCC

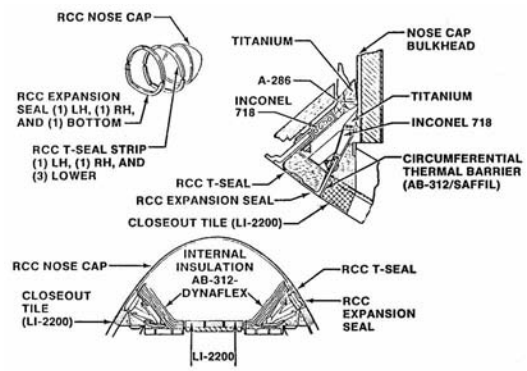
Forward RCC Mandatory NDE Inspection Locations



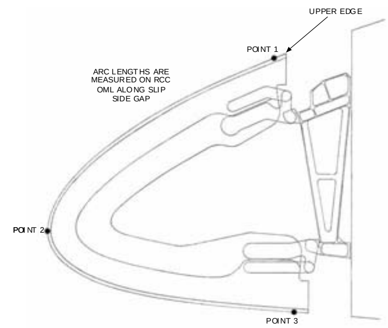
- **Hot convective surfaces on outer mold line (OML) of the nose cap dome, lower gap seals, and chin panel are mandatory for flight-to-flight NDE inspection**

Radiative surfaces on RCC Interior (lugs, ribs, flanges, gap seal webs) are NOT mandatory for flight-to-flight NDE inspection

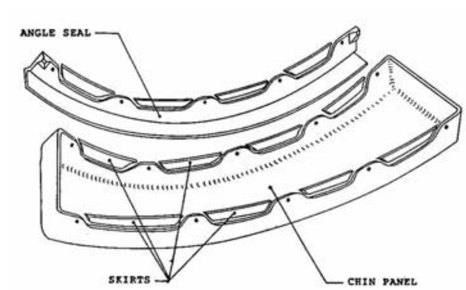
RCC Component Configurations



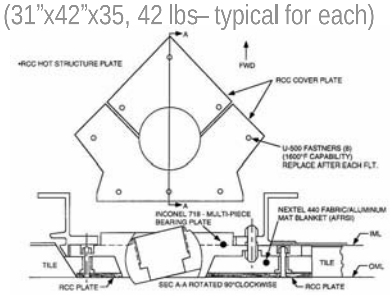
Nose Cap Assembly (78"x66"x41", 544 lbs)



Wing Leading Edge Assembly
22 panel/seal sets on each wing
(31"x42"x35, 42 lbs – typical for each)



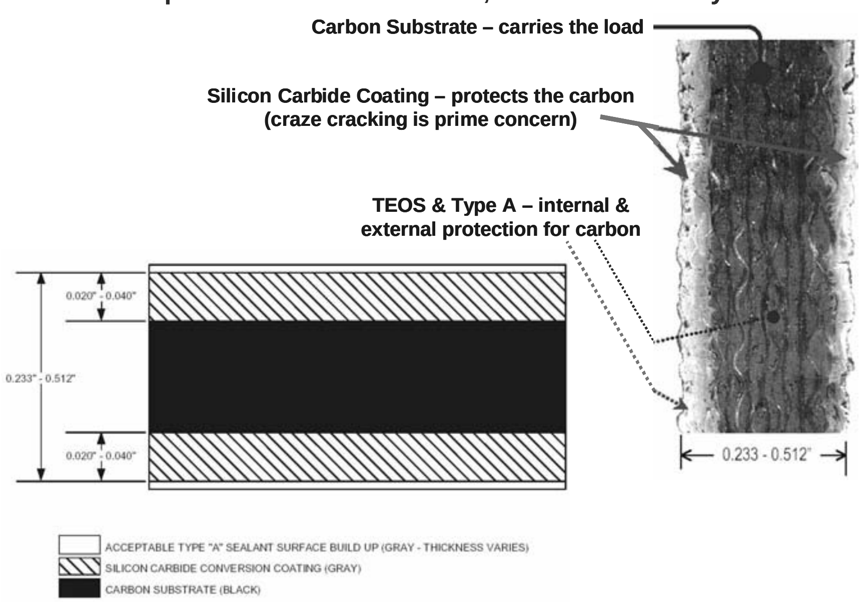
Chin Panel Assembly (67"x22"x18, 57 lbs)



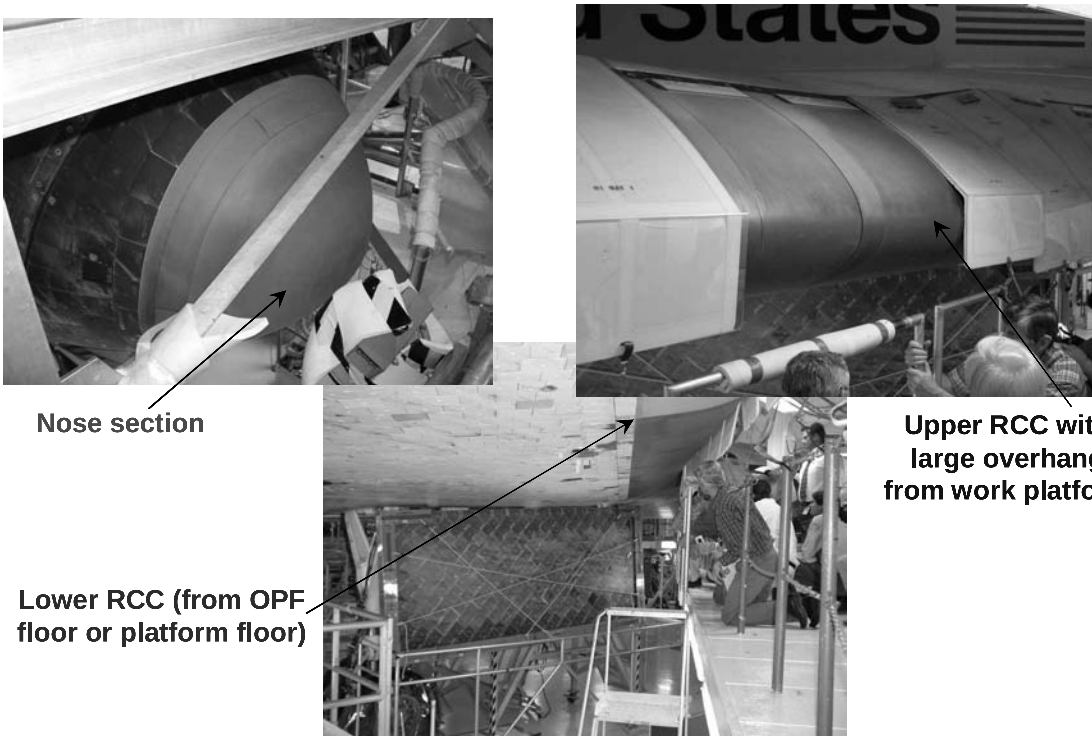
ET Arrowhead Assembly
(17"x14"x0.25", 2 lbs)

Composition of RCC Heat Shield Panels

RCC is composed of carbon substrate, SiC conversion layer and sealant



Deployment of NDI Devices in Orbiter Processing Facility



Nose section

Upper RCC with large overhang from work platform

Lower RCC (from OPF floor or platform floor)

Shuttle In-Situ NDI Program

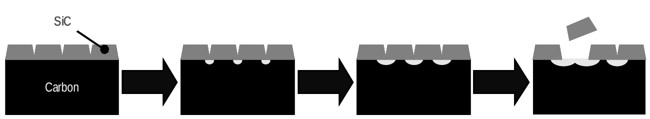
Dark streaks showing projectile impact area

Repetitive flight certification effort –

- **Production NDI: UT, EC, X-ray, tap test**
- **In situ NDI: consisted of visual and tactile inspections**

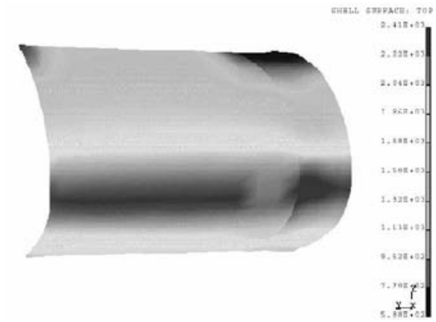
Goal: deploy a variety of NDI methods to detect RCC degradation that may compromise LESS performance

RCC Damage Scenarios - impact damage, loss of coating integrity on the outer surfaces, carbon cracks/fracture, delaminations, disbonds at Si-C to C-C interface, SiC craze cracks & subsequent subsurface oxidation produces mass loss & reduction in strength.

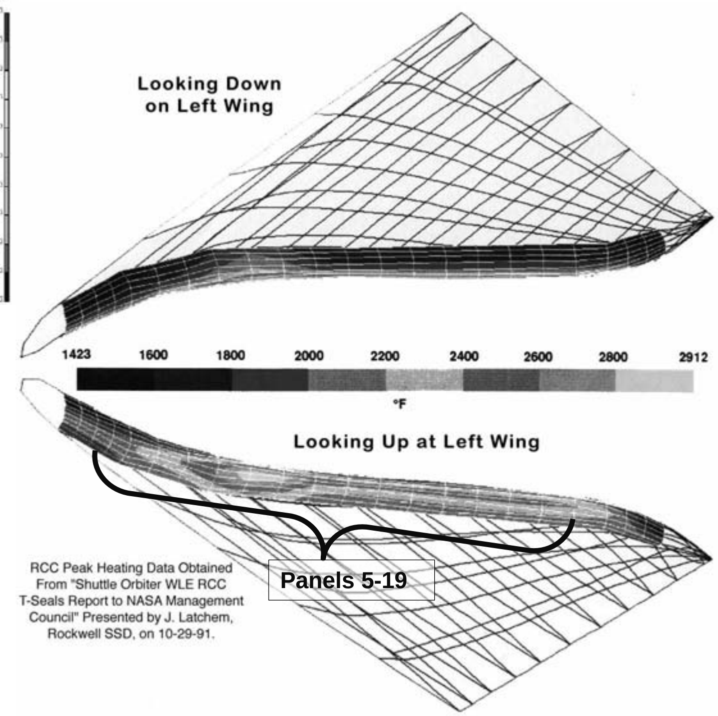


SiC Coating Loss Mechanism via Convective Mass Loss

LESS Thermal Data: WLE Temperature Profile



RCC Panel 19 Temp Contour Plot



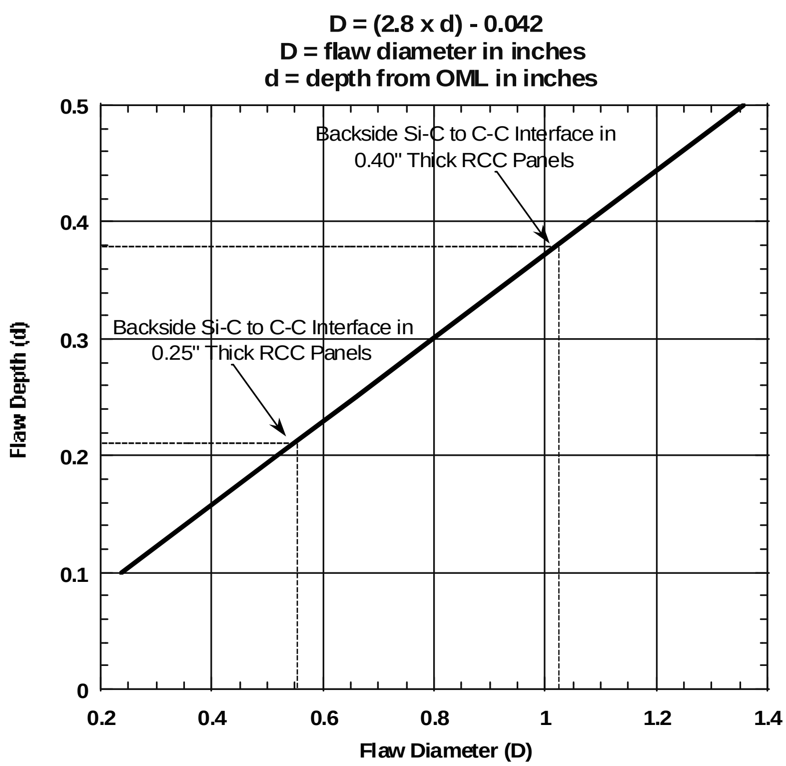
RCC Panel Inspection Requirements

- NDE Feature Detection Criteria
  - Delaminations, Laminar Voids and Local Mass Loss
    - Detect delaminations, laminar voids & local mass loss in C-C using IR thermography.
    - Detection sensitivity at SiC/C-C interface on OML side: 1/8" diameter with 0.005" thickness.
    - Detection sensitivity at 0.12” depth from OML: 3/8" diameter with 0.005" thickness.
    - Everywhere else in C-C, interpolate/extrapolate this criteria.
      - D = 2.8 x d - 0.042“, where D = diameter in inches, d = depth from OML in inches.
  - Cracks
    - IR Thermography is not required to detect OML cracks, but any cracks (excluding craze cracks) detected by IR thermography shall be reported.
    - Detection Sensitivity: A crack with 1/2" length and 0.030" depth in C-C (or 0.060" surface depth from OML for nominal coating thickness of 0.030”) and complete separation between crack faces.

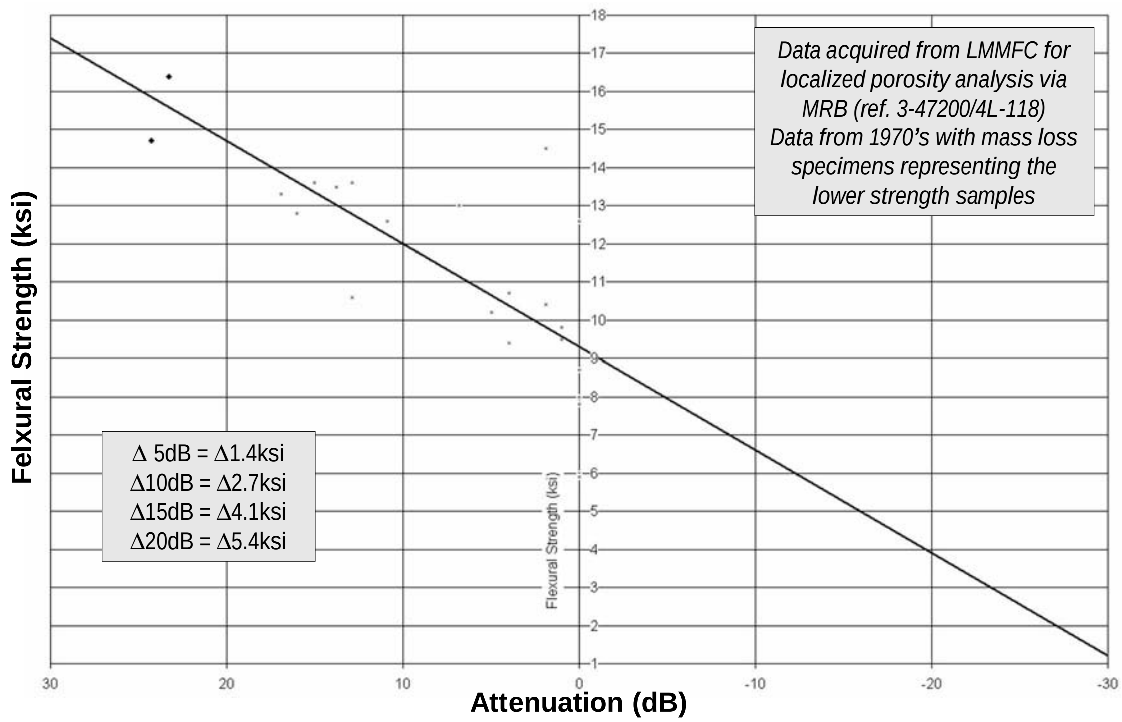
RCC Panel Inspection Requirements

- NDE Feature Detection Criteria
  - – Suspect area is identified by visual inspections, IR inspections, or evidence of an impact/damage event.
  - – Criteria for further evaluation of suspect area using in-situ NDE.
    - Delaminations and impact damage
      - – Detection sensitivity: 1/4” dia. Use ultrasonic hand scanning.
    - Coating
      - – SiC coating thickness measurement range: 0.005" thru 0.060". Spot size ≤ 1/4" dia. Use eddy current.
    - Cracks
      - – Detection sensitivity: Same as for screening inspection. Use eddy current.
  - – C-scan is not mandatory but handheld mapping is required.
    - Cover the entire suspect area at the suspect location.

Flaw Detection Requirements for Depths Beyond the Initial Si-C to C-C Interface

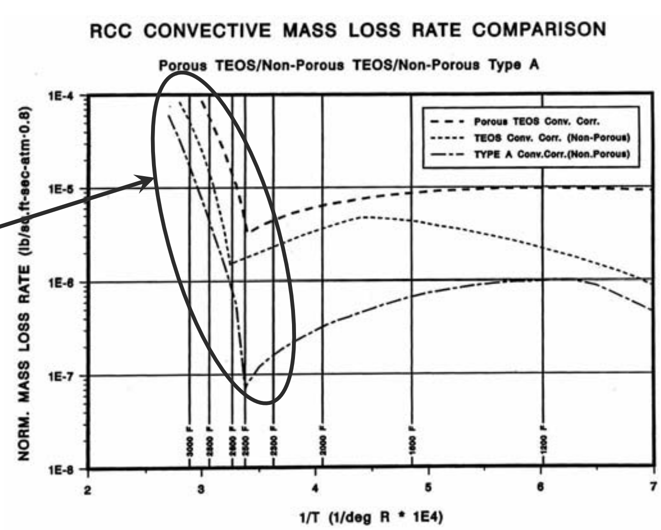


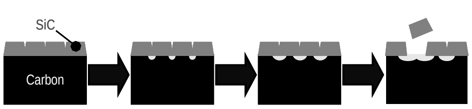
Ultrasonic Attenuation vs. Flexural Strength



RCC Mass Loss Relationships

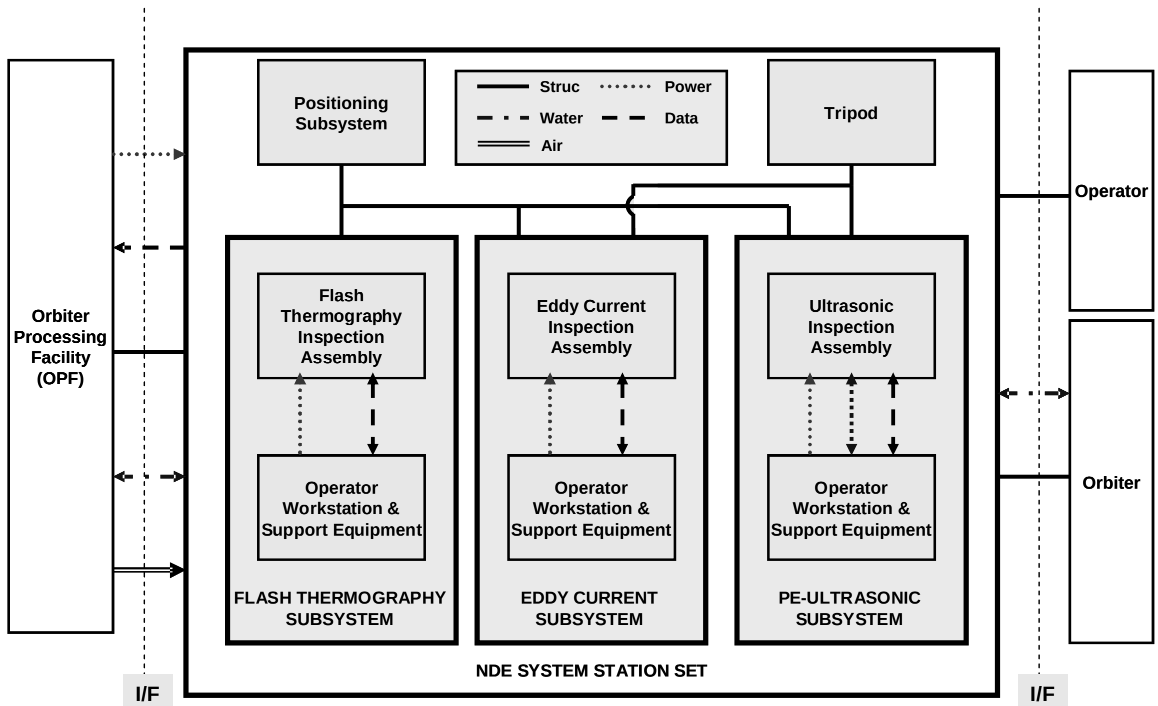
- Mass loss of RCC substrate is directly related to temperature – especially over 2500°F
  - Radiant areas (lugs, ribs, flanges) lose mass uniformly through the thickness and have a 0.10 psf loss limit
  - Convective areas (OML) loose mass preferentially at the coating interface and have a 0.03 psf mass loss limit
- "Invisible" RCC defects are caused by subsurface mass loss in the convective regions
  - This is the key item for flight-to-flight NDE inspections





SiC Coating Loss Mechanism via Convective Mass Loss

Interface Block Diagram of Shuttle Inspection in Orbiter Processing Facility



2.0 Description of Pulse-Echo Ultrasonic NDI Technique

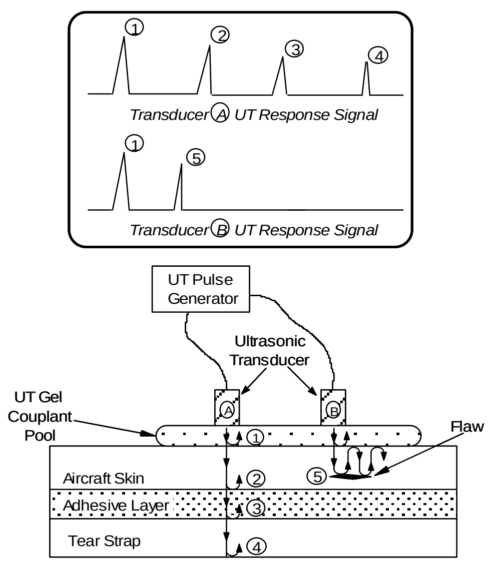
<u>Pulse-Echo Ultrasonic</u> (P-E UT) inspections, short bursts of high frequency sound waves are introduced into materials for the detection of surface and subsurface flaws in the material. The sound waves travel through the material with some attendant loss of energy (attenuation) and are reflected at interfaces. The reflected beam is displayed and then analyzed to define the presence and location of flaws. Complete reflection, partial reflection, scattering, or other detectable effect on the ultrasonic waves can be used as the basis of flaw detection. In addition to wave reflection, other variations in the wave that can be monitored include: time of transit through the test piece, attenuation, and features of the spectral response. The types of RCC flaws detectable by the ultrasonic method include cracks, delaminations, voids, local mass loss, global mass loss, and impact damage.

<u>Wide Area Inspections Aided by C-Scan Mode</u> - It is sometimes difficult to clearly identify flaws using ultrasonic A-Scan signals alone. Small porosity pockets commonly found in composites, coupled with signal fluctuations caused by material nonuniformities can create signal interpretation difficulties. Significant improvements in disbond and delamination detection can be achieved by taking the A-Scan signals and transforming them into a single C-Scan image of the part being inspected. C-scans are two-dimensional images (area maps) produced by digitizing the point-by-point signal variations of an interrogating sensor while it is scanned over a surface. A computer converts the point-by-point data into a color representation and displays it at the appropriate point in an image. Specific "gates" can be set within the data acquisition software to focus on response signals from particular regions within the structure. C-

Scan area views provide the inspector with easier-to-use and more reliable data with which to recognize flaw patterns. This format provides a quantitative display of signal amplitudes or time-of-flight data obtained over an area. The X-Y position of flaws can be mapped and time-of-flight data can be converted and displayed by image processing-equipment to provide an indication of flaw depth.

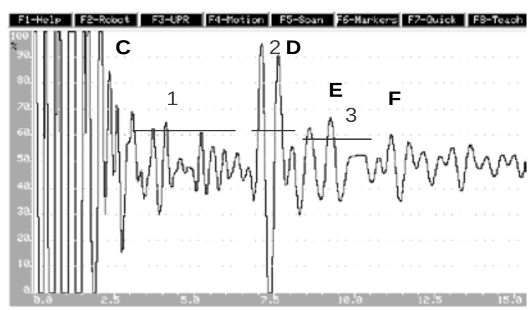
<u>Amplitude and Time-of-Flight Data</u> - Once the digitized A-scan waveforms are recorded during the ultrasonic pulse-echo inspection of the RCC material, the amplitude and time of flight peak signals can be displayed as a C-scan image and analyzed to determine if a flaw exists within the material. The reflected beam from the back surface of the RCC material can be used as the starting point for this analysis. The pseudo colored C-scan image can reveal several variations within the RCC material. The peak amplitude from the back surface is affected by the attenuation within the material and will be displayed in the pseudo colored C-scan image. Any large amplitude change (>12db) in the C-scan image shall be reported. Depending upon the geometry of a flaw and location within the RCC material, the amplitude might not appear very different than that of the surrounding back surface. This is where the time of flight C-scan image can show a slight shift in the pseudo color of the back surface. By analyzing both pseudo colored images (amplitude and time of flight) and the A-scan waveforms, the inspector can determine if a flaw exists within the RCC material. The time of flight C-scan image also shows thickness variations or the taper along the edges of the RCC panel.

Pulse-Echo Ultrasonic NDI



Schematic of Pulse-Echo Ultrasonic Inspection and Reflection of UT Waves at Assorted Interfaces

Transducer is both transmitter & receiver to keep footprint small

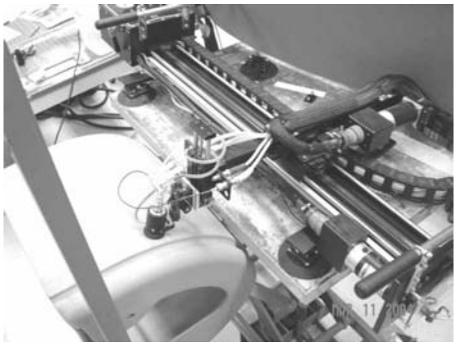


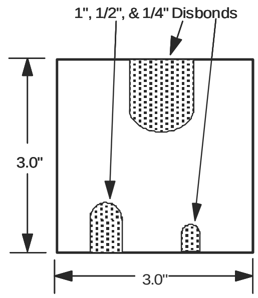
Composite Doubler
A-Scan Signal Trace –
Gate 1: delam & porosity
Gate 2: bond interface
Gate 3: alum. back wall echo

Gates allow users to focus on specific phenomenon

UT Niche – penetration for deep flaw detection

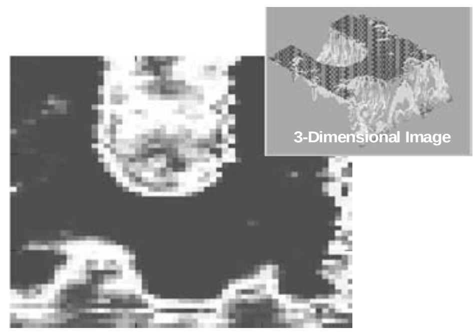
Pulse-Echo Ultrasonic NDI – C-scan Approach





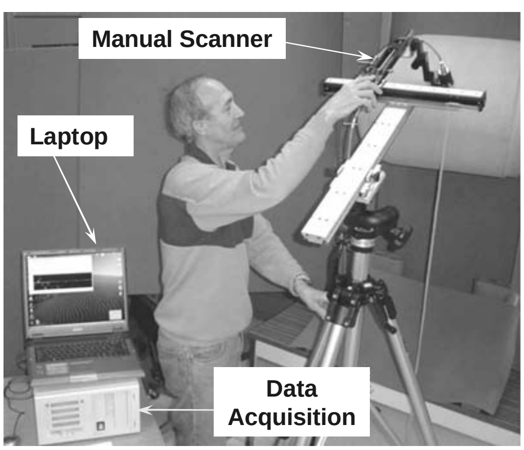
C-Scan Approach

Color coded image produced from relative characteristics of the sum total of signals received

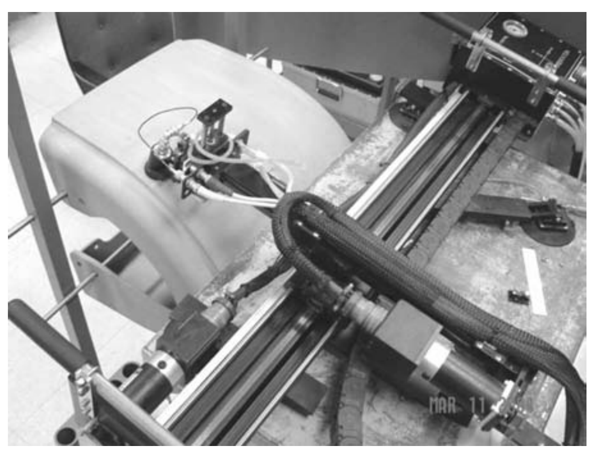


- **Gate settings, appropriate gain, & data acquisition mode are key elements**
- **Dynamic display of data is best for flaw detection**
- **Optimum probe (signal strength) is critical in highly attenuative RCC material**

Pulse-Echo Ultrasonic NDI – C-Scan Approach



Manual Scanner

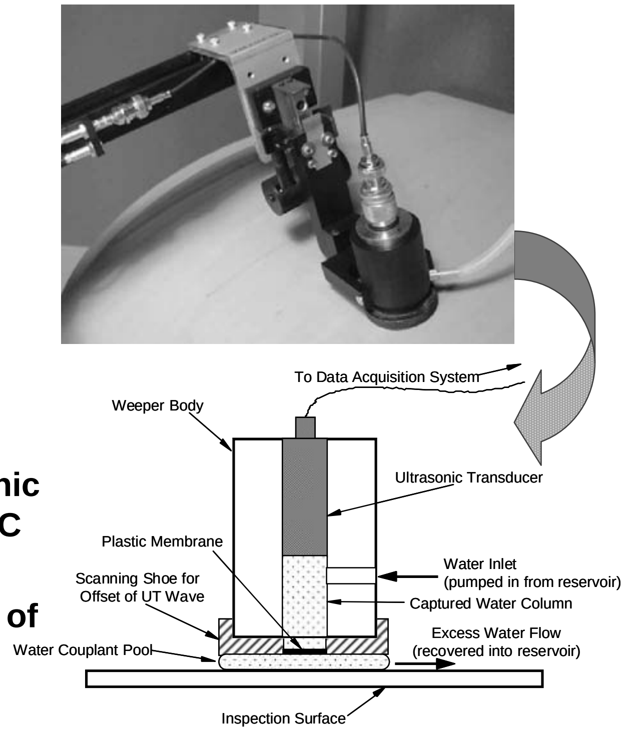


Automated Scanner

Inspection Impediments and Considerations
- **Thickness of structure and energy level of excitation**
- **Attenuation & near-surface signal clarity**
- **Optimizing S/N ratios; flaw size & depth sensitivity**

Pulse-Echo Ultrasonic Set-Up

- **Smallest footprint for best coverage and navigation of curved or uneven surfaces**
- **Probe variables studied:**
  - Ø **1", 2", 3", 5" focus**
  - Ø **0.5", 1", 1.5" dia.**
  - Ø **1- 2.25 MHz freq.**
  - Ø **flat & focused beam**
- **Probe optimization – Harisonic 1 MHz, 1" dia., 2" focus (RCC mat'l passes 1.5 MHz)**
- **Probe offset – water column of 1.1" to 1.2"**



Pulse-Echo Ultrasonic NDI – Flaw Detection Applicability

Goal: detect structural anomalies at all depths within RCC

Technique	Physical Contact Required	Detect Deep Flaws	Delams	Large Voids	Significant Porosity	Local Mass Loss	Impact Damage	Coating Msmts.	Fasteners/ Tubular Voids
Contact P-E Ultrasonics	X	X	X	X	X	X	X		Voids

Sensitivity issue (ref. arc jet disks)

NDE Requirements Document:

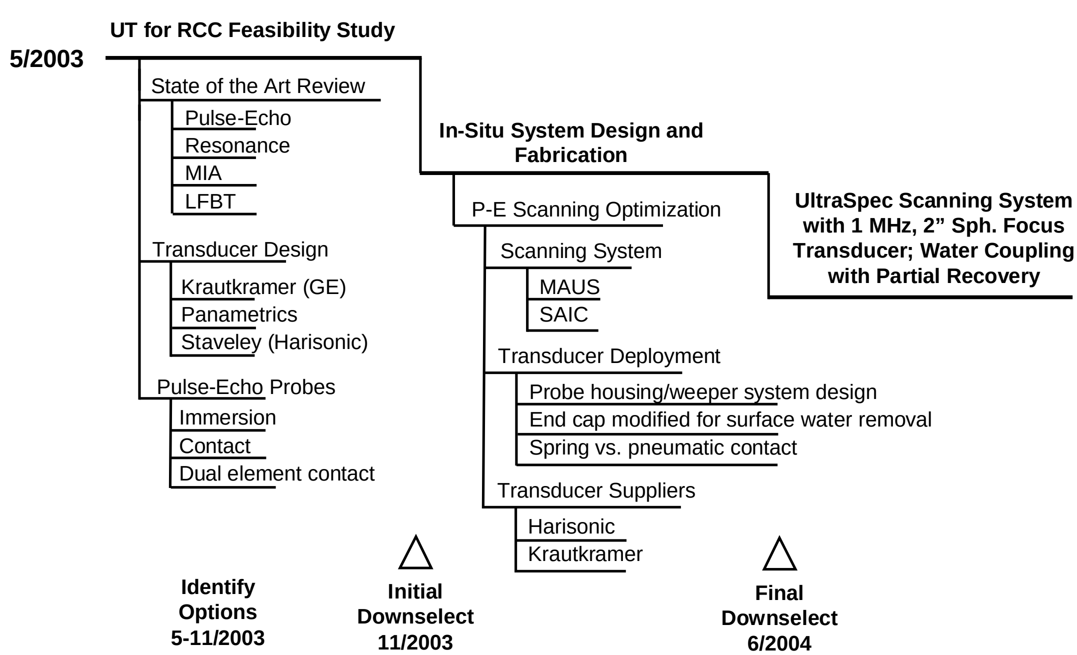
Pulse-Echo Ultrasonics (P-E UT) will detect structural anomalies with at least 0.25" X 0.25" planform dimensions (minimum aspect ratio of 1.0), at any depth within the RCC material at or below the outer surface interface between the Si-C and C-C, and within 0.5" of the panel edge at the interface with the T-seal. Inspections will be performed using a frequency of 1 MHz. Structural variations that manifest themselves as attenuation of an interrogating ultrasonic wave will be assessed in accordance with existing guidance for allowable attenuation levels in a Through-Transmission Ultrasonic (TTU) inspection. Attenuation levels produced in TTU will be related to equivalent attenuation levels in P-E UT so that the same resolution and sensitivity can be achieved. Attenuation levels will be obtained by reference to adjacent locations of the same thickness. Structural anomalies detected as per the above discussion include: cracks, delaminations, and voids/porosity/mass loss. They do not include coating thickness measurements.

Ultrasonic Method Trade Study

- Feasibility study for in-situ RCC ultrasonic inspection performed May to November 2003
  - Assessed multiple ultrasonic composite inspection options using RCC test specimens: pulse-echo UT, resonance, mechanical impedance analysis, low frequency bond test
  - Research performed by Sandia Labs with support from Lockheed-Martin, General Electric Corp. Research, SAIC, Boeing, Krautkramer, and Staveley
  - Assessed scanner systems based on following criteria: wide area inspection, automated X-Y coverage, portability, established I/O (data acquisition & reduction software), lab and field technical support, rapid accommodation of customization needs
  - Results presented at RCC NDE downselect TIM November 2003

- Decision to proceed with UT for in-situ inspection received Dec. 2003
  - UltraSpec scanner system with 1 MHz**,** 1” dia., 2” spherical focus transducer selected for thru-thickness flaw detection

Timeline and Decision Tree for Ultrasonic Method



UltraSpec Pulse-Echo Scanning - Equipment Summary

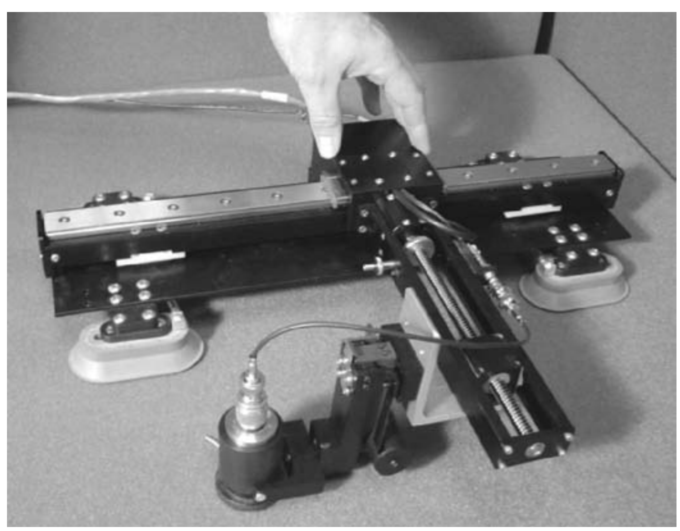
- Probe Assembly
  - Sensor
  - Sensor Housing
  - Gimbal Assembly
  - Z-Axis Assembly
- Scanner Assembly
- Support Equipment
  - I/O Box
  - Water Management
- Operator Workstation

SAIC Ultraspec-MP with LPS-100 Manual Scanner

Technical Specifications

Physical Characteristics

· Scanner height: 2.00 inches
· Scanner width: 6.0 inches
· Scanner length: 12.0 inches
· Scanner weight: 7.0 pounds



RCC system specs

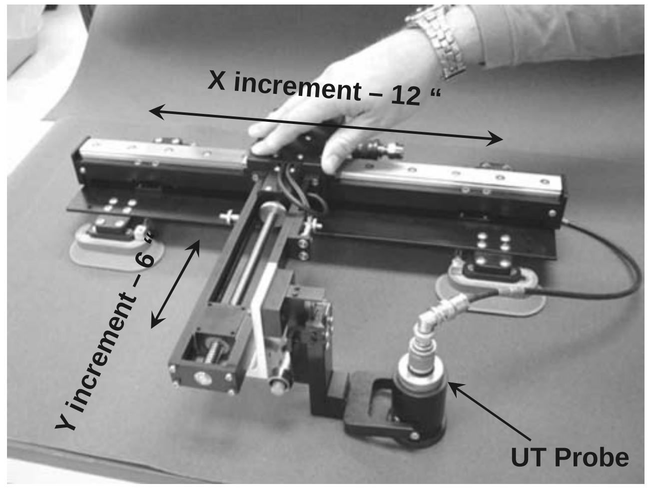
· Encoder resolution:	910 pulses/inch
· Positional accuracy:	+ or - 0.005 inches
· Repeatability:	0.005 inches
· Stroke:	6.0 inches X-axis, 12 inches Y-axis

Pulse-Echo Ultrasonic NDI System

- **Lightweight (6 lb.), manual scanner**
- **<u>Local</u> flaw detection assessment in areas identified by thermography**
- **Can scan up to 12” X 6” area**

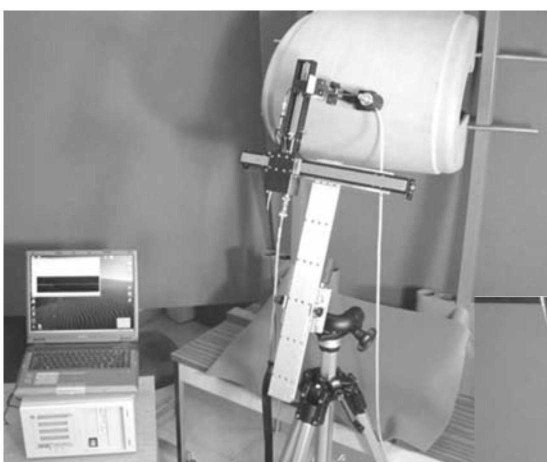
Advantage: easier & more rapid to deploy

Limitation: restricted to small area scans



Pulse-Echo UT System Components

- LPS-100 manual scanner, Data Acquisition System (DAS), laptop
- NASA LaRC linear spring probe mount; probe housing, weeper couplant



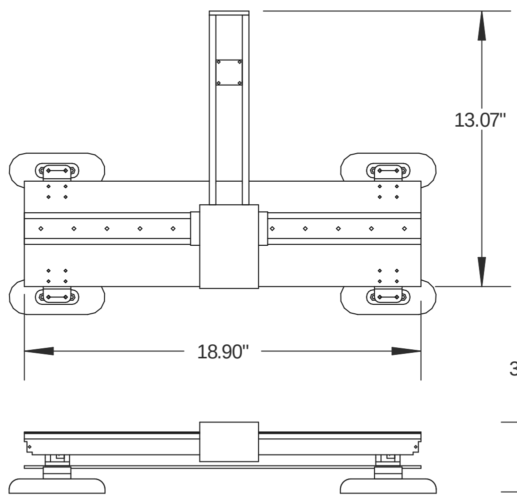
LPS-100 Scanner, Tripod positioning mechanism, DAS and Laptop

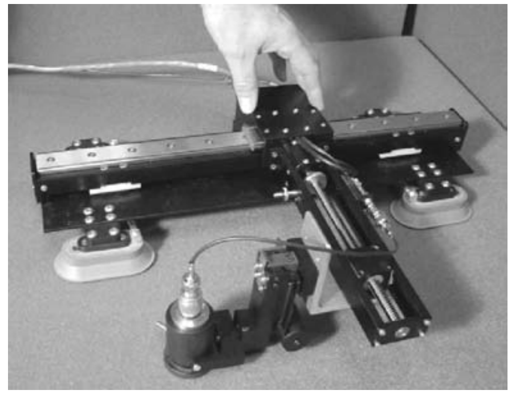
UT Transducer and Housing

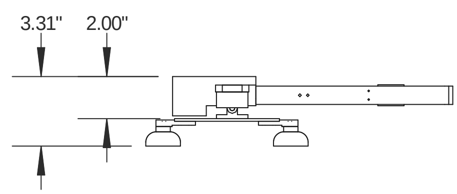
LaRC Linear Spring

UT/EC Manual Scanner (LPS-100)

- **Integrates with existing SAIC scanning station**
- **Designed for 12” X 6” max scan area**
- **Weight with UT probe is 7 lbs.**

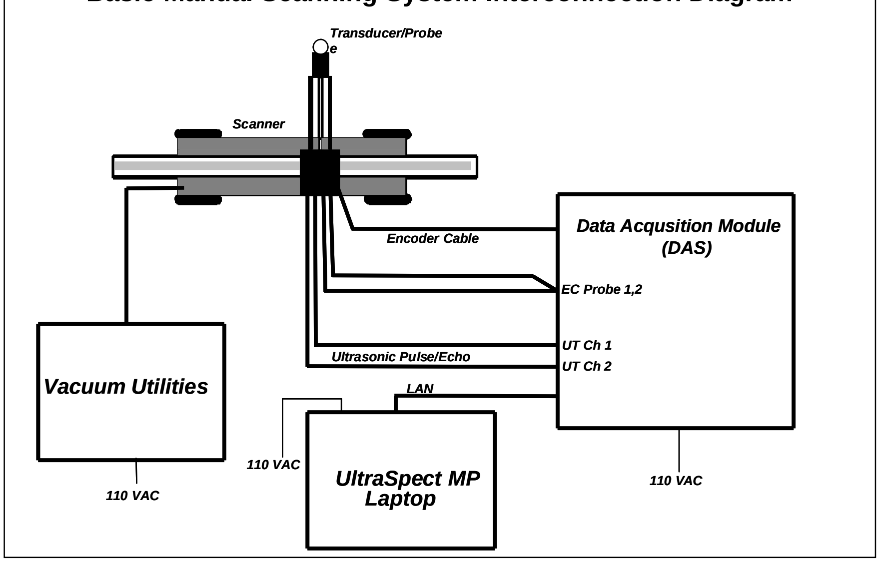






UltraSpect-MP

Basic Manual Scanning System Interconnection Diagram



- Dimensions

  Laptop – Sony VAIO, Model PCG-8N1L

  13.9” x 11.8” x 2.0” (Closed)

  13.9” x 11.8” x 13.1” (Open @ 90 deg)

  DAS Unit – 16.5” x 12.6” x 7.4”

  Utility Box (Vacuum) – 20.5” x 16.5” X 16.5”

  Manual Scanner – 20” x 15” x 3.5”

UltraSpect-MP Electrical System

Output Voltage Levels: Maximum Values

- Ø Encoder Cable – 5 V
- Ø UT Pulser – 400 V, maximum duration 1000 nsec
- Ø EC Coil Drive – 20 V

Output Amperage Levels:

- Ø Encoder output to the scanner encoders is 5VDC and is fused at 1.25 amps, however, the actual encoders only draw about 35 milli amps
- Ø UT Pulser (peak amperage) - UT pulser charges a capacitor of 0.3 microfarad. It is then discharged to generate a pulse. At the maximum pulser voltage of 400 V, and a given transducer impedance (typical value 50 ohms), the current draw (according to Ohm's law) is 400/50 = 8 amps for the duration of the pulse. If a square wave pulser is used, this duration can be varied up to 1000 nanoseconds.
- Ø UT Pulser (RMS amperage) -

  RMS current = peak current * SQRT (T1/T2) where T1 is the pulse on time (width) and T2 is the off time, which is related to scan speed and grid size.

  Apply Sandia Labs inspection set-up:
  Transducer impedance = 75 ohms
  Pulser voltage/duration = 300 V, 700 nanoseconds
  Scan speed 6 in/sec
  Scan index = 0.020" (estimate)
  Max current = 300 v/75 ohms = 4 amps
  T1 = 700 nsec = 700 x 10^-9 sec
  T2 = 1/ ((6 in/sec) / 0.020" index) = 1/300 pts/sec = 0.003333 sec

  RMS current = 4 * SQRT[700*10E(-9)/0.003333] = 58 milli amps

** For the safety of the operator, never change a UT probe with the pulser running. Always close the UT calibration application before changing probes since it is possible to generate a spark between the connector and probe if the connect/disconnect is made while the pulser is running.*

UltraSpect Software Description

Analysis package is the UltraSpect System. The data acquisition software is used to set up the the process for collecting the information from the different inspection methodologies. The analysis package allows the acquired data to be analyzed on another computer without tying up the Control Laptop computer.

The set-up features for data acquisition software does the following:

<u>Ultrasound</u>
Pick the type of scanner
Set up the scanner parameters (x & y scan length, grid size, scan speed)
Ultrasonic parameters (i.e. number of transducers, frequency, time base, number of gates, and other UT parameters)
Display data acquisition results while scanning.
<u>Eddy Current</u>
Pick the type of scanner
Set up the scanner parameters (x & y scan length, grid size, scan speed)
Eddy Current parameters (i.e. number of probes, frequency, time base, etc)
Display data acquisition results while scanning.
<u>Data analysis for UT</u>
This allows the data acquired to be viewed in various formats (A-scan, B-scan, C-scan). Specific areas can be zoomed in to view features, gate position and amplitude can be moved to create additional views
<u>Data Analysis for ET</u>
This allows the data acquired to be viewed in various formats (Lissajous pattern, strip chart, color C-scan) Certain parameters may be changed to create new images without rescanning the part

A list of the software items follows:

UltraSpect-MP system with Ultrasonic and Eddy Current Capability

Each scanner system includes the following software:
Ultrasonic Data Acquisition Acquisition software
Ultrasonic Data Analysis software.
Eddy Current Data Acquisition software
Eddy Current Data Analysis Software

Microsoft Windows XP Operating System
Microsoft Office XP

Additional Ultrasonic Data Analysis software and Eddy Current Data Analysis software was purchased (2nd seat) to allow the acquired data to be analyzed on another computer without tying up the Control Laptop computer.

The procedures for the use of the software is included in the training/operating manuals.

The latest version of software is Version 6.12.2

UT Sensor Description

- **Manufacturer**: GE Inspection Technologies / Krautkramer
  Benchmark Series
  Immersion Transducer
  1 MHz / 1 inch diameter
  2 inch spherical focus

- **Transducer Part Number** : 389-058-620

- **Special Descriptor for Custom NASA Probe**:
  SPFPA-IS8B1NOKNURL2"UHF

Equipment List (For One UT Scanner Unit)

LPS-100 Scanner & DAS – SAIC

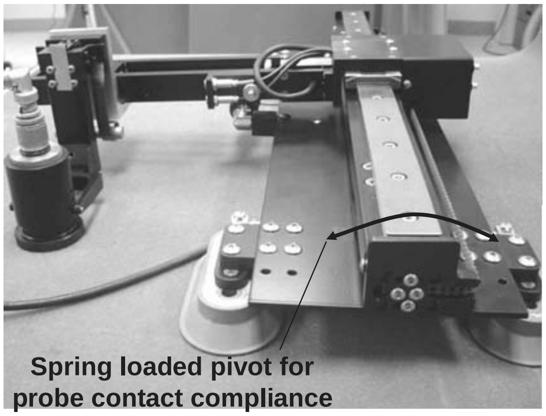
UT Transducer – GE/Krautkramer

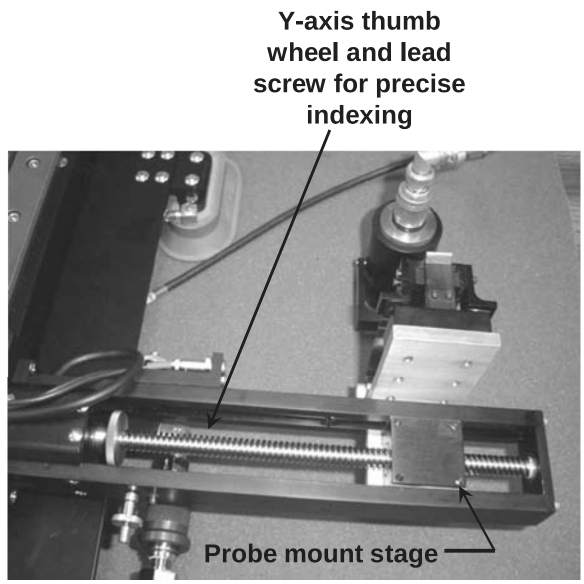
Weeper System & Transducer Housing – Test Tech

Linear Spring - NASA

Recommended Spares: transducers, scanner cable bundles, transducer housing, transducer articulation (yoke, linear spring), weeper system with recovery

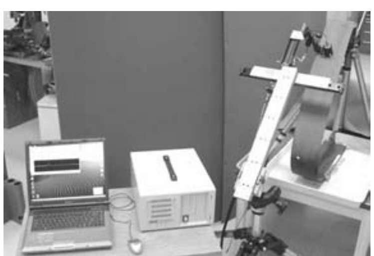
UT/EC LPS-100 Manual Scanner Details



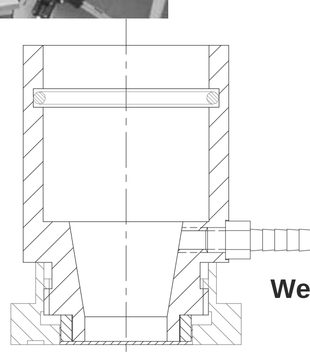


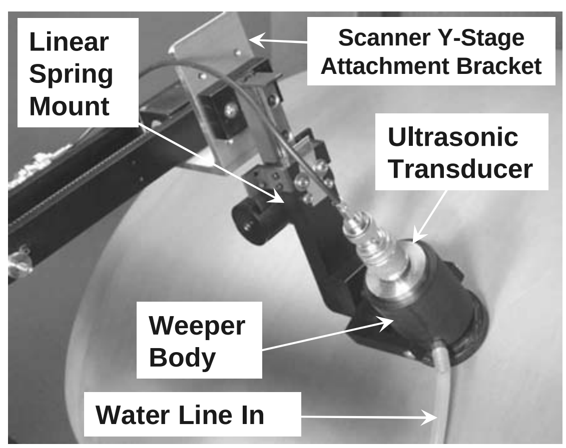
Pulse-Echo UT System Components

- Component list:
  - Operator workstation → Laptop and DAS software
  - I/O Controller → Data acquisition module
  - Sensor housing → Weeper body/transducer with yoke & spring



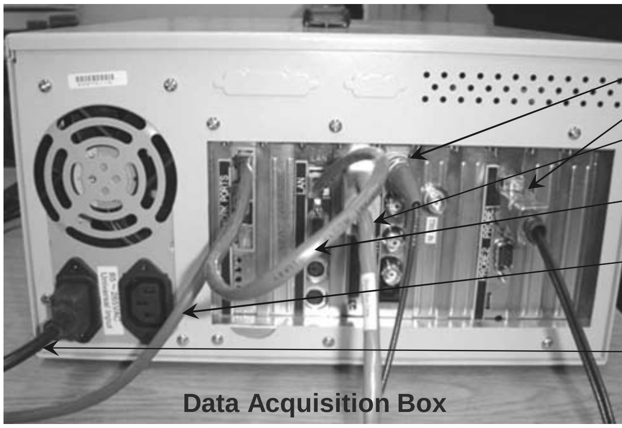
Laptop computer, DAS control box, Manual Scanner





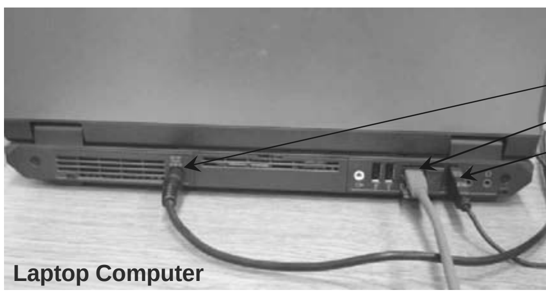
Weeper Body Holding UT Transducer

UT and EC Scanner System Hook-Up


Data Acquisition Box

<u>Connections on Back of DAS Box</u>:

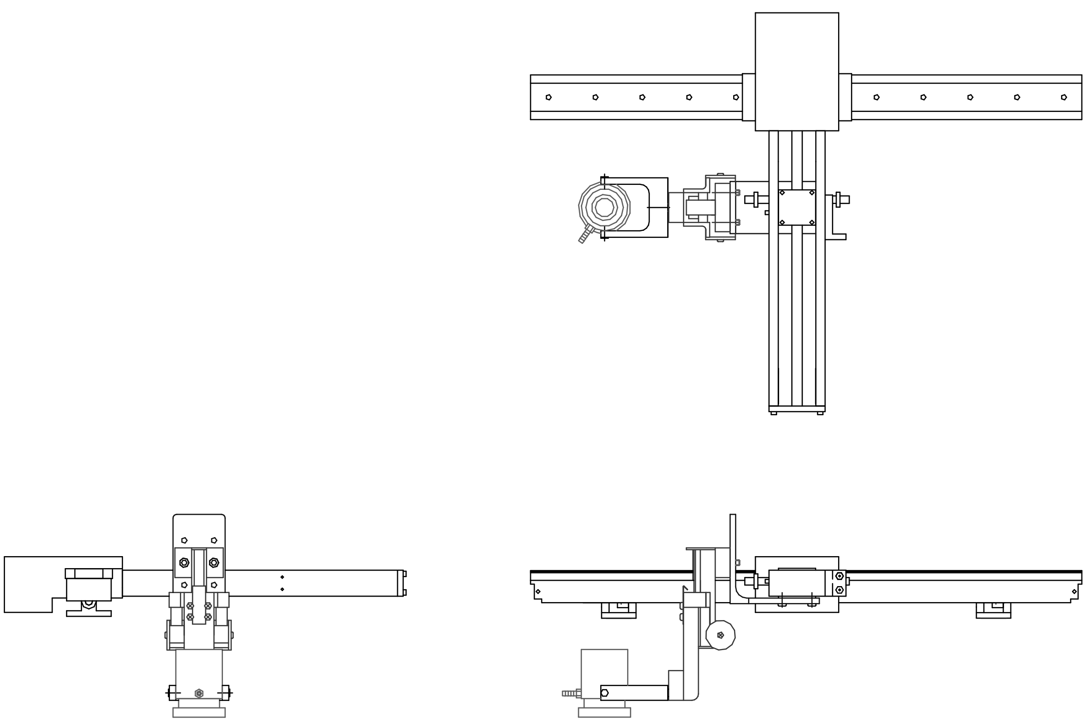
1. UT transducer ⇒ T/R1 (BNC connector)
2. EC transducer ⇒ Probe 1 (9 pin, male)
3. Scanner position encoders ⇒ 9 pin female connector
4. Network jumper (blue cable) ⇒ connect LAN to top Network Port
5. DAS-to-computer (orange cable) ⇒ second port on Network Ports card
6. Power supply to DAS


Laptop Computer

<u>Connections on Back of Laptop</u>:

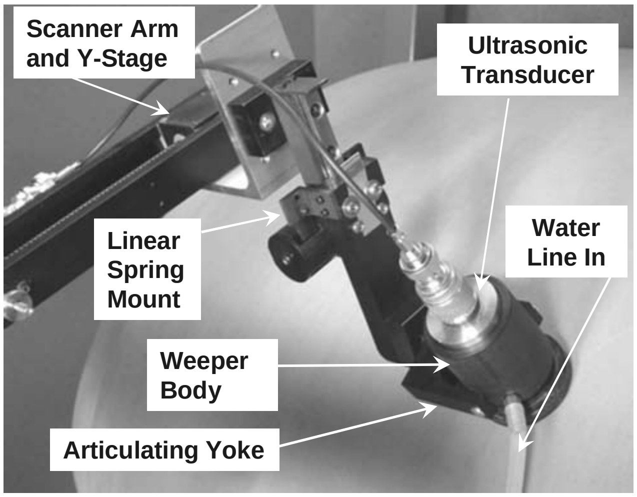
1. Power supply to computer
2. Computer-to-DAS (orange cable)
3. Mouse

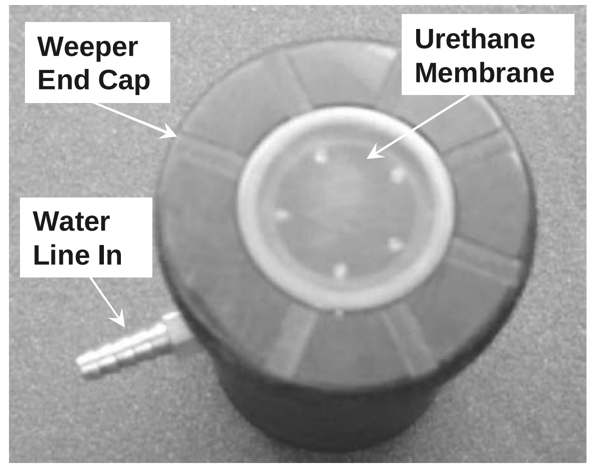
Manual Scanner with Linear Spring and Probe Attached



UT Sensor Housing, Gimbal Assembly, and Z-Axis Tracking Hardware

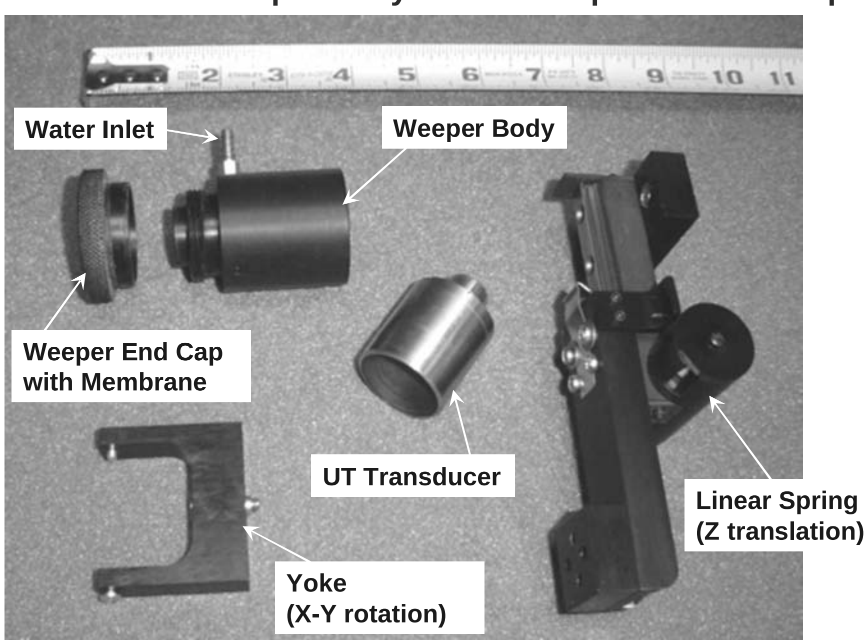
Assembled View of Weeper Body/Transducer with Yoke & Spring



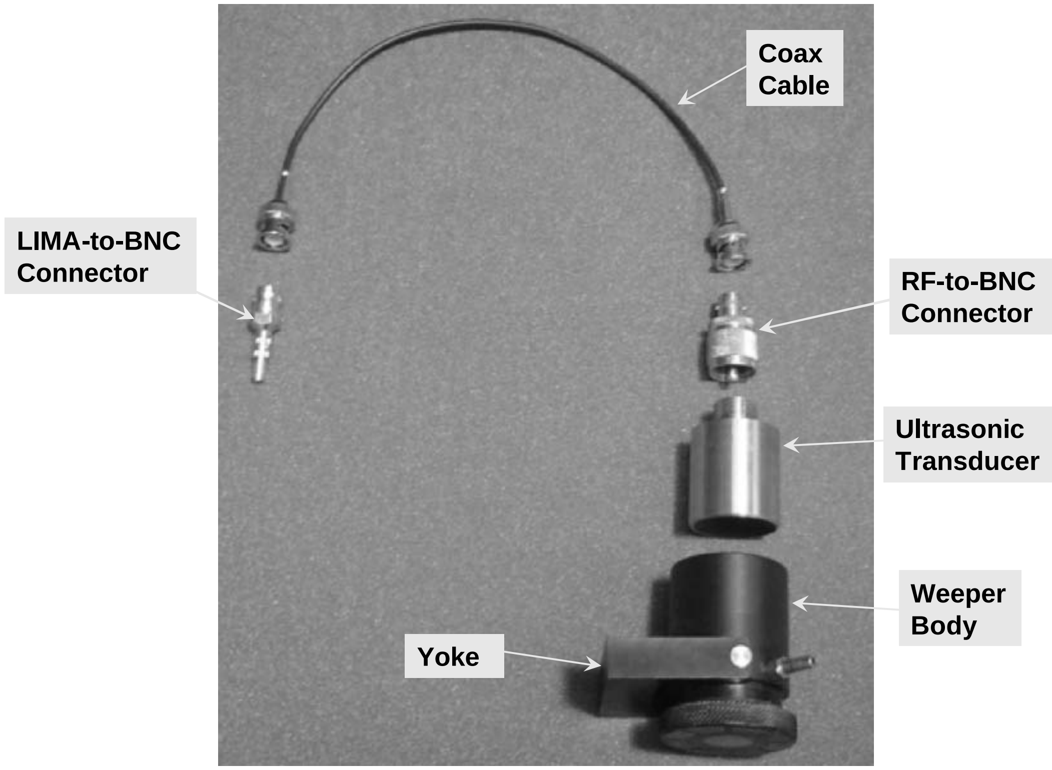


UT Sensor Housing, Gimbal Assembly, & Z-Axis Hardware

Individual View of Weeper Body and End Cap with Yoke & Spring

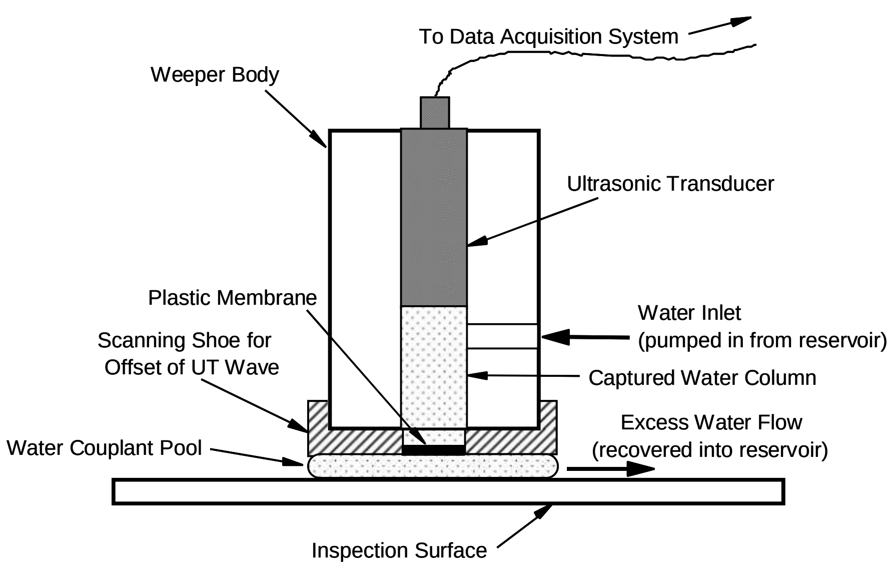


Individual View of Weeper Body, Ultrasonic Transducer, Connectors and Coax Cable



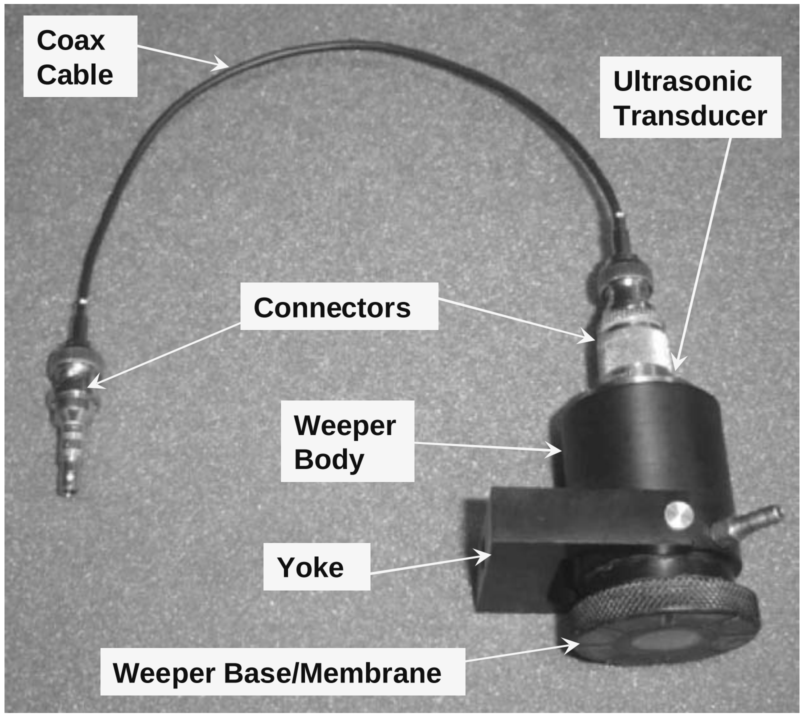
Schematic of Assembled Ultrasonic Sensor System

Weeper Body and Ultrasonic Transducer

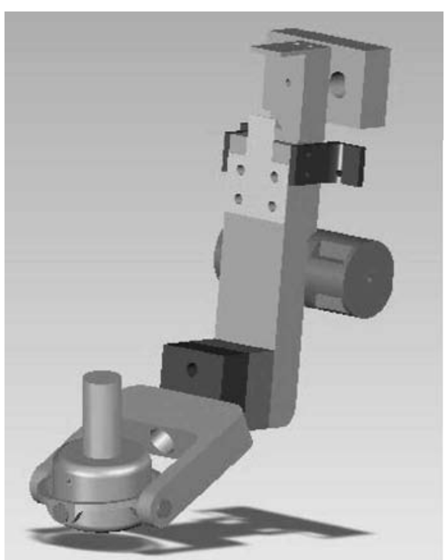


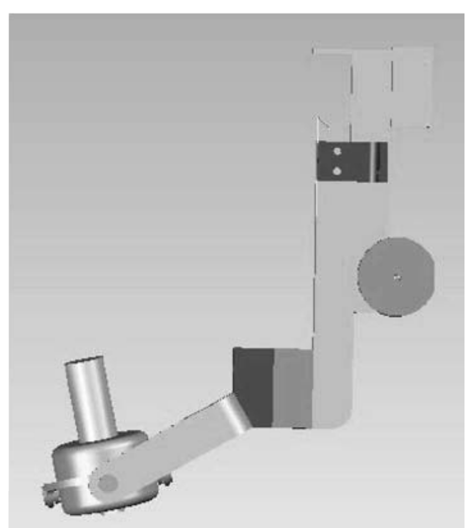
View of Assembled Ultrasonic Sensor System

Weeper Body, Yoke, Ultrasonic Transducer, Connectors, and Coax Cable

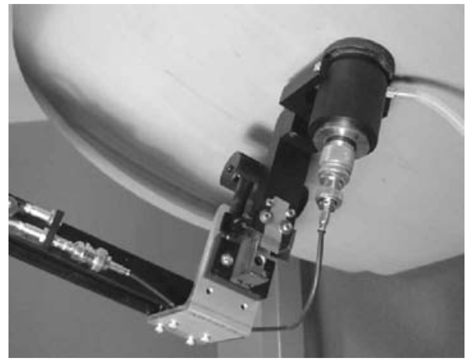


UT/EC Sensor Surface Following with Z-Axis Linear Spring





UT Sensor Housing, Gimbal Assembly, & Z-Axis Hardware



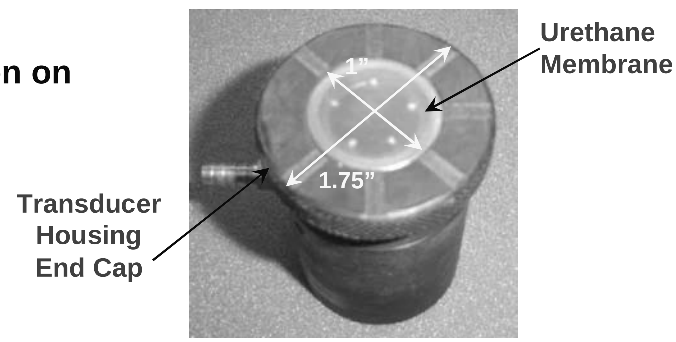
Component Weights

1. **Ultrasonic Probe – 178.9 g (6.3 oz.)**
2. **Probe Housing – 56.8 g (2 oz.)**
3. **Linear Spring – 147.7 g (5.2 oz.)**

Linear Spring Force

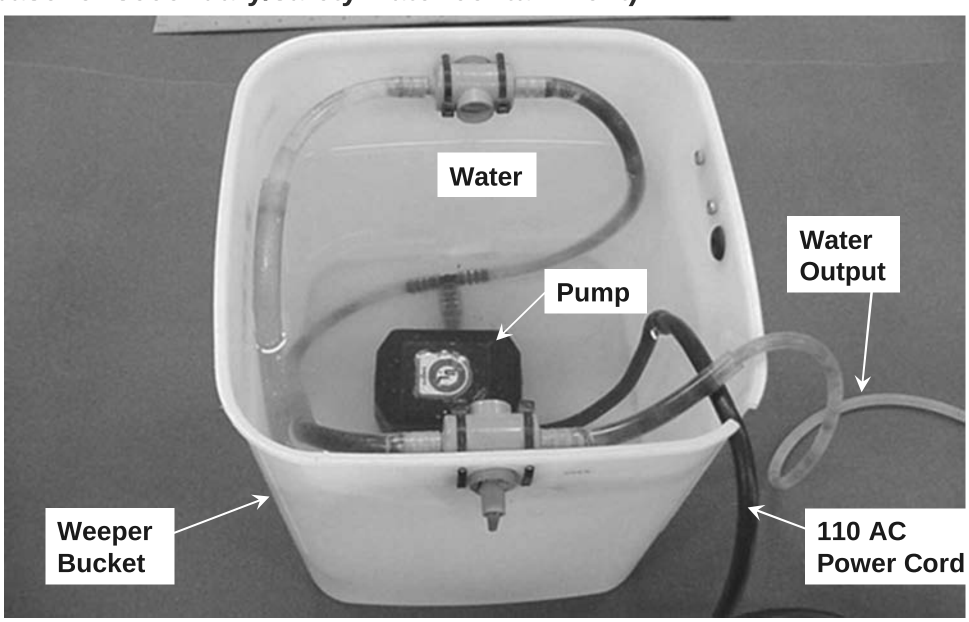
- **Left Spring – 1.12 lbs.**
- **Right Spring – 1.12 lbs.**
- **Both Springs Engaged – 2.24 lbs.**

Pressure Loads – see section on shear and normal force assessment

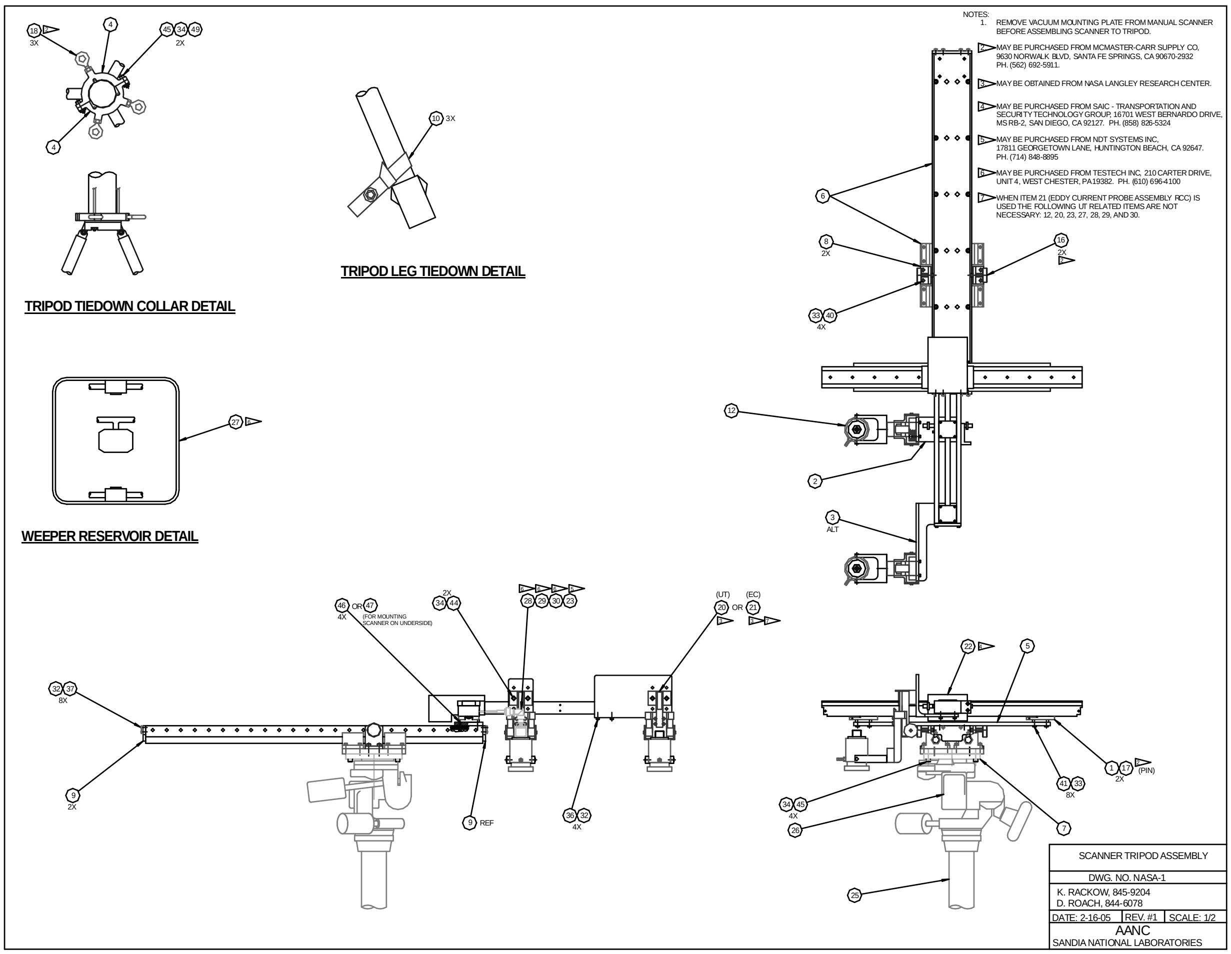


Water Management Equipment Description

Weeper Water Supply and Return (not shown: reservoir top and base for secondary/safety water containment)



Top Level Drawing of Pulse-Echo Scanner System



Pulse-Echo Scanner System – Top Assembly List of Materials

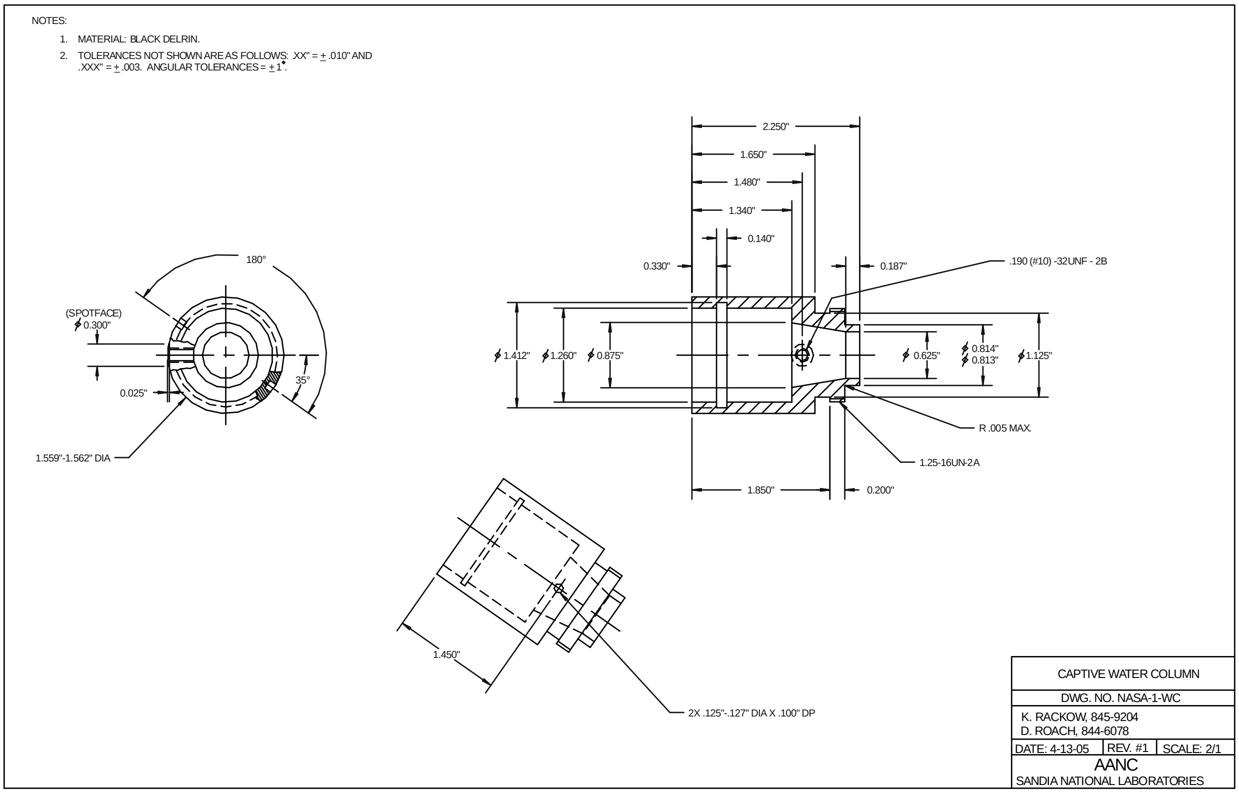
Scanner Tripod Assembly List of Materials				
Qty	**Part No.**	**Description**	**Note**	**Item No.**
				50
2		Nut, Hex, Plain, Steel, .190 (#10)-32UNF-2B		49
				48
4		Screw, 82 Csnk Head, Steel, .190 (# 10) - 32UNF - 2A X 1.50" Lg.		47
4		Screw, 82 Csnk Head, Steel, .190 (# 10) - 32UNF - 2A X .625" Lg.		46
6		Screw, Socket Head, Steel, .190 (# 10) - 32UNF - 2A X .75" Lg.		45
2		Screw, Socket Head, Steel, .190 (# 10) - 32UNF - 2A X .625" Lg.		44
				43
				42
8		Screw, Pan Head, Steel, .164 (# 8) - 32UNC - 2A X .625" Lg.		41
4		Screw, Socket Head, Steel, .164 (# 8) - 32UNC - 2A X .50" Lg.		40
				39
				38
8		Screw, Socket Head, Steel, .138 (# 6) - 32UNC - 2A X .50" Lg.		37
4		Screw, Socket Head, Steel, .138 (# 6) - 32UNC - 2A X .375" Lg.		36
				35
8		Washer, Lock, Nom. I.D. # 10 (.190")		34
12		Washer, Lock, Nom. I.D. # 8 (.164")		33
12		Washer, Lock, Nom. I.D. # 6 (.138")		32
				31
1	30701AM067	BNC to BNC 12" lg. RG174 (50 ohm) Coaxial Cable	6	30
1	30701AM063	BNC/RA Adapter	6	29
1	30701AM62	UHF/BNC Adapter	6	28
1	30701AM100	Weeper Captive Water Column Kit	6	27
1	PSC-3057	Bogen Tripod, Head, Model 3057		26
1	PSC-3058	Bogen Tripod, Model 3058		25
				24
1	ALRB02	Lemo Right Angle Plug/BNC Receptacle	5	23
1	LPS100	SAIC Ultra Spec Manual Scanner System	4	22
1	1245825	Eddy Current Probe Assembly RCC	3	21
1	1245938	Ultrasonic Probe Assembly RCC	3	20
				19
3	3032T64	Eyebolt, Stainless Steel, W/ Nut, 1/4"-20 thd.	2	18
2	92373A115	Spring Pin, Steel, .062" dia X 1.00" Lg.	2	17
2	90079A245	Knurled Head Pilot (Dog Point) Thumb Screw 1/4"-20 x 1.00" Lg.	2	16
				15
				14
				13
1	NASA-3-WC	Probe Holder Assembly		12
				11
3	NASA-10-SC	Tripod Leg Tiedown Strap		10
2	NASA-9-SC	Linear Slide Stop Plate		9
2	NASA-8-SC	Linear Slide Positioning Stop		8
1	NASA-7-SC	Modified Tripod Head Mounting Plate		7
1	NASA-6-SC	Modified Linear Slide Mount		6
1	NASA-5-SC	Scanner Mounting Plate		5
1	NASA-4-SC	Tripod Tiedown Collar		4
1	NASA-3-SC	Probe Holder Extended Attachment Bracket		3
1	NASA-2-SC	Probe Holder Standard Attachment Bracket		2
2	NASA-1-SC	Scanner Spring Lock Shim		1

Design Drawing Set for Pulse-Echo Ultrasonic System

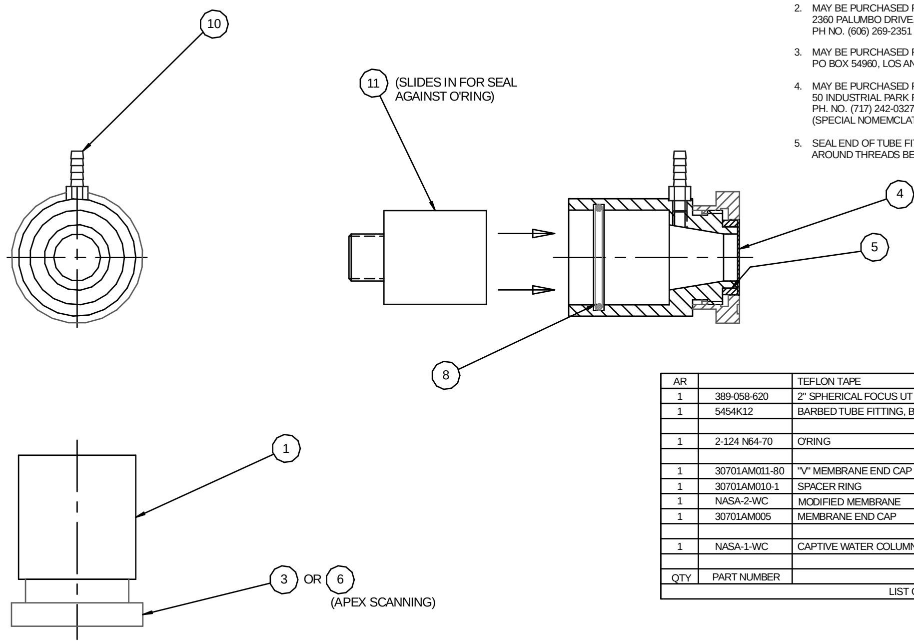
SNL Drawings for NASA Scanner Assembly	
Drawing Title	**Drawing No.**
Captive Water Column	NASA-1-WC
Modified Membrane	NASA-2-WC
Probe Holder Assembly	NASA-3-WC
Scanner Spring Lock Shim	NASA-1-SC
Probe Holder Standard Attachment Bracket	NASA-2-SC
Probe Holder Extended Attachment Bracket	NASA-3-SC
Tripod Tiedown Collar	NASA-4-SC
Scanner Mounting Plate	NASA-5-SC
Modified Linear Slide Mount	NASA-6-SC
Modified Tripod Head Mounting Plate	NASA-7-SC
Linear Slide Positioning Stop	NASA-8-SC
Linear Slide Stop Plate	NASA-9-SC
Tripod Leg Tiedown Strap	NASA-10-SC
Scanner Tripod Assembly	NASA-1
Maximum Height Tripod Deployment Layout	NASA-2
Minimum Height Tripod Deployment Layout	NASA-3

UT Transducer Housing

Drawing of Delrin body, for proper probe offset from inspection surface, and water coupling



UT Transducer Housing



NOTES:

1. MAY BE PURCHASED FROM: TESTECH INC. , 210 CARTER DR., UNIT 14, WEST CHESTER, PA 19382, PH. (610) 696-4100.
2. MAY BE PURCHASED FROM: PARKER SEAL GROUP, O'RING DIVISION, 2360 PALUMBO DRIVE, PO BOX 11751, LEXINGTON, KY 40512. PH NO. (606) 269-2351
3. MAY BE PURCHASED FROM: MCMASTER-CARR SUPPLY COMPANY, PO BOX 54960, LOS ANGELES, CA 90054-0960. PH. NO. (562) 692-5911
4. MAY BE PURCHASED FROM: GE INSPECTION TECHNOLOGIES, 50 INDUSTRIAL PARK ROAD, LEWISTOWN, PA 17044. PH. NO. (717) 242-0327 (SPECIAL NOMEMCLATURE: SPFPA-IS8B1NOKNURL2"SUHF)
5. SEAL END OF TUBE FITTING BY WRAPPING TEFLON TAPE AROUND THREADS BEFORE ASSEMBLING.

QTY	PART NUMBER	DESCRIPTION	NOTE	ITEM
AR		TEFLON TAPE	5	12
1	389-058-620	2" SPHERICAL FOCUS UT TRANSDUCER, 1MHZ, 1" DIA	4	11
1	5454K12	BARBED TUBE FITTING, BRASS	3	10
				9
1	2-124 N64-70	O'RING	2	8
				7
1	30701AM011-80	"V" MEMBRANE END CAP	1	6
1	30701AM010-1	SPACER RING	1	5
1	NASA-2-WC	MODIFIED MEMBRANE		4
1	30701AM005	MEMBRANE END CAP	1	3
				2
1	NASA-1-WC	CAPTIVE WATER COLUMN		1

LIST OF MATERIALS

PROBE HOLDER ASSEMBLY

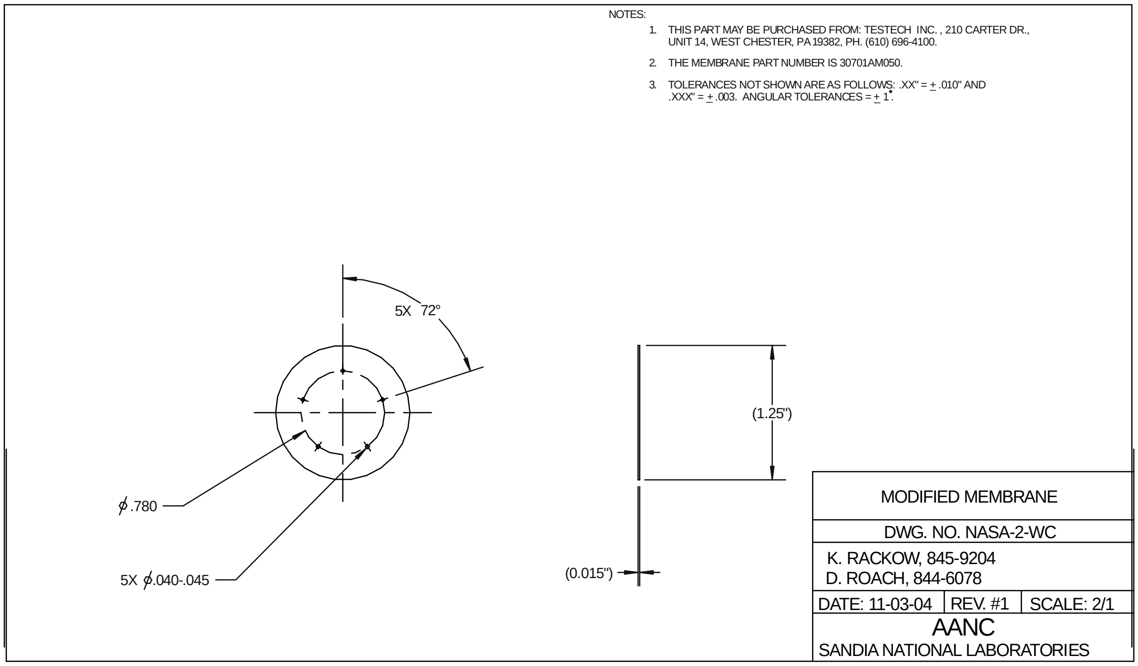
DWG. NO. NASA-3-WC

K. RACKOW, 845-9204
D. ROACH, 844-6078

DATE: 2-22-05 | REV. #1 | SCALE: 2/1

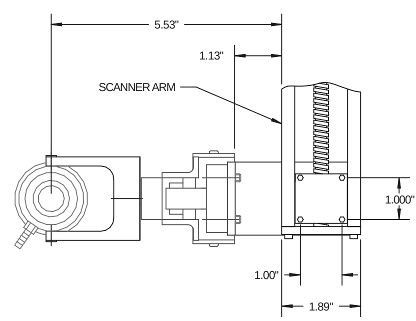
AANC
SANDIA NATIONAL LABORATORIES

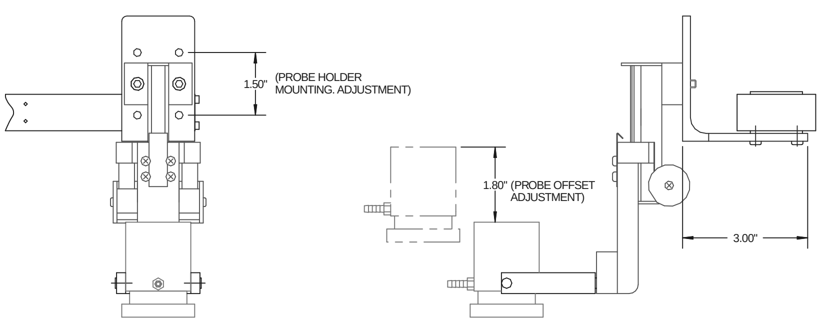
UT Transducer Housing – Water Column Membrane



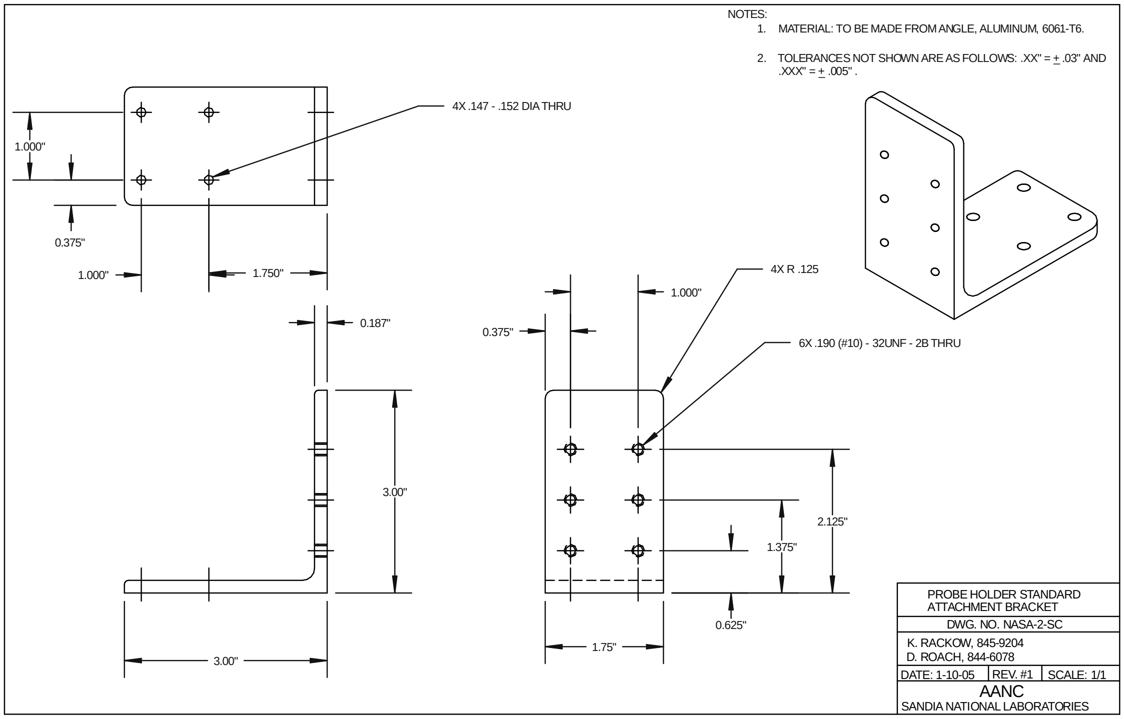
UT Sensor Housing, Gimbal Assembly, & Z-Axis Hardware

Assembled View of Weeper Body/Transducer with Yoke & Spring

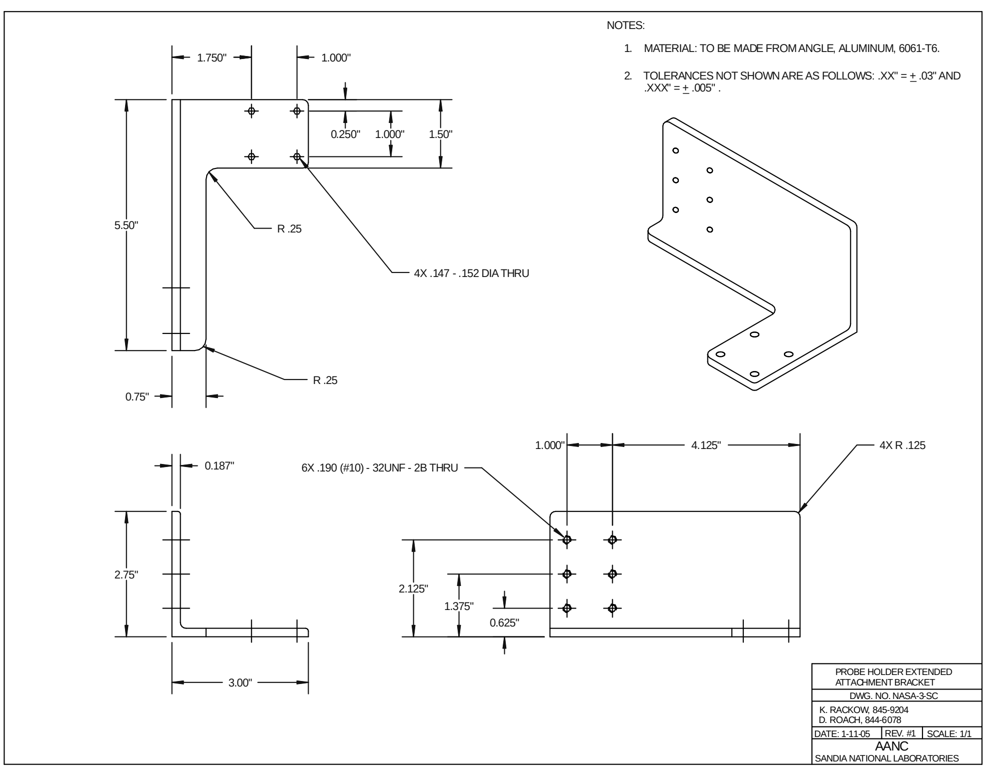




Normal Bracket for Connecting Probe Housing to Scanner Arm



Reach Extension Bracket for Connecting Probe Housing to Scanner Arm



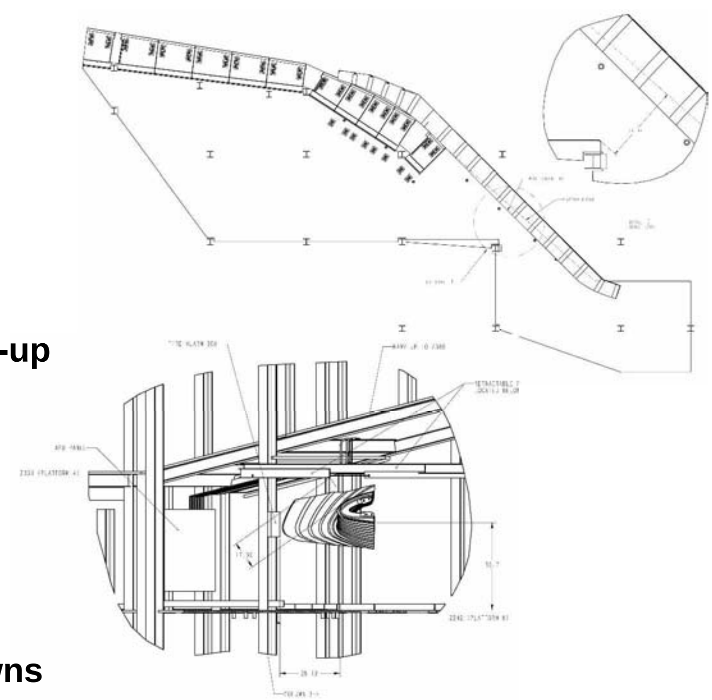
3.0 Tripod Positioning Mechanism for Manual Ultrasonic Scanner

Tripod Positioning Mechanism Design Parameters

<u>**Vertical Reach**</u>
Upper height: 70”
Lower height: 46”

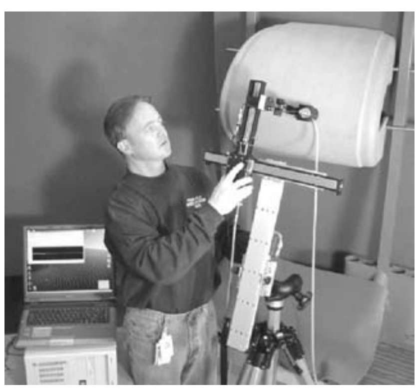
<u>**Horizontal Reach**</u>*****
Max: 18”
Min: 1”

- **Easy transport & set-up**
- **Can support 16 lbs.**
- **Provide upright and inverted scanning**
- **Positioning locks**
- **Stabilized by tie-downs**

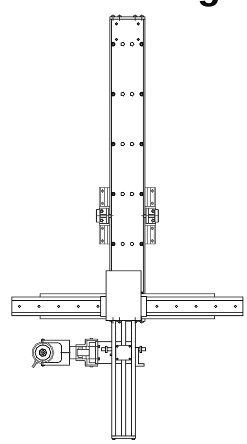


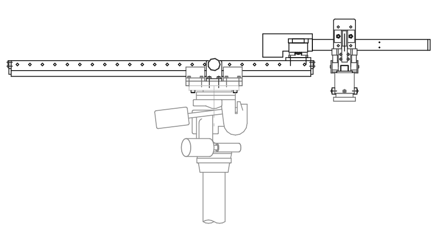
**** Assumes PIC boards are not in place & are not available for supporting tripod legs***

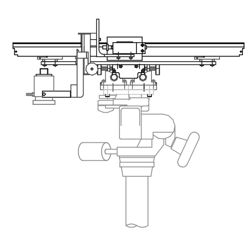
Integration of Manual Scanner with Tripod Positioning



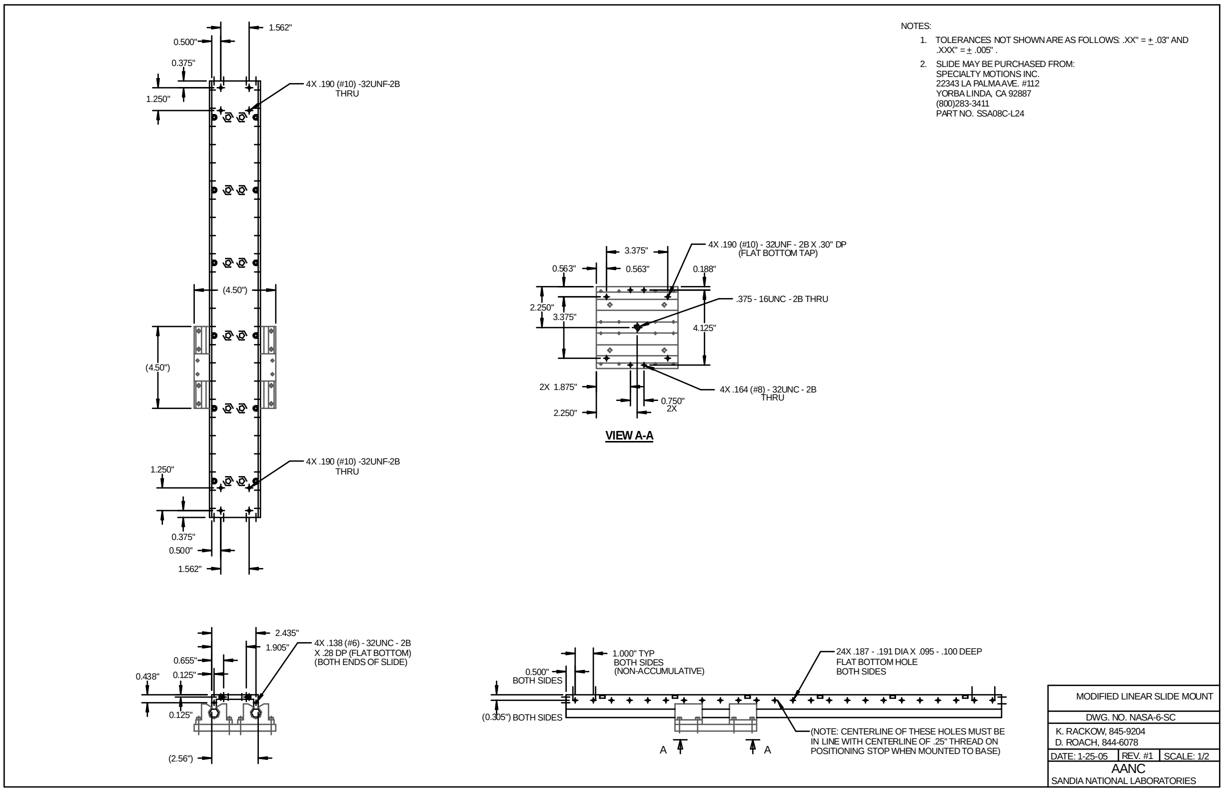
Linear slide (with motion locks) mounted on tripod – Allows for inverted scanning and scanning in vertical direction



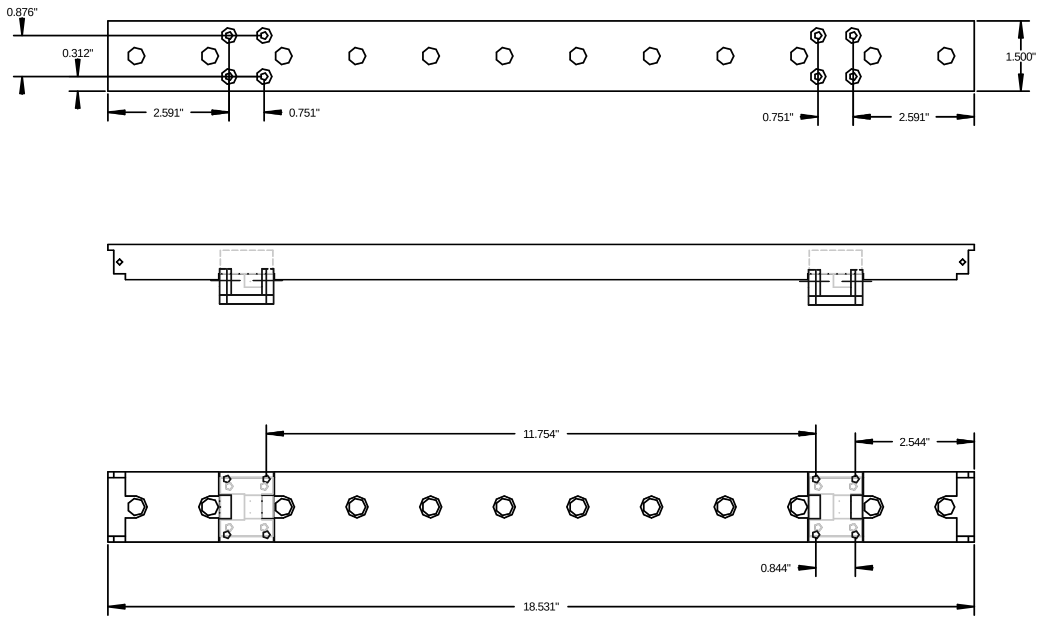




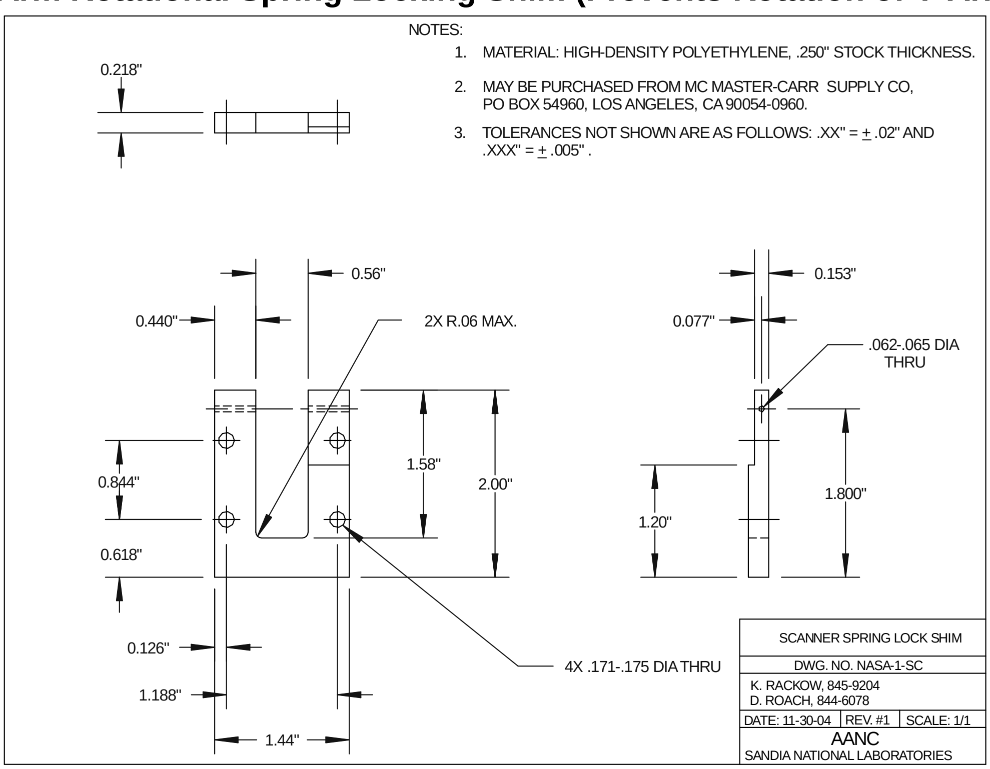
Modified COTS Linear Slide Mount for Scanner Base – Placed on Top of Tripod



Existing Scanner Rail Base for Connecting Manual Scanner to Tripod Positioner



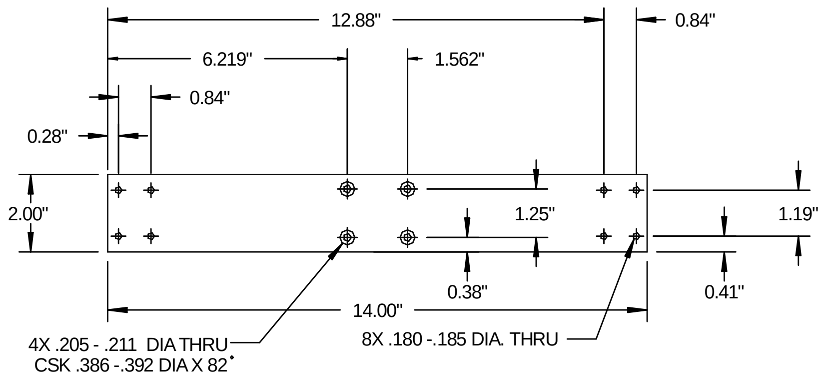
Y-Arm Rotational Spring Locking Shim (Prevents Rotation of Y-Arm)



Mounting Plate for Placing Scanner on Tripod Positioning Mechanism

NOTES:

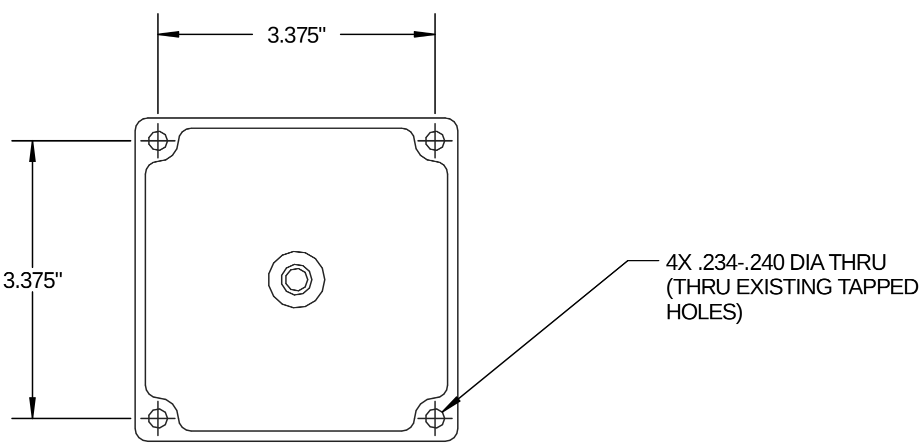
1. MATERIAL: ALUMINUM, 6061-T6, .250" THK.
2. TOLERANCES NOT SHOWN ARE AS FOLLOWS: .XX" = ± .03" AND .XXX" = ± .005" .



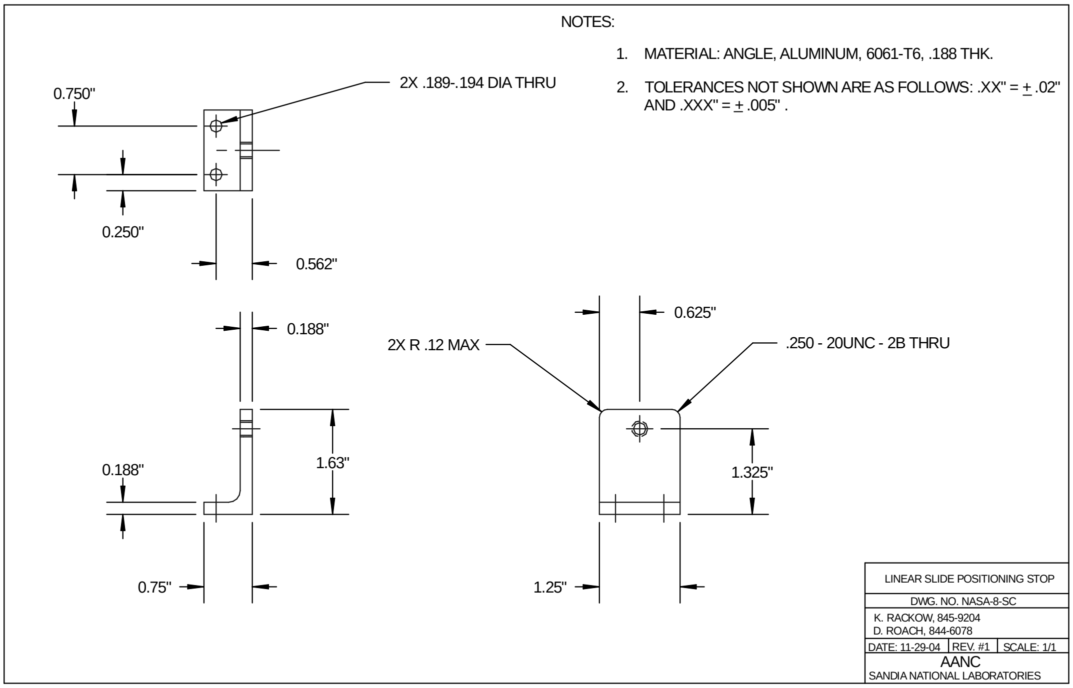
Adapter Plate for Mounting Linear Slide on Tripod

NOTES:

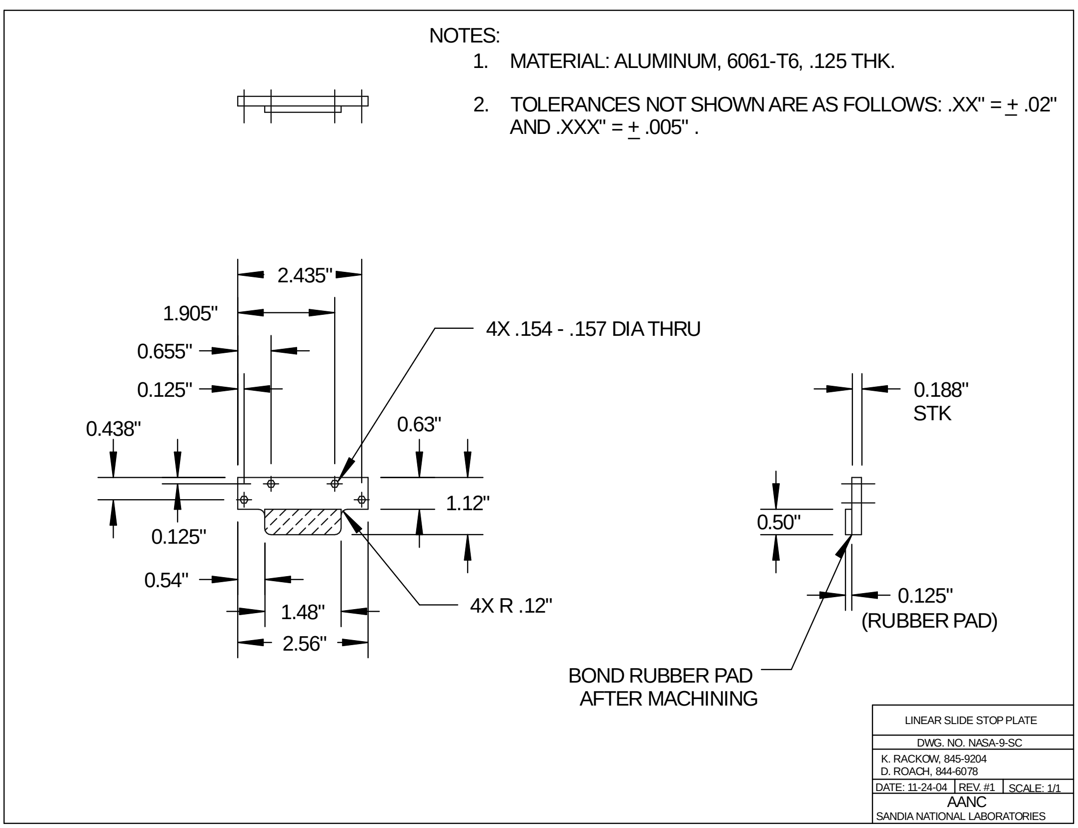
1. PART TO BE MODIFIED IS A BOGEN ADAPTER PLATE PART NO. 3297.



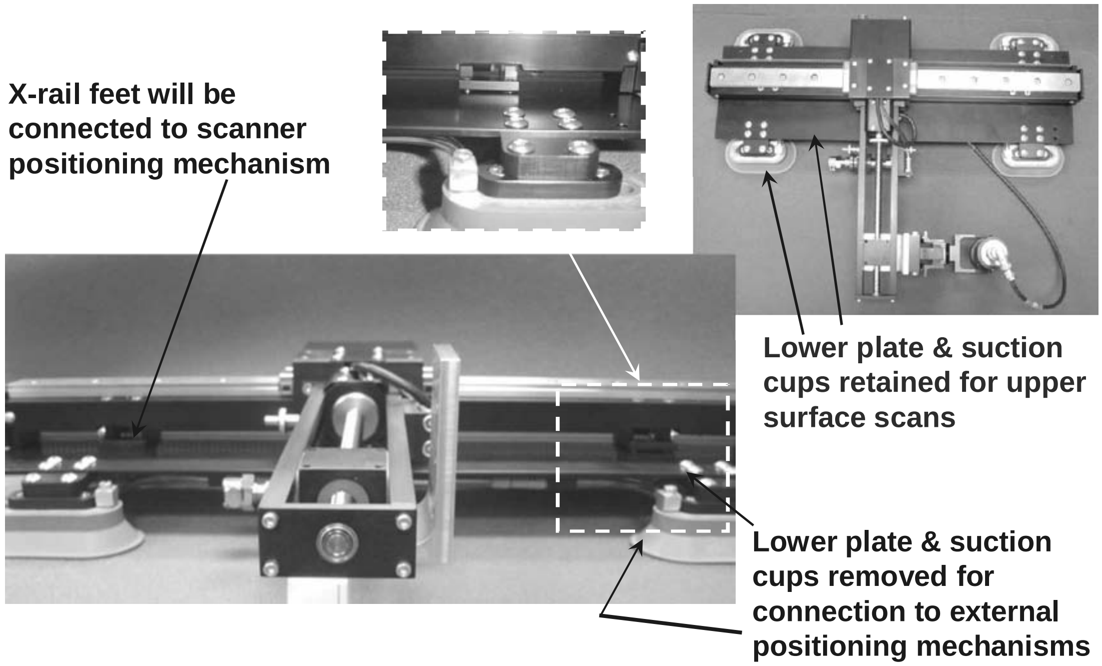
Locking Plates for Holding Linear Slide Position



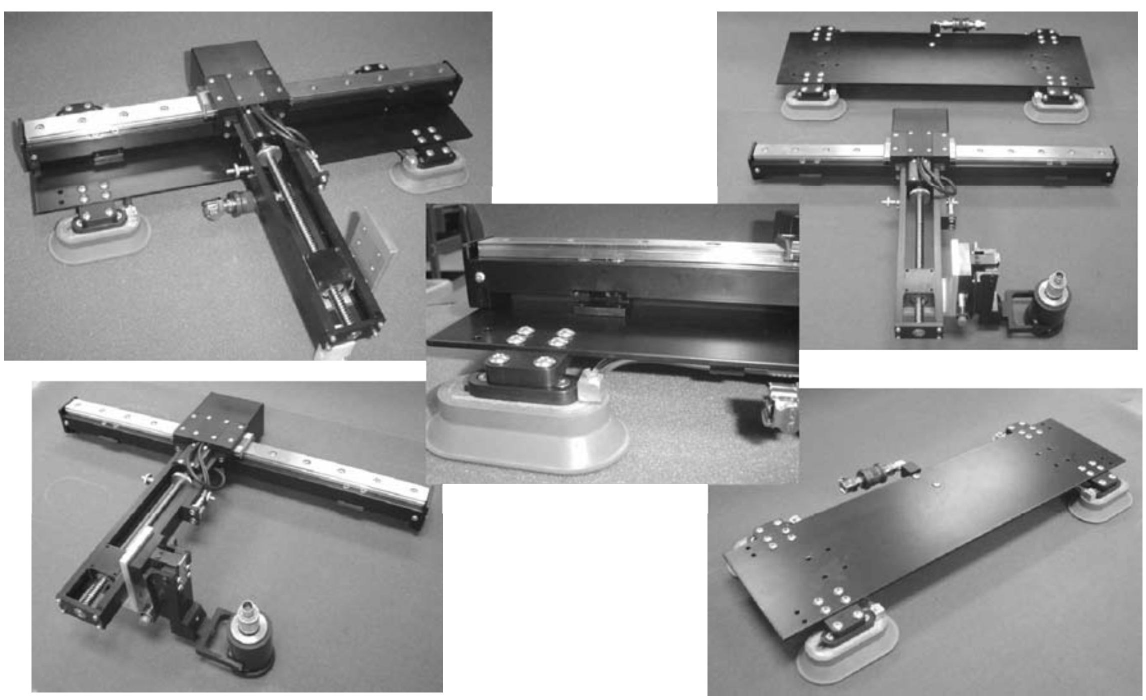
Safety Stop Plate for Retaining Linear Slide on Tripod



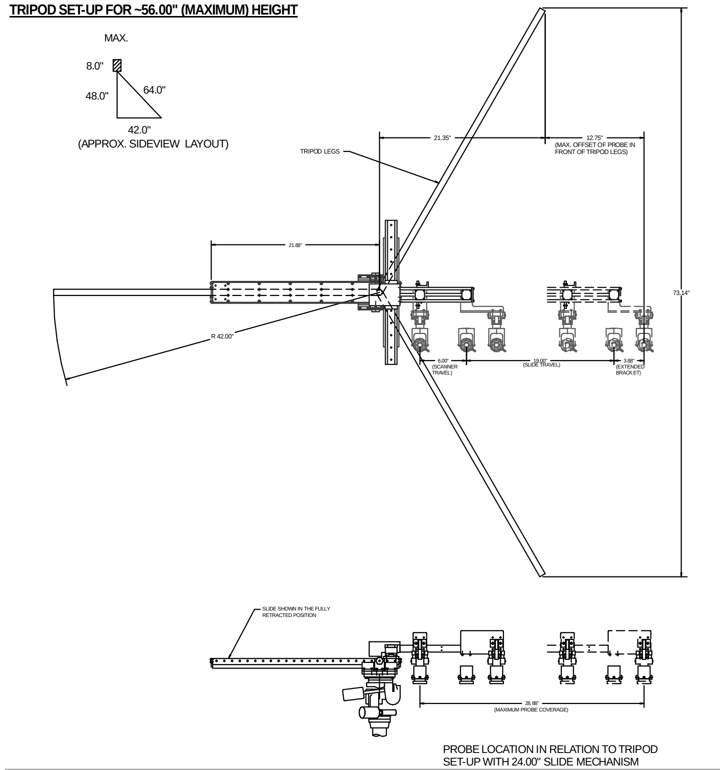
Connection of Manual Scanner to Positioning Mechanisms



Integration of Manual Scanner with Positioning Mechanisms

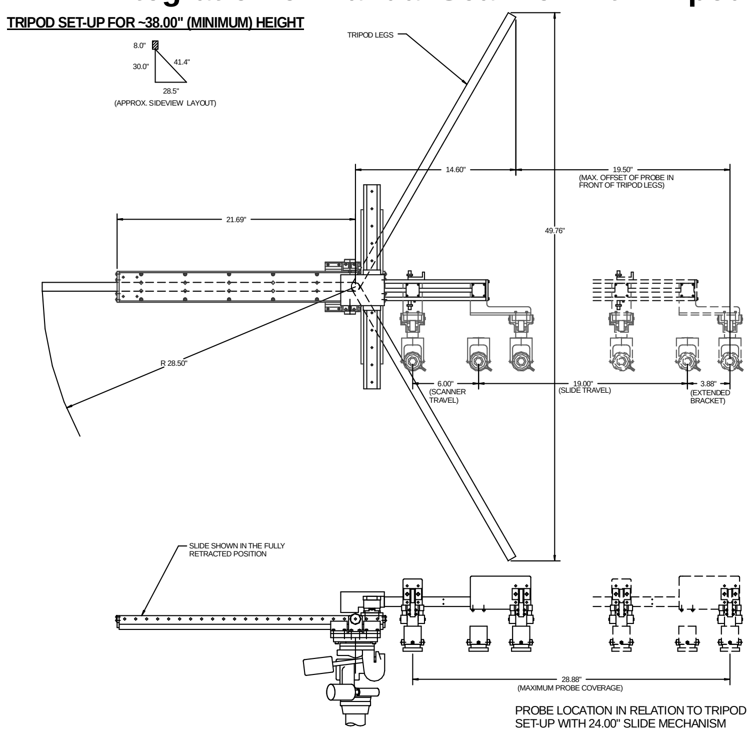


Integration of Manual Scanner with Tripod Positioning



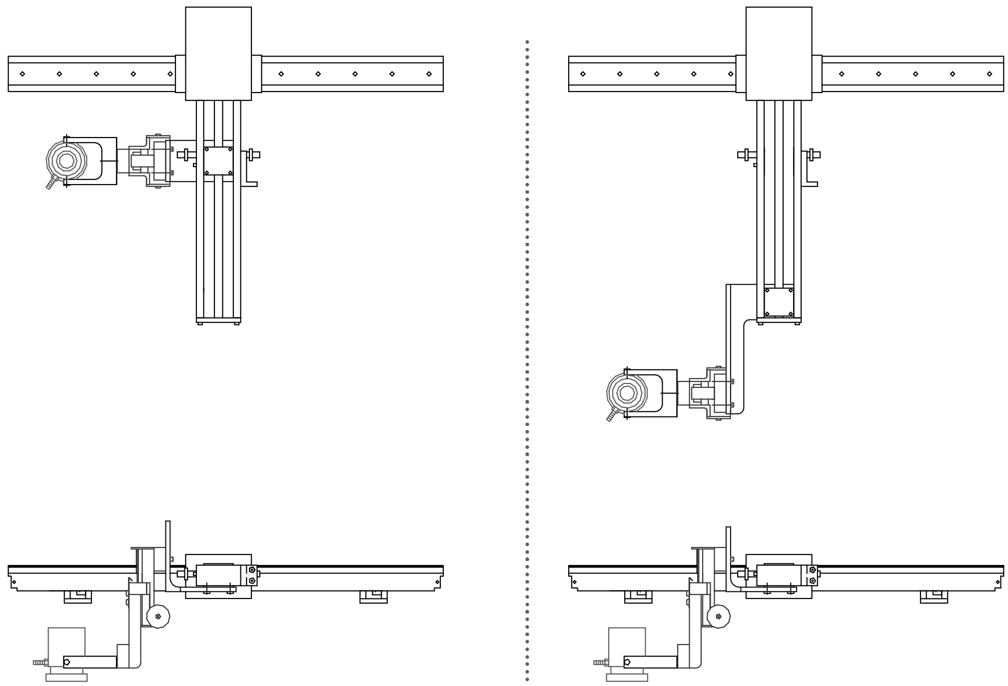
Tripod Configuration and Scanner Reach for <u>Maximum Underwing Height</u> Inspections of 56”

Integration of Manual Scanner with Tripod Positioning



Tripod Configuration and Scanner Reach for <u>Minimum Underwing Height</u> Inspections of 38”

Manual Scanner and UT Probe Configuration

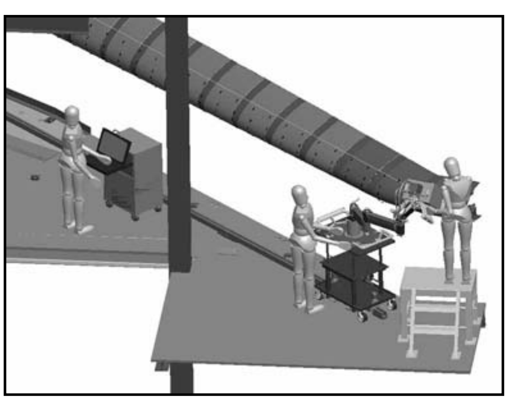


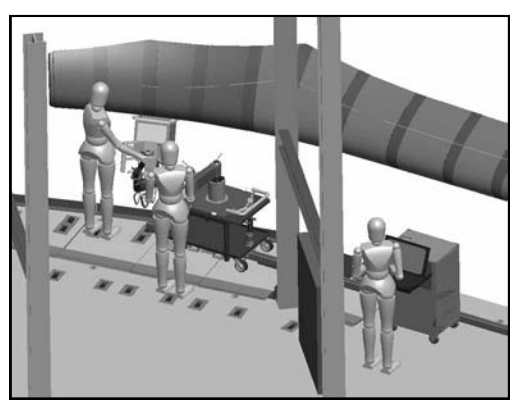
Normal Probe Deployment   Optional Probe Reach Extension

4.0 Scanner Deployment in Orbiter Processing Facility

Concept Of Operations on Wing Leading Edge

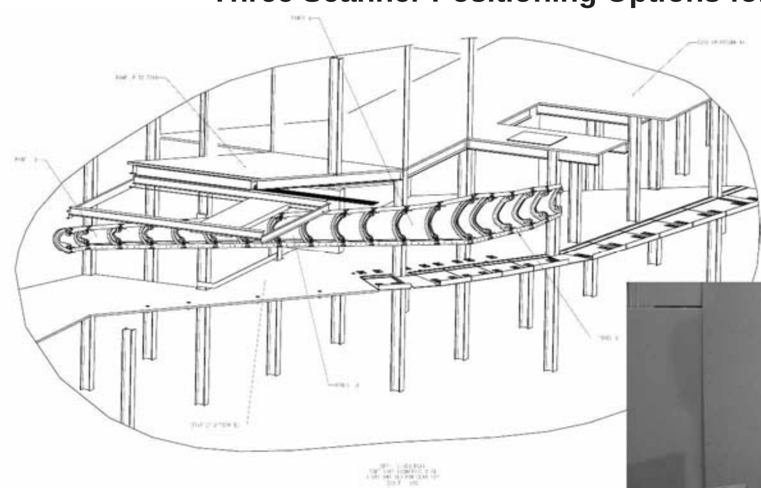
- Portable step-up stands (supplied by KSC) will be used as needed to reach upper WLE surfaces
- Rail cart (shown below) is first option for positioning all NDI devices





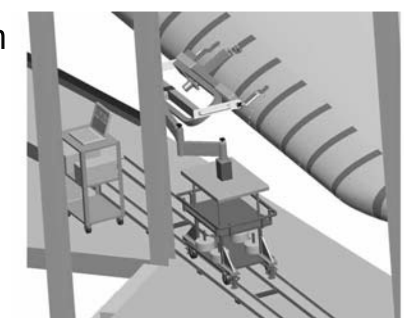
RCC Panel Layout with Respect to OPF Floor

Three Scanner Positioning Options for Inspections

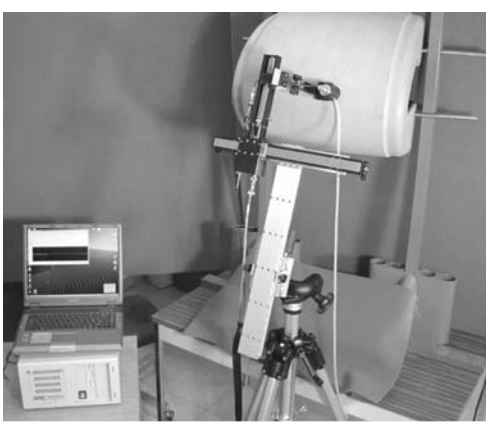


Three Types of UT/EC Scanner Deployment

1. Connection to OSS positioning mechanism
2. Connection to tripod positioner
3. Resting on top of RCC panel



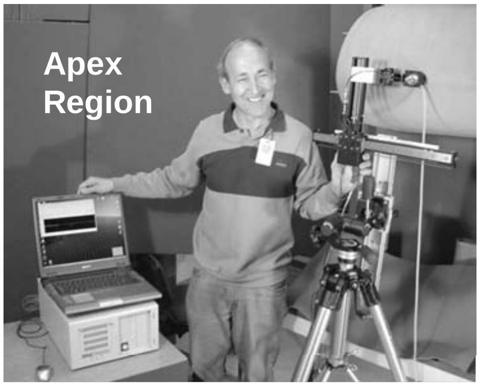
Option 1



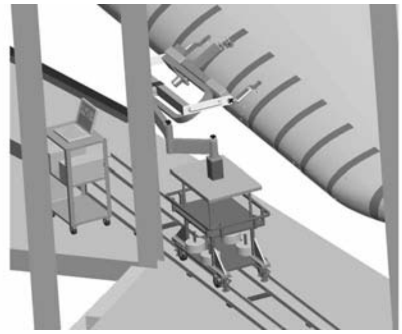
Option 2

Option 3

Scanner Deployment in Orbiter Processing Facility



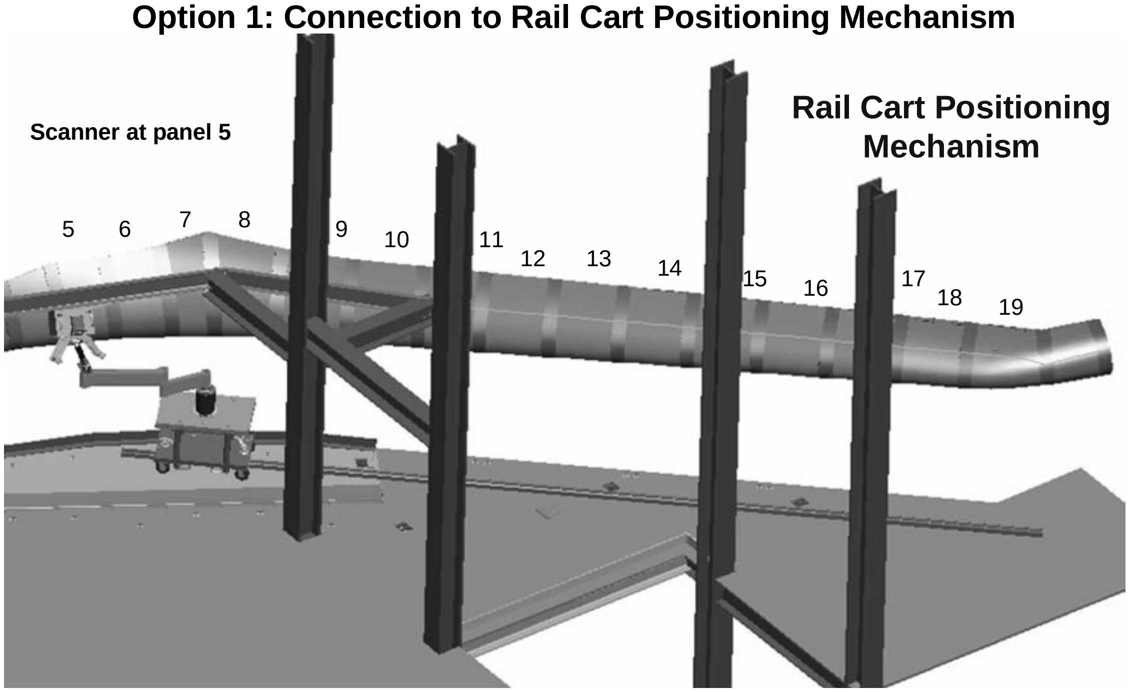
Gantry
Positioning
Mechanism



Tripod with
Linear Slide

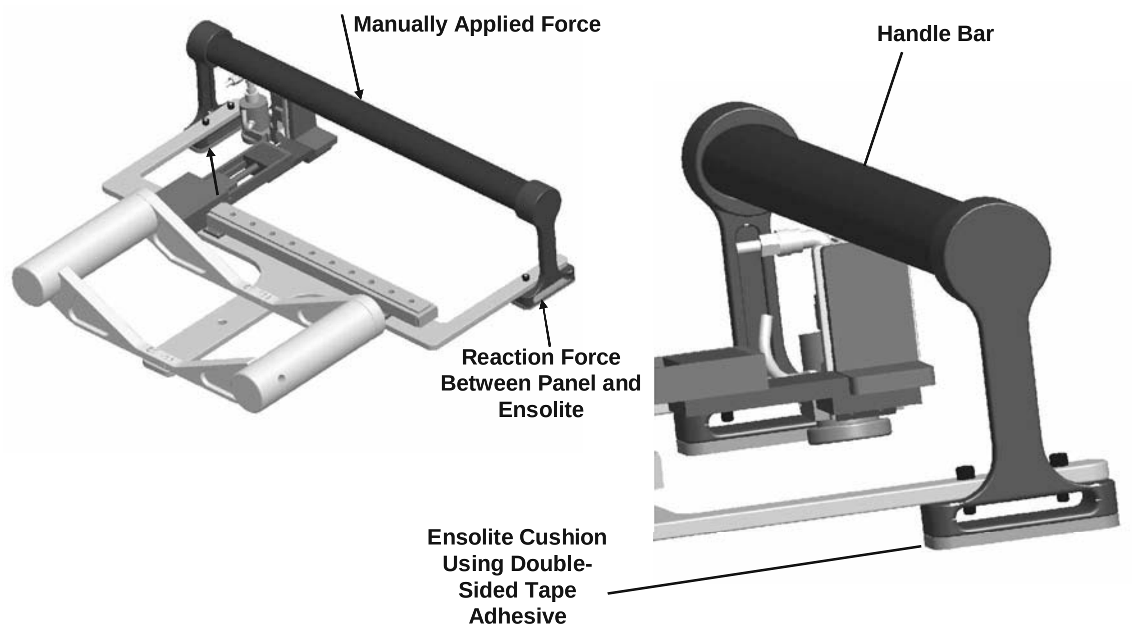
Scanner Deployment in Orbiter Processing Facility

Option 1: Connection to Rail Cart Positioning Mechanism

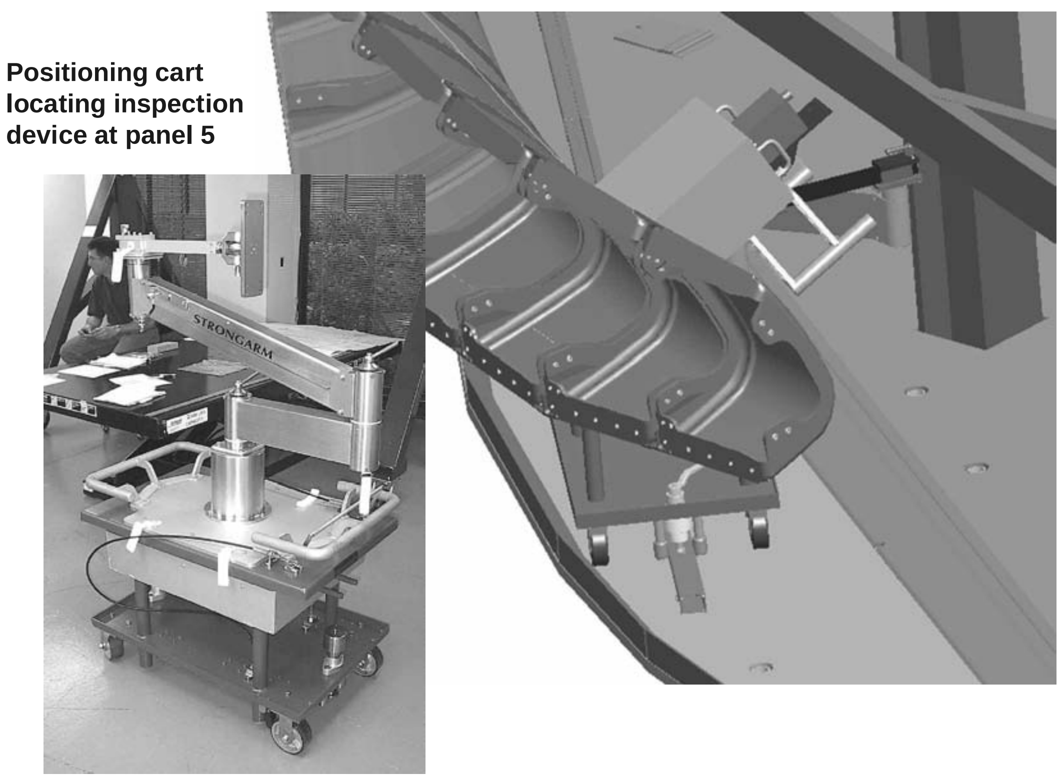


Scanner Deployment Option 1: Connection to Rail Cart Positioning Mechanism

Connection of Manual Scanner to Rail Cart Arm

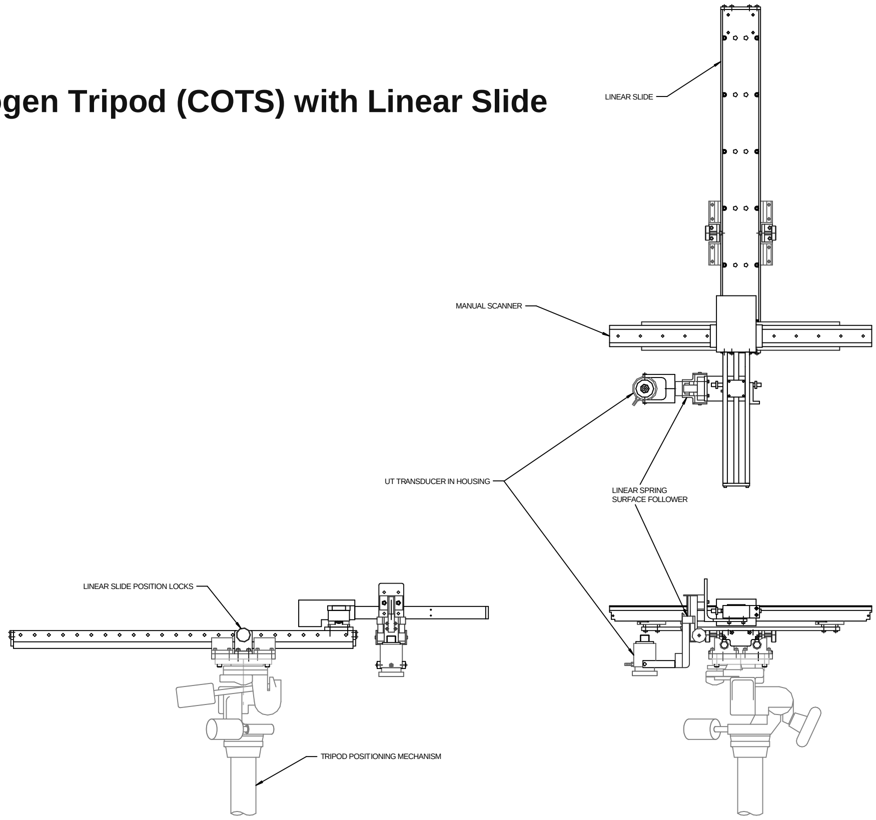


Scanner Deployment in Orbiter Processing Facility



Option 2: Scanner Deployed on Tripod Positioning Mechanism

Bogen Tripod (COTS) with Linear Slide



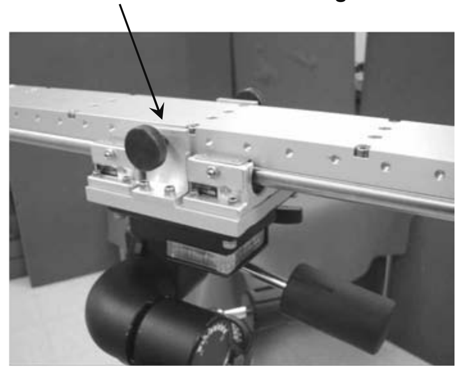
Tripod Positioning Mechanism

Manual Scanner Mounting plate

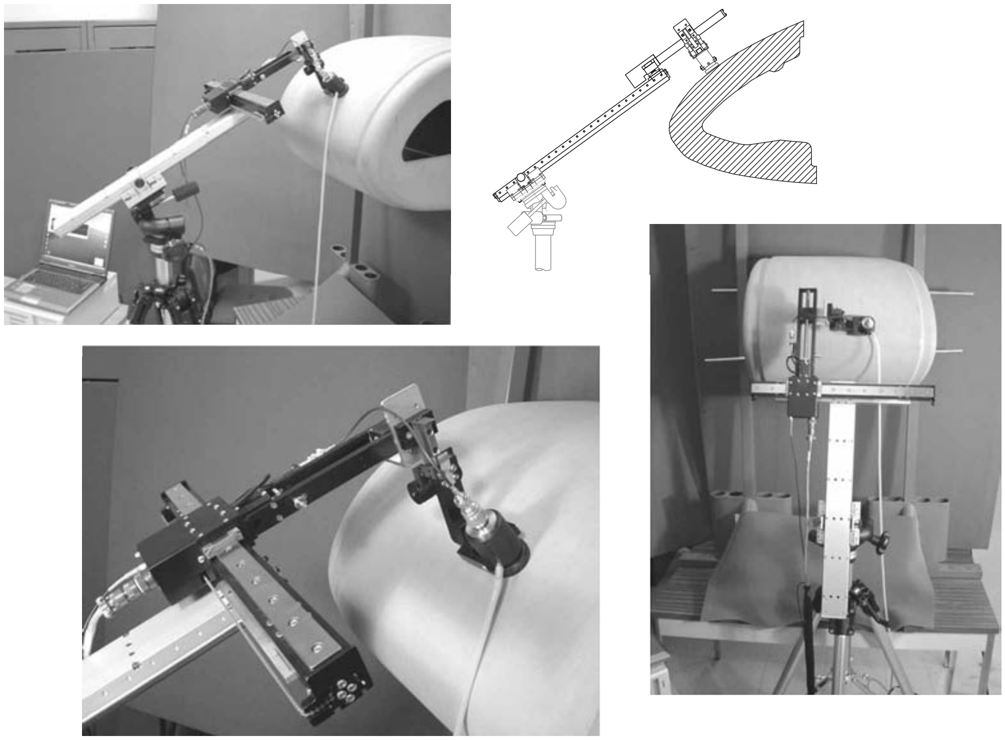
Linear Slide for Extending Scanner Over and Under RCC Panel

Tripod

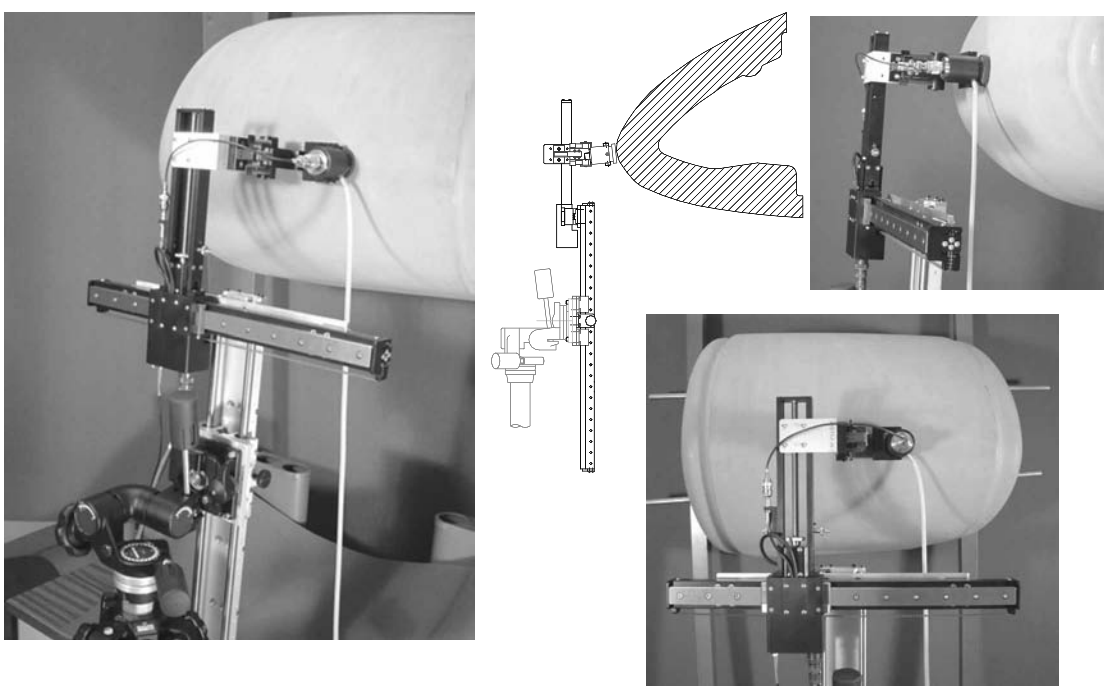
Linear slide and Y-Position Locking Mechanism



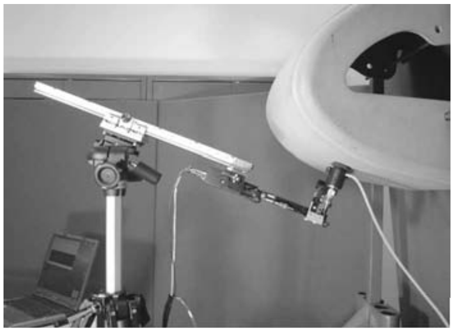
Manual Scan of RCC Upper Surface

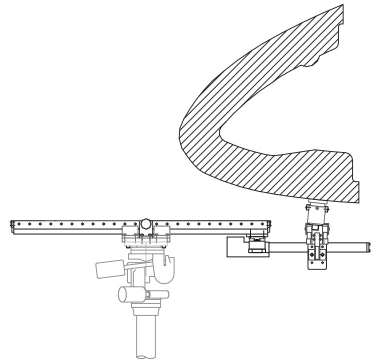


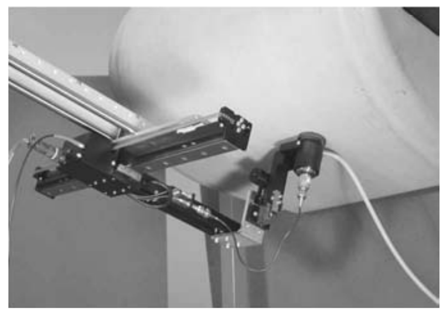
Manual Scan of RCC Apex Region



Manual Scan of RCC Lower Surface

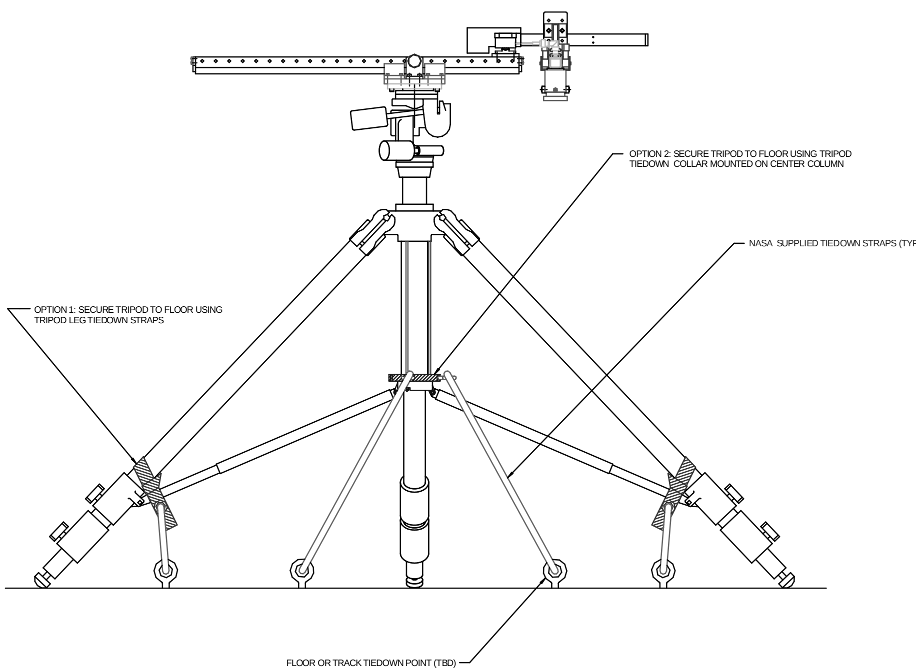






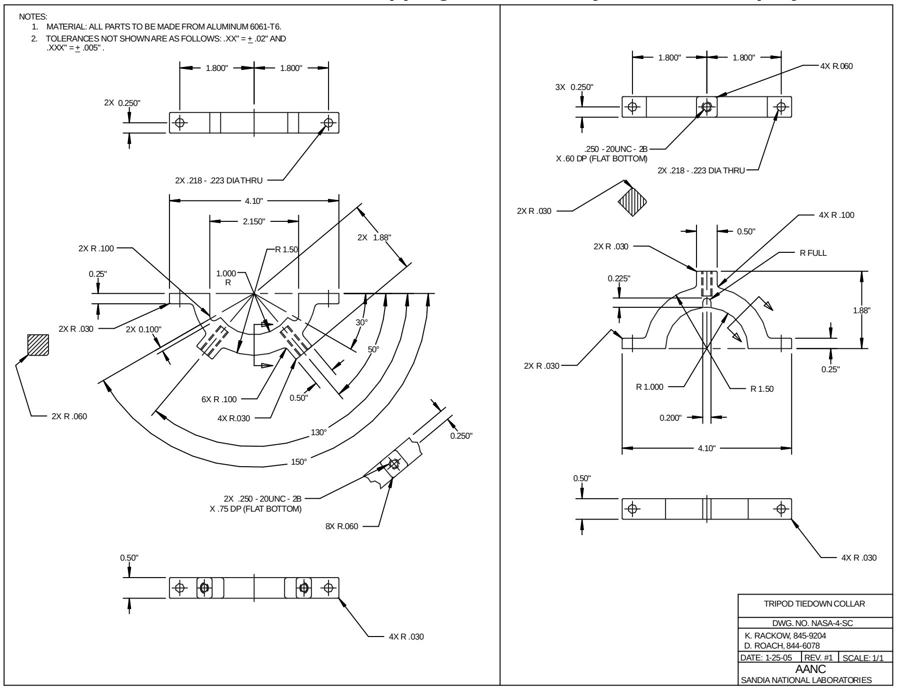
Manual Scanner Tripod Tiedown Options

Either the center-column collar fixture or the leg straps can be used to secure the tripod to the floor in the OPF inspection area



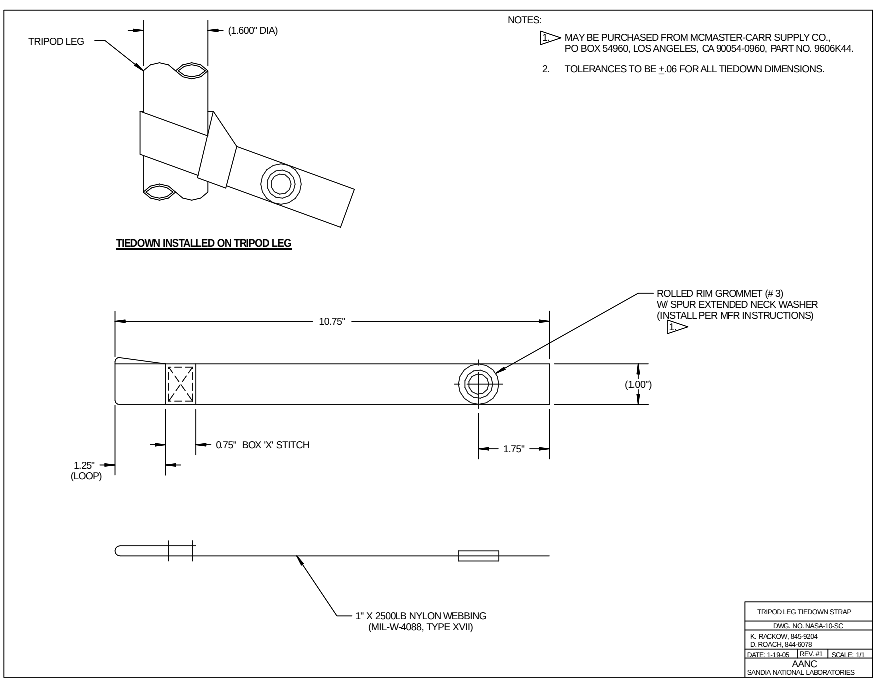
Tripod Tie-Down Collar

- **Mounts to center column of tripod positioning mechanism and is connected to OPF floor**
- **Prevents unintentional movement or tipping of scanner system when deployed on LE RCC panels**

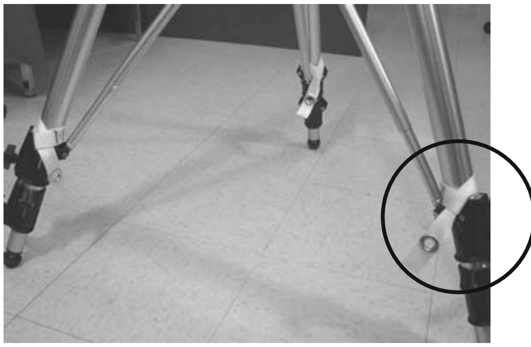


Tripod Tie-Down Strap

- **Mounts to each leg of tripod positioning mechanism and is connected to OPF floor**
- **Prevents unintentional movement or tipping of scanner system when deployed on LE RCC panels**



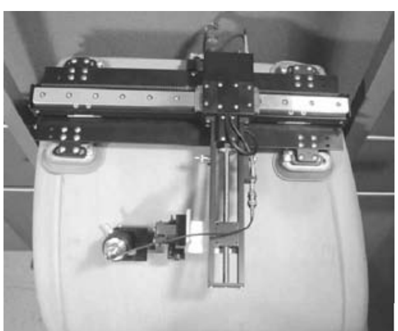
Tripod Positioning Mechanism – Floor Tiedown Fixtures



Straps (2000 lb. Nylon) Attached to each Tripod Leg

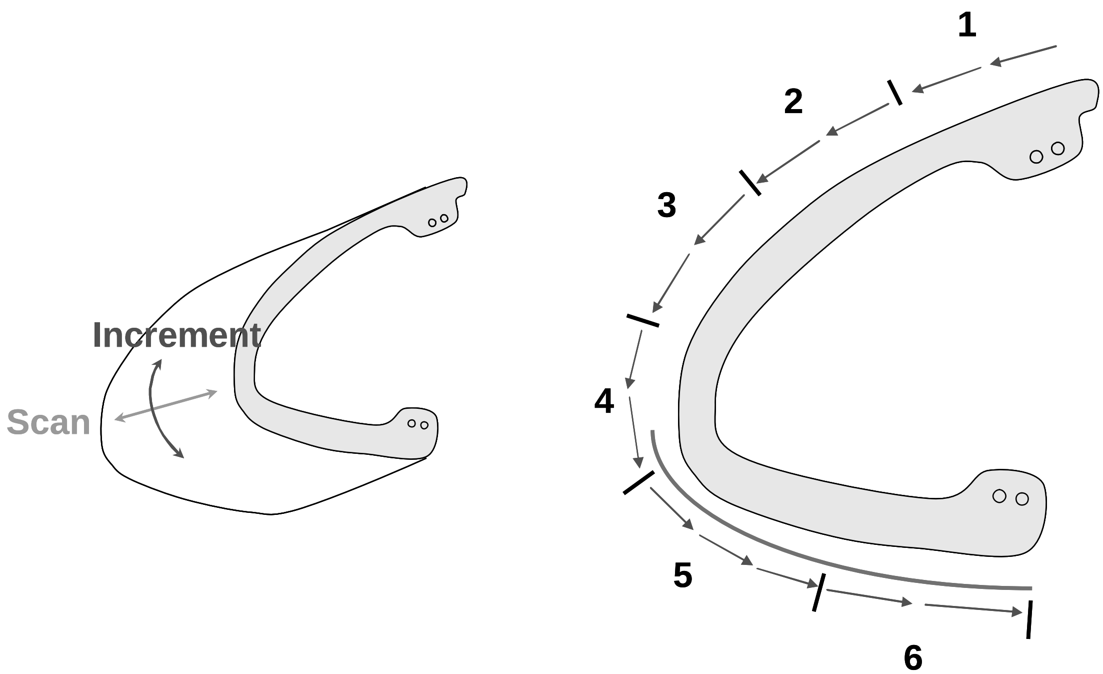
Restraint Collar Attached to Tripod Center Column

Inspecting Upper Surface - Scanner Resting on Top of RCC Panel



Option 3

Pulse-Echo UT – Scanner Deployment & Data Acquisition



Class 1, Div 2 Compliance Status

- Class 1 Div 2 compliant Flash Thermography equipment enclosures being evaluated by OSS.

A larger enclosed box is placed over the Rack mounted components and purge gas is maintained at positive pressure throughout the enclosure.

Investigating commercially available class 1 Div 2 enclosures. Requires re-packaging of Equipment.

5.0 Performance Assessment of Pulse-Echo Ultrasonic Inspection System

Validation Plan for UT System

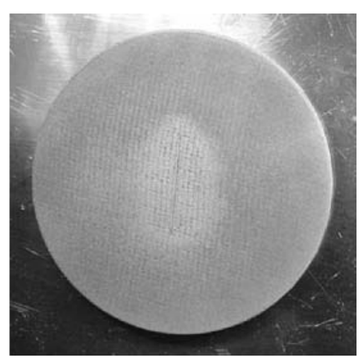
Complete inspections on all RCC test specimens using PE-UT system hardware

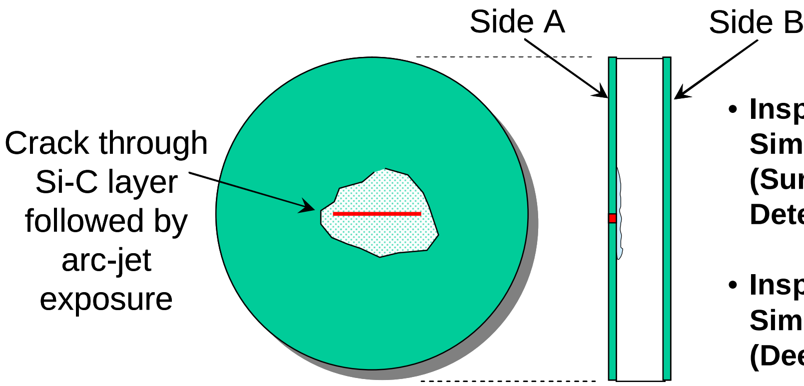
Sample Specimens Include:

1. **Boeing disks with arc jet exposure**
2. **0.25” th. RCC central section**
3. **0.44” th. RCC edge section**
4. **0.25” th., 2” X 6” Boeing coupon**
5. **8L flight hardware (Bill’s Box)**
6. **Columbia panel with flaws of different aspect ratios**
7. **Slotted specimens (sloping, straight, & corner slots)**
8. **NASA impact panels**
9. **Coupons from 9L RCC panel with engineered flaws**
10. **11L RCC panel with engineered flaws**

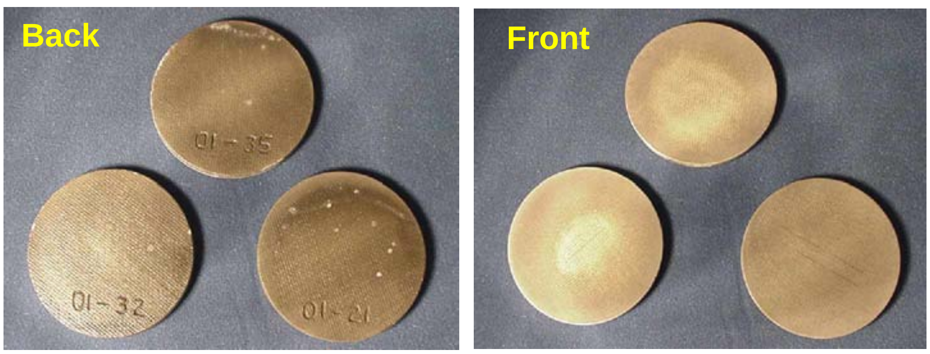
Pulse-Echo Ultrasonic Inspection of Boeing Disks
(Arc Jet Specimen Set)

Backside Inspection

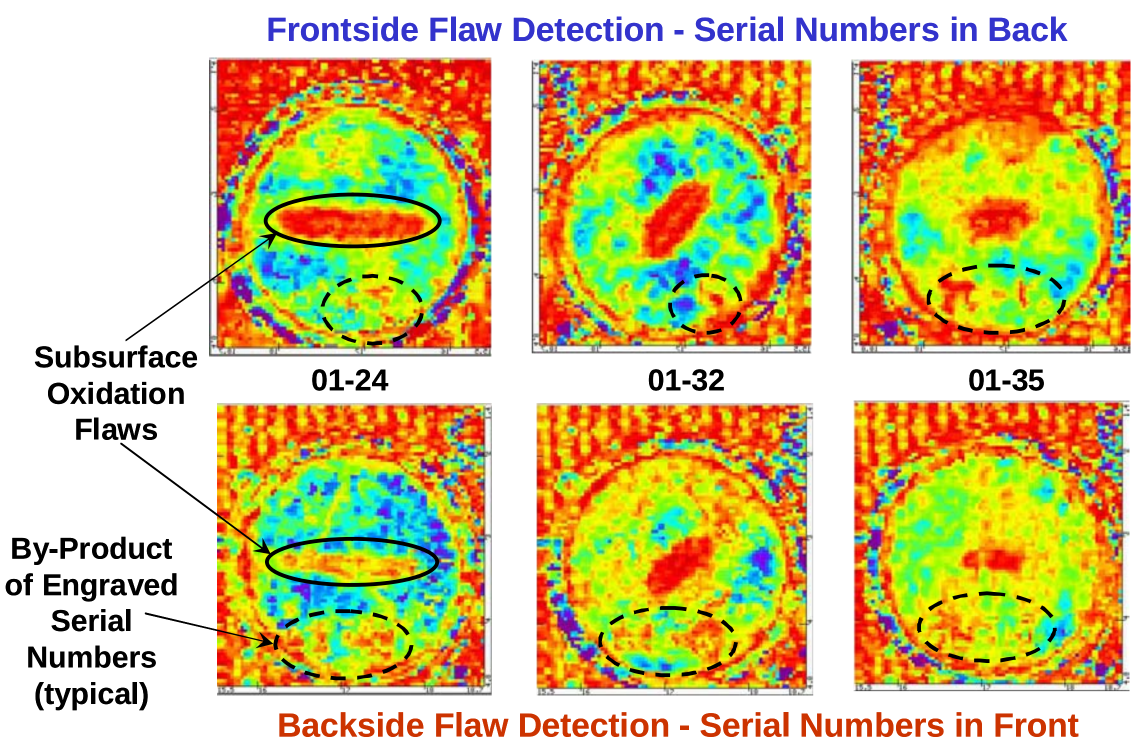




- **Inspection from Side A Simulates Nearside (Surface) Flaw Detection**
- **Inspection from Side B Simulates Backside (Deep) Flaw Detection**

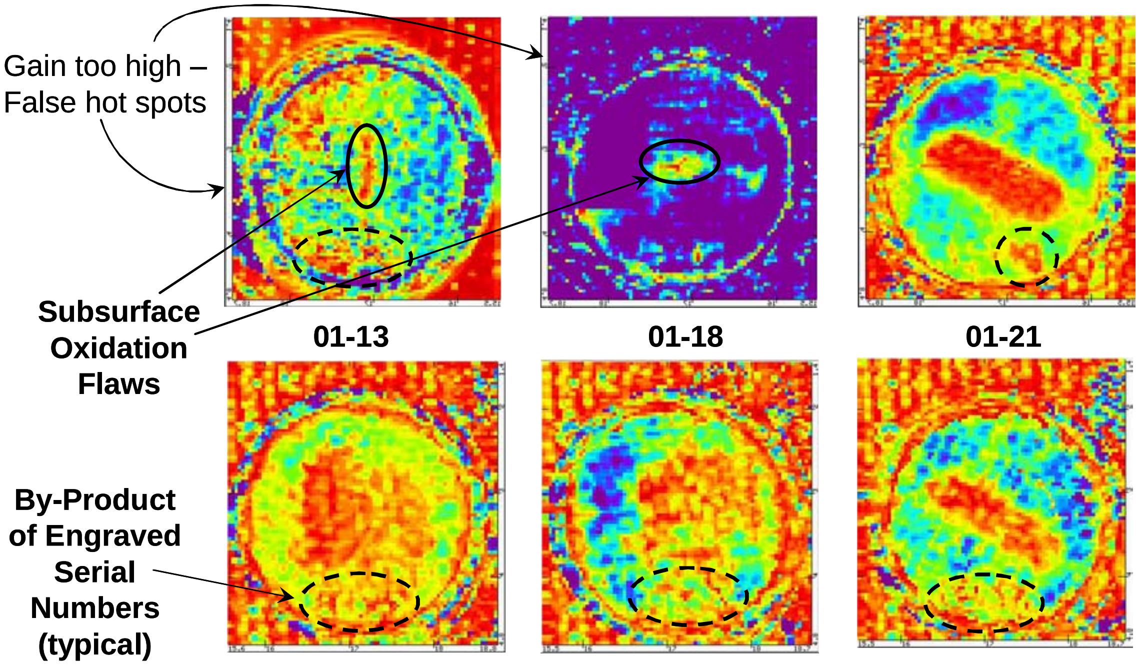


Arc Jet Disk Inspection with P-E Ultrasonics



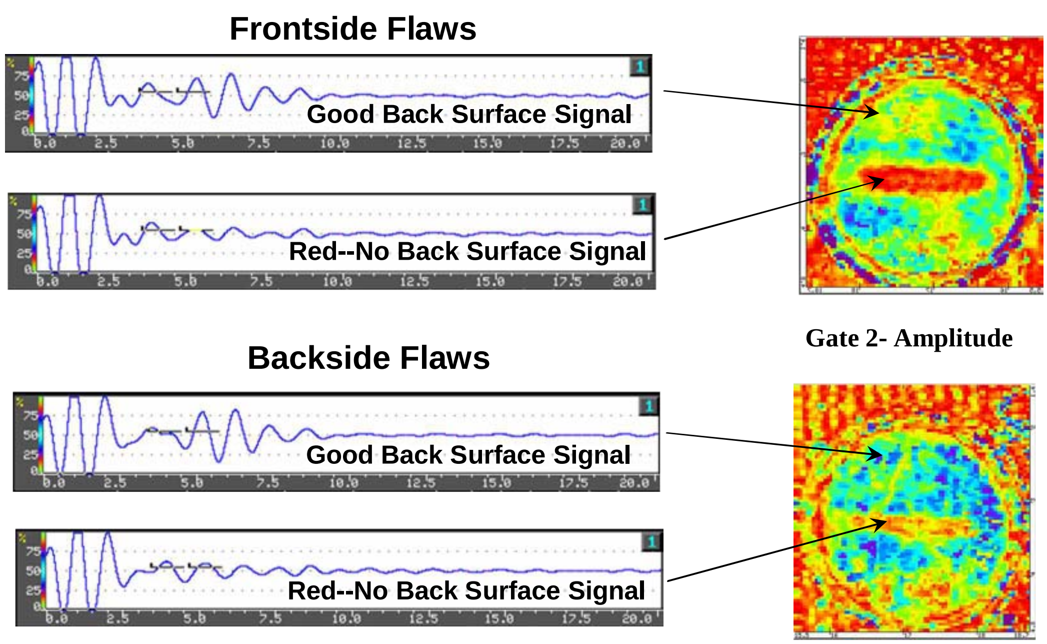
Arc Jet Disk Inspection with P-E Ultrasonics (cont.)

Frontside Flaw Detection - Serial Numbers in Back



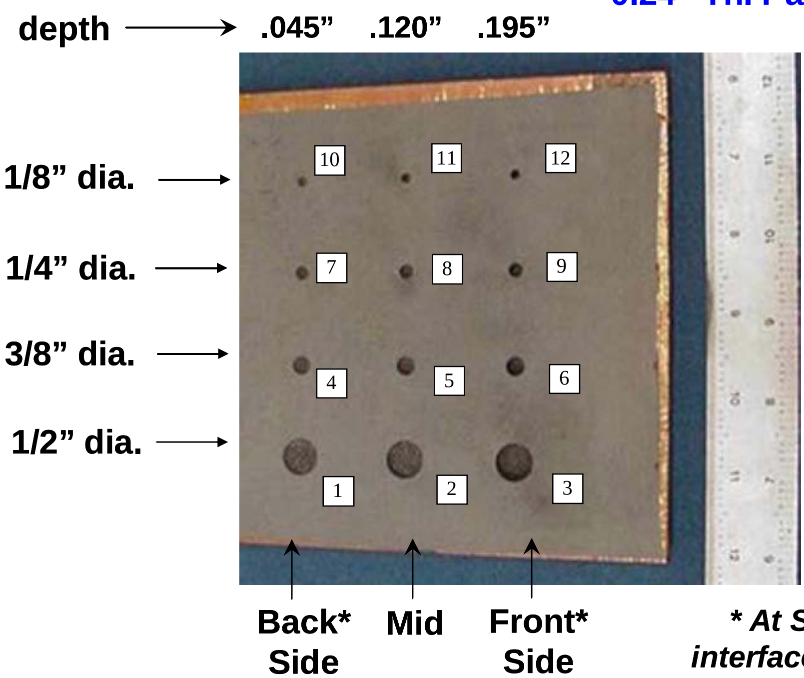
Backside Flaw Detection - Serial Numbers in Front

Waveform Comparisons – UT PE Signals from Flawed and Good Areas of ARC JET Specimen #01-24



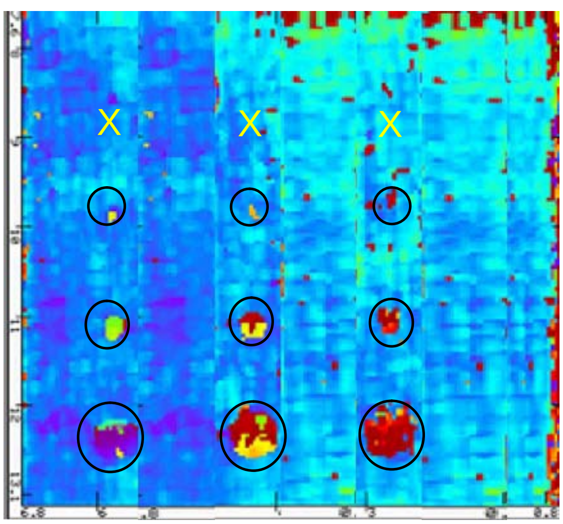
Sample Results RCC Flight Hardware

0.24” Th. Panel with Coating

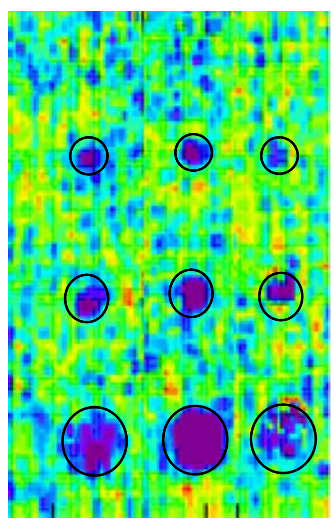


*** At Si-C to C-C interface on back or front of panel**

RCC Flight Hardware – 0.24” Th. Panel with Coating

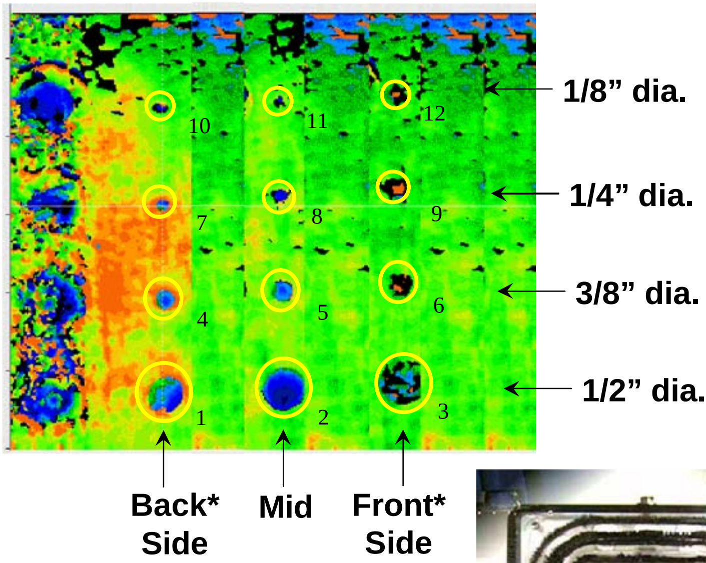


1 MHz Pulse-Echo UT Flaw detection obtained with weeper coupling

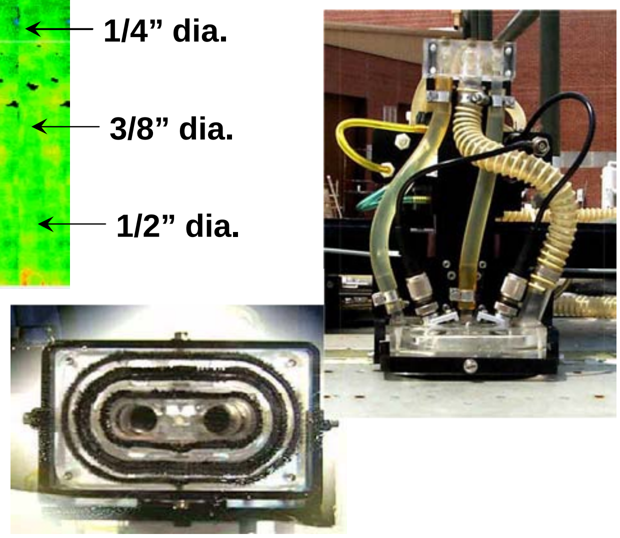


Gate 1 - Amplitude

RCC Flight Hardware – 0.24” Th. Panel with Coating



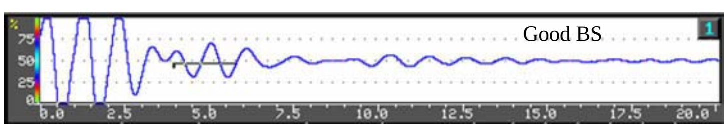
Pulse-Echo UT
Flaw detection obtained with optimum coupling (dripless bubbler)

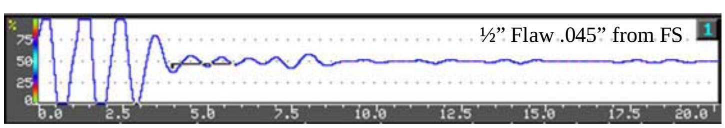


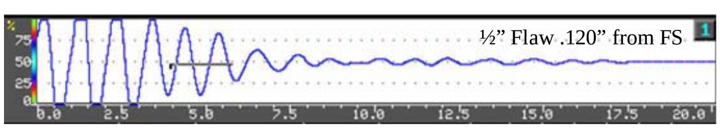
Sample P- E Ultrasonic Signals

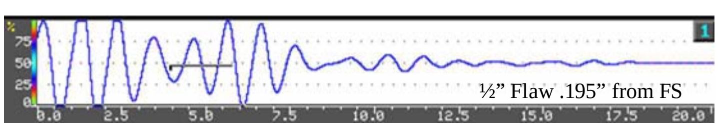
Acquired from 1MHz Probe on NASA 0.24” Specimen

Longitudinal wave velocity in RCC is ~ 0.1 inches/microsecond so the back wall reflection is seen at 5 microseconds for movement back and forth through the 0.25“ specimen

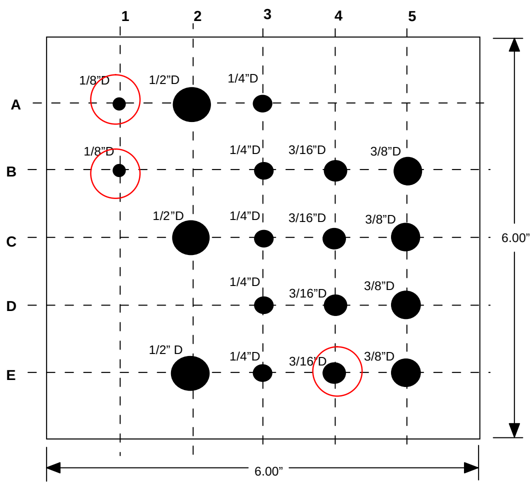


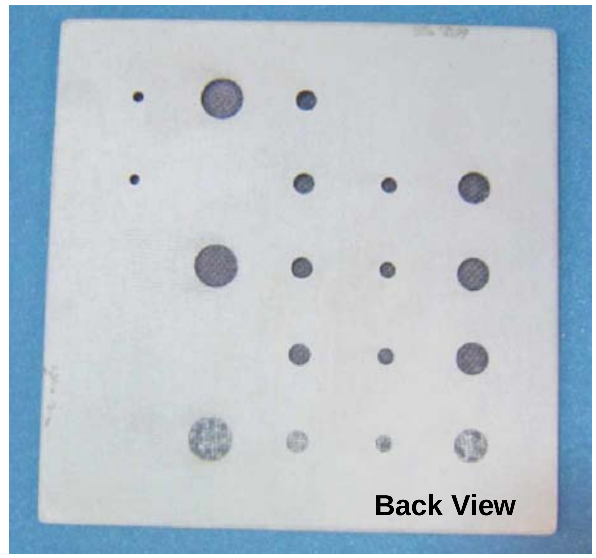




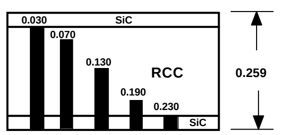


Validation Standards S03-48 and S03-49





Diameter	Depth	ID Location
1/8"	0.030"	A1
1/8"	0.070"	B1
1/4"	0.030"	A3
1/4"	0.070"	B3
1/4"	0.130"	C3
1/4"	0.190"	D3
1/4"	0.230"	E3
3/16"	0.090"	A4
3/16"	0.130"	B4
3/16"	0.190"	C4
3/16"	0.230"	E4
3/8"	0.070"	A5
3/8"	0.130"	B5
3/8"	0.190"	C5
3/8"	0.230	D5
1/2"	0.130"	A2
1/2"	0.190"	C2
1/2'	0.230"	E2

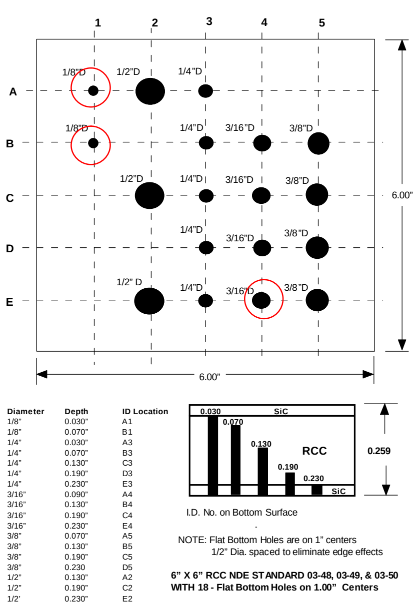


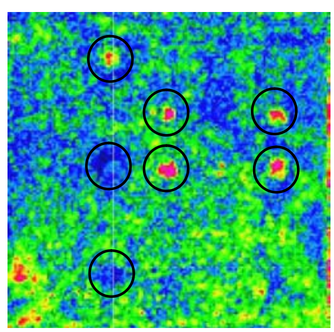
I.D. No. on Bottom Surface

NOTE: Flat Bottom Holes are on 1" centers
1/2" Dia. spaced to eliminate edge effects

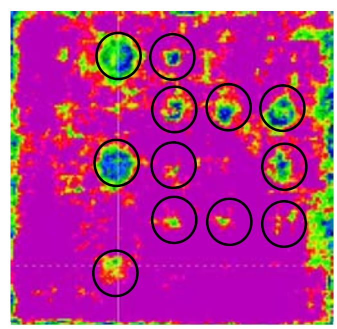
6" X 6" RCC NDE STANDARD 03-48, 03-49, & 03-50
WITH 18 - Flat Bottom Holes on 1.00" Centers

Validation Results, Standard S03-48

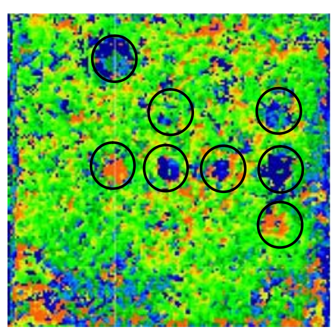




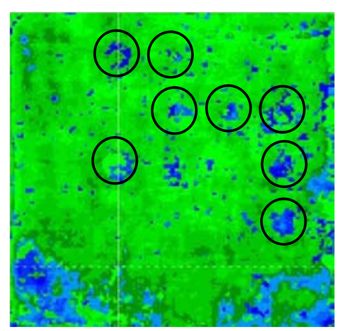
Amplitude 1



Amplitude 2



Time of Flight 1

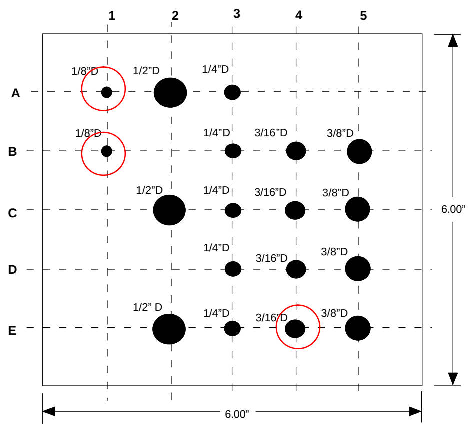


Time of Flight 2

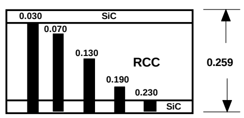
Flaws not found

Sample Scan Images

Validation Results, Standard S03-49



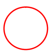
Diameter	Depth	ID Location
1/8"	0.030"	A1
1/8"	0.070"	B1
1/4"	0.030"	A3
1/4"	0.070"	B3
1/4"	0.130"	C3
1/4"	0.190"	D3
1/4"	0.230"	E3
3/16"	0.090"	A4
3/16"	0.130"	B4
3/16"	0.190"	C4
3/16"	0.230"	E4
3/8"	0.070"	A5
3/8"	0.130"	B5
3/8"	0.190"	C5
3/8"	0.230	D5
1/2"	0.130"	A2
1/2"	0.190"	C2
1/2'	0.230"	E2



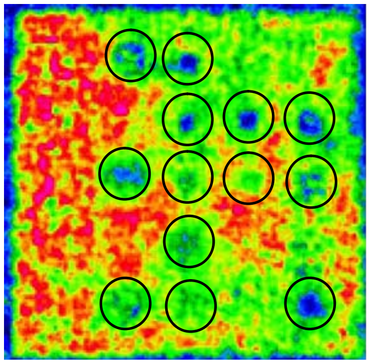
I.D. No. on Bottom Surface

NOTE: Flat Bottom Holes are on 1" centers
1/2" Dia. spaced to eliminate edge effects

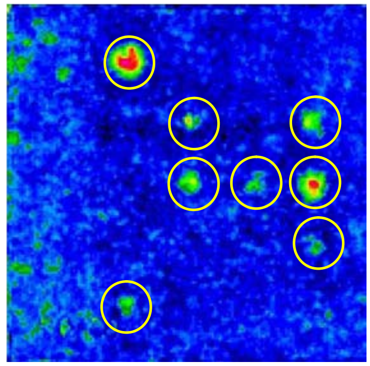
6" X 6" RCC NDE STANDARD 03-48, 03-49, & 03-50
WITH 18 - Flat Bottom Holes on 1.00" Centers



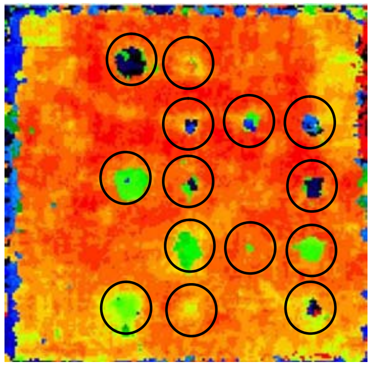
Flaws not found



Amplitude



Amplitude

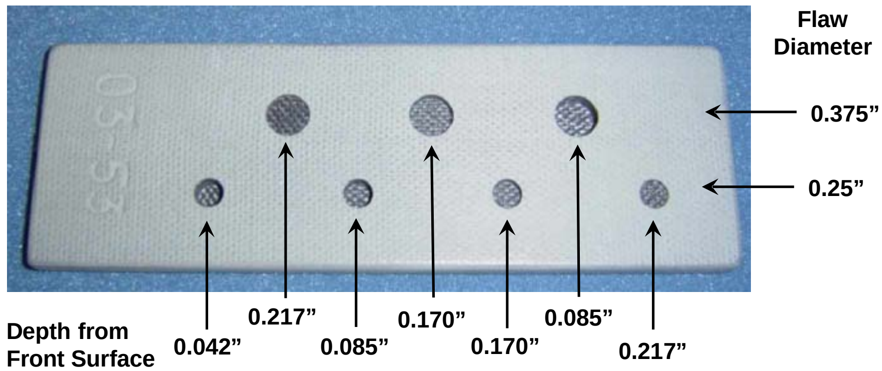


Time of Flight

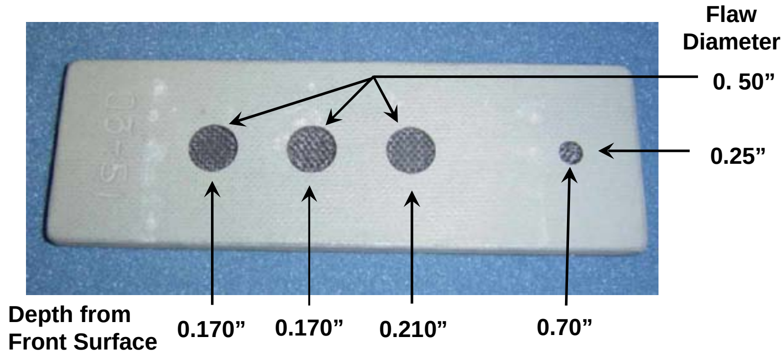
Sample Scan Images

Validation Results, Standards S03-51 and S03-53

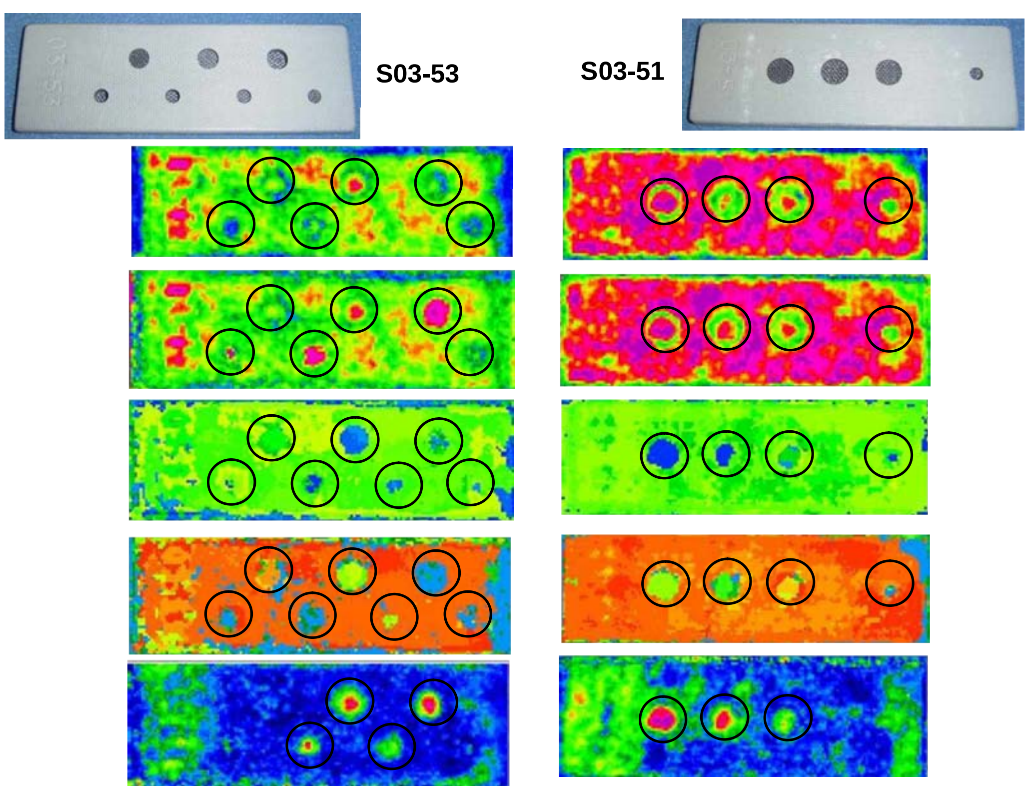
Specimen 03-53
0.257” th. RCC
2” W X 6” L plate



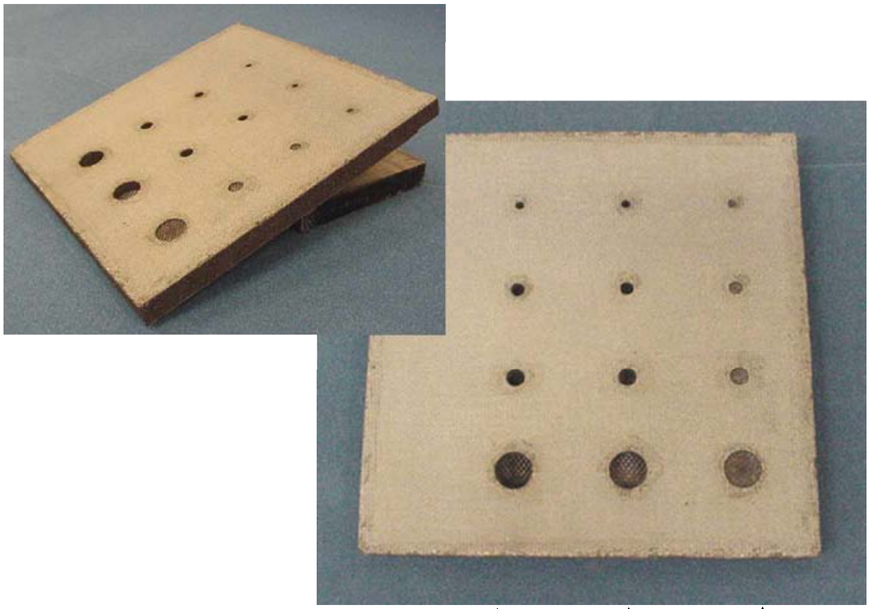
Specimen 03-51
0.252” th. RCC
2” W X 6” L plate



Validation Results, Standard S03-51 and S03-53



RCC Flight Hardware – 0.44” Th. Panel with Coating



1/8” dia.

1/4” dia.

3/8” dia.

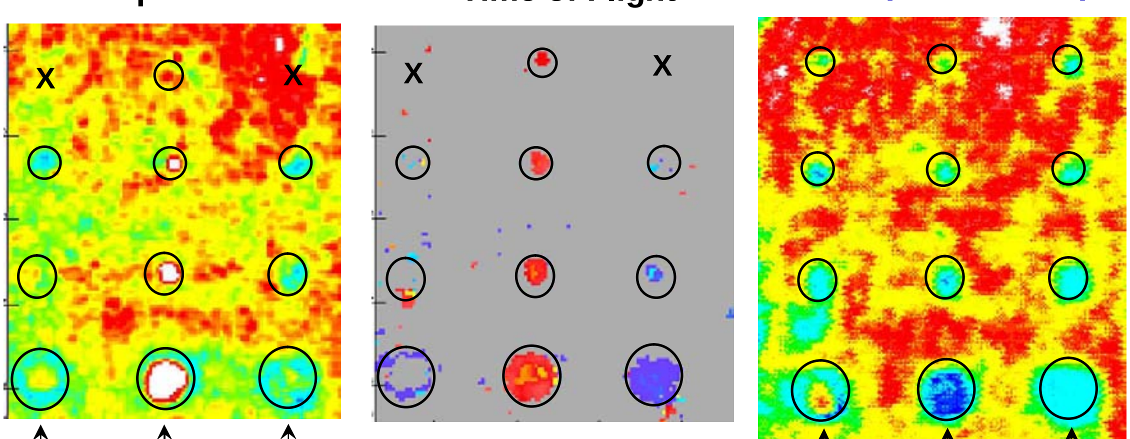
1/2” dia.

Front* Side | Mid | Back* Side

* At Si-C to C-C interface on back or front of panel

RCC Flight Hardware – 0.44” Th. Panel with Coating

Amplitude | Time of Flight | P-E UT Optimum Coupling

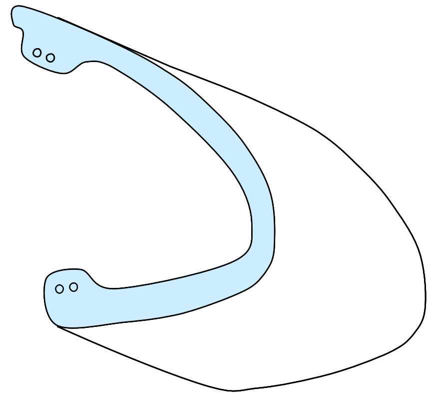


Amplitude: Back Side 0.4” | Mid 0.22” | Front Side 0.04”

P-E UT Optimum Coupling: Back Side 0.4” | Mid 0.22” | Front Side 0.04”

RCC Panel Recovered from Columbia Orbiter

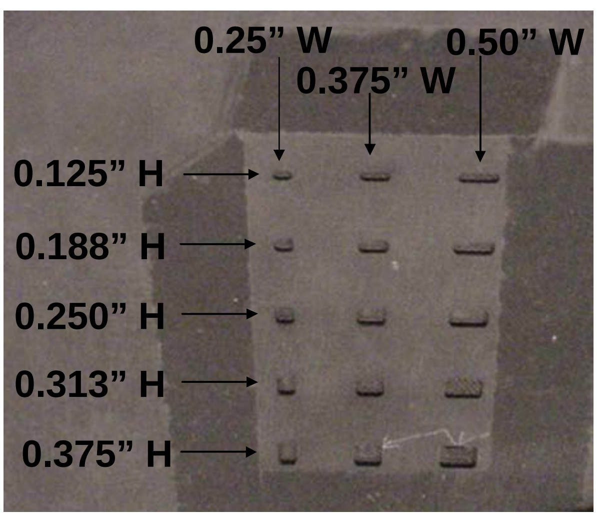
UT inspections revealed different attenuation levels in the panel

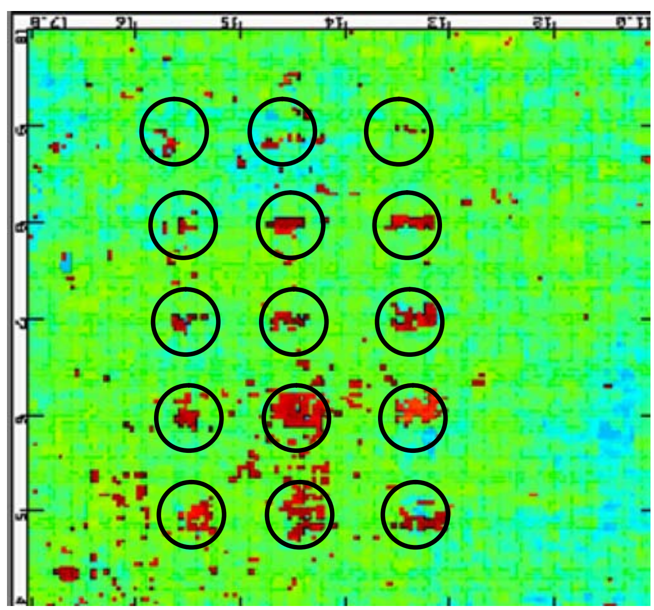


Flaws with different aspect ratios were engineered into panel

Columbia Panel with Flaws of Different Aspect Ratios

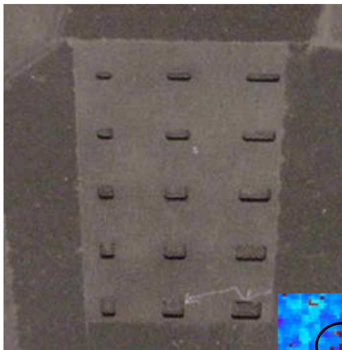
Flaw detection in the presence of varying/high attenuation

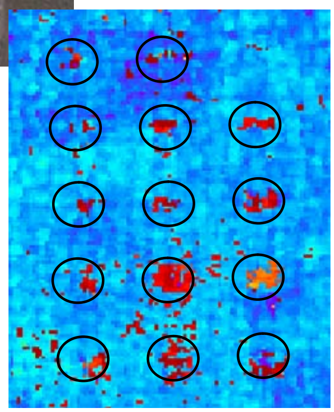




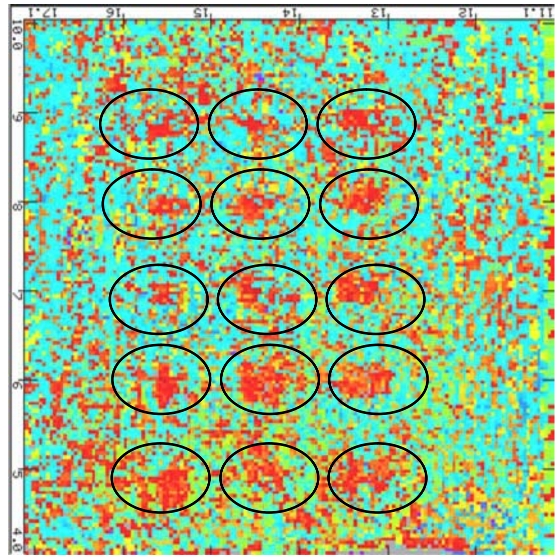
Gate 2 Time of Flight

Columbia Panel with Flaws of Different Aspect Ratios



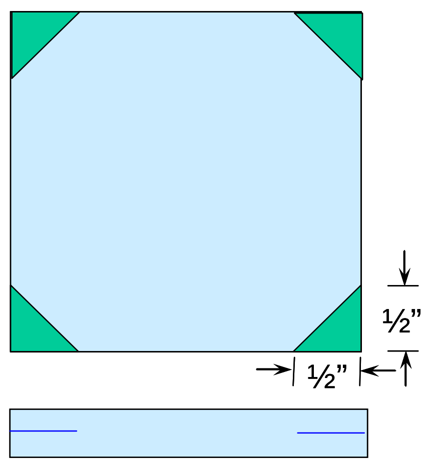


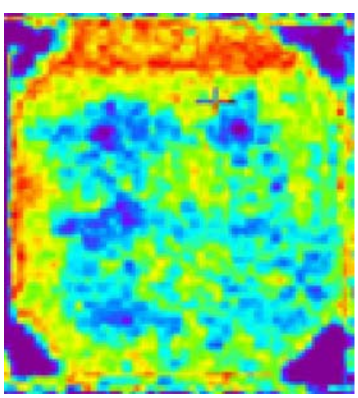
Gate 2 Time of Flight (Color Adjusted)



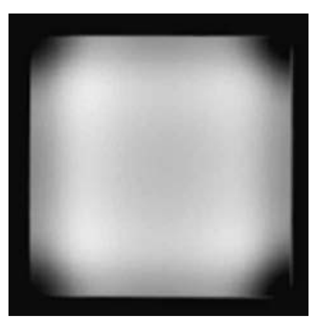
Gate 2 Time of Flight
Krautkramer UT Transducer

Phase 1 Specimen #03-63 with Corner Slots





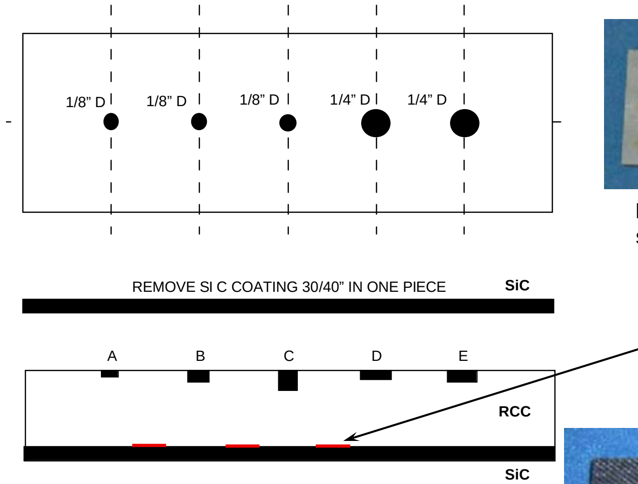
Pulse-Echo UT Image



IR Image

Validation Results, Standard S03-54

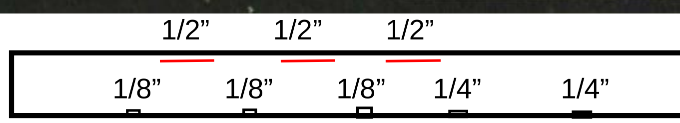
2” X 6” X 0.205” th. RCC panel



Flaws are flat bottom holes and side slots across width of specimen

ID	Diameter	Depth
A	1/8”	0.005”
B	1/8”	0.010”
C	1/8”	0.020”
D	1/4”	0.005”
E	1/4”	0.010”

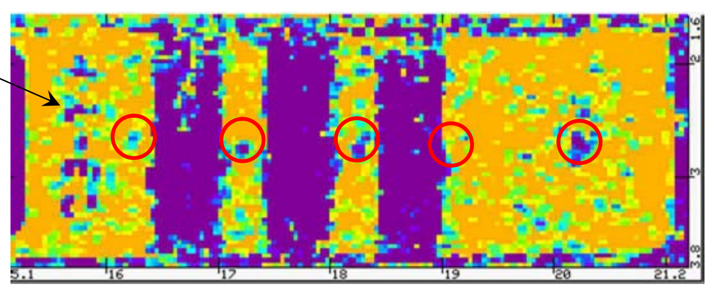
Phase 1 Specimen #03-54 with Side Slots and FBH (back surface)



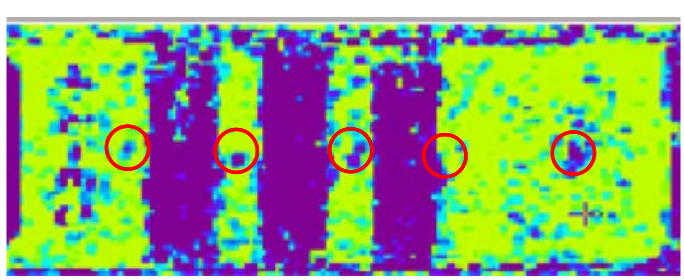
Side View

Flaw Depth From Front → **0.198”** **0.195”** **0.185”** **0.198”** **0.188”**

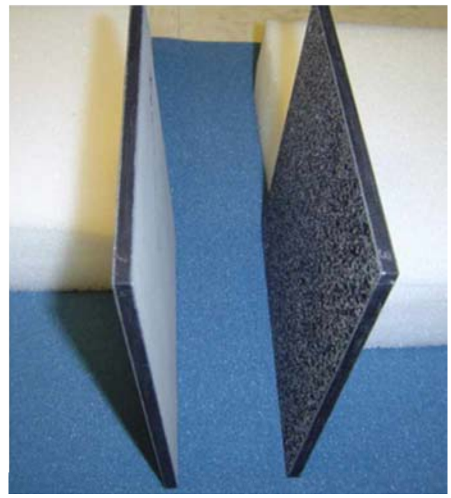
Engraved Specimen Number



Amplitude

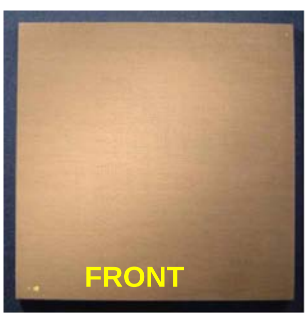


Inspection of NASA Impact Panels

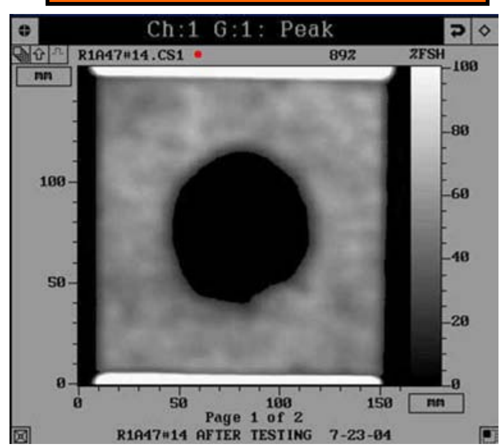


NASA Impact Panel R1-117-14 (R1-47-14)

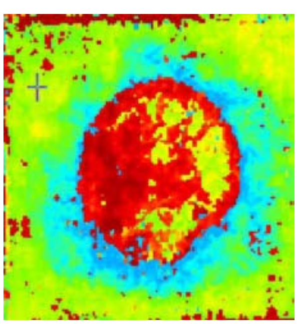
Lowest impact velocity of 1470 ft/s with no visible impact damage



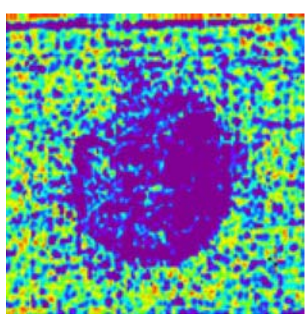
Foam-sized area of delamination



TTU Ultrasound



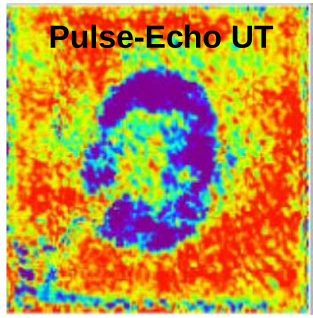
Gate 2 Time of Flight



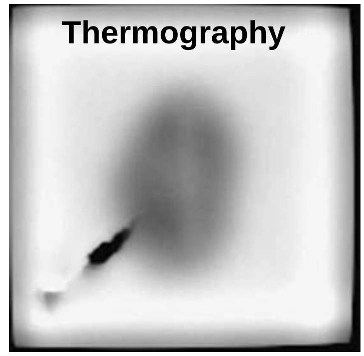
Gate 1 Amplitude

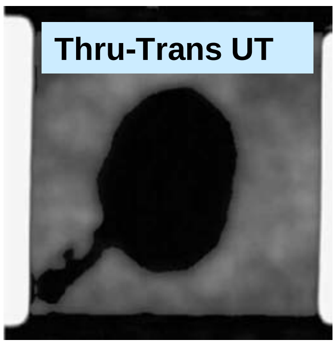
Pulse-Echo UT

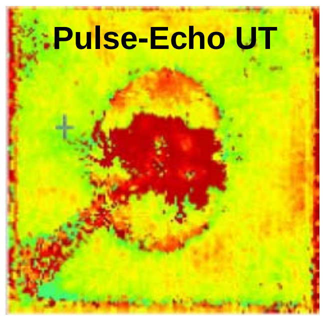
NASA Impact Panel T8015-1



Gate 1 Amp



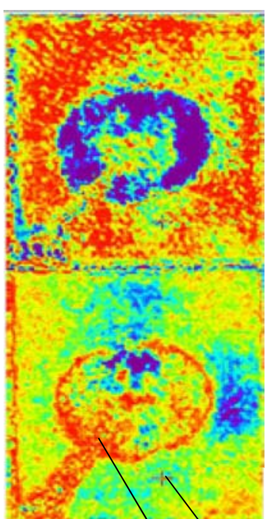




Gate 2 ToF

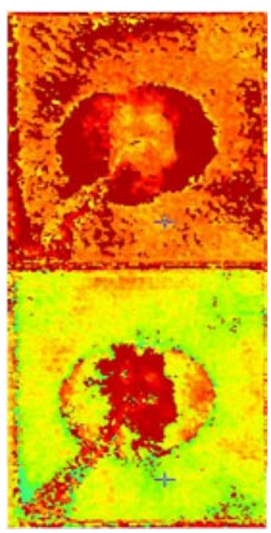
90 degree impact at 2054 fps

NASA Impact Panel T8015-1 - UT PE Images & Waveforms



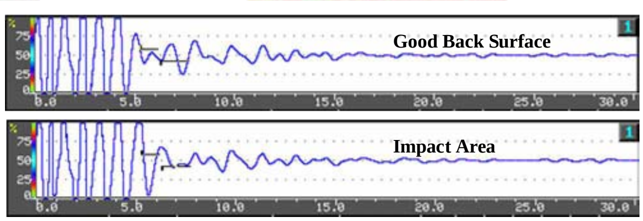
Gate 1 Amplitude

Gate 2 Amplitude



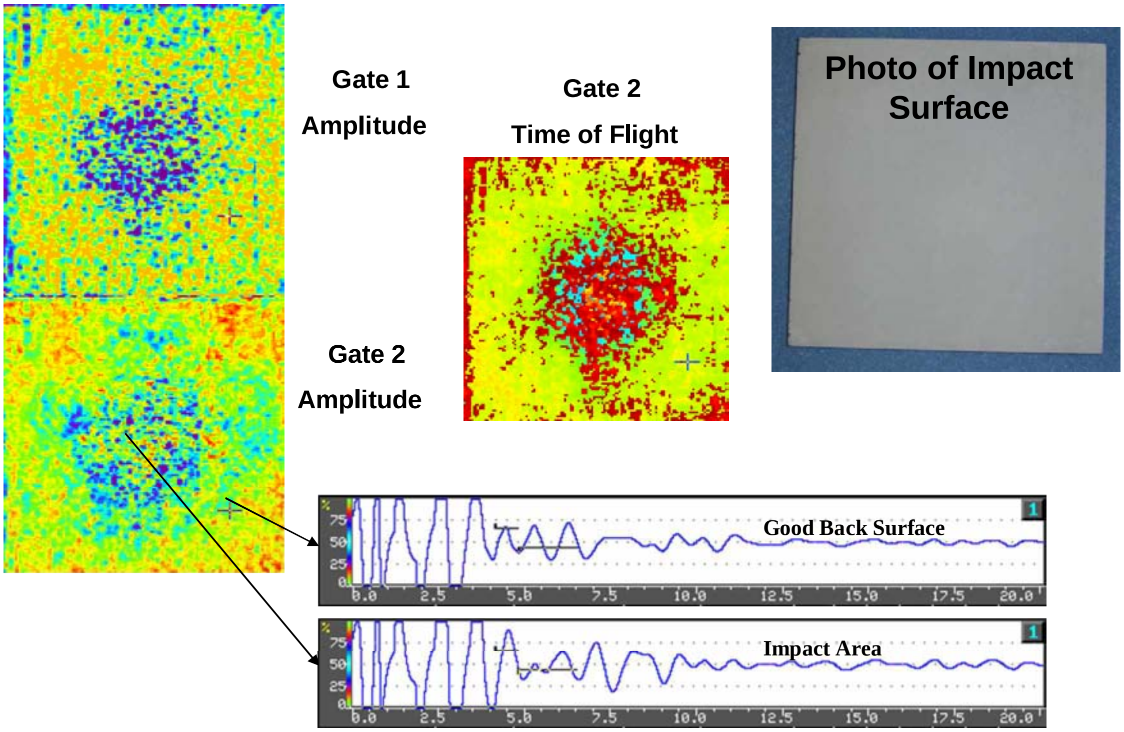
Gate 1 Time of Flight

Gate 2 Time of Flight



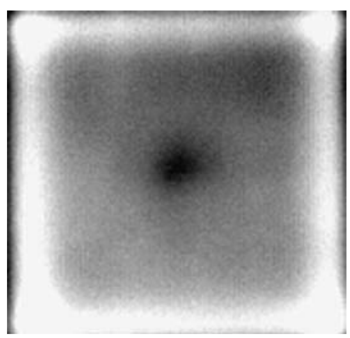
NASA Impact Panel T8015-3

Impact velocity of 1717 ft/s with no visible impact damage

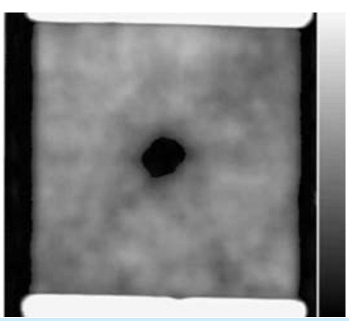


NASA Impact Panel 8015-4

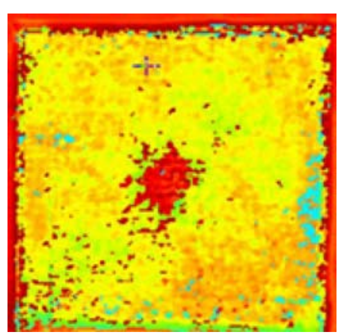
Impact velocity of 1720 ft/s with no visible impact damage



Thermography Image

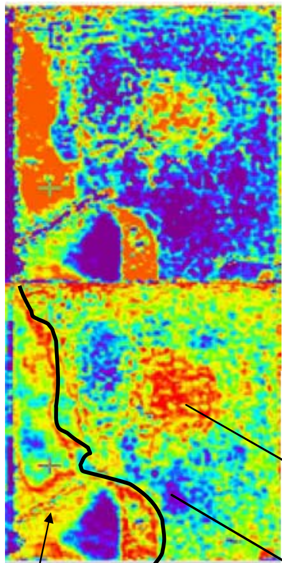


TTU Ultrasound Image



Pulse-Echo UT (Gate 2 ToF)

NASA Impact Panel 146-2



Gate 1

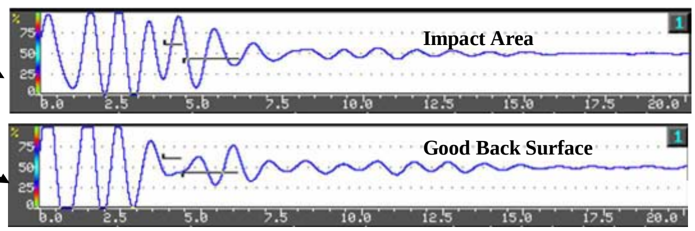
Amplitude

Gate 2

Amplitude

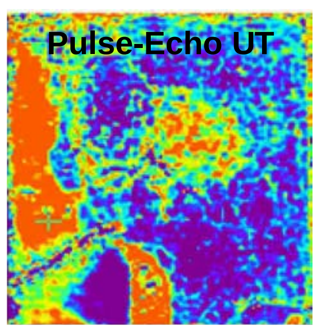
This region is completely delaminated

Ultrasonic Pulse-Echo Images & Waveforms from A146-2

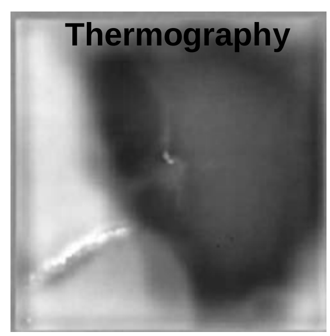


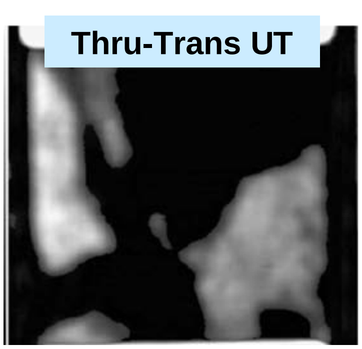
Note: The ultrasonic signal can be affected by water seeping into the edge of the delamination area.

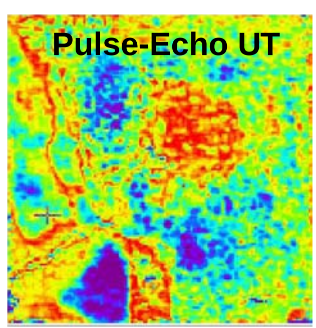
NASA Impact Panel 146-2



Gate 1 Amp



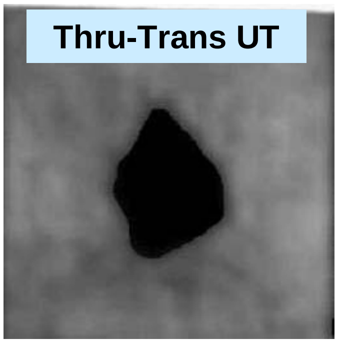


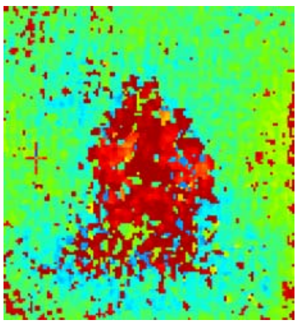


Gate 2 Amp

90 degree impact at 2002 fps

NASA Impact Panel 284-20



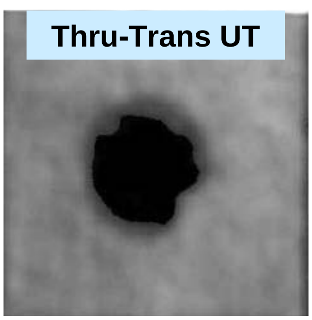


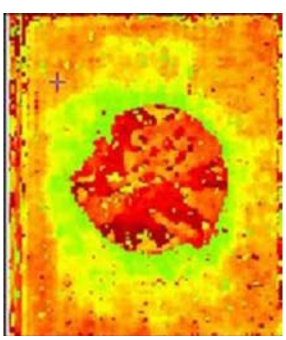
Pulse-Echo UT

Gate 2 Time of Flight

45 degree impact at 2230 fps – visible damage on backside only

NASA Impact Panel 20L-23

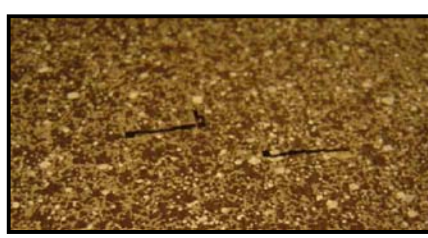




Pulse-Echo UT

Gate 2 Time of Flight

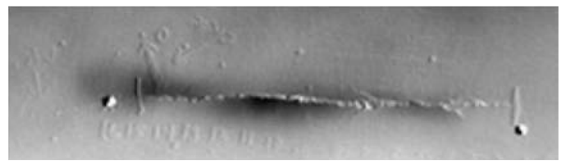
90 degree impact at 2077 fps – no visible damage on front; small cracks visible on back side



Impact Test - OV105 Panel 16R

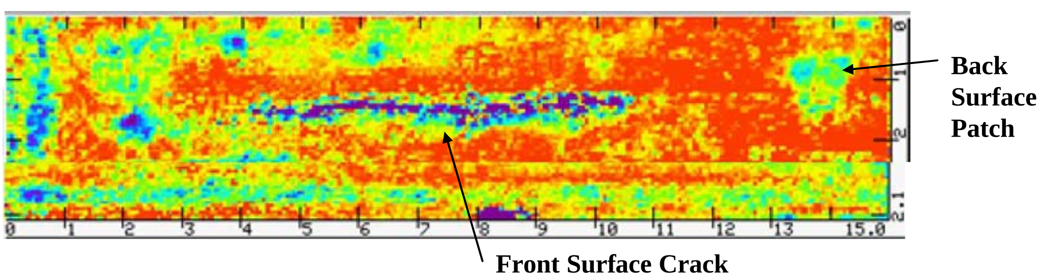
Photo of Crack at Apex

Thermography Image After panel was Impacted with Ablator Projectile

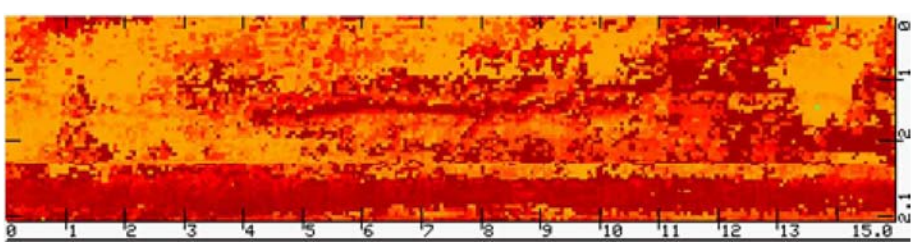


Ultrasonic Pulse Echo C-scan of OV105 Panel 16R

Amplitude

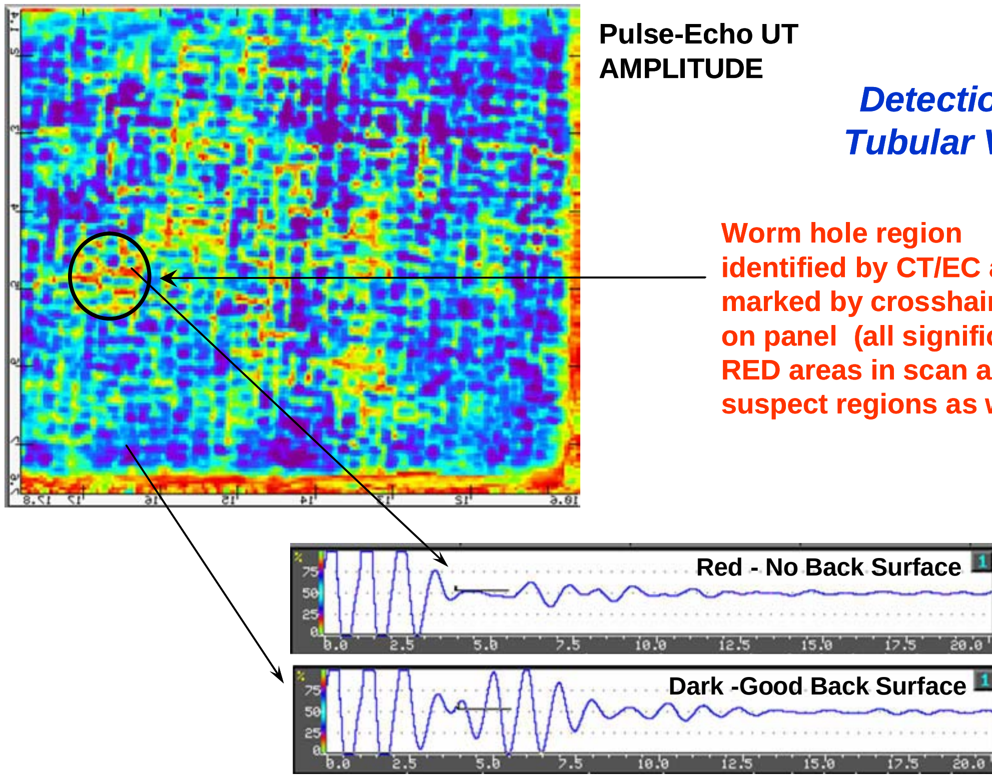


Time of Flight



NDI Image of “Argonne” Specimen

Supplied by Sam Russell with suspected “worm holes” in 0.25” th. plate

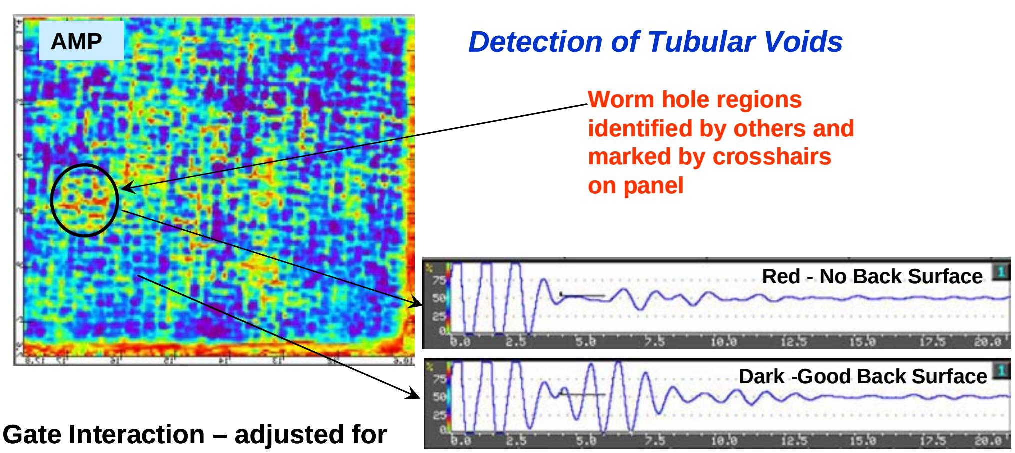


Pulse-Echo UT AMPLITUDE

Detection of Tubular Voids

Worm hole region identified by CT/EC and marked by crosshairs on panel (all significant RED areas in scan are suspect regions as well)

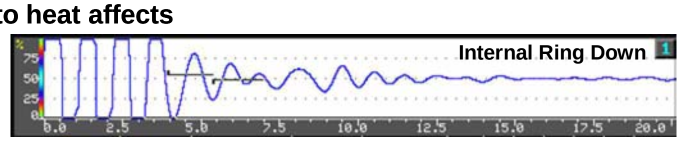
Pulse-Echo Ultrasonic Scan of 0.25” th. Flight Hardware RCC Panel



Detection of Tubular Voids

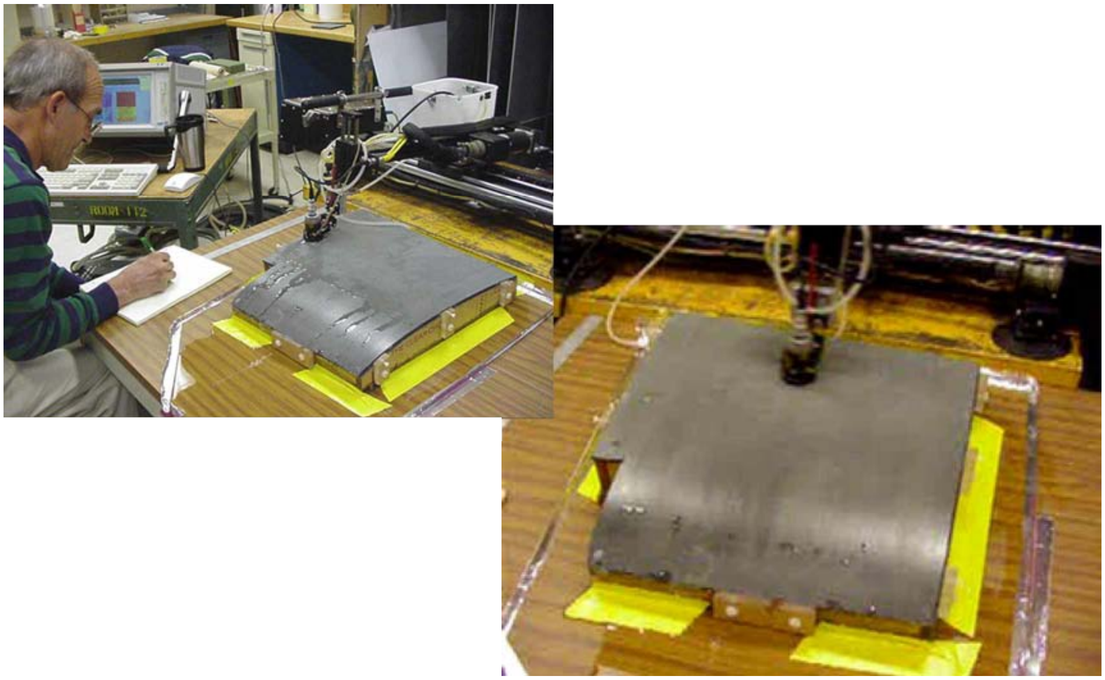
Worm hole regions identified by others and marked by crosshairs on panel

Gate Interaction – adjusted for attenuation levels; 6-12 dB range due to heat affects

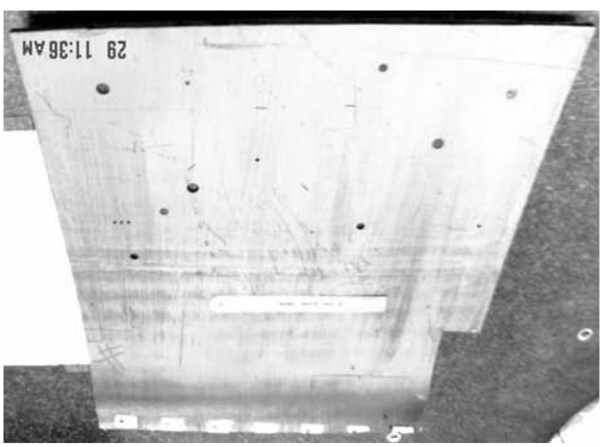


Gate 1 interaction for near-surface delaminations

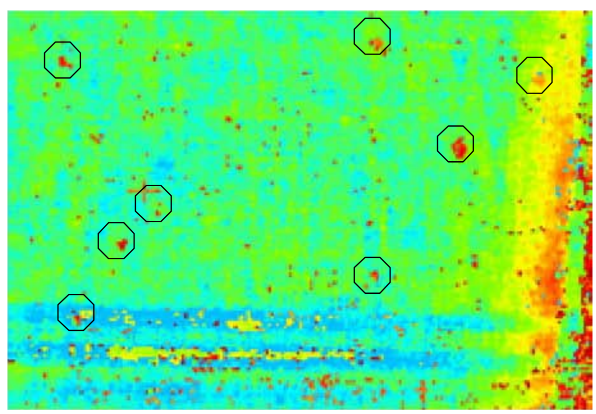
Pulse-Echo UT Inspection of "Bill's Box" NASA RCC Panel



Pulse-Echo UT Inspection of "Bill's Box" NASA RCC Panel

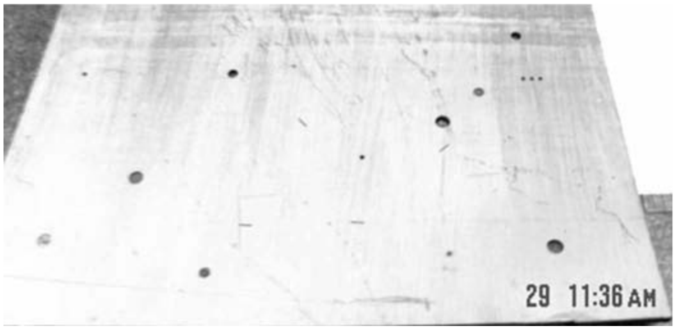


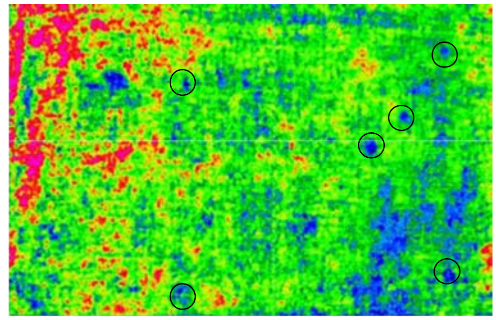
Flaw Profile

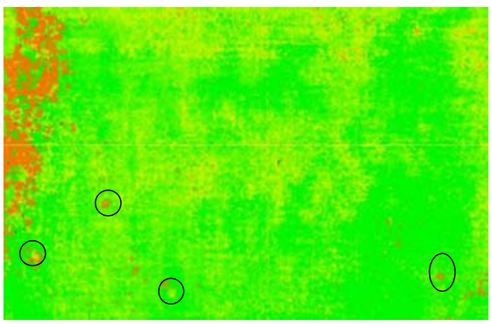


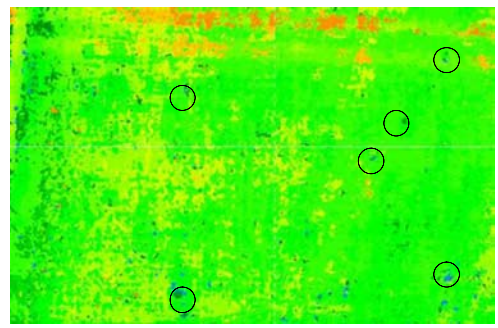
Gate 2 Time of Flight

Pulse-Echo UT Inspection of "Bill's Box" NASA RCC Panel



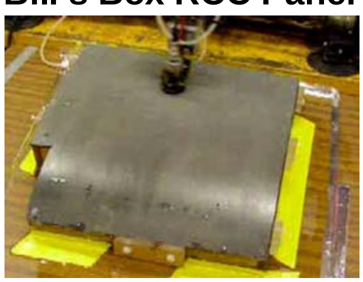


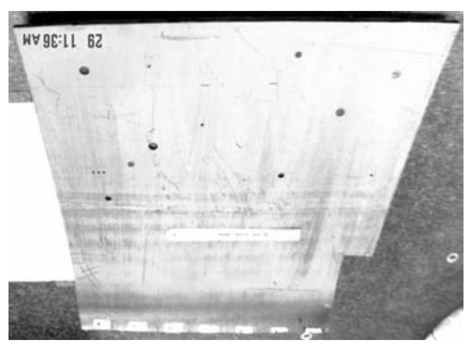




Pulse-Echo UT System Results Using Manual Scanning

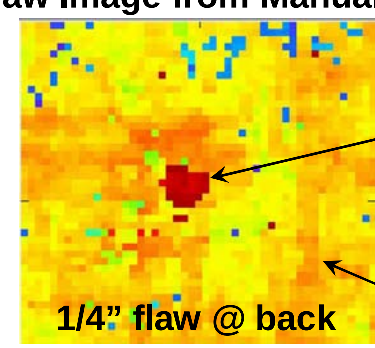
Bill's Box RCC Panel



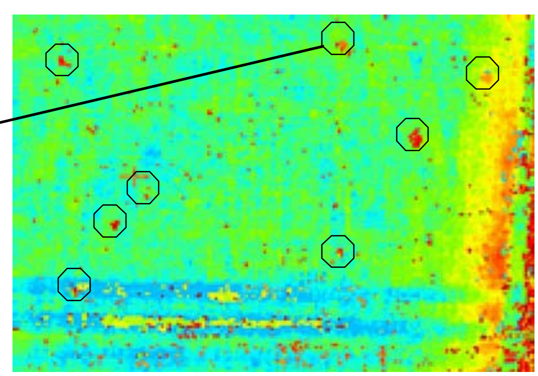


Flaw Profile

Flaw Image from Manual Scan

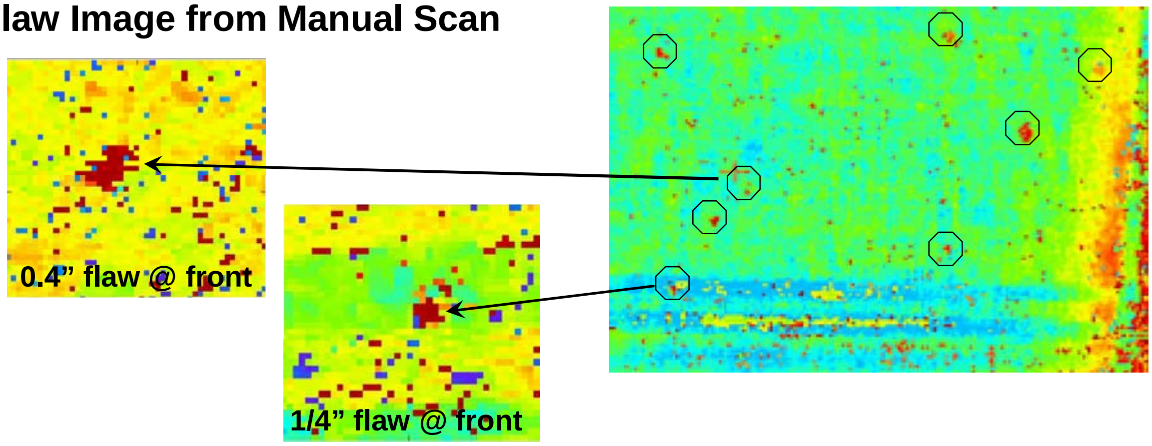


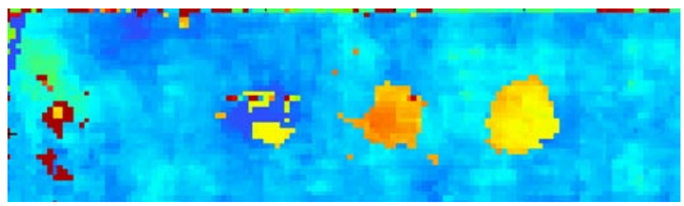
2" X 2" area



Pulse-Echo UT System Results Using Manual Scanning

Flaw Image from Manual Scan

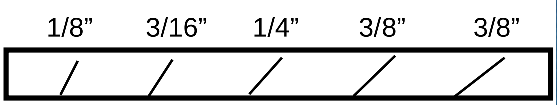




Flaw Image from Manual Scan

Pulse-Echo UT System Results Using Manual Scanning

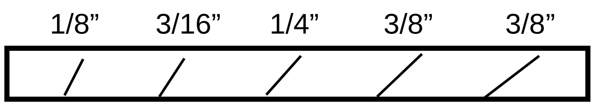
2" X 6" X 0.25" th. Specimen 03-58 with Sloped Slots



Side View

Pulse-Echo UT System Results Using Manual Scanning

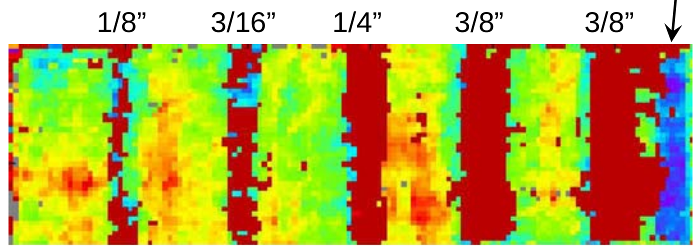
2" X 6" X 0.25" th. Specimen 03-58 with Sloped Slots



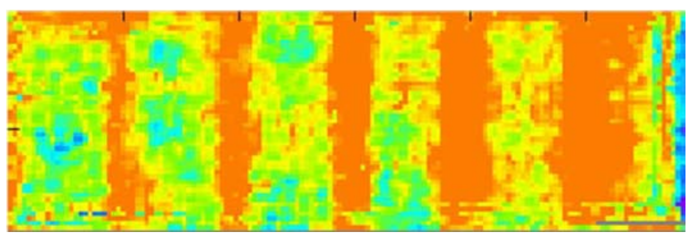
Side View

SiC coating removed on back side at end of coupon

Time of Flight



Amplitude

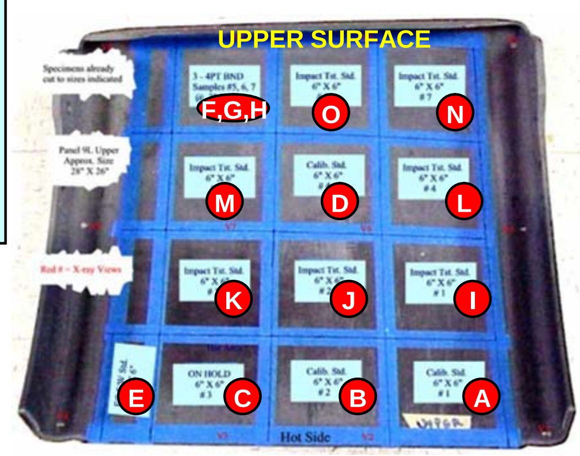


Min Δ dB at flaw = 9 dB
Max Δ dB at flaw = 14 dB

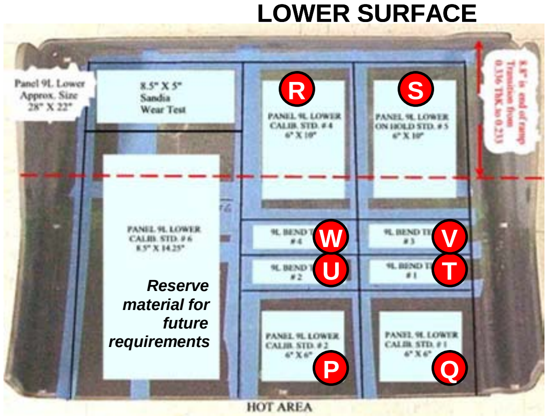
RCC Panel 9L Validation Test Series

15 Individual standards from Upper Surface of 9L:

- **Four Thermography/ Ultrasonic Calibration Standards**
  - **2 from Hot Zone (A, B)**
  - **1 from Cold Zone (D)**
- **1 Eddy Current Standard (E)**
  - **From Hot Zone**
- **3 Four-Point Bend Specimens (if all successful)-- (F, G, H)**
- **7 Impact Specimens (if all successful)-- (I-O)**



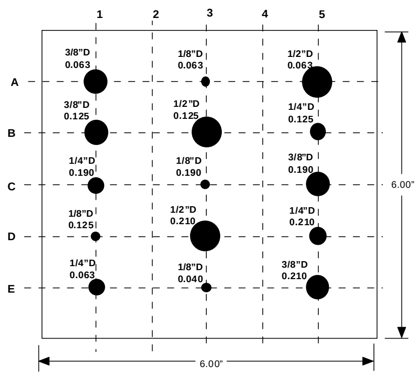
LOWER SURFACE

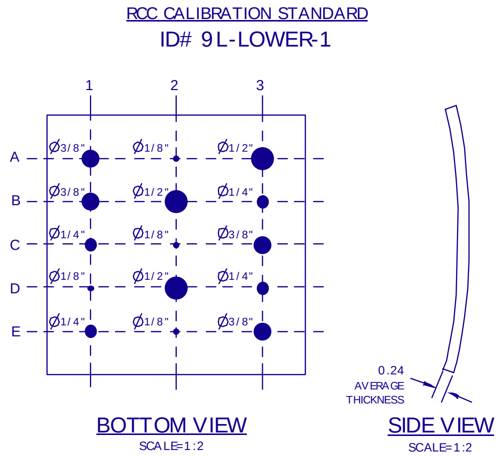


9 Standards from Lower Surface of 9L:

- **4 Calibration Standards**
  - **2 from Hot Zone (P, Q)**
  - **2 from Transitional Zone (R, S)**
- **3 Four-Point Bend Specimens - (T-W)**
- **14.25" X 8.5" (for future requirements)**
- **Wear test specimen for Sandia**

Validation Results, Phase 2 Specimen 9L – Lower 1 (Q)



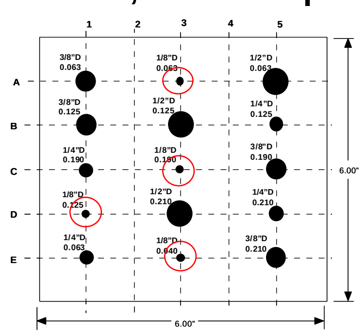


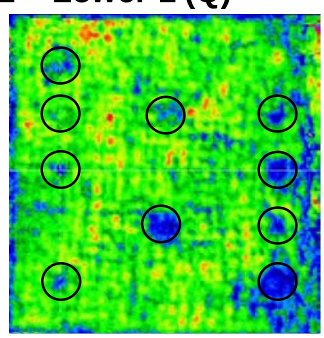
F/B HOLE DEPTH

	1	2	3
A	0.060	0.065	0.060
B	0.125	0.125	0.125
C	0.172	0.175	0.188
D	0.130	0.188	0.189
E	0.063	0.041	0.207

NOTES:
1. 6x6" SAMPLE SIZE
2. ALL DIMS INCHES

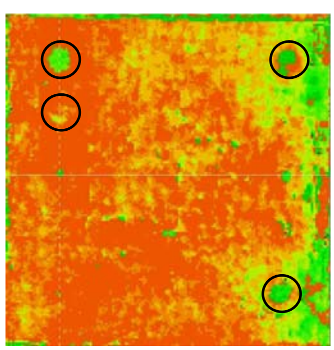
Validation Results, Phase 2 Specimen 9L – Lower 1 (Q)



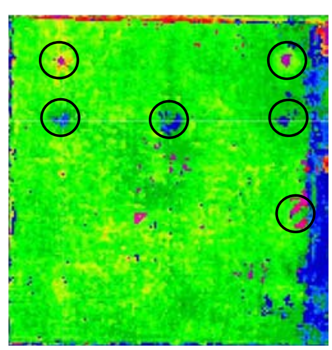


Amplitude 3

Flaws not found (red circles)

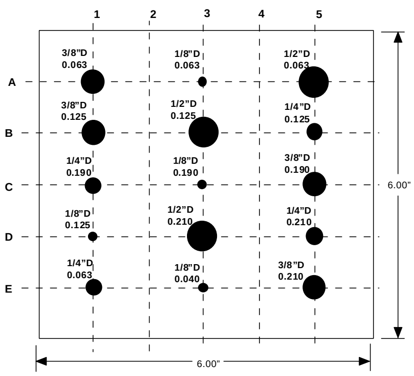


Time of flight 3



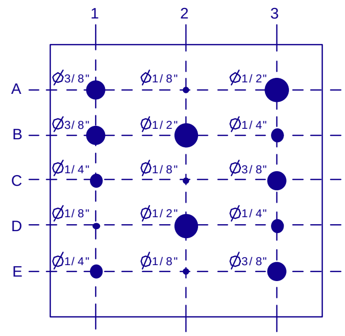
Time of flight 4

Validation Results, Phase 2 Specimen 9L – Lower 2 (P)



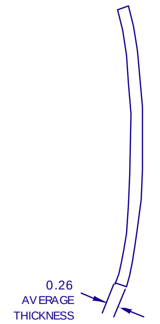
RCC CALIBRATION STANDARD

ID# 9L-LOWER-2



BOTTOM VIEW

SCALE=1:2



SIDE VIEW

SCALE=1:2

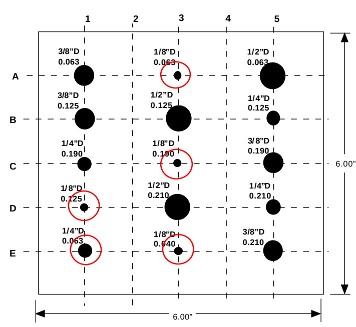
F/ B HOLE DEPTH

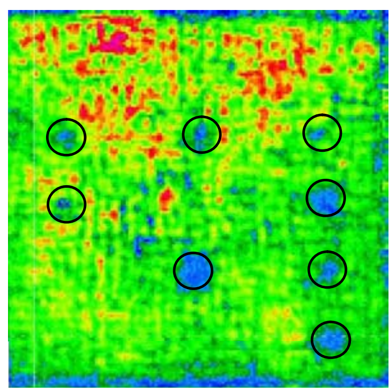
	1	2	3
A	0.062	0.063	0.063
B	0.123	0.126	0.125
C	0.169	0.176	0.188
D	0.133	0.188	0.192
E	0.064	0.039	0.203

NOTES:
1. 6x6" SAMPLE SIZE
2. ALL DIMS INCHES

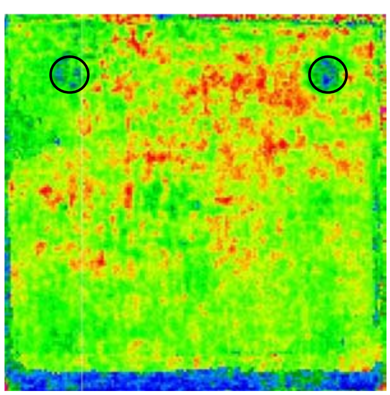
Validation Results, Phase 2 Specimen 9L – Lower 2 (P)

Flaws not found





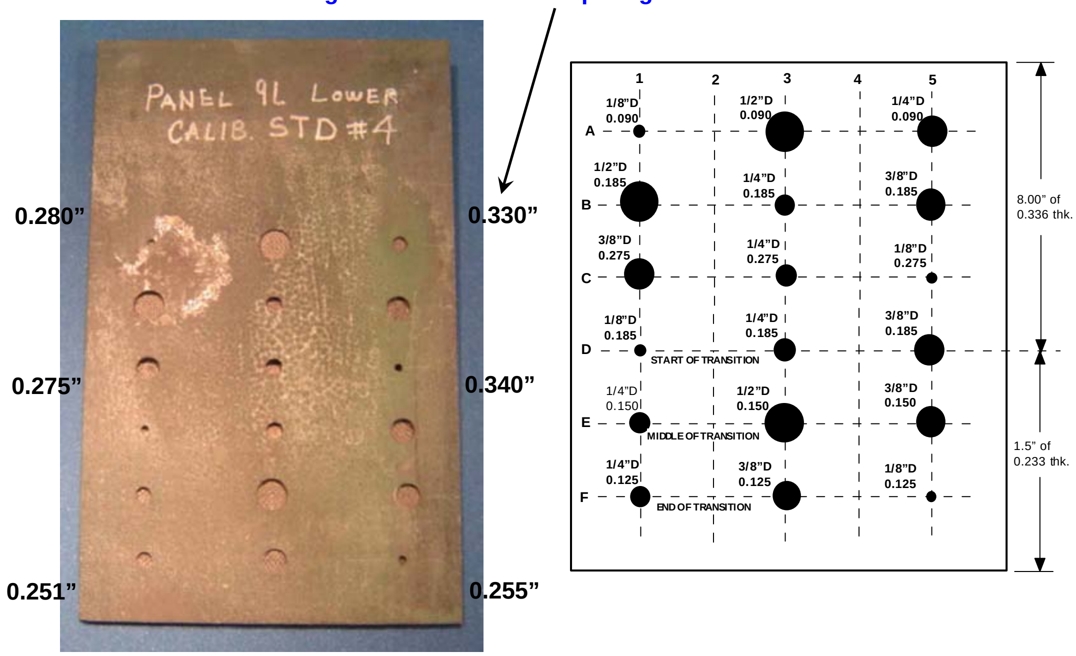
Amplitude 1



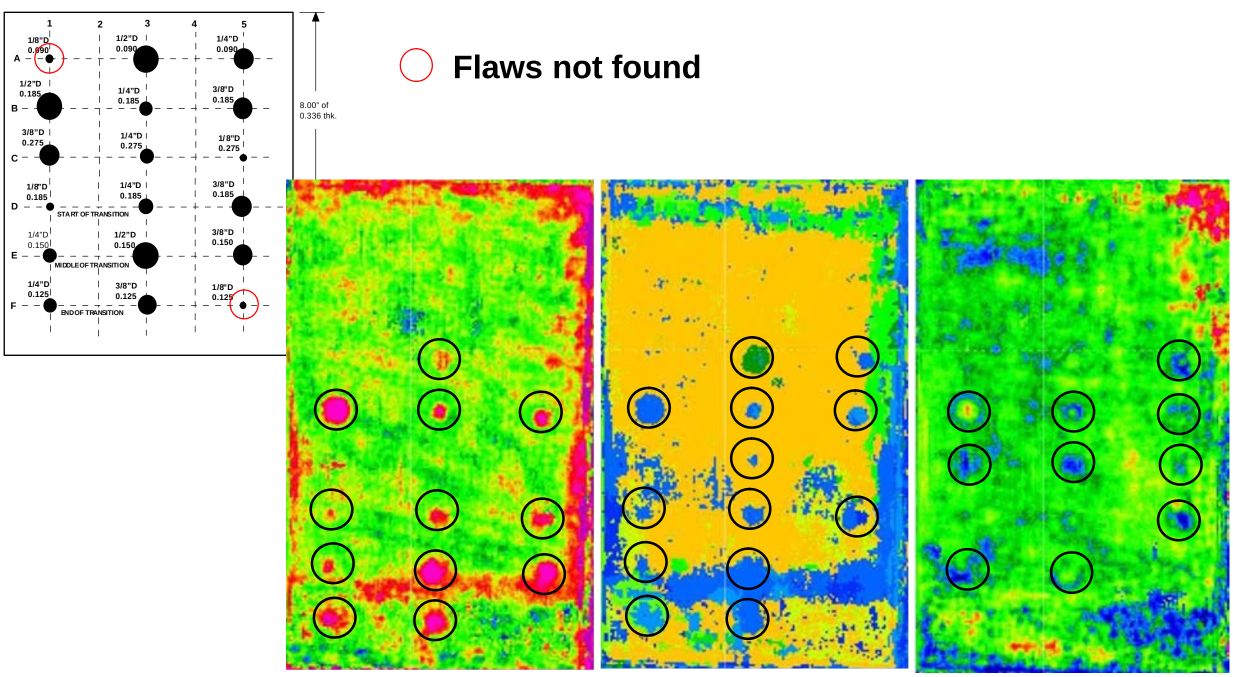
Amplitude 2

Validation Results, Phase 2 Specimen 9L – Lower 4 (R)

Transition Region with Thickness Tapering from 0.233" to 0.340"

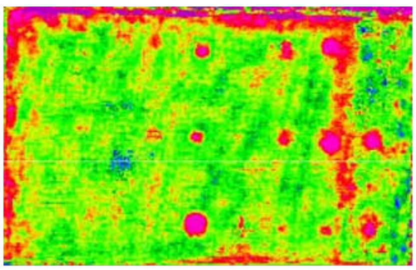
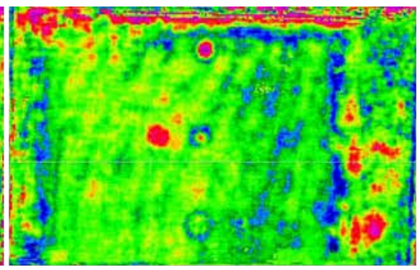
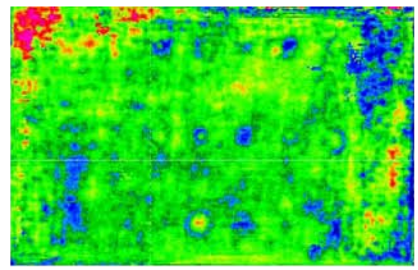
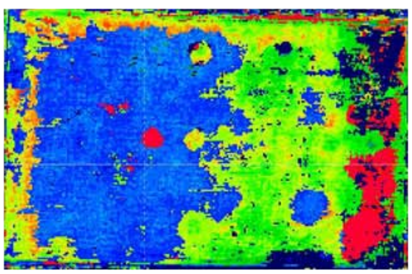
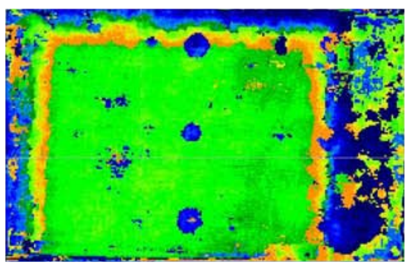
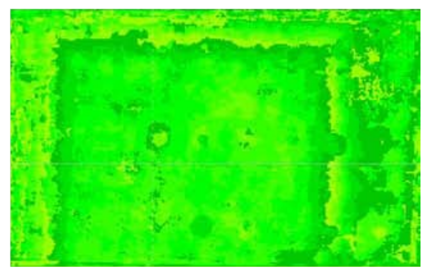
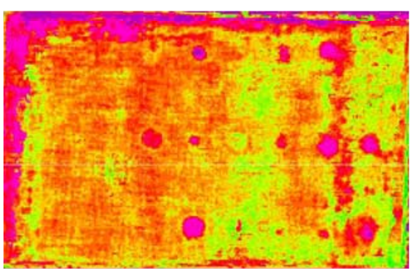
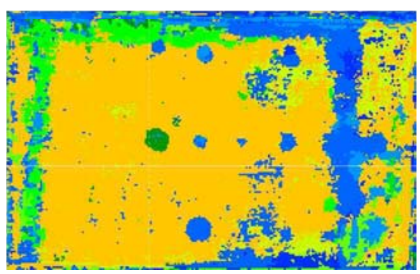


Validation Results, Phase 2 Specimen 9L – Lower 4 (R)



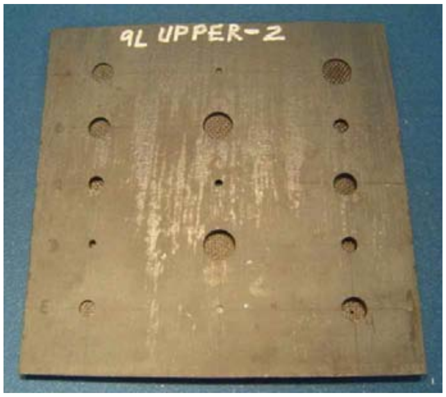
Amplitude 1 **Time of Flight 4** **Amplitude 3**

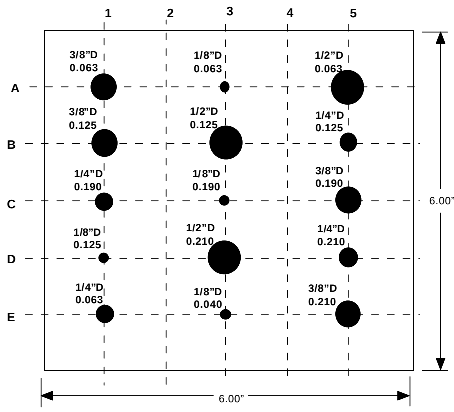
Validation Results, Phase 2 Specimen 9L – Lower 4 (R)

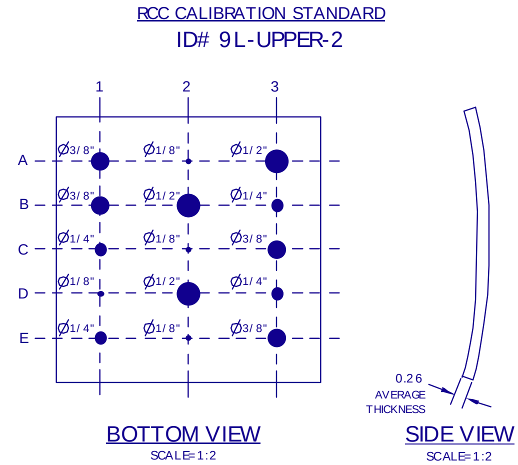









Sample of the Total "Amplitude" and "Time of Flight" Data Set Used to Detect Flaws

Validation Results, Phase 2 Specimen 9L – Upper 2 (B)





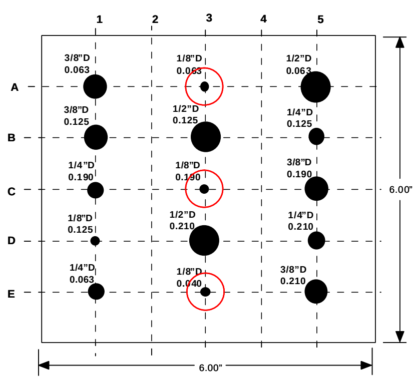


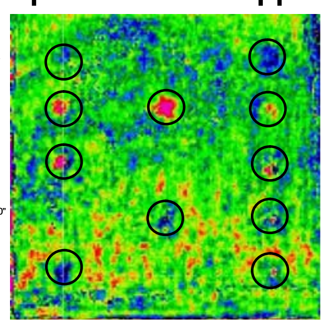
F/ B HOLE DEPTH

	1	2	3
A	0.059	0.065	0.066
B	0.122	0.123	0.126
C	0.170	0.180	0.183
D	0.140	0.184	0.190
E	0.063	0.040	0.202

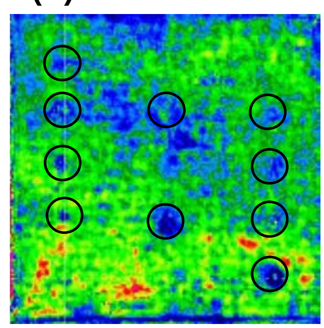
NOTES:
1. 6x6" SAMPLE SIZE
2. ALL DIMS INCHES

Validation Results, Phase 2 Specimen 9L – Upper 2 (B)



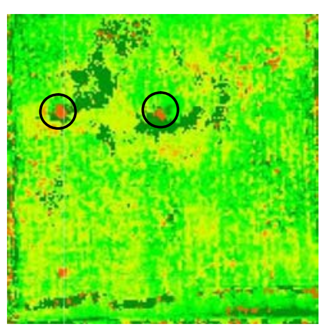


Amplitude 1



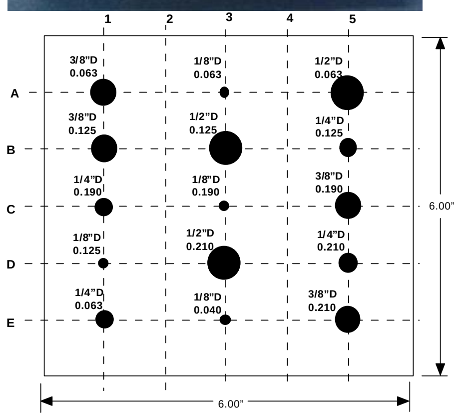
Amplitude 2

Flaws not found



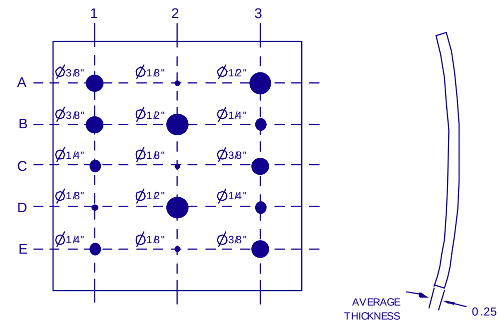
Time of Flight 1

Validation Results, Phase 2 Specimen 9L – Upper 3 (A)



RCC CALIBRATION STANDARD

ID# 9L-UPPER-3



BOTTOM VIEW
SCALE=1:2

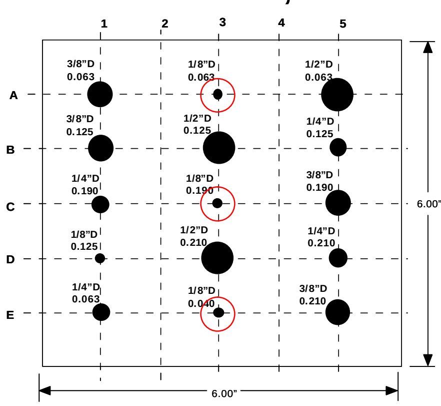
SIDE VIEW
SCALE=1:2

F/B HOLE DEPTH

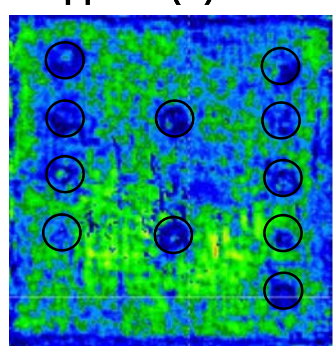
	1	2	3
A	0.066	0.066	0.047
B	0.126	0.125	0.123
C	0.170	0.179	0.188
D	0.132	0.189	0.189
E	0.062	0.040	0.208

NOTES:
1. 6x6" SAMPLE SIZE
2. ALL DIMS INCHES

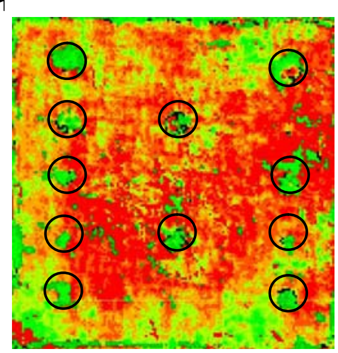
Validation Results, Phase 2 Specimen 9L – Upper 3 (A)



Amplitude 3



Flaws not found

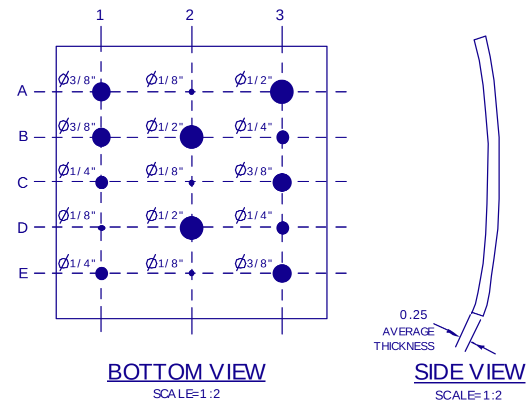


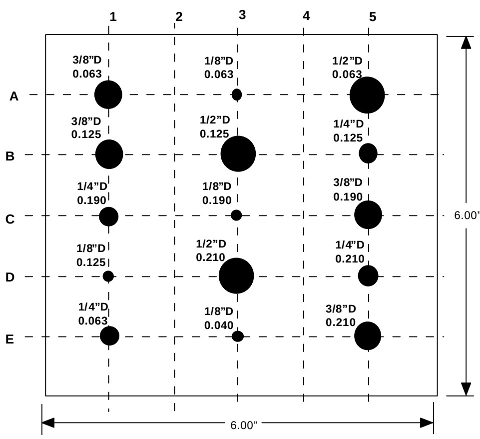
Time of Flight 3

Validation Results, Phase 2 Specimen 9L – Upper 4 (D)

RCC CALIBRATION STANDARD

ID# 9L-UPPER-4



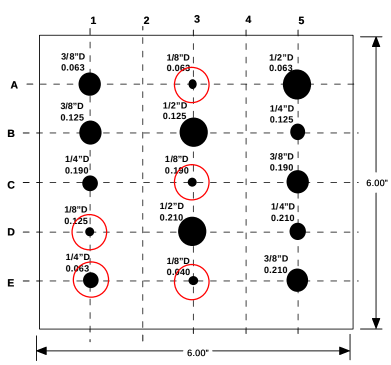


F/ B HOLE DEPTH

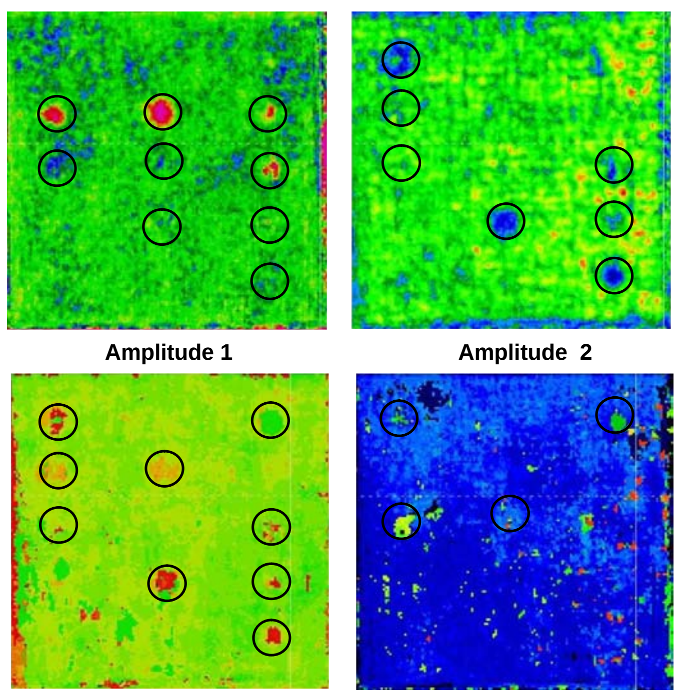
	1	2	3
A	0.065	0.063	0.063
B	0.125	0.121	0.124
C	0.170	0.184	0.169
D	0.132	0.188	0.188
E	0.059	0.042	0.189

NOTES:
1. 6x6" SAMPLE SIZE
2. ALL DIMS INCHES

Validation Results, Phase 2 Specimen 9L – Upper 4 (D)



Flaws not found



Amplitude 1

Amplitude 2

Time of Flight 4

Time of Flight 3

Flaw Detection Summary for 1/8” Dia. Flaws in 9L Specimens

Detection of 1/8" Diameter Flaws in RCC 9L Specimens									
Specimen	Flaw Identification and Flaw Depth from Front Surface (inches)							Detection by Pulse-Echo UT	
	0.200 (+)	0.178	0.120	0.080	0.070	0.050	0.040 (-)	Yes	No
9L-Lower 1 (Q)		A-2							X
9L-Lower 1 (Q)					C-2				X
9L-Lower 1 (Q)			D-1						X
9L-Lower 1 (Q)	E-2								X
9L-Lower 2 (P)	A-2								X
9L-Lower 2 (P)				C-2					X
9L-Lower 2 (P)			D-1						X
9L-Lower 2 (P)	E-2								X
9L-Lower 4 (R)	A-1								X
9L-Lower 4 (R)						C-5		X	
9L-Lower 4 (R)		D-1						X	
9L-Lower 4 (R)			F-5						X
9L-Upper 2 (B)	A-2								X
9L-Upper 2 (B)				C-2					X
9L-Upper 2 (B)			D-1						X
9L-Upper 2 (B)	E-2							X	
9L-Upper 3 (A)		A-2							X
9L-Upper 3 (A)					C-2				X
9L-Upper 3 (A)			D-1					X	
9L-Upper 3 (A)	E-2								X
9L-Upper 4 (D)		A-2							X
9L-Upper 4 (D)					C-2				X
9L-Upper 4 (D)			D-1						X
9L-Upper 4 (D)	E-2								X

1/8” dia. flaw detection = 16.8%

Flaw Detection Summary for 1/4” Dia. Flaws in 9L Specimens

Detection of 1/4" Diameter Flaws in RCC 9L Specimens									
Specimen	Flaw Identification and Flaw Depth from Front Surface (inches)							Detection by Pulse-Echo UT	
	0.200 (+)	0.178	0.120	0.080	0.070	0.050	0.040 (-)	Yes	No
9L-Lower 1 (Q)			B-3					X	
9L-Lower 1 (Q)					C-1			X	
9L-Lower 1 (Q)						D-3		X	
9L-Lower 1 (Q)		E-1						X	
9L-Lower 2 (P)			B-3					X	
9L-Lower 2 (P)				C-1				X	
9L-Lower 2 (P)					D-3			X	
9L-Lower 2 (P)	E-1								X
9L-Lower 4 (R)	A-5							X	
9L-Lower 4 (R)			B-3					X	
9L-Lower 4 (R)							C-3	X	
9L-Lower 4 (R)			D-3					X	
9L-Lower 4 (R)			E-1					X	
9L-Lower 4 (R)			F-1					X	
9L-Upper 2 (B)			B-3					X	
9L-Upper 2 (B)				C-1				X	
9L-Upper 2 (B)					D-3			X	
9L-Upper 2 (B)	E-1							X	
9L-Upper 3 (A)			B-3					X	
9L-Upper 3 (A)				C-1				X	
9L-Upper 3 (A)					D-3			X	
9L-Upper 3 (A)		E-1						X	
9L-Upper 4 (D)			B-3					X	
9L-Upper 4 (D)				C-1				X	
9L-Upper 4 (D)					D-3			X	
9L-Upper 4 (D)	E-1								X

1/4” dia. flaw detection = 92%

Flaw Detection Summary for 3/8” Dia. Flaws in 9L Specimens

Detection of 3/8" Diameter Flaws in RCC 9L Specimens									
Specimen	Flaw Identification and Flaw Depth from Front Surface (inches)							Detection by Pulse-Echo UT	
	0.200 (+)	0.178	0.120	0.080	0.070	0.050	0.040 (-)	Yes	No
9L-Lower 1 (Q)		A-1						X	
9L-Lower 1 (Q)			B-1					X	
9L-Lower 1 (Q)						C-3		X	
9L-Lower 1 (Q)							E-3	X	
9L-Lower 2 (P)	A-1							X	
9L-Lower 2 (P)			B-1					X	
9L-Lower 2 (P)					C-3			X	
9L-Lower 2 (P)						E-3		X	
9L-Lower 4 (R)			B-3					X	
9L-Lower 4 (R)							C-1	X	
9L-Lower 4 (R)			D-5					X	
9L-Lower 4 (R)			E-5					X	
9L-Lower 4 (R)			F-3					X	
9L-Upper 2 (B)	A-1							X	
9L-Upper 2 (B)			B-1					X	
9L-Upper 2 (B)				C-3				X	
9L-Upper 2 (B)						E-3		X	
9L-Upper 3 (A)		A-1						X	
9L-Upper 3 (A)			B-1					X	
9L-Upper 3 (A)					C-3			X	
9L-Upper 3 (A)						E-3		X	
9L-Upper 4 (D)		A-1						X	
9L-Upper 4 (D)			B-1					X	
9L-Upper 4 (D)				C-3				X	
9L-Upper 4 (D)					E-3			X	

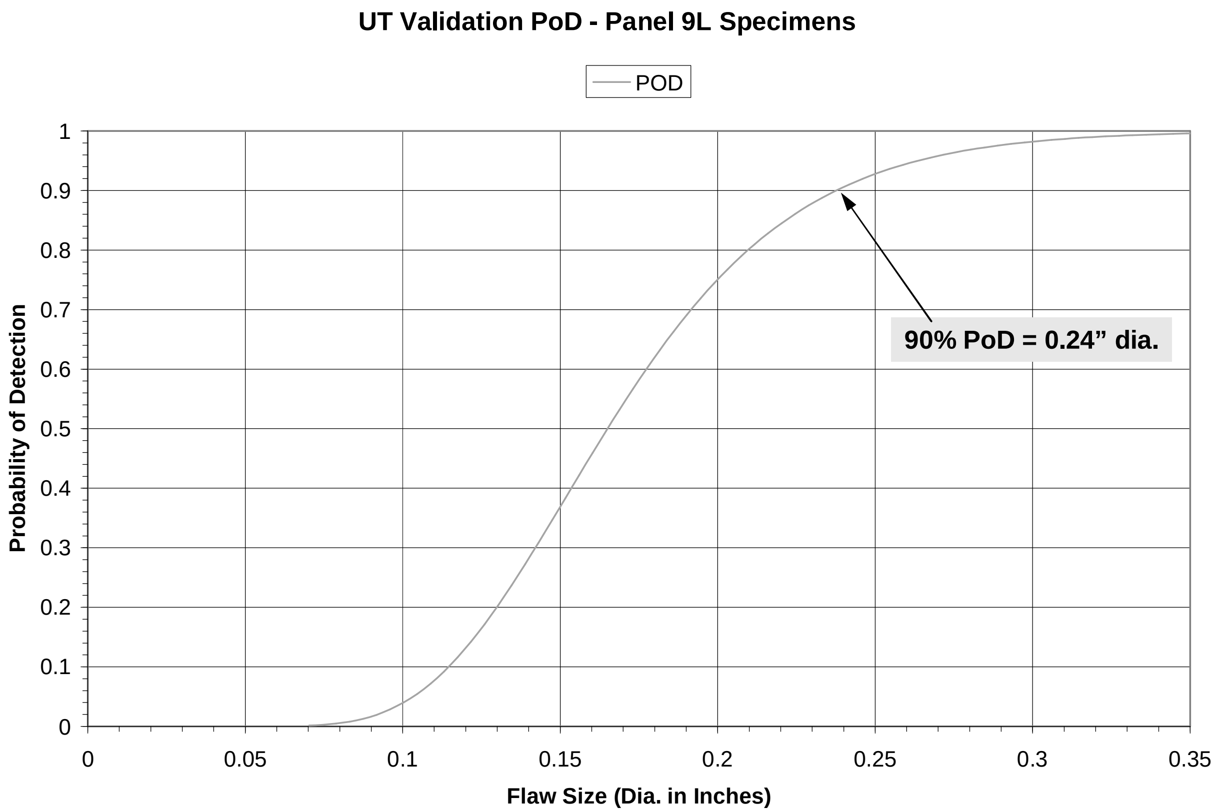
3/8” dia. flaw detection = 100%

Flaw Detection Summary for 1/2” Dia. Flaws in 9L Specimens

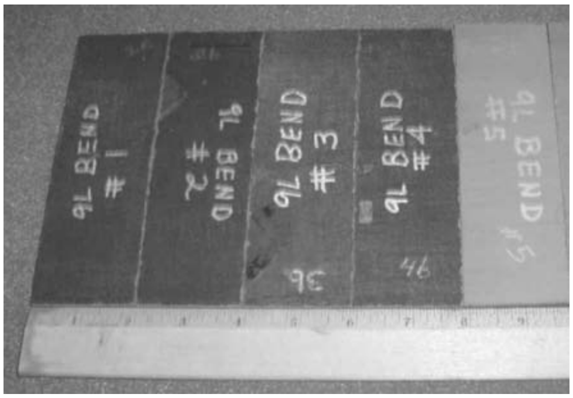
Detection of 1/2" Diameter Flaws in RCC 9L Specimens									
Specimen	Flaw Identification and Flaw Depth from Front Surface (inches)							Detection by Pulse-Echo UT	
	0.200 (+)	0.178	0.120	0.080	0.070	0.050	0.040 (-)	Yes	No
9L-Lower 1 (Q)		A-3						X	
9L-Lower 1 (Q)			B-2					X	
9L-Lower 1 (Q)						D-2		X	
9L-Lower 2 (P)	A-3							X	
9L-Lower 2 (P)			B-2					X	
9L-Lower 2 (P)					D-2			X	
9L-Lower 4 (R)	A-3							X	
9L-Lower 4 (R)				B-1				X	
9L-Lower 4 (R)		E-3						X	
9L-Upper 2 (B)	A-3							X	
9L-Upper 2 (B)			B-2					X	
9L-Upper 2 (B)					D-2			X	
9L-Upper 3 (A)	A-3							X	
9L-Upper 3 (A)			B-2					X	
9L-Upper 3 (A)					D-2			X	
9L-Upper 4 (D)	A-3							X	
9L-Upper 4 (D)			B-2					X	
9L-Upper 4 (D)					D-2			X	

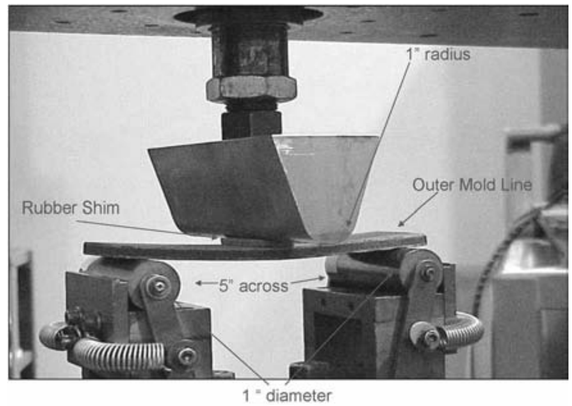
1/2” dia. flaw detection = 100%

Probability of Detection Curve for Pulse-Echo UT Flaw Detection in Panel 9L – NDI Reference Standard Specimens



Validation Results, Phase 2 Specimen 9L – 3 Pt. Bend





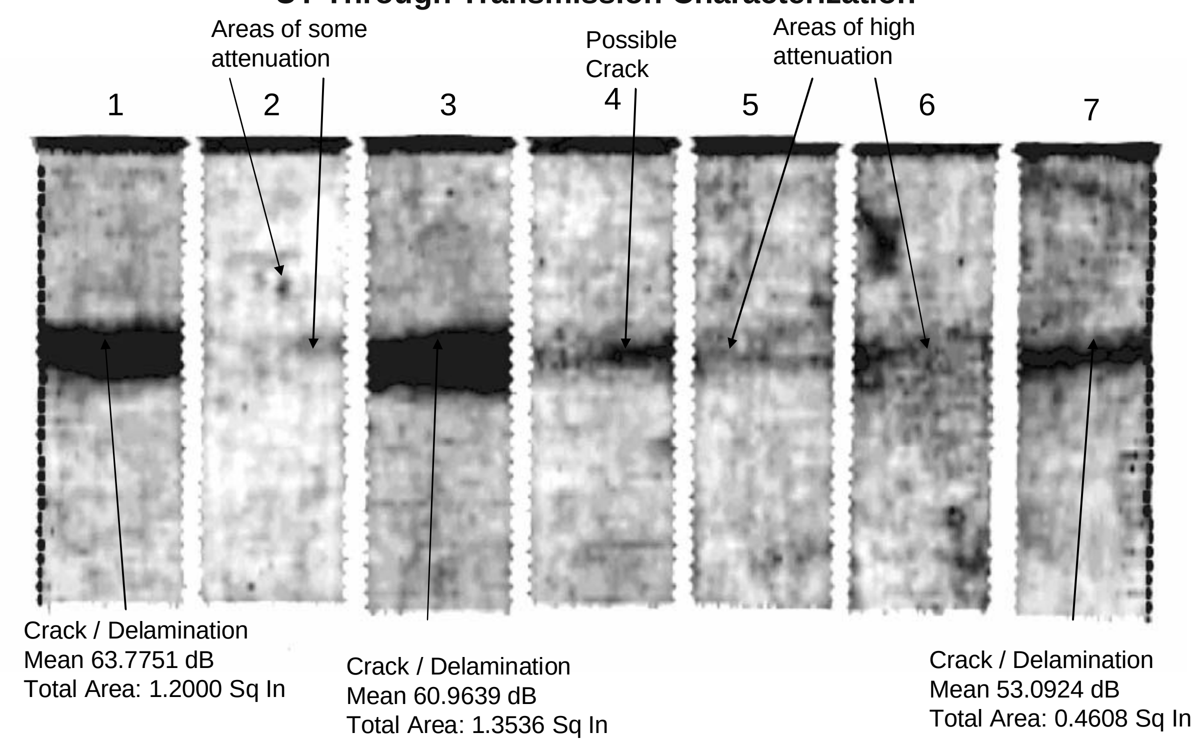
RCC Specimen Undergoing 3 Pt. Bend Test

3 Pt. Bend Specimens 1 (T), 2 (U), 3 (V), 4 (W), 5 (F), 6 (G), 7(H)

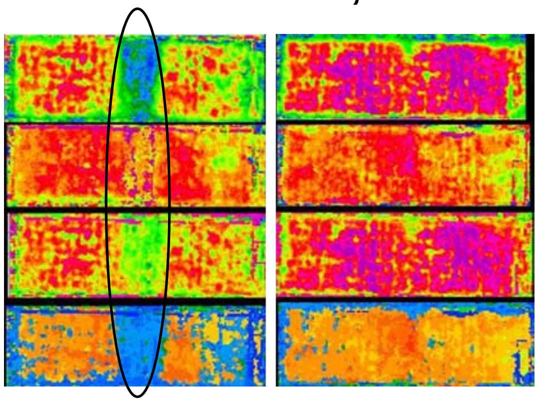
Specimens 1-4 from Lower Surface; 5-7 from Upper Surface

Validation Results, Phase 2 Specimen 9L – 3 Pt. Bend

UT Through Transmission Characterization



Validation Results, Phase 2 Specimen 9L – 3 Pt. Bend



Amplitude 1

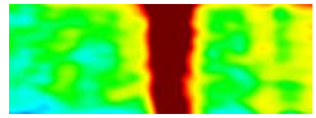
Time of Flight 1

Amplitude 2

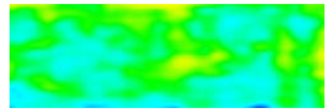
Time of Flight 2

Specimen #1 **Specimen #2**

Spec. #1 MWM EC Results at 5.0 MHz



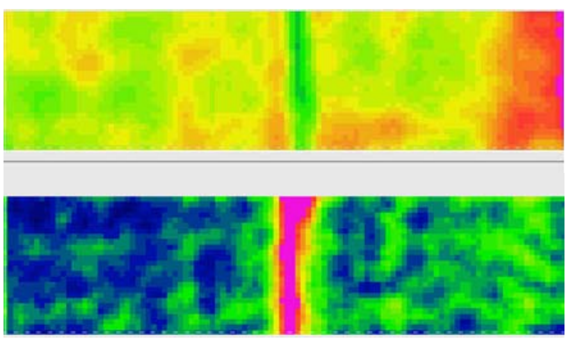
Spec. #2 MWM EC Results at 5.0 MHz



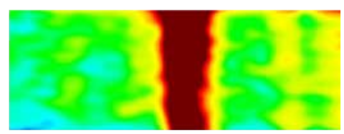
Specimen 1 (side view showing crack)

Eddy Current Inspection Results for Comparison to P-E Ultrasonics Testing

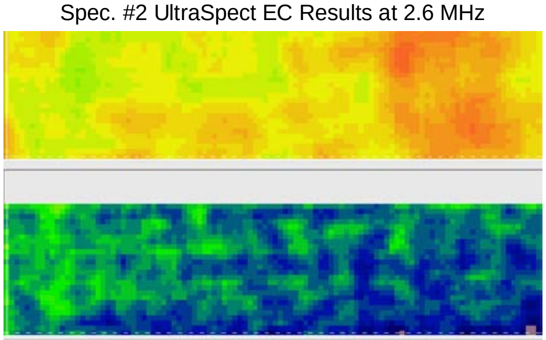
Spec. #1 UltraSpect EC Results at 2.6 MHz



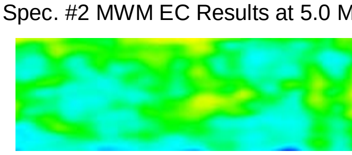
Spec. #1 MWM EC Results at 5.0 MHz



Spec. #2 UltraSpect EC Results at 2.6 MHz

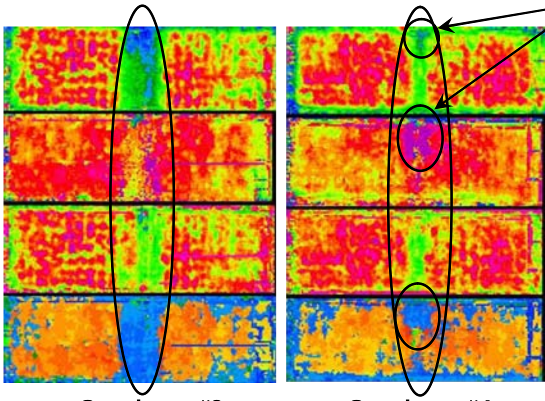


Spec. #2 MWM EC Results at 5.0 MHz



Validation Results, Phase 2 Specimen 9L – 3 Pt. Bend

Stronger indications on one side of specimen



Specimen #3 Specimen #4

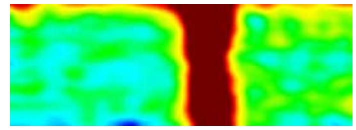
Amplitude 1

Time of Flight 1

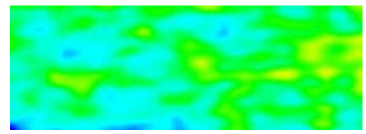
Amplitude 2

Time of Flight 2

Spec. #3 MWM EC Results at 5.0 MHz



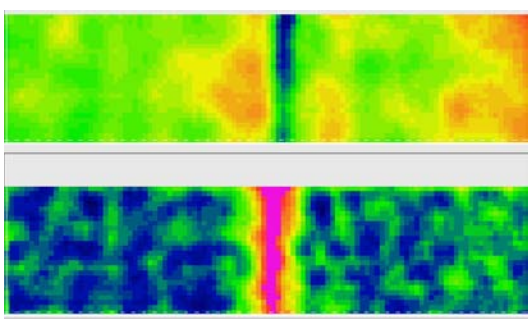
Spec. #4 MWM EC Results at 5.0 MHz



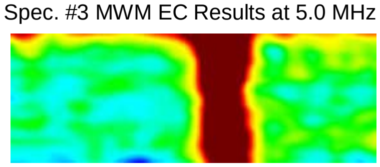
Specimen 3 (side view showing crack)

Eddy Current Inspection Results for Comparison to P-E Ultrasonics Testing

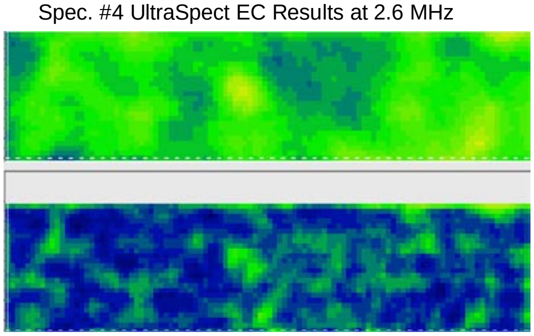
Spec. #3 UltraSpect EC Results at 2.6 MHz



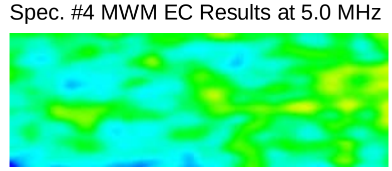
Spec. #3 MWM EC Results at 5.0 MHz



Spec. #4 UltraSpect EC Results at 2.6 MHz

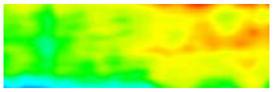


Spec. #4 MWM EC Results at 5.0 MHz

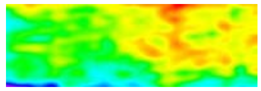


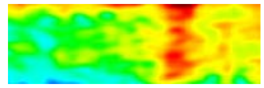
Validation Results, Phase 2 Specimen 9L – 3 Pt. Bend

Spec. #5 MWM EC Results at 2.5 MHz

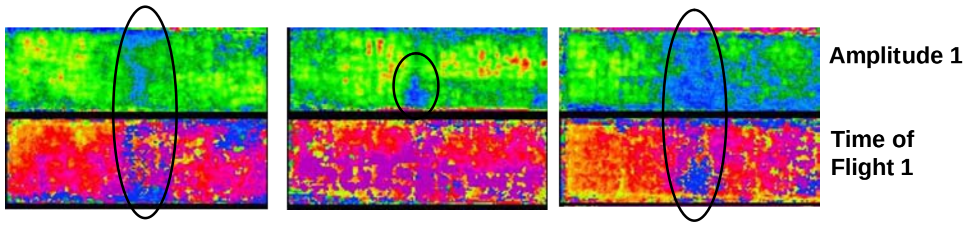


Spec. #7 MWM EC Results at 5.0 MHz





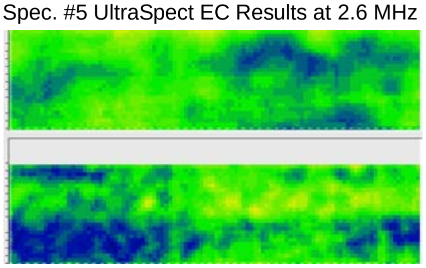
Spec. #6 MWM EC Results at 5.0 MHz



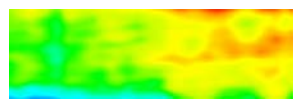
Specimen #5 **Specimen #6** **Specimen #7**

Eddy Current Inspection Results for Comparison to P-E Ultrasonics Testing

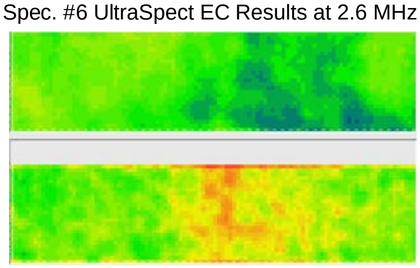
Spec. #5 UltraSpect EC Results at 2.6 MHz



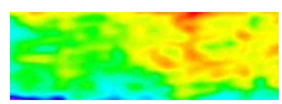
Spec. #5 MWM EC Results at 2.5 MHz



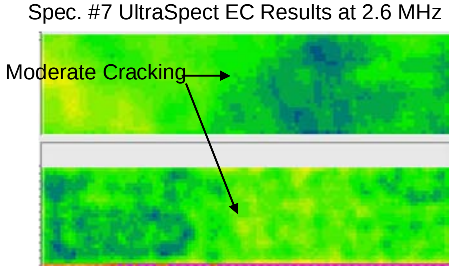
Spec. #6 UltraSpect EC Results at 2.6 MHz



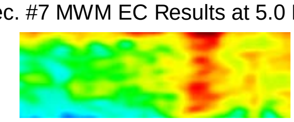
Spec. #6 MWM EC Results at 5.0 MHz



Spec. #7 UltraSpect EC Results at 2.6 MHz



Spec. #7 MWM EC Results at 5.0 MHz



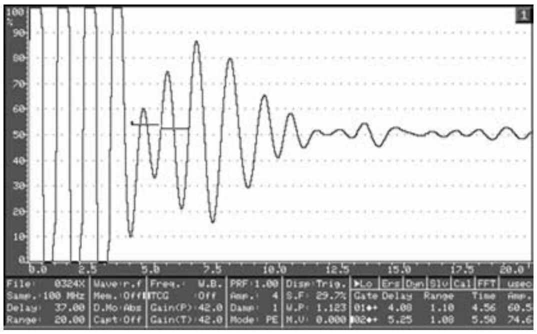
Use of UT Signal Database to Assess Structural Integrity

Comparison of Current UT Signature with UT History

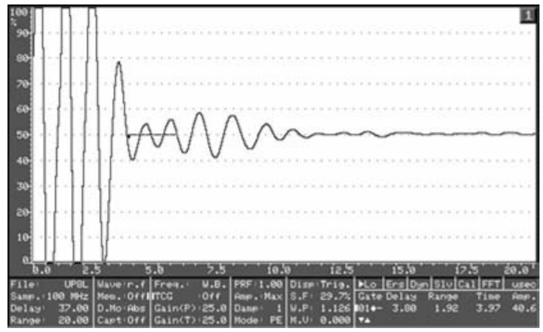
Comparison of signal from Boeing 03-24 specimen when gain is set to:

1) gain used in NASA Upper 8L specimen

2) gain used to optimize set-up on Boeing 03-24 disk



Gain used for Boeing 03-24 Specimen



Gain used for NASA Upper 8L Specimen

(indicates that attenuation in pucks is higher than in 8L specimen)

Validation Testing with RCC Panels 11L & 12L

Objectives of Validation Testing on Retired, Orbiter RCC Panels 11L & 12L

The objectives of this test program are:

- **To validate the functionality of the Ultraspec Ultrasonic data acquisition system with LPS 100 manual scanner by performing blind in situ inspection of a full scale RCC Orbiter Wing leading edge (WLE) Panel and Tee Seal (Panel 11L and Tee Seal 12L) installed on a test stand to represent actual installed hardware on the Orbiter.**
- **To validate the ability of each system to detect artificially induced flaws (such as flat bottom holes) in undeclared locations within four test zones machined into the inner mold line (IML) of Panel 11L ranging from 0.040 to 0.190 inches in depth and from 0.125 to 0.5 inches in diameter**
- **To validate the ability of each system to detect artificially induced flaws on the IML and web junction of Tee Seal 12L**
- **To validate the ability of each system to accurately inspect hardware in a configuration that encompasses curvature and thickness variations representative of a RCC Panel (upper, lower, apex and thickness transition areas) and a RCC Tee Seal (Tee section, vent holes and non-parallel surfaces)**
- **To validate that the inspection processes are capable of meeting the applicable requirements of relevant Boeing MT specifications (MT0501-510 for UT) as witnessed by a Boeing Level 3 NDE engineer.**
- **To quantify the range of detection capability of each system on a relevant hardware configuration per Boeing and USA Level 3 NDE data assessment**

Validation Testing with RCC Panel 11L and 12L – Ref. TPS #KF0520168

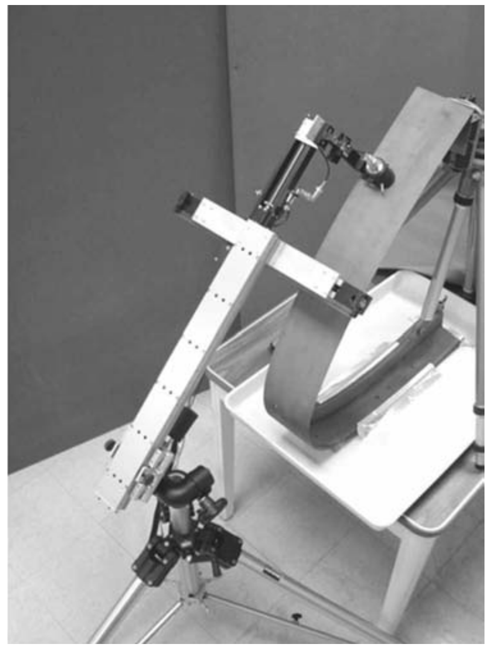
Final Results and Grading from

Ultrasonic Pulse-Echo Validation Tests for Inspection of Shuttle RCC Material

Test Articles: Orbiter Leading Edge Panel 11L and Tee Seal 12L

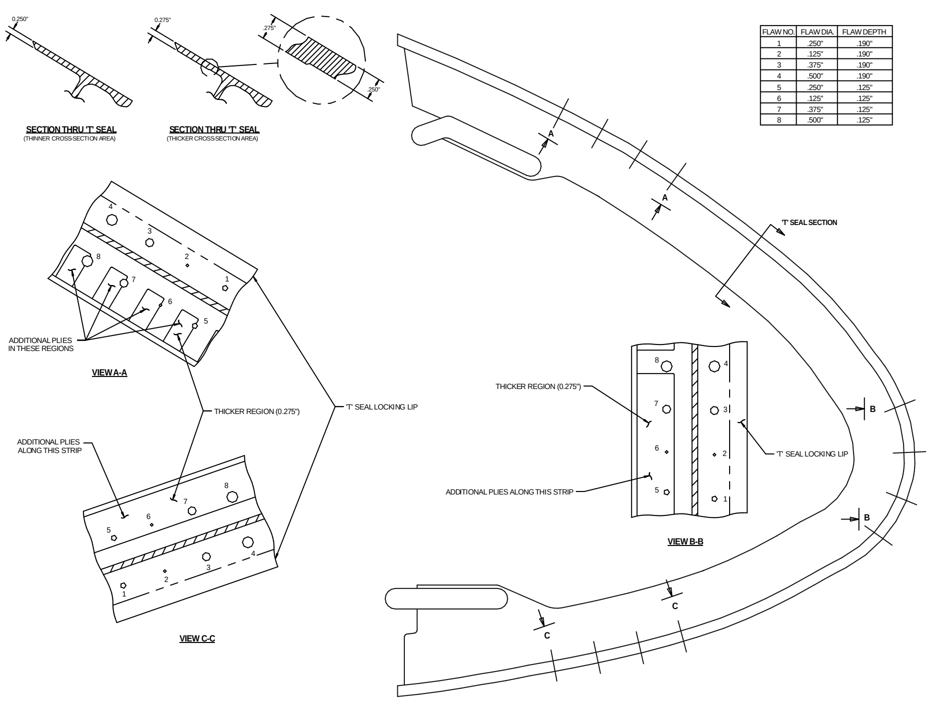
Full Scale Mock-up of Wing Leading Edge at OSS

Panel 11L



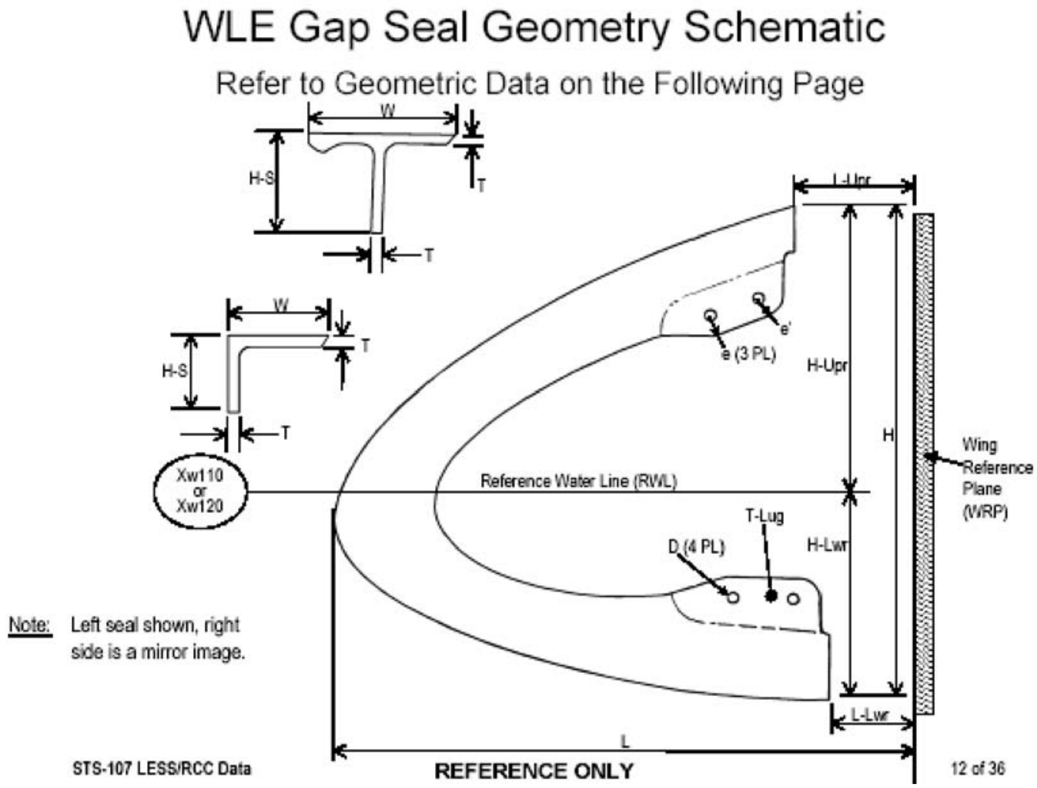
Panel 12L T-Seal

Wing Leading Edge RCC T-Seal



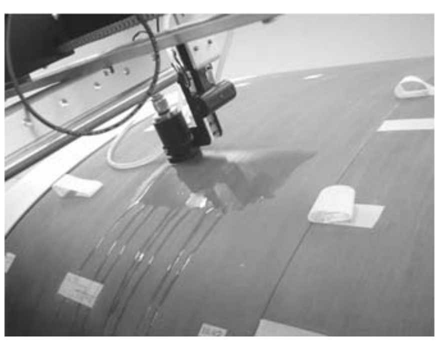
FLAW NO.	FLAW DIA.	FLAW DEPTH
1	.250"	.190"
2	.125"	.190"
3	.375"	.190"
4	.500"	.190"
5	.250"	.125"
6	.125"	.125"
7	.375"	.125"
8	.500"	.125"

Wing Leading Edge RCC T-Seal

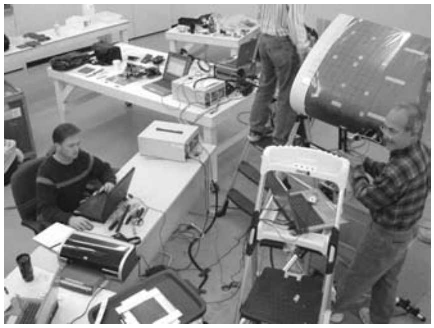


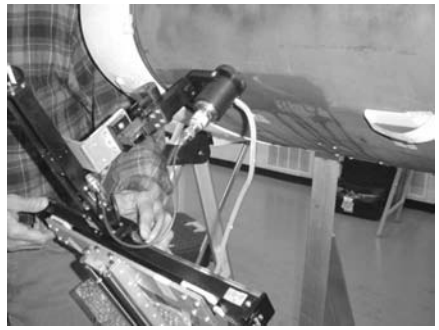
RCC Panel 11L – Seven Zones (4 val., 3 ref.)
RCC T Seal 12L – Three Zones (Z1 – Z3)

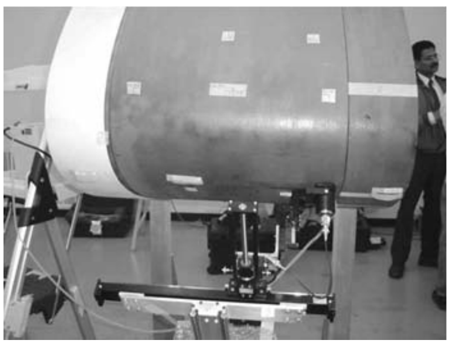




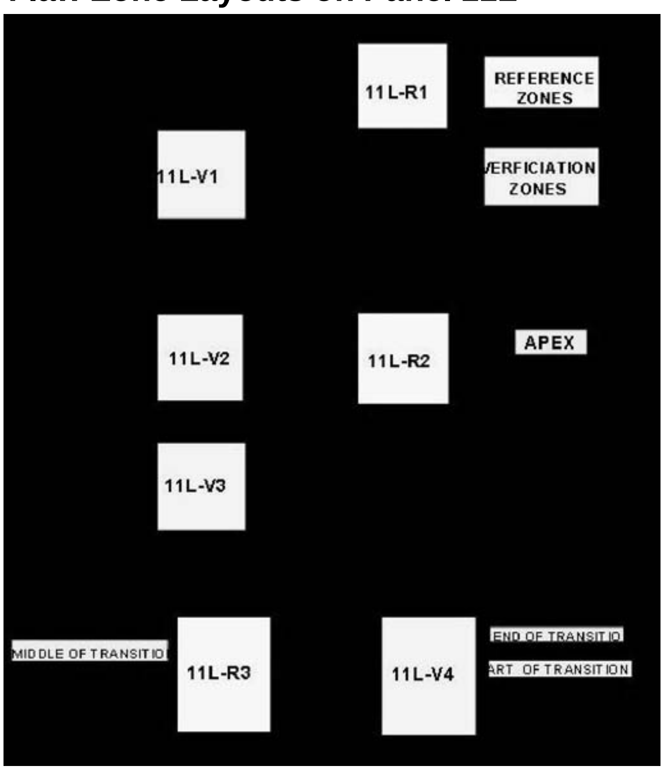

RCC Panel 11L – Seven Zones (4 val., 3 ref.)
RCC T Seal 12L – Three Zones (Z1 – Z3)







Flaw Zone Layouts on Panel 11L

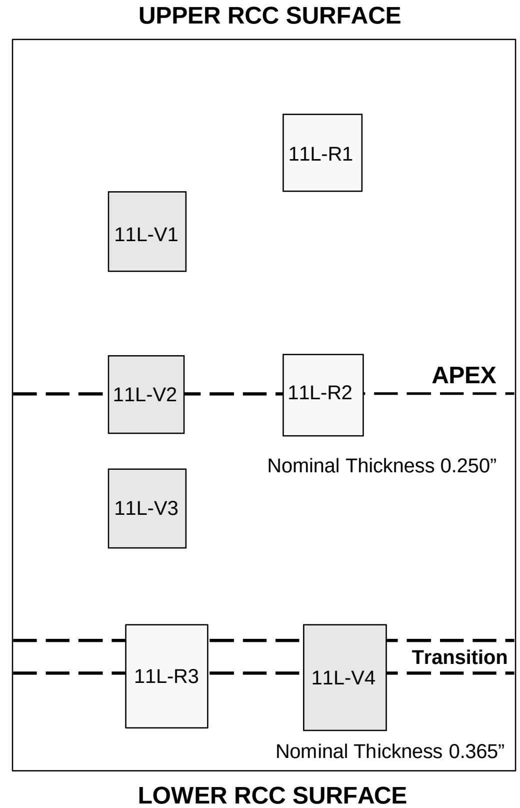


Each region was scanned in two sections:
(a) designation is for upper portion of region
(b) designation is for lower portion of region

Note that scan (a) and scan (b) are <u>NOT</u> related so the X-Y scales on the two plots <u>CANNOT</u> be used together for flaw placement from one window to the next; they have similar but slightly different scan windows

Reference and Validation Zones Inside Panel 11L

0.250" Thick Area			
FBH Ǿ	**Remaining Material Thickness**		
	0.040	**0.115**	**0.190**
1/8	X	X	X
1/4	X	X	X
3/8	X	X	X
1/2	X	X	X
0.365" Thick & Transition Area			
FBH Ǿ	**Remaining Material Thickness**		
	0.040	**0.182**	**0.325**
1/8	X	X	X
1/4	X	X	X
3/8	X	X	X
1/2	X	X	X



Flaw Regions Included in Test

1. 11L-R1 Reference Zone 1 (upper surface)
2. 11L-R2 Reference Zone 2 (apex surface)
3. 11L-R3 Reference Zone 3 (lower surface)
4. 11L-V1 Validation Zone 1 (upper surface)
5. 11L-V2 Validation Zone 2 (apex surface)
6. 11L-V3 Validation Zone 3 (lower surface)
7. 11L-V4 Validation Zone 4 (lower transition surface)
8. 12L-V1 Validation Zone 1 (upper surface)
9. 12L-V2 Validation Zone 2 (apex surface)
10. 12L-V3 Validation Zone 3 (lower surface)

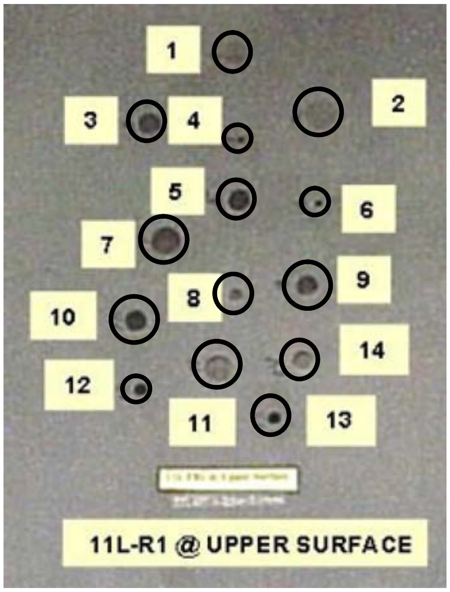
Items 1–7: **Orbiter Leading Edge RCC Panel 11L**

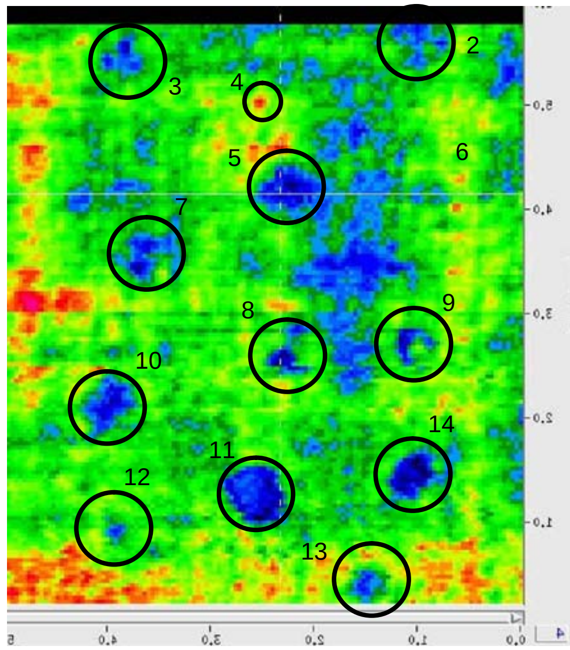
Items 8–10: **Orbiter Leading Edge RCC Tee Seal 12L**

Flaw Detection Grading Designations

D = detected
U = undetected
F = false call
M = mislocated
A = ambiguous

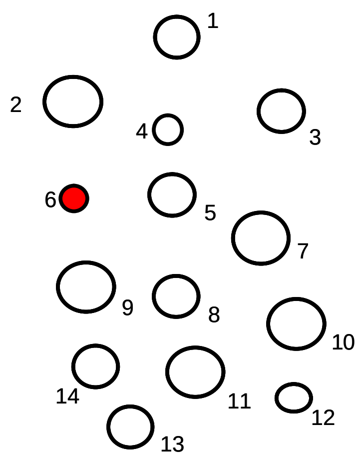
11L Reference Zone 1 (11L-R1)



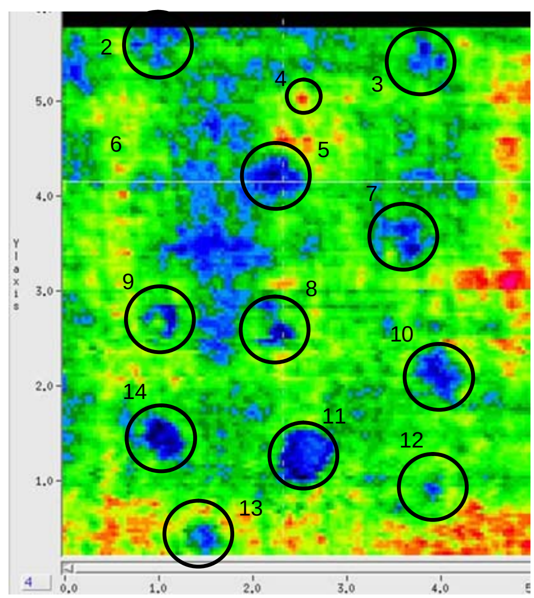


Gate 2 Amplitude (a)

11L Reference Zone 1 (11L-R1)

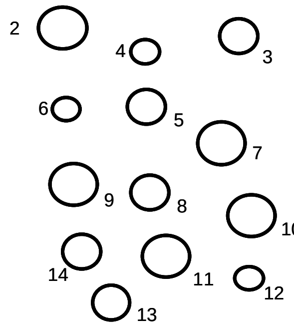


Flaw Profile
(mirrored to match UT scans)

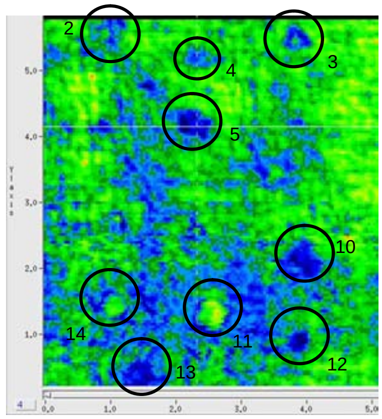


Gate 2 Amplitude (a)

= flaw not detected
#6, (1/8" dia.) was not detected in Zone 11L-R1

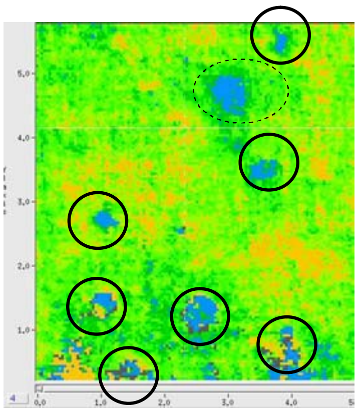


Flaw Profile

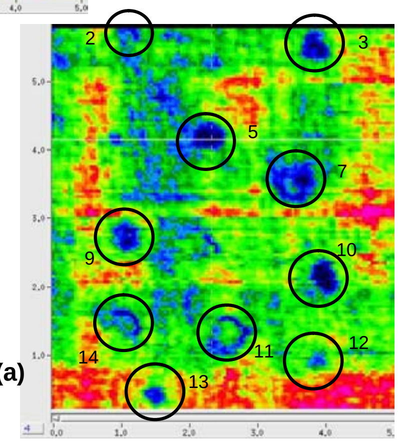


Gate 3 Amplitude (a)

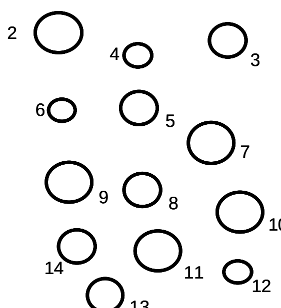
11L Reference Zone 1 (11L-R1)



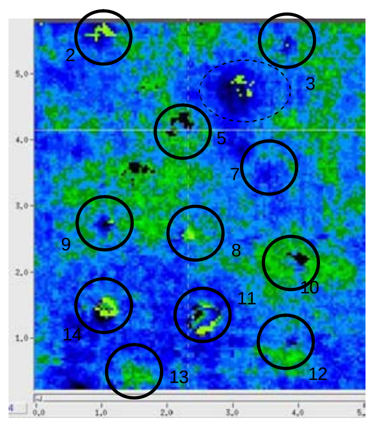
Gate 1 Time of Flight (a)



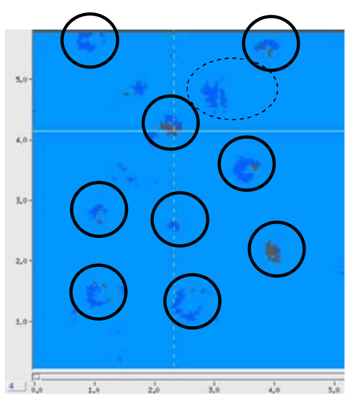
Gate 4 Amplitude (a)



Flaw Profile



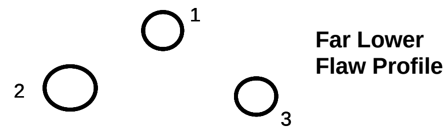
Gate 2 Time of Flight (a)

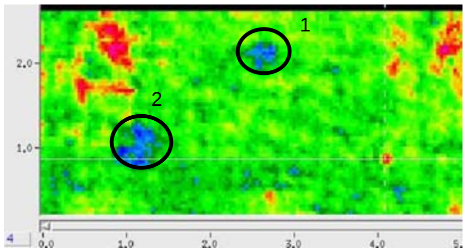


Gate 4 Time of Flight (a)

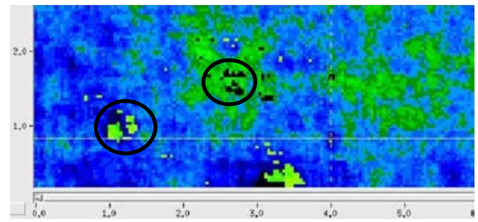
11L Reference Zone 1 (11L-R1)

11L Reference
Zone 1 (11L-R1)

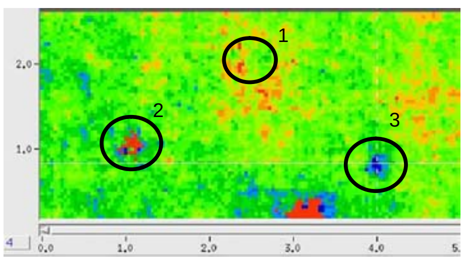




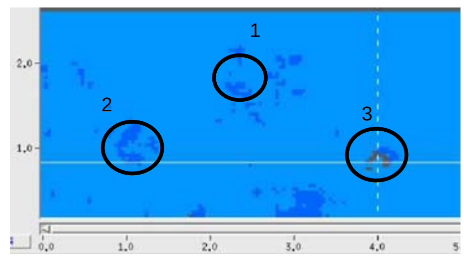
Gate 1 Amplitude (b) mod



Gate 2 Time of Flight (b)



Gate 1 Time of Flight (b)

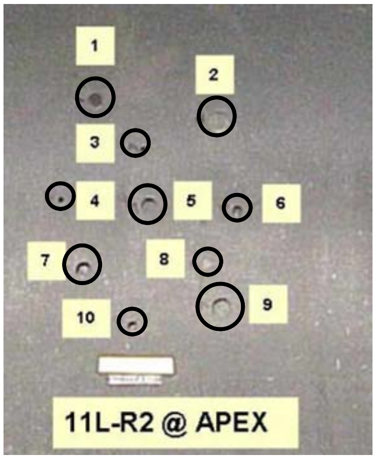


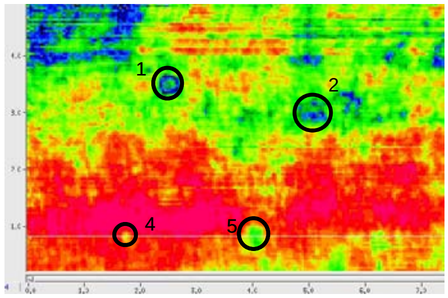
Gate 4 Time of Flight (b)

Flaw Detection Summary for Panel 11L Upper Surface Reference Zone 1

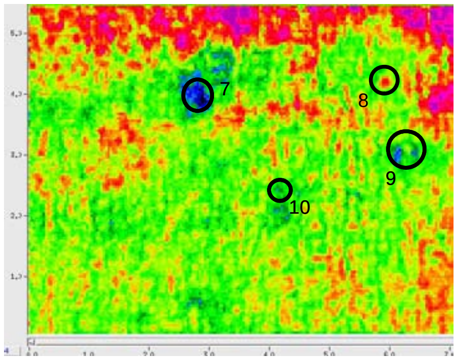
Zone 11L-R1								
	Drilled FBH	**Laser Measurements**				**FBH Detected by NDE**		
Reference Hole #	**FBH Ø @ Hole Depth**	**Ø**	**Remaining Material Thickness**	**Thickness Near Hole**	**Actual Hole Depth**	**ET**	**MWM**	**UT PE**
1	3/8 @ 0.040	0.381	0.222	0.251	0.029	N/A	N/A	D
2	1/2 @ 0.040	0.509	0.220	0.249	0.029	N/A	N/A	D
3	3/8 @ 0.115	0.383	0.138	0.247	0.109	D	D	D
4	1/8 @ 0.115	0.128	0.130	0.246	0.116	U	D	D
5	3/8 @ 0.190	0.381	0.057	0.246	0.189	D	D	D
6	1/8 @ 0.190	0.132	0.058	0.249	0.191	D	D	U
7	1/2 @ 0.115	0.512	0.140	0.249	0.109	D	D	D
8	1/4@ 0.040	0.241	0.215	0.250	0.035	N/A	N/A	D
9	3/8 @ 0.115	0.384	0.136	0.250	0.114	D	D	D
10	3/8 @ 0.190	0.384	0.061	0.251	0.190	D	D	D
11	1/2 @ 0.040	0.507	0.212	0.250	0.038	N/A	N/A	D
12	1/4 @ 0.115	0.235	0.130	0.250	0.120	D	D	D
13	1/4 @ 0.190	0.236	0.057	0.250	0.193	D	D	D
14	3/8 @ 0.040	0.380	0.213	0.251	0.038	N/A	N/A	D

11L Reference Zone 2 (11L-R2) - Apex



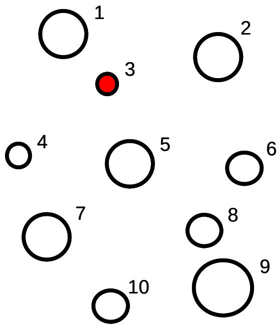


Gate 4 Amp dB (b)

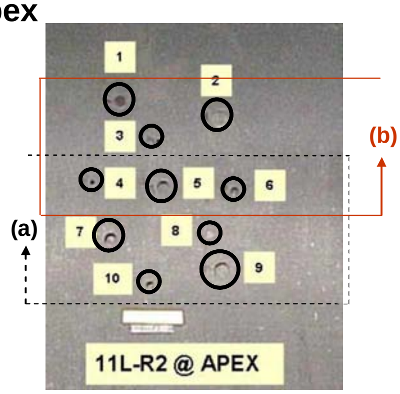


Gate 3 Amp dB (a)

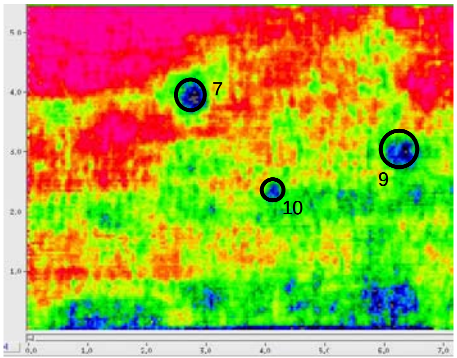
11L Reference Zone 2 (11L-R2) - Apex



Flaw Profile

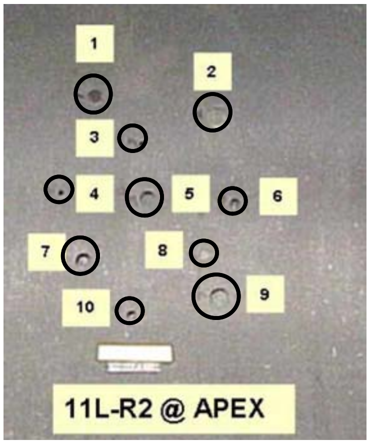


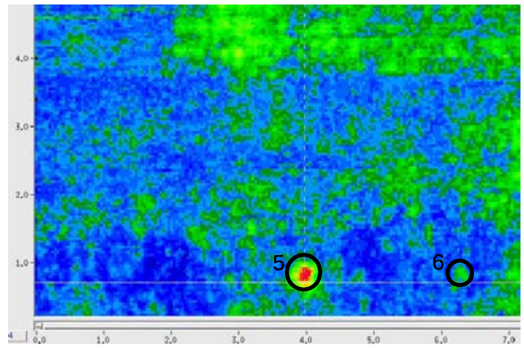
= flaw not detected
#3 (1/8") was not detected in Zone 11L-R2



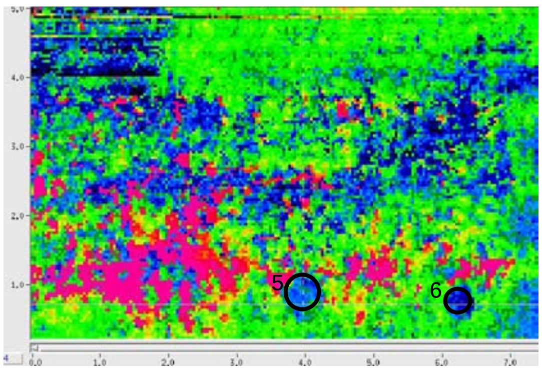
Gate 4 Amp dB (a)

11L Reference Zone 2 (11L-R2) - Apex





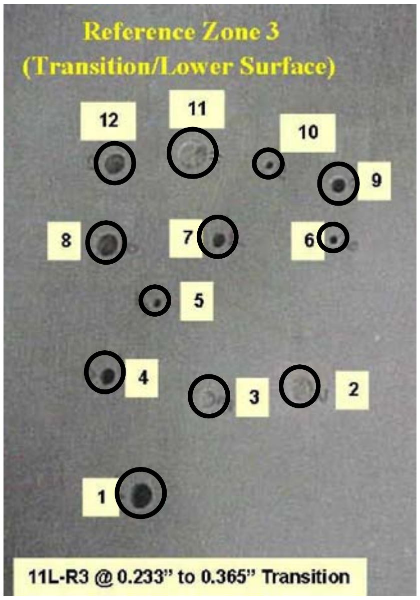
Gate 1 Amp dB (b)

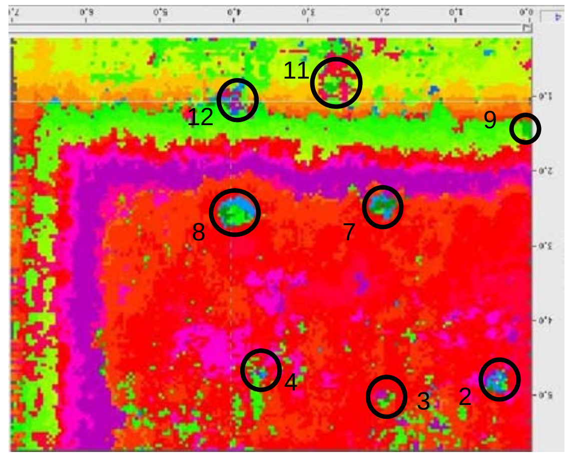


Flaw Detection Summary for Panel 11L Apex Surface Reference Zone 2

Zone 11L-R2								
Zones	Drilled FBH	Laser Measurements				FBH Detected by NDE		
Reference Hole #	FBH Ø @ Hole Depth	Ø	Remaining Material Thickness	Thickness Near Hole	Actual Hole Depth	ET	MWM	UT PE
1	3/8 @ 0.040	0.378	0.221	0.258	0.037	N/A	N/A	D
2	1/2 @ 0.040	0.501	0.225	0.254	0.029	N/A	N/A	A
3	1/8 @ 0.115	0.129	0.148	0.259	0.111	U	A	U
4	1/8 @ 0.190	0.131	0.093	0.252	0.159	D	D	D
5	3/8 @ 0.115	0.382	0.142	0.252	0.110	D	D	D
6	1/4 @ 0.115	0.244	0.137	0.248	0.111	D	D	D
7	3/8 @ 0.190	0.383	0.072	0.254	0.182	D	D	D
8	1/4 @ 0.040	0.242	0.224	0.255	0.031	N/A	N/A	A
9	1/2 @ 0.115	0.510	0.144	0.252	0.108	D	D	D
10	1/4 @ 0.190	0.246	0.070	0.251	0.181	D	D	D

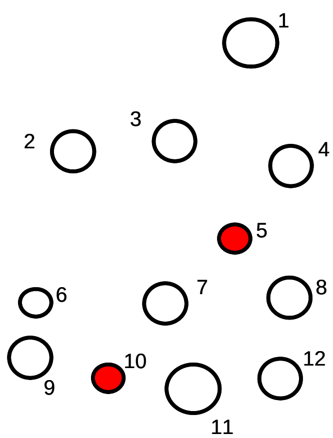
11L Reference Zone 3 (11L-R3)





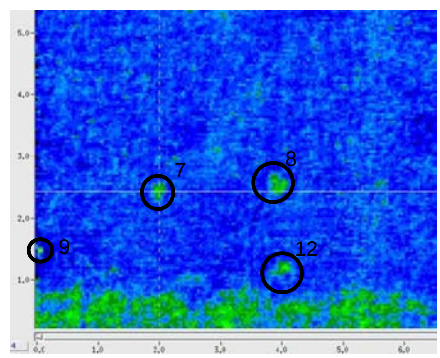
Gate 4 Time of Flight (a)

11L Reference Zone 3 (11L-R3)

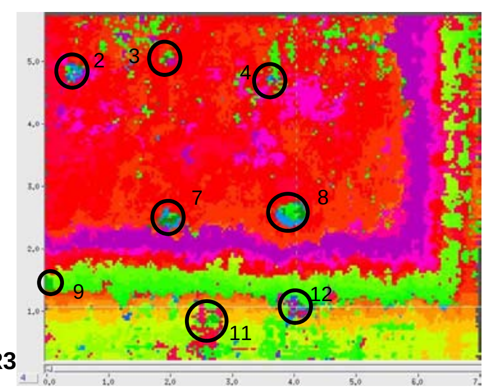


Flaw Profile
(rotated 180º to match UT scans)

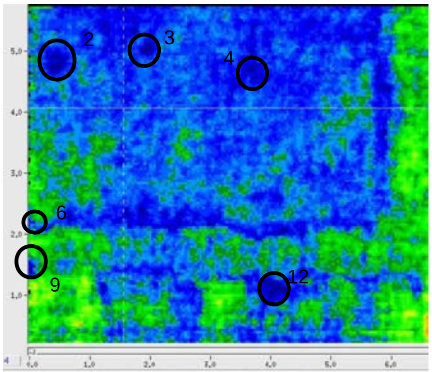
● = flaw not detected
#5 (1/8") and #10 (1/8") were not detected in Zone 11L-R3
#9 (1/4") is outside scan region so it is removed from comparison and listed as N/A



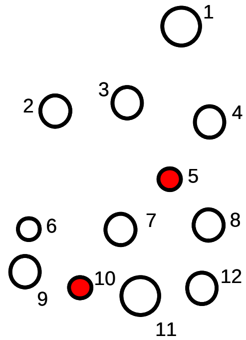
Gate 1 Amplitude (a)



Gate 4 Time of Flight (a)

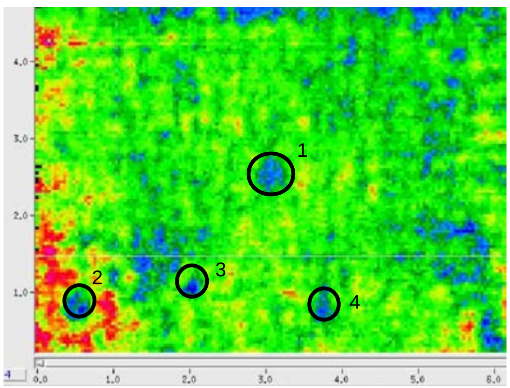


Gate 2 Amplitude (a)

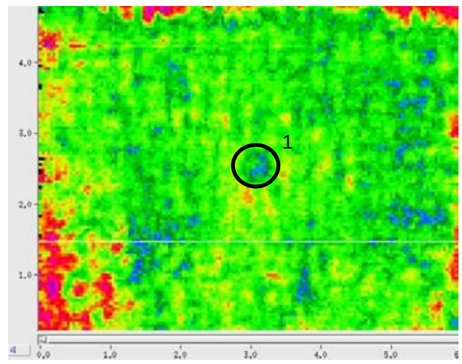


Flaw Profile

11L Reference Zone 3 (11L-R3)



Gate 2 Amplitude (b)



Gate 3 Amplitude (b)

Flaw Detection Summary for Panel 11L Lower Surface Reference Zone 3

Zone 11L-R3								
	Drilled FBH	Laser Measurements				FBH Detected by NDE		
Reference Hole #	FBH Ø @ Hole Depth	Ø	Remaining Material Thickness	Thickness Near Hole	Actual Hole Depth	ET	MWM	UT PE
1	3/8 @ 0.325	0.384	0.056	0.355	0.299	D	D	D
2	3/8 @ 0.040	0.380	0.324	0.359	0.035	N/A	N/A	D
3	1/4 @ 0.182	0.256	0.223	0.357	0.134	U	U	D
4	1/4 @ 0.325	0.257	0.060	0.354	0.294	D	D	D
5	1/8 @ 0.300	0.146	0.078	0.354	0.227	D	D	U
6	1/8 @ 0.185	0.129	0.165	0.345	0.181	U	U	D
7	1/4 @ 0.182	0.257	0.173	0.347	0.174	D	D	D
8	3/8 @ 0.185	0.381	0.173	0.348	0.179	D	D	D
9	1/4 @ 0.185	0.257	0.110	0.291	0.181	D	D	N/A
10	1/8 @ 0.185	0.129	0.085	0.267	0.182	D	D	U
11	1/2@ 0.040	0.503	0.220	0.260	0.040	N/A	N/A	D
12	3/8 @ 0.150	0.381	0.085	0.267	0.182	D	D	D

11L Validation Zone 1 (11L-V1)

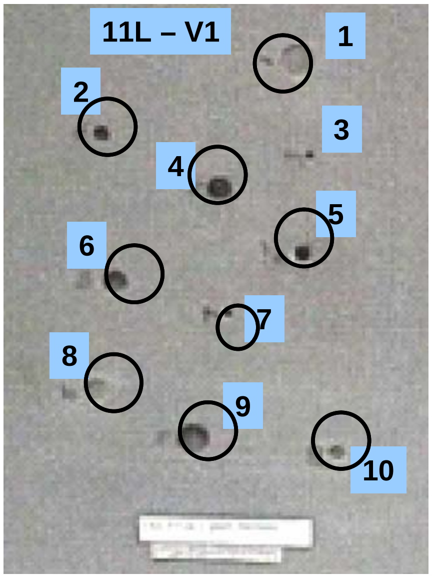
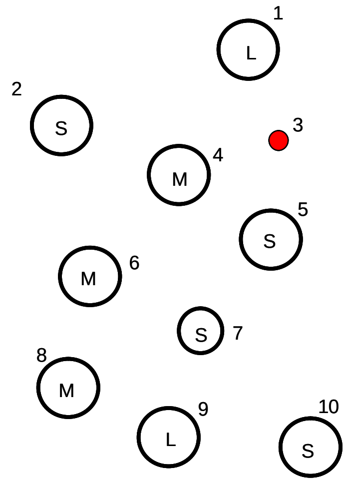


Photo of Flaw Layout with Sandia Flaw Calls Superimposed

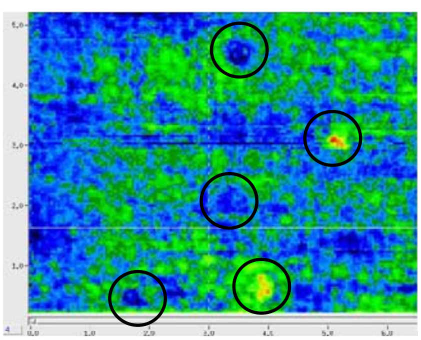
Sandia Labs Flaw Call Layout (see C-scan images that follow)



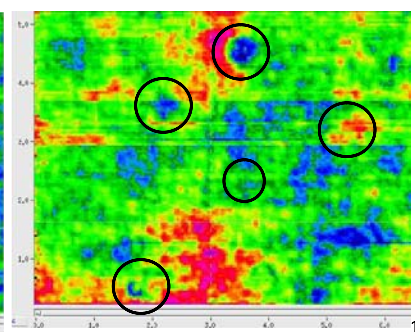
= flaw not detected
#3, (1/8" dia.) was not detected in Zone 11L-V1

L = large flaw
M = medium flaw
S = small flaw

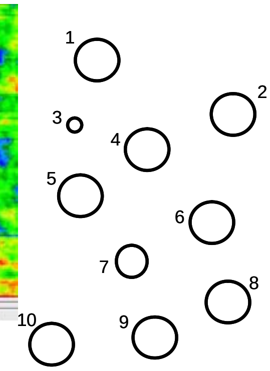
11L Validation Zone 1 (11L-V1)



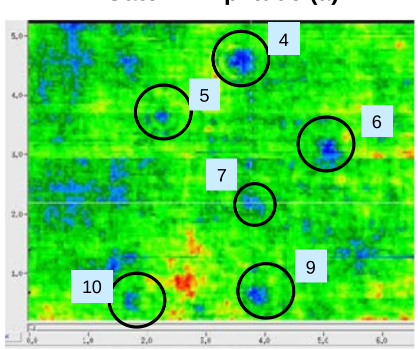
Gate 1 Amplitude (a)



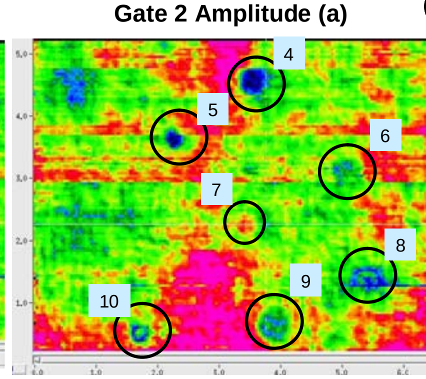
Gate 2 Amplitude (a)



Flaw Profile (mirrored to match UT scans)

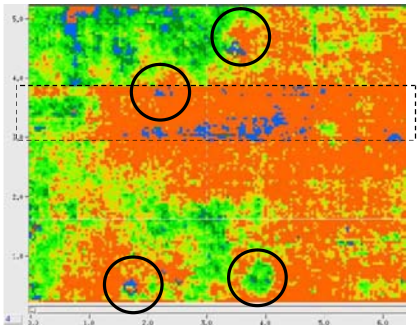


Gate 3 Amplitude (a)

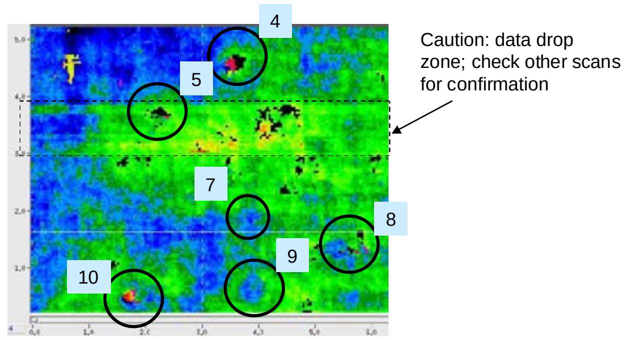


Gate 4 Amplitude (a)

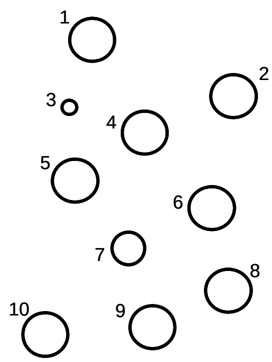
11L Validation Zone 1 (11L-V1)



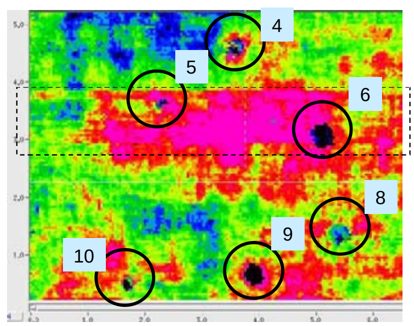
Gate 1 Time of Flight (a)



Gate 2 Time of Flight (a)

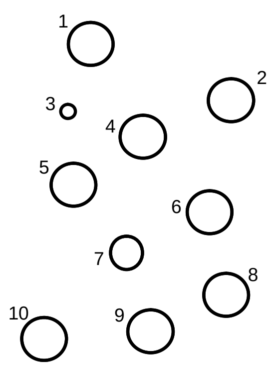


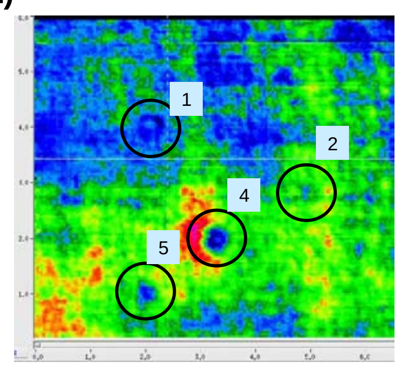
Flaw Profile
(mirrored to match UT scans)



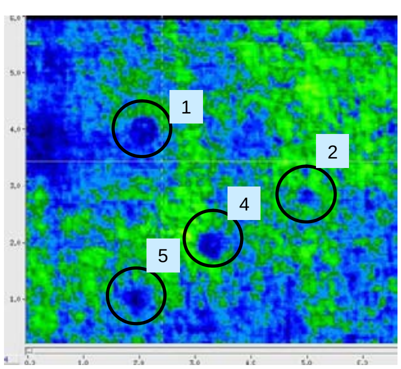
Gate 4 Time of Flight (a)

11L Validation Zone 1 (11L-V1)

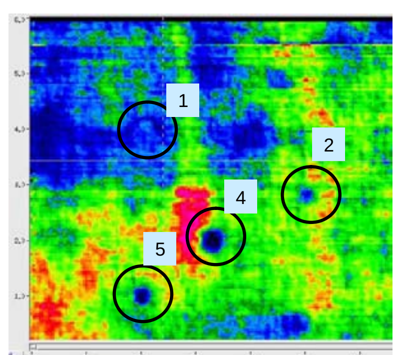




Gate 2 Amplitude (b)



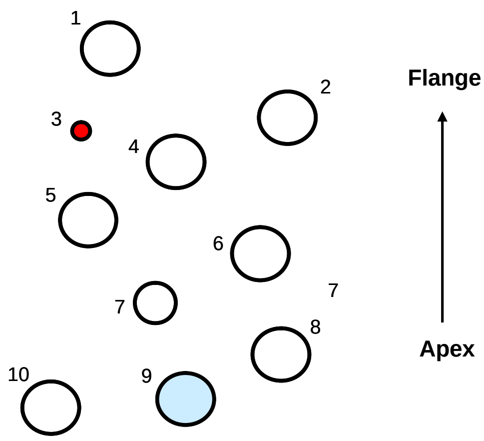
Gate 3 Amplitude (b)



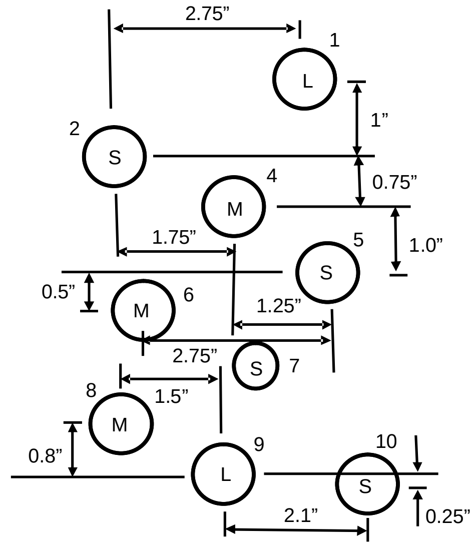
Gate 4 Amplitude (b)

11L Validation Zone 1 (11L-V1)

Flaw Pattern and Size Prediction



Orientation from Scan Surface



Orientation from Backside Surface (reversed pattern)

= flaw not detected
#3, (1/8” dia.) was not detected in Zone 11L-V1

Approximate dimensions labeled

L = large flaw
M = medium flaw
S = small flaw

Flaw Detection Summary for Panel 11L Upper Surface Validation Zone 1

Zone 11L-V1								
	Drilled FBH	**Laser Measurements**				**FBH Detected by NDE**		
Verification Hole #	**Ø @ Hole Depth**	**Ø**	**Remaining Material Thickness**	**Thickness Near Hole**	**Actual Hole Depth**	**ET**	**MWM**	**UT PE**
1	1/2 @ 0.040	0.496	0.218	0.246	0.028	N/A	N/A	D
2	1/4 @ 0.115	0.257	0.134	0.246	0.112	D	D	D
3	1/8 @ 0.115	0.128	0.123	0.241	0.118	U	D	U
4	3/8 @ 0.190	0.381	0.059	0.242	0.183	D	D	D
5	1/4 @ 0.190	0.257	0.058	0.251	0.193	D	D	D
6	3/8 @ 0.115	0.381	0.141	0.250	0.109	D	D	D
7	1/8 @ 0.115	0.128	0.138	0.252	0.114	A	D	D
8	3/8 @ 0.040	0.381	0.218	0.252	0.034	N/A	N/A	D
9	1/2 @ 0.115	0.512	0.137	0.247	0.110	D	D	D
10	1/4 @ 0.040	0.256	0.213	0.249	0.036	N/A	N/A	D

11L Validation Zone 2 (11L-V2) - Apex

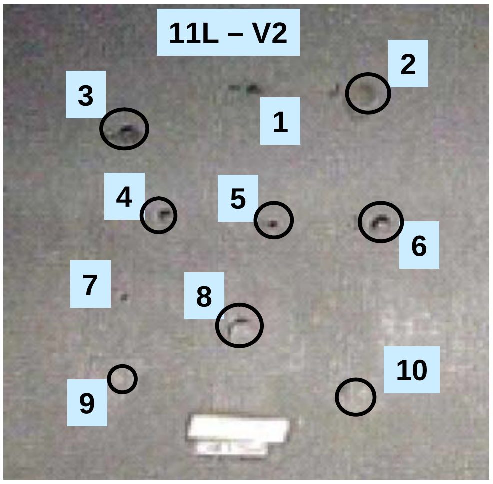
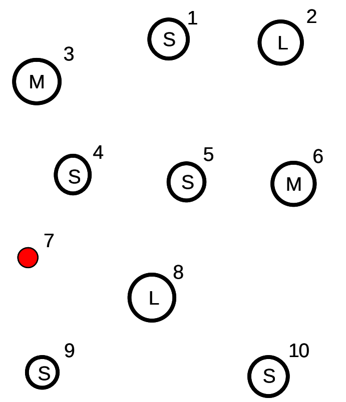


Photo of Flaw Layout with Sandia Flaw Calls Superimposed

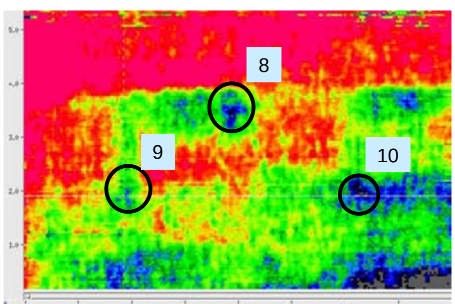
Sandia Labs Flaw Call Layout
(see C-scan images that follow)



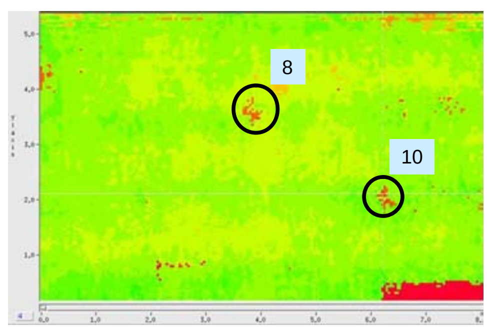
= flaw not detected
#7 (1/8") was not detected in Zone 11L-V2

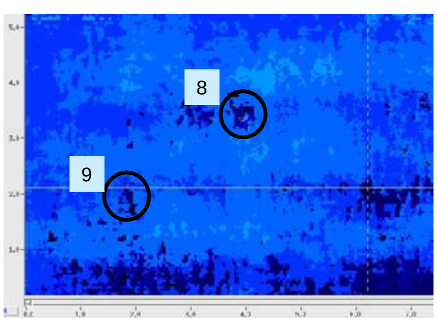
L = large flaw
M = medium flaw
S = small flaw

11L Validation Zone 2 (11L-V2) - Apex

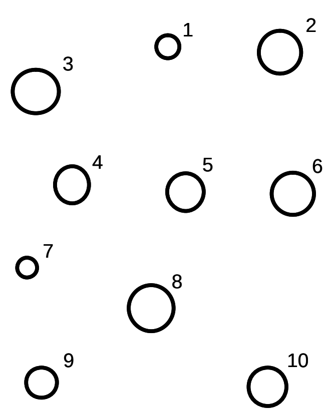


Gate 4 Amp dB (a)



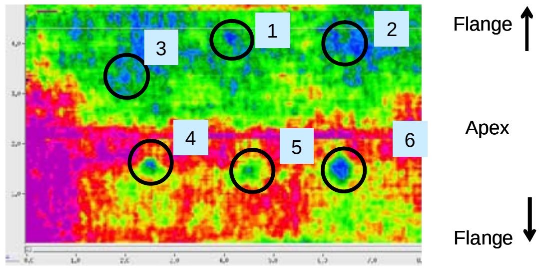


Gate 3 Time of Flight (a)

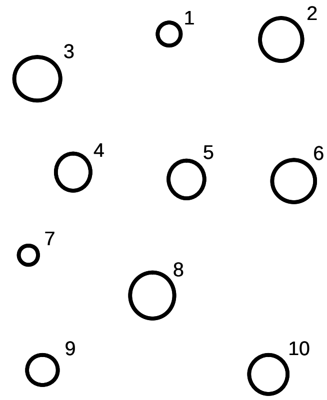


Flaw Profile

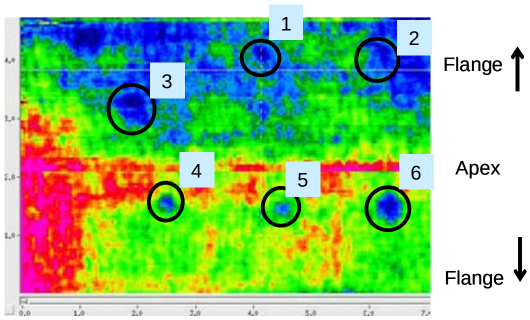
11L Validation Zone 2 (11L-V2) - Apex



Gate 3 Amp (b)

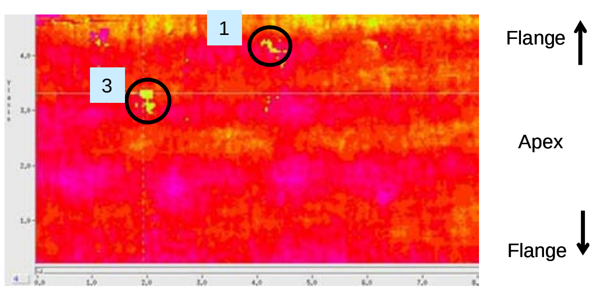


Flaw Profile

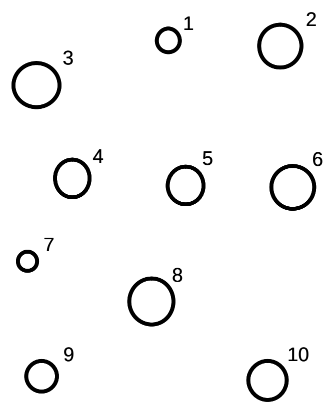


Gate 4 Amp (b)

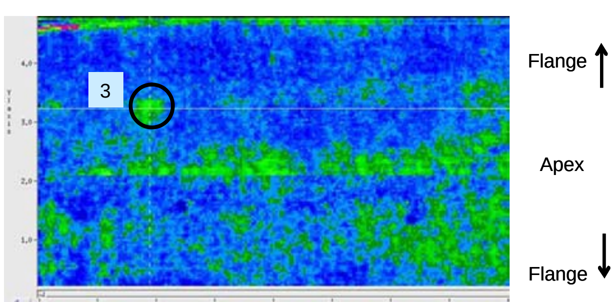
11L Validation Zone 2 (11L-V2) - Apex



Gate 2 Time of Flight (b)



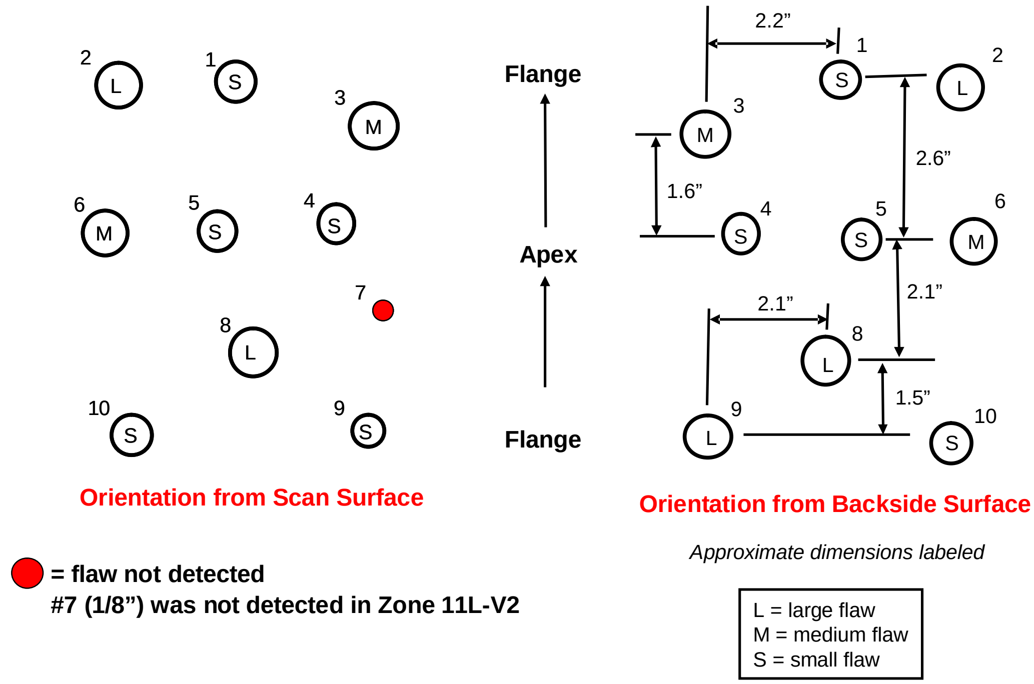
Flaw Profile



Gate 4 Time of Flight (b)

11L Validation Zone 2 (11L-V2)

Flaw Pattern and Size Prediction



Flaw Detection Summary for Panel 11L Apex Surface Validation Zone 2

Zone 11L-V2								
	Drilled FBH	Laser Measurements				FBH Detected by NDE		
Verification Hole #	Ø @ Hole Depth	Ø	Remaining Material Thickness	Thickness Near Hole	Actual Hole Depth	ET	MWM	UT PE
1	1/4 @ 115	0.245	0.156	0.259	0.103	D	D	D
2	1/2 @ 0.040	0.496	0.230	0.256	0.026	N/A	N/A	D
3	3/8 @ 0.115	0.381	0.140	0.254	0.114	D	D	D
4	1/4 @ 0.190	0.243	0.067	0.253	0.186	D	D	D
5	1/8 @ 0.115	0.128	0.126	0.253	0.127	D	D	D
6	3/8 @ 0.190	0.382	0.073	0.253	0.180	D	D	D
7	1/8 @ 0.115	0.129	0.140	0.253	0.113	A	A	U
8	1/2 @ 0.115	0.511	0.138	0.253	0.115	D	D	D
9	3/8 @ 0.040	0.376	0.221	0.248	0.027	N/A	N/A	D
10	1/4 @ 0.040	0.244	0.213	0.250	0.037	N/A	N/A	D

11L Validation Zone 3 (11L-V3)

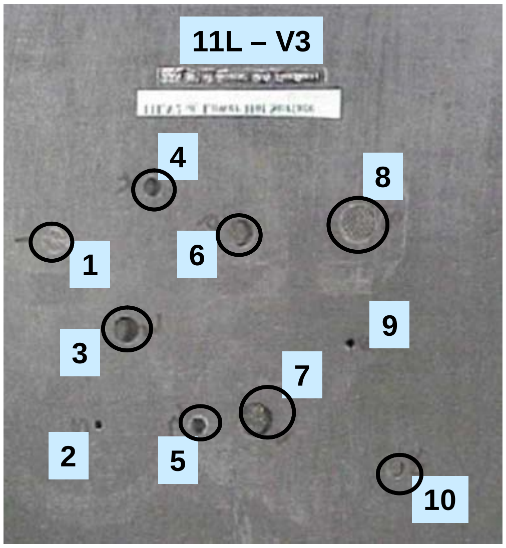
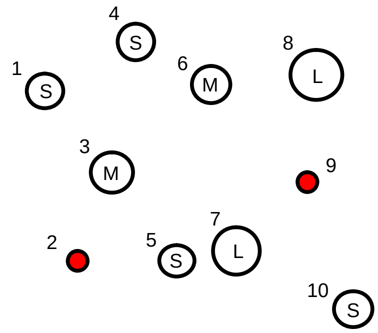


Photo of Flaw Layout with
Sandia Flaw Calls Superimposed

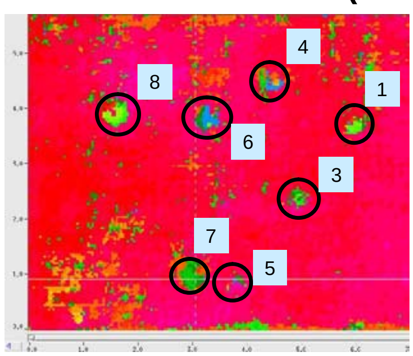
Sandia Labs Flaw Call Layout
(see C-scan images that follow)



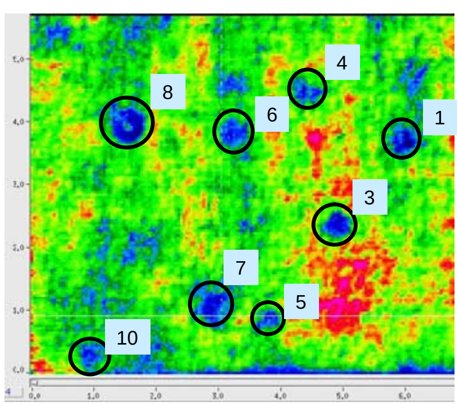
= flaw not detected
#2, (1/8" dia.) and #9 (1/8") were not detected in Zone 11L-V3

L = large flaw
M = medium flaw
S = small flaw

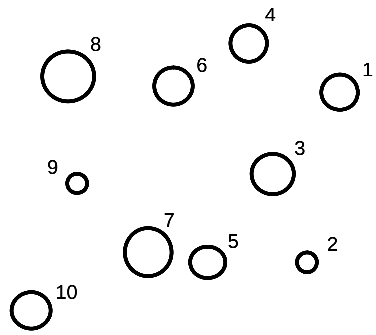
11L Validation Zone 3 (11L-V3)



Gate 2 Time of Flight (a)

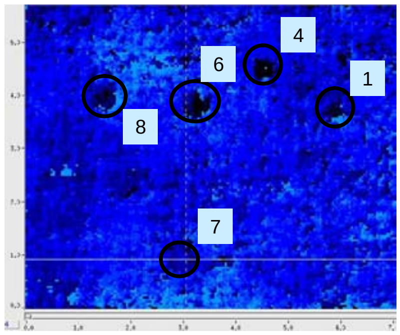


Gate 4 Amplitude (a)

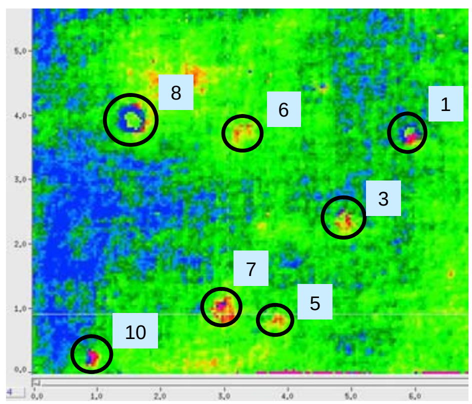


Flaw Profile
(mirrored to match
UT scans)

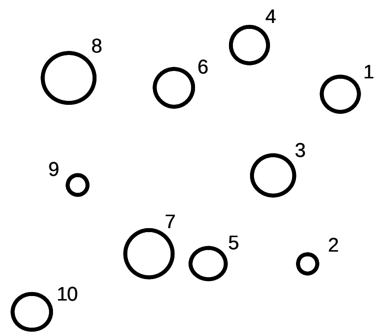
11L Validation Zone 3 (11L-V3)



Gate 1 Time of Flight (a)

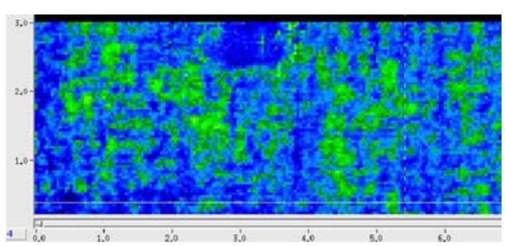


Gate 4 Time of Flight (a)

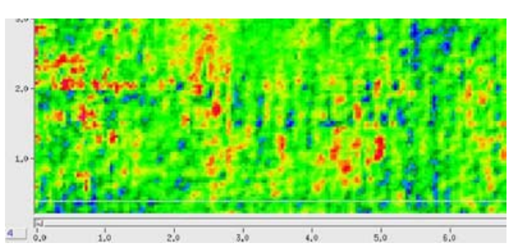


Flaw Profile (mirrored to match UT scans)

11L Validation Zone 3 (11L-V3)

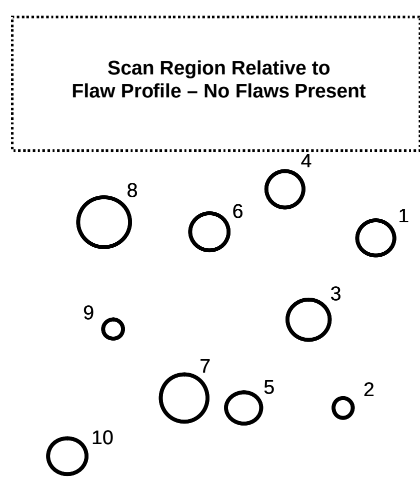


Gate 1 Amplitude (b)



Gate 3 Amplitude (b)

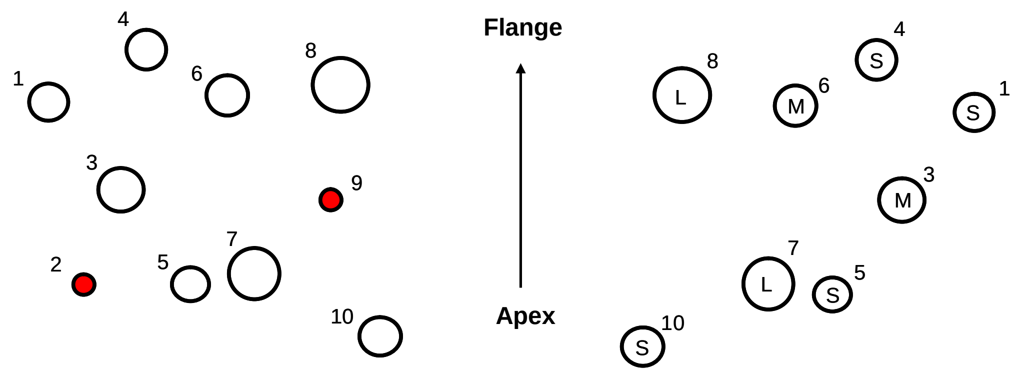
No Flaws Found in Upper Region (part b) of 11L V3 Zone



Flaw Profile (mirrored to match UT scans)

11L Validation Zone 3 (11L-V3)

Flaw Pattern and Size Prediction



Orientation from Backside Surface

Orientation from Scan Surface (reversed pattern)

= flaw not detected
#2, (1/8" dia.) and #9 (1/8") were not detected in Zone 11L-V3

Approximate dimensions labeled

L = large flaw
M = medium flaw
S = small flaw

Flaw Detection Summary for Panel 11L Lower Surface Validation Zone 3

Zone 11L-V3									
	Drilled FBH	**Laser Measurements**				**FBH Detected by NDE**		
Verification Hole #	**Ø @ Hole Depth**	**Ø**	**Remaining Material Thickness**	**Thickness Near Hole**	**Actual Hole Depth**	**ET**	**MWM**	**UT PE**
1	3/8 @ 0.040	0.383	0.207	0.241	0.034	N/A	N/A	D
2	1/8 @ 0.190	0.127	0.077	0.242	0.165	D	D	U
3	3/8 @ 0.190	0.384	0.056	0.240	0.184	D	D	D
4	1/4 @ 0.115	0.257	0.136	0.241	0.105	D	D	D
5	1/4 @ 0.190	0.243	0.059	0.241	0.182	D	D	D
6	3/8 @ 0.115	0.383	0.137	0.244	0.107	D	D	D
7	1/2 @ 0.115	0.497	0.145	0.242	0.097	D	D	D
8	1/2 @ 0.040	0.502	0.211	0.247	0.036	N/A	N/A	D
9	1/8 @ 0.115	0.125	0.133	0.240	0.107	A	D	U
10	1/4 @ 0.040	0.258	0.211	0.247	0.036	N/A	N/A	D

11L Validation Zone 4 (11L-V4)

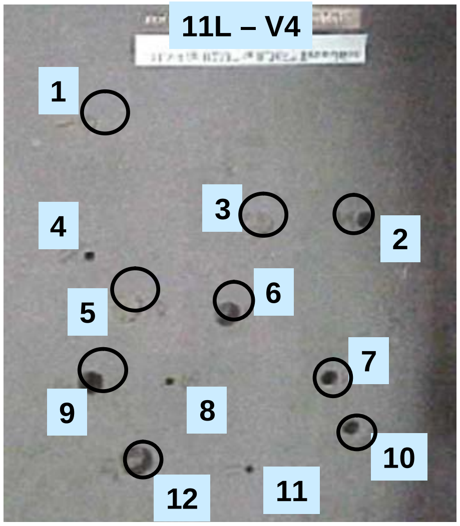
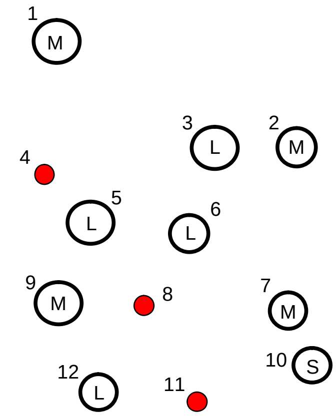


Photo of Flaw Layout with Sandia Flaw Calls Superimposed

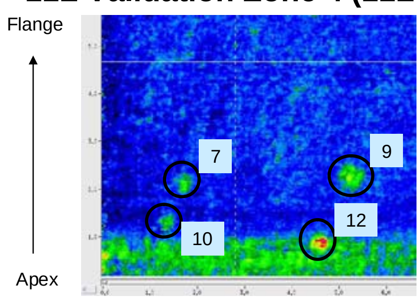
Sandia Labs Flaw Call Layout (see C-scan images that follow)



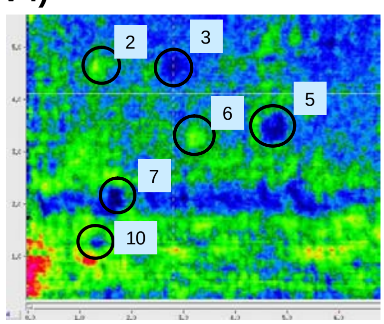
= flaw not detected
#4, (1/8" dia.), #8 (1/8"), and #11 (1/8") were not detected in Zone 11L-V4

L = large flaw
M = medium flaw
S = small flaw

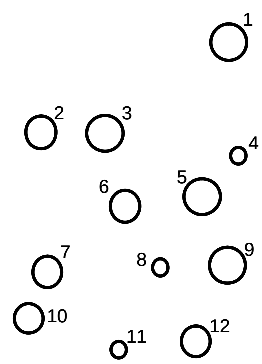
11L Validation Zone 4 (11L-V4)



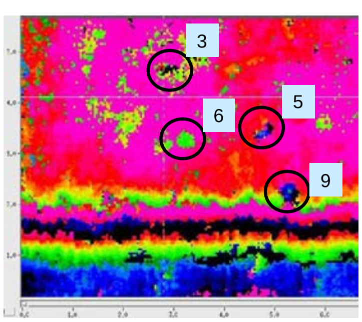
Gate 1 Amplitude (a)



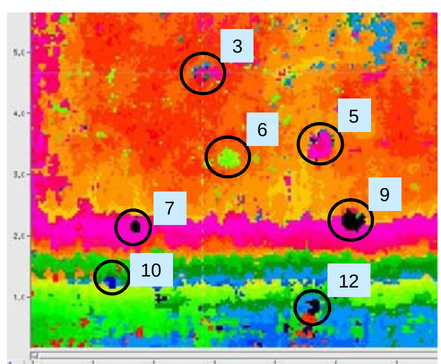
Gate 2 Amplitude (a)



Flaw Profile (mirrored to match UT scans)



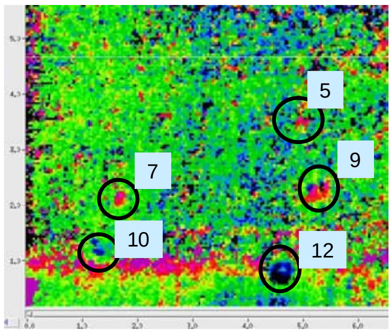
Gate 2 Time of Flight (a)



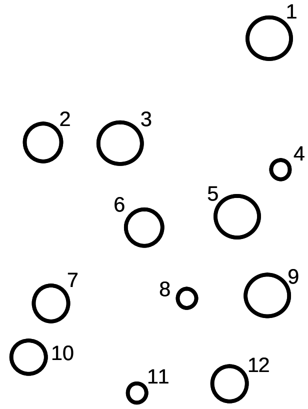
Effects of Thickness Taper Region

Gate 4 Time of Flight (a)

11L Validation Zone 4 (11L-V4)



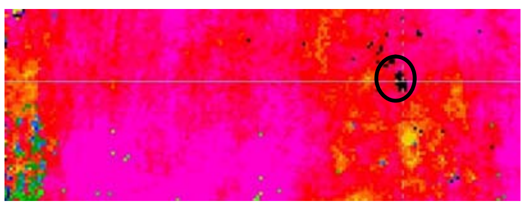
Gate 1 Time of Flight (a)



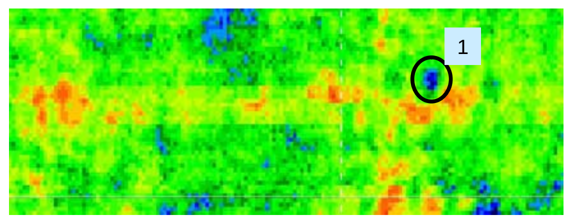
Flaw Profile (mirrored to match UT scans)

Flange

Apex



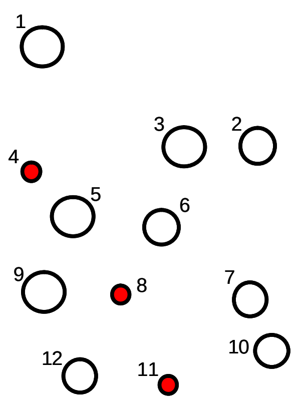
Gate 2 Time of Flight (b)

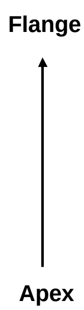


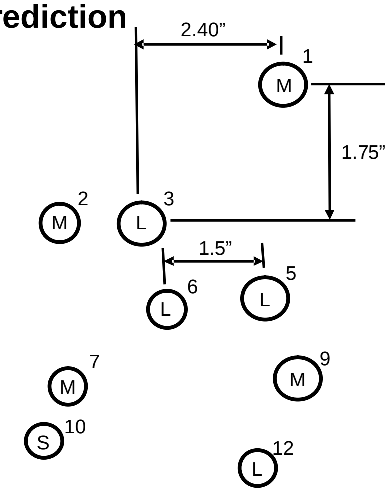
Gate 2 Amp dB (b)

11L Validation Zone 1 (11L-V4)

Flaw Pattern and Size Prediction







Orientation from Backside Surface

Orientation from Scan Surface (reversed pattern)

= flaw not detected
#4, (1/8" dia.), #8 (1/8"), and #11 (1/8") were not detected in Zone 11L-V4

Approximate dimensions labeled

L = large flaw
M = medium flaw
S = small flaw

Flaw Detection Summary for Panel 11L Lower Surface Validation Zone 4

Zone 11L-V4								
	Drilled FBH	Laser Measurements				FBH Detected by NDE		
Verification Hole #	Ø & Hole Depth	Ø	Remaining Material Thickness	Thickness Near Hole	Actual Hole Depth	ET	MWM	UT PE
1	1/4 @ 0.040	0.255	0.327	0.355	0.028	N/A	N/A	D
2	1/4 @ 0.115	0.257	0.241	0.359	0.118	U	U	D
3	3/8 @ 0.182	0.381	0.224	0.358	0.134	U	U	D
4	1/8 @ 0.300	0.120	0.066	0.359	0.293	D	D	U
5	3/8 @ 0.300	0.382	0.244	0.357	0.113	U	U	D
6	1/2 @ 0.040	0.509	0.328	0.358	0.030	N/A	N/A	D
7	1/4 @ 0.185	0.257	0.155	0.341	0.186	A	D	D
8	1/8 @ 0.185	0.131	0.160	0.342	0.182	U	U	U
9	3/8 @ 0.190	0.384	0.155	0.340	0.185	D	D	D
10	1/4 @ 0.150	0.257	0.141	0.285	0.144	D	D	D
11	1/8 @ 0.190	0.125	0.051	0.248	0.197	D	D	U
12	1/2 @ 0.125	0.514	0.140	0.257	0.117	D	D	D

Flaw Detection Summary for 1/8” Flaws in RCC Panel 11L

Detection of 1/8" Diameter Flaws in RCC 11L Specimen					
Specimen	Flaw Identification and Flaw Depth from Front Surface (inches)			Detection by Pulse-Echo UT	
	0.190	0.120	0.060	Yes	No
11L-Reference Zone 1 (upper)		4		X	
11L-Reference Zone 1 (upper)			6		X
11L-Reference Zone 2 (apex)	3				X
11L-Reference Zone 2 (apex)			4	X	
11L-Reference Zone 3 (lower)			5		X
11L-Reference Zone 3 (lower)	6			X	
11L-Reference Zone 3 (lower)		10			X
11L-Validation Zone 1 (upper)		3			X
11L-Validation Zone 1 (upper)		7		X	
11L-Validation Zone 2 (apex)		5		X	
11L-Validation Zone 2 (apex)		7			X
11L-Validation Zone 3 (lower)			2		X
11L-Validation Zone 3 (lower)		9			X
11L-Validation Zone 4 (lower)			4		X
11L-Validation Zone 4 (lower)	8				X
11L-Validation Zone 4 (lower)			11		X

1/8” dia. flaw detection = 31%

Flaw Detection Summary for 1/4" Flaws in RCC Panel 11L

Detection of 1/4" Diameter Flaws in RCC 11L Specimen					
Specimen	Flaw Identification and Flaw Depth from Front Surface (inches)			Detection by Pulse-Echo UT	
	0.190	0.120	0.060	Yes	No
11L-Reference Zone 1 (upper)			8	X	
11L-Reference Zone 1 (upper)		12		X	
11L-Reference Zone 1 (upper)	13			X	
11L-Reference Zone 2 (apex)		6		X	
11L-Reference Zone 2 (apex)	8			X	
11L-Reference Zone 2 (apex)			10	X	
11L-Reference Zone 3 (lower)	3			X	
11L-Reference Zone 3 (lower)			4	X	
11L-Reference Zone 3 (lower)	7			X	
11L-Reference Zone 3 (lower)	9			N/A *	
11L-Validation Zone 1 (upper)		2		X	
11L-Validation Zone 1 (upper)			5	X	
11L-Validation Zone 1 (upper)	7			X	
11L-Validation Zone 2 (apex)	1			X	
11L-Validation Zone 2 (apex)			4	X	
11L-Validation Zone 2 (apex)	10			X	
11L-Validation Zone 3 (lower)		4		X	
11L-Validation Zone 3 (lower)			5	X	
11L-Validation Zone 3 (lower)	10			X	
11L-Validation Zone 4 (lower)	1			X [Δ]	
11L-Validation Zone 4 (lower)	2			X	
11L-Validation Zone 4 (lower)		7		X	
11L-Validation Zone 4 (lower)		10		X	

1/4" dia. flaw detection = 100%

** Flaw #9 out of scan region*

Δ Flaw #1 is in scan by itself so no location info available

Flaw Detection Summary for 3/8" Flaws in RCC Panel 11L

Detection of 3/8" Diameter Flaws in RCC 11L Specimen					
Specimen	Flaw Identification and Flaw Depth from			Detection by	
	0.190	0.120	0.060	Yes	No
11L-Reference Zone 1 (upper)	1			X	
11L-Reference Zone 1 (upper)		3		X	
11L-Reference Zone 1 (upper)			5	X	
11L-Reference Zone 1 (upper)		9		X	
11L-Reference Zone 1 (upper)			10	X	
11L-Reference Zone 1 (upper)	14			X	
11L-Reference Zone 2 (apex)	1			X	
11L-Reference Zone 2 (apex)		5		X	
11L-Reference Zone 2 (apex)			7	X	
11L-Reference Zone 3 (lower)			1	X	
11L-Reference Zone 3 (lower)	2			X	
11L-Reference Zone 3 (lower)	8			X	
11L-Reference Zone 3 (lower)		12		X	
11L-Validation Zone 1 (upper)			4	X	
11L-Validation Zone 1 (upper)		6		X	
11L-Validation Zone 1 (upper)	8			X	
11L-Validation Zone 2 (apex)		3		X	
11L-Validation Zone 2 (apex)			6	X	
11L-Validation Zone 2 (apex)	9			X	
11L-Validation Zone 3 (lower)	1			X	
11L-Validation Zone 3 (lower)			3	X	
11L-Validation Zone 3 (lower)		6		X	
11L-Validation Zone 4 (lower)	3			X	
11L-Validation Zone 4 (lower)	5			X	
11L-Validation Zone 4 (lower)		9		X	

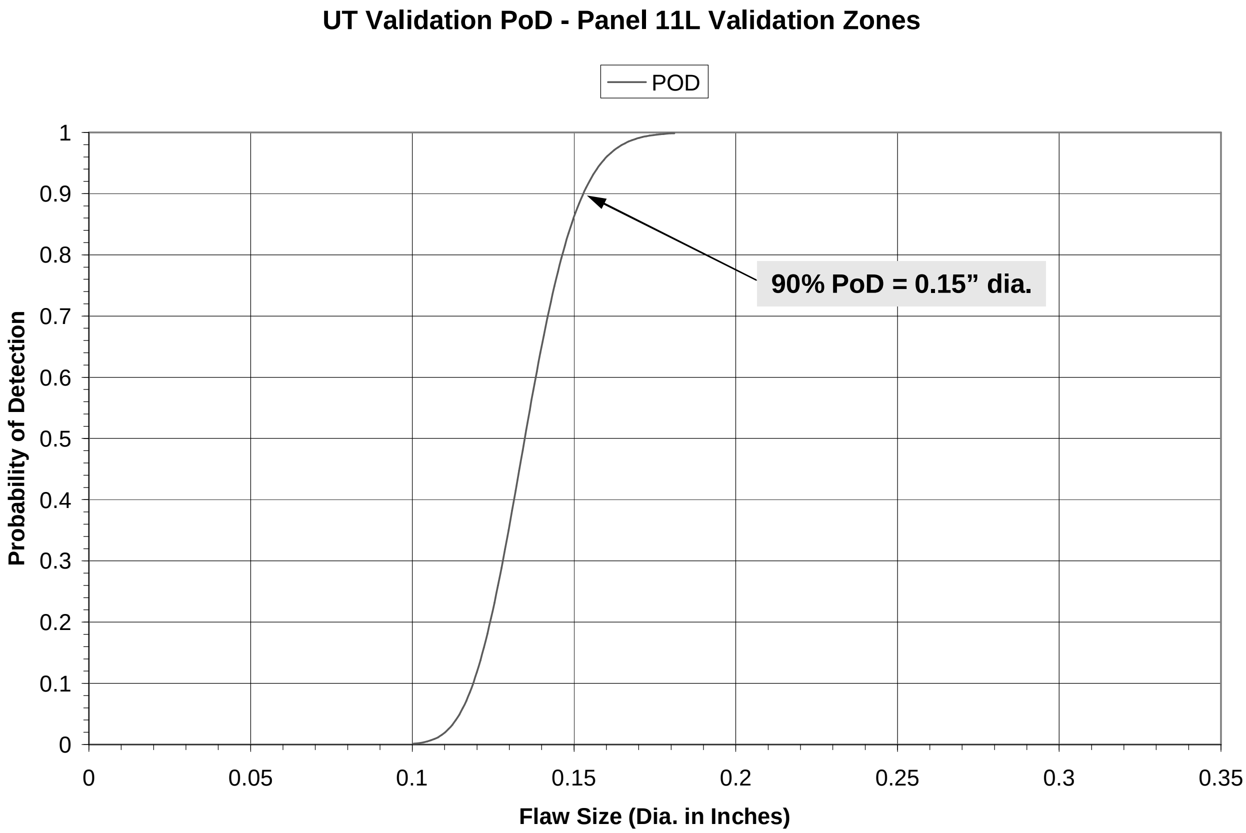
3/8" dia. flaw detection = 100%

Flaw Detection Summary for 1/2” Flaws in RCC Panel 11L

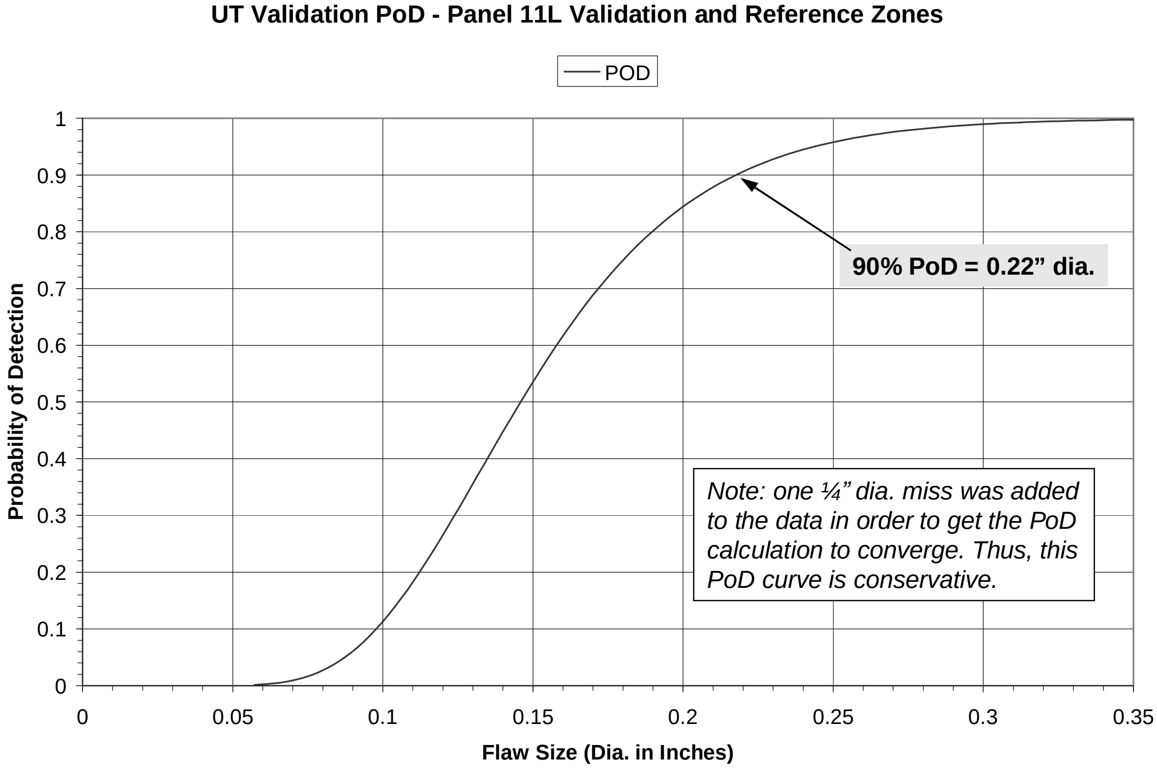
Detection of 1/2" Diameter Flaws in RCC 11L Specimen					
Specimen	Flaw Identification and Flaw Depth from			Detection by	
	0.190	0.120	0.060	Yes	No
11L-Reference Zone 1 (upper)	2			X	
11L-Reference Zone 1 (upper)		7		X	
11L-Reference Zone 1 (upper)	11			X	
11L-Reference Zone 2 (apex)	2			X	
11L-Reference Zone 2 (apex)		9		X	
11L-Reference Zone 3 (lower)	1			X	
11L-Validation Zone 1 (upper)	1			X	
11L-Validation Zone 1 (upper)		10		X	
11L-Validation Zone 2 (apex)	2			X	
11L-Validation Zone 2 (apex)		8		X	
11L-Validation Zone 3 (lower)		7		X	
11L-Validation Zone 3 (lower)	8			X	
11L-Validation Zone 4 (lower)	6			X	
11L-Validation Zone 4 (lower)		12		X	

1/2” dia. flaw detection = 100%

Probability of Detection Curve for Pulse-Echo UT Flaw Detection in Panel 11L – Flaws in Validation Zones Only

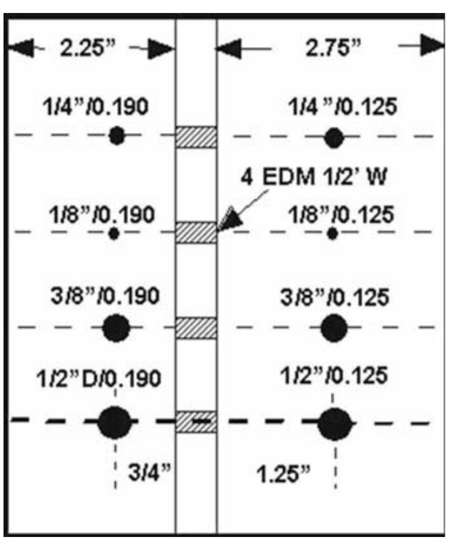


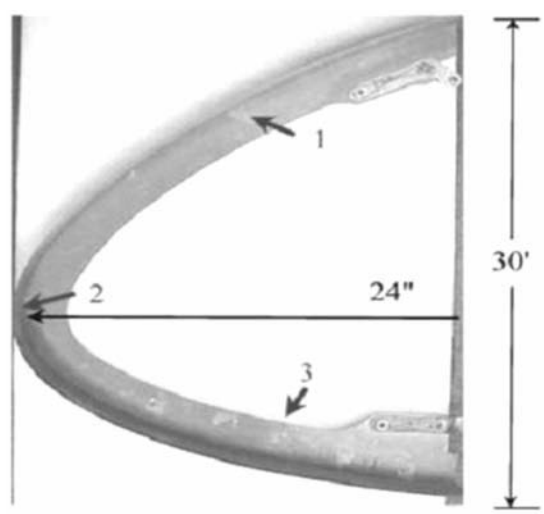
Probability of Detection Curve for Pulse-Echo UT Flaw Detection in Panel 11L – Flaws in Reference and Validation Zones

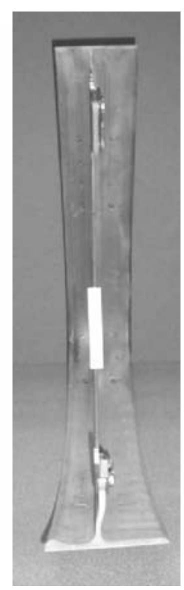


12L Tee Seal

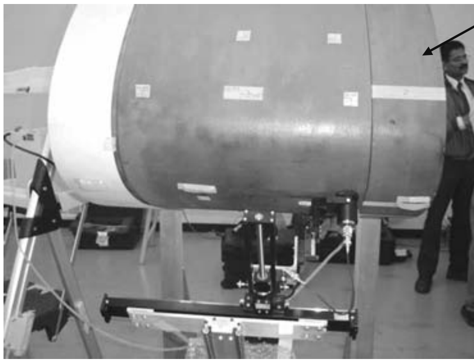
Three Similar Flaw Zones (1, 2, 3) – 2 rows of flaws on each side of middle flange in each zone



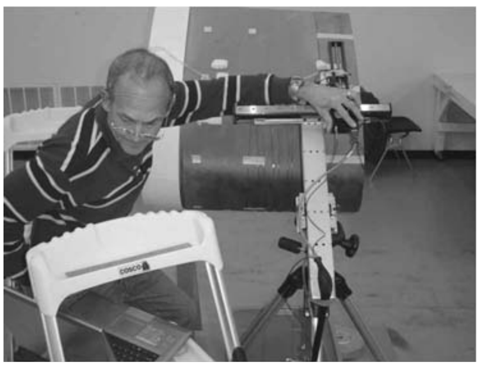


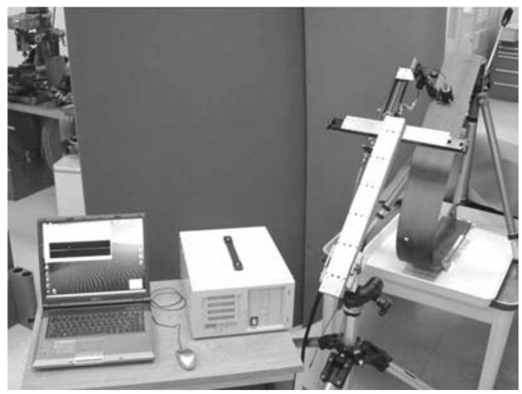


12L Tee Seal Inspection



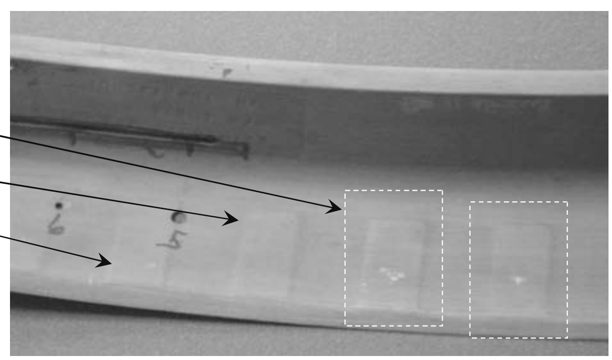
Tee Seal

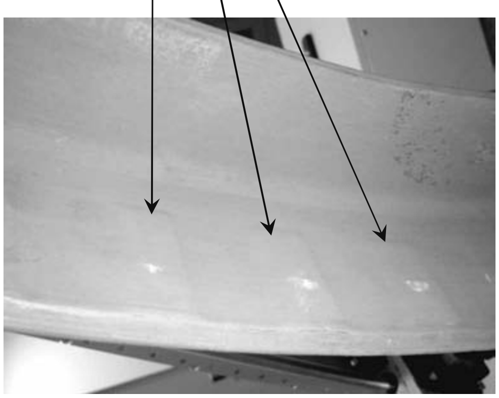




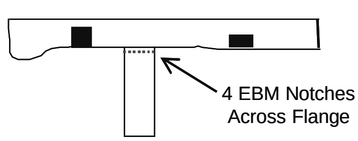
12L Tee Seal

Raised regions (heat vent tabs) on one side of T-seal flange that impede UT inspection



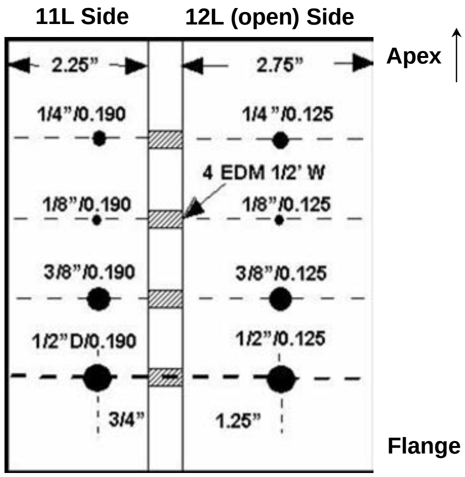


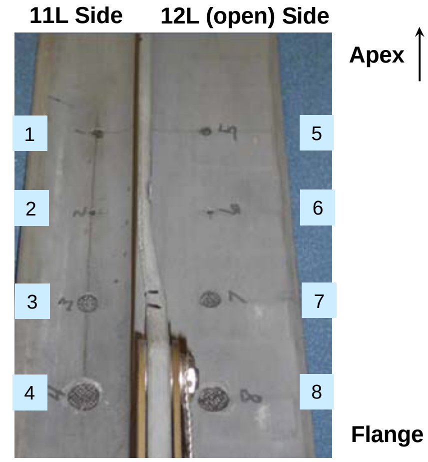
Tee Seal Cross Section



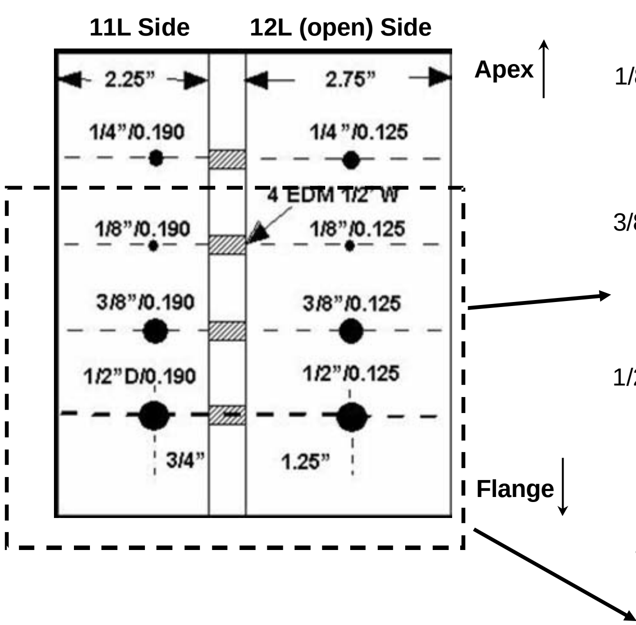
12L Tee-Seal
8 - Flat Bottom Holes 1/8”, 1/4”, 3/8”, 1/2” dia. at Depths Indicated & 4 - EDM Notches @ Junction

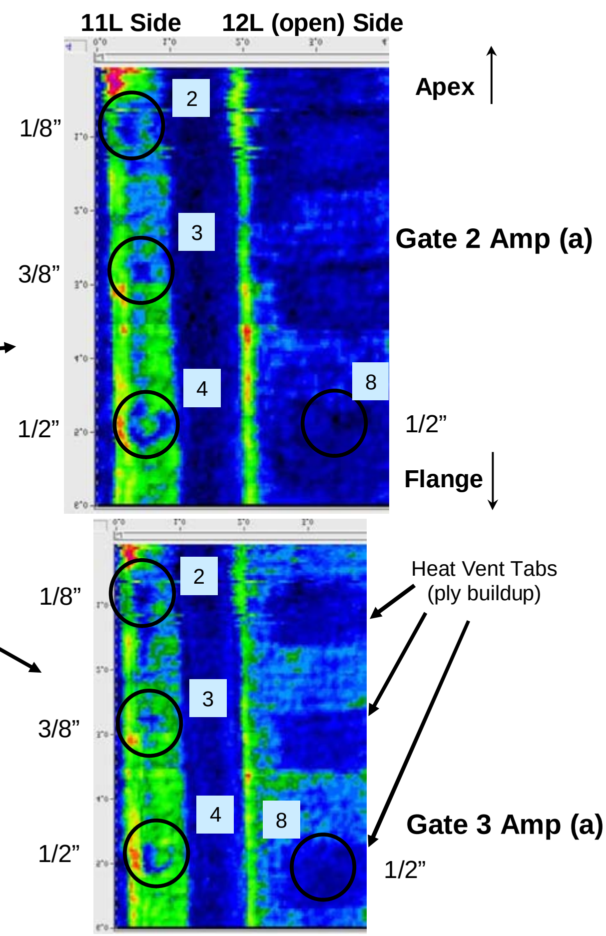
12L Tee Seal – Zone 1



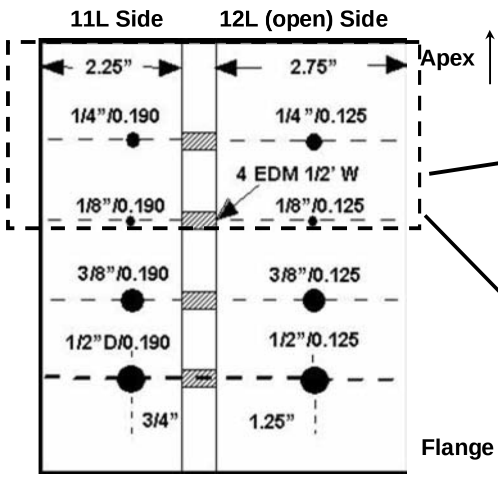


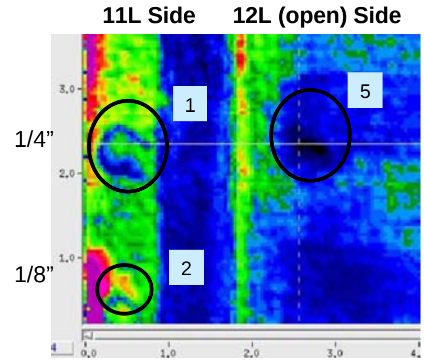
12L Tee Seal – Zone 1



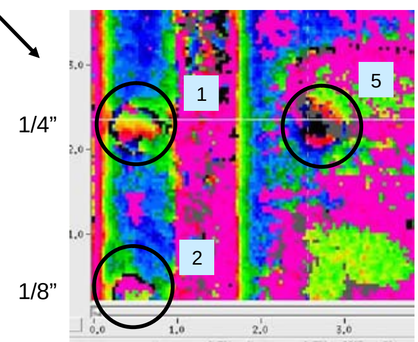


12L Tee Seal – Zone 1



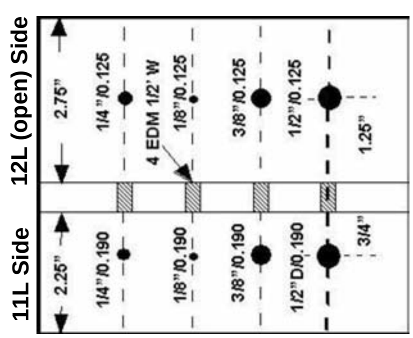


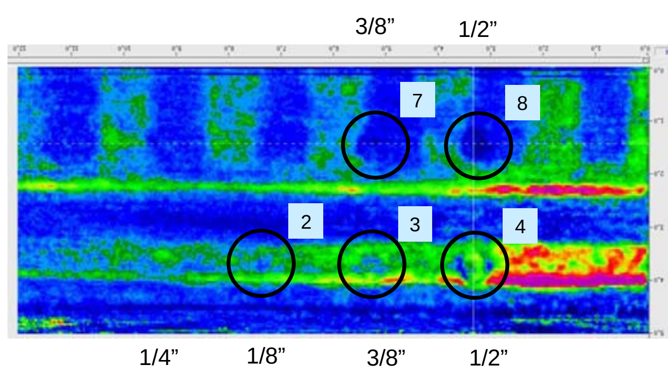
Gate 3 Amp (b)



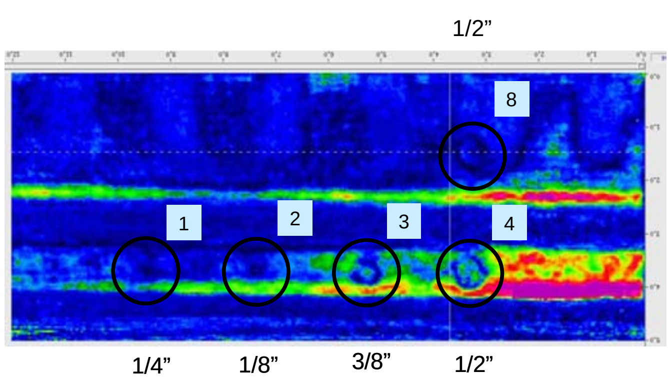
Gate 2 Time of Flight (b)

12L Tee Seal – Zone 1



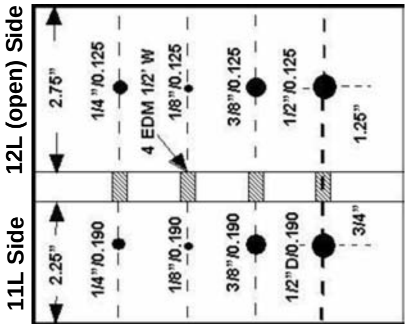


Gate 1 Amplitude

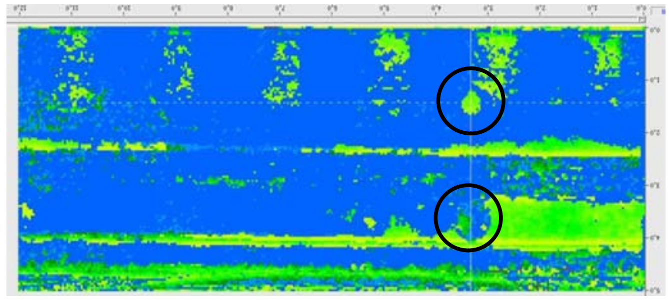


Gate 1 Time of Flight

12L Tee Seal – Zone 1



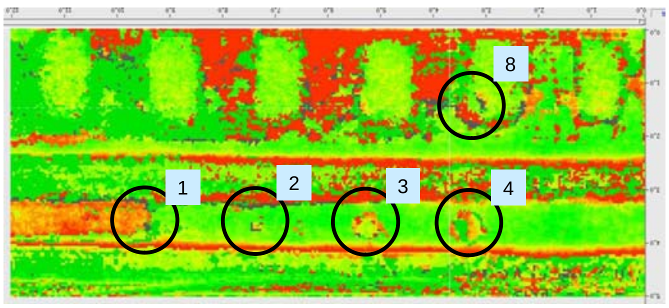
1/2"



1/2"

Gate 1 Time of Flight

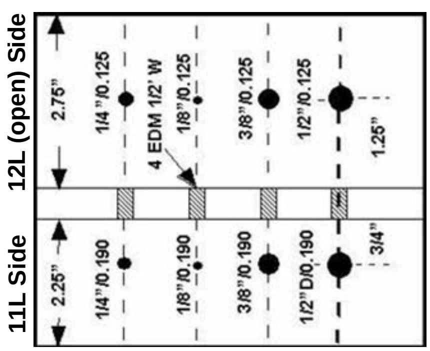
1/2"



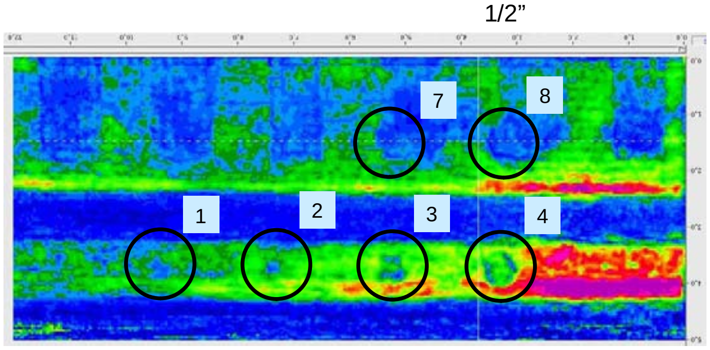
1/4" 1/8" 3/8" 1/2"

Gate 1 Amplitude

12L Tee Seal – Zone 1



1/2"



1/4" 1/8" 3/8" 1/2"

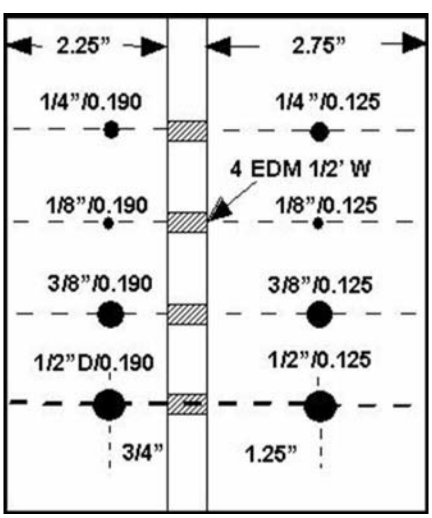
Gate 4 Amplitude

Flaw Detection Summary for Panel 12L Tee Seal
Upper Surface Validation Zone 1

Zone 12L-1								
	Drilled FBH	Laser Measurement				FBH Detected by NDE		
Lock Side Hole #	Ø & Hole Depth	Ø	Remaining Material Thickness	Thickness Near Hole	Actual Hole Depth	ET	MWM	UT PE
1	1/4 @ 0.190	0.249	0.190	0.249	0.059	D	D	D
2	1/8 @ 0.190	0.119	0.164	0.294	0.130	D	D	D
3	3/8 @ 0.190	0.382	0.218	0.296	0.078	U	D	D
4	1/2 @ 0.190	0.507	0.232	0.299	0.067	U	D	D
Slip Side								
5	1/4 @ 0.125	0.244	0.231	0.292	0.061	U	U	D
6	1/8 @ 0.125	0.120	0.212	0.296	0.084	U	U	U
7	3/8 @ 0.125	0.379	0.213	0.301	0.088	U	U	D
8	1/2 @ 0.125	0.509	0.249	0.300	0.051	U	U	D
Notch #	1/2 Width EDM Notches Machined @ the Web Junction							
1	1/2 Width	N/A		N/A		U	U	U
2	1/2 Width	N/A		N/A		U	U	U
3	1/2 Width	N/A		N/A		U	U	U
4	1/2 Width	N/A		N/A		U	U	U

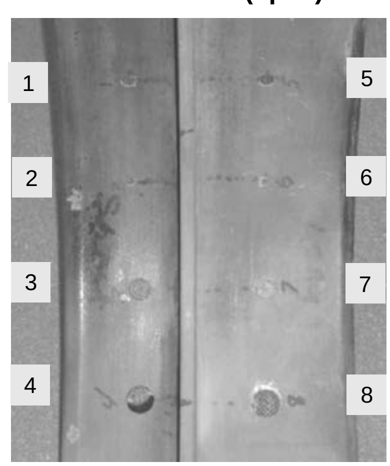
12L Tee Seal – Zone 2 (Apex Region)

11L Side 12L (open) Side

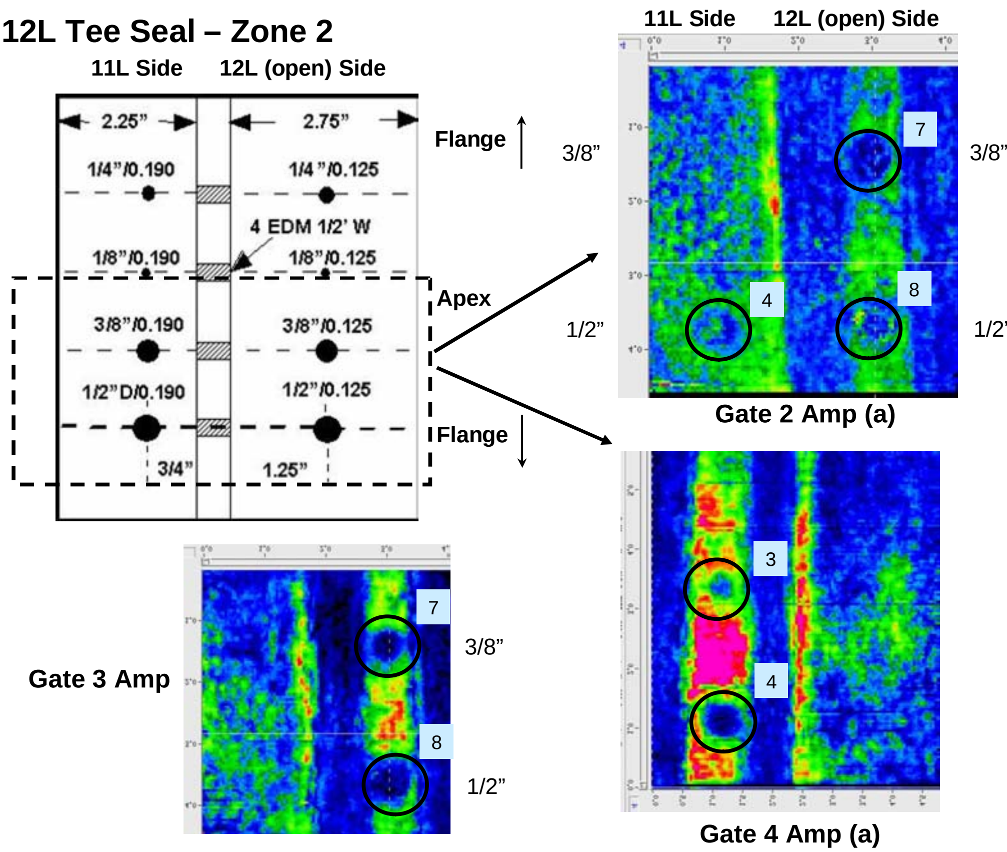


Flange
Apex
Flange

11L Side 12L (open) Side



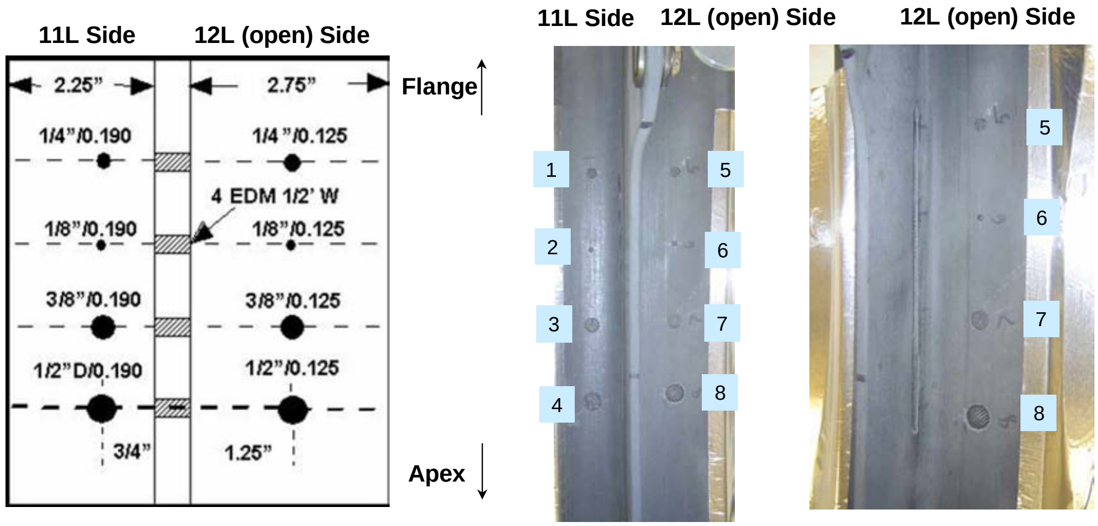
Flange
Apex
Flange



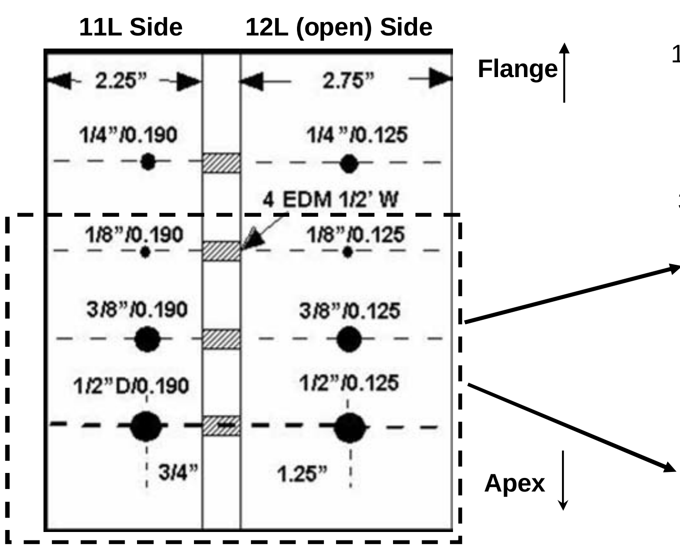
Flaw Detection Summary for Panel 12L Tee Seal
Apex Surface Validation Zone 2

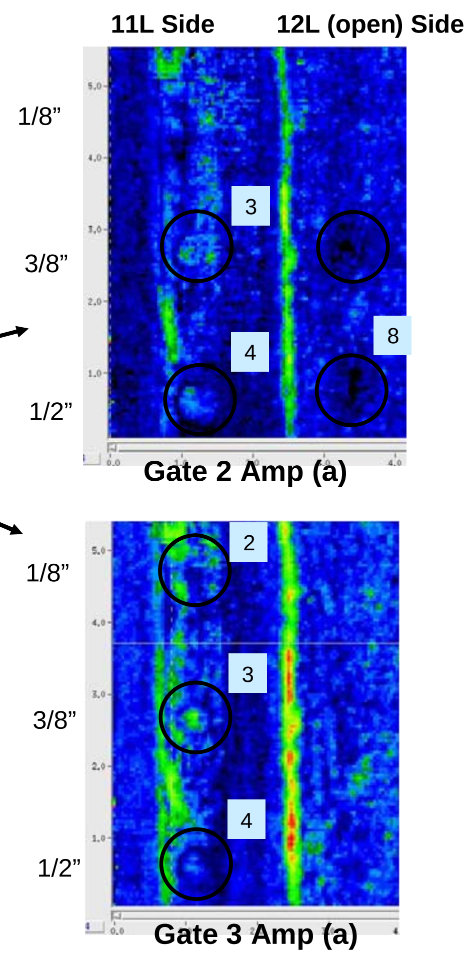
Zone 12L-2								
	Drilled FBH	Laser Measurement				FBH Detected by NDE		
Lock Side Hole #	**Ø & Hole Depth**	**Ø**	**Remaining Material Thickness**	**Thickness Near Hole**	**Actual Hole Depth**	**ET**	**MWM**	**UT PE**
1	1/4 @ 0.190	0.249	0.206	0.280	0.074	U	U	U
2	1/8 @ 0.190	0.124	0.213	0.276	0.063	U	U	U
3	3/8 @ 0.190	0.380	0.093	0.276	0.183	D	D	D
4	1/2 @ 0.190	0.500	Drilled Through	0.284		D	D	D
Slip Side								
5	1/4 @ 0.125	0.247	0.187	0.308	0.121	U	U	U
6	1/8 @ 0.125	0.119	0.226	0.301	0.075	U	U	U
7	3/8 @ 0.125	0.374	0.193	0.294	0.101	D	D	D
8	1/2 @ 0.125	0.500	0.207	0.277	0.070	U	U	D
Notch #	**1/2 Width EDM Notches Machined @ the Web Junction**							
1	1/2 Width	N/A		N/A		U	U	U
2	1/2 Width	N/A		N/A		U	U	U
3	1/2 Width	N/A		N/A		U	U	U
4	1/2 Width	N/A		N/A		U	U	U

12L Tee Seal – Zone 3

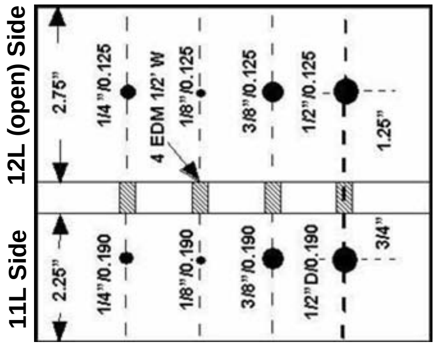


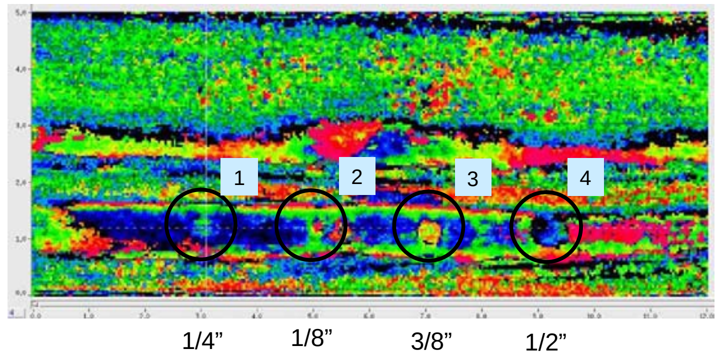
12L Tee Seal – Zone 3



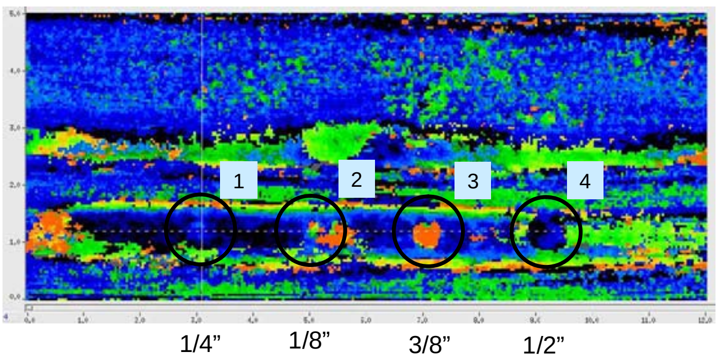


12L Tee Seal – Zone 3





Gate 2 Time of Flight



Gate 4 Time of Flight

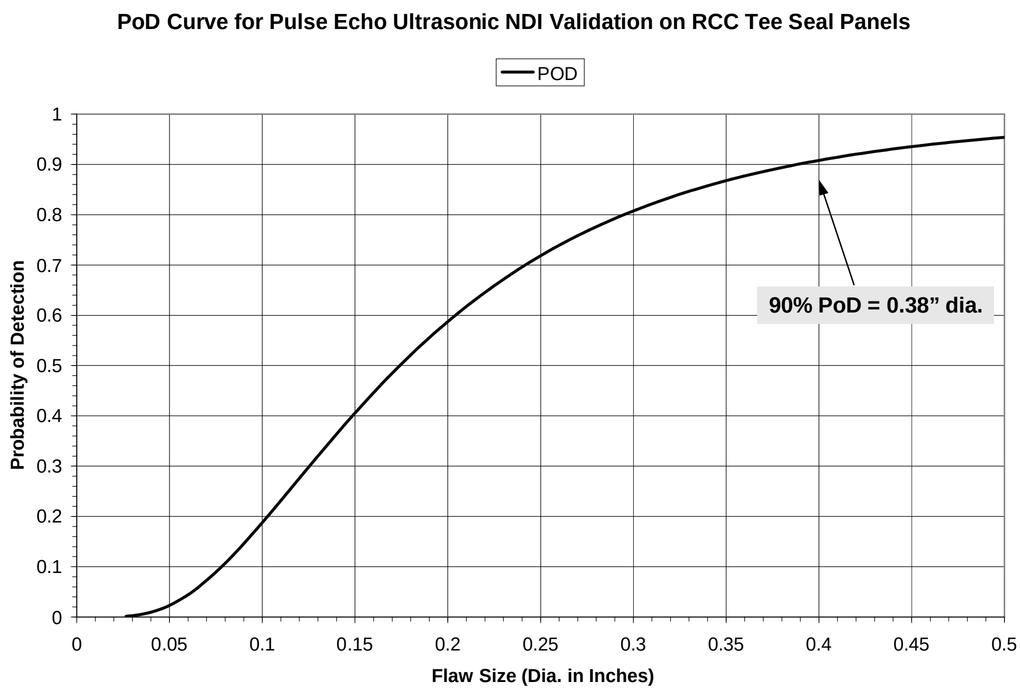
Flaw Detection Summary for Panel 12L Tee Seal
Lower Surface Validation Zone 3

Zone 12L-3								
	Drilled FBH	Laser Measurement				FBH Detected by NDE		
Lock Side Hole #	Ø & Hole Depth	Ø	Remaining Material Thickness	Thickness Near Hole	Actual Hole Depth	ET	MWM	UT PE
1	1/4 @ 0.190	0.248	0.178	0.281	0.103	D	D	D
2	1/8 @ 0.190	0.119	0.193	0.280	0.087	U	U	D
3	3/8 @ 0.190	0.373	0.212	0.284	0.072	U	D	D
4	1/2 @ 0.190	0.495	0.193	0.290	0.097	D	D	D
Slip Side								
5	1/4 @ 0.125	0.248	0.245	0.302	0.057	D	U	U
6	1/8 @ 0.125	0.119	0.222	0.302	0.080	U	U	U
7	3/8 @ 0.125	0.373	0.234	0.296	0.062	U	D	U
8	1/2 @ 0.125	0.500	0.222	0.294	0.072	D	D	D
Notch #	1/2 Width EDM Notches Machined @ the Web Junction							
1	1/2 Width	N/A		N/A		U	U	U
2	1/2 Width	N/A		N/A		U	U	U
3	1/2 Width	N/A		N/A		U	U	U
4	1/2 Width	N/A		N/A		U	U	U

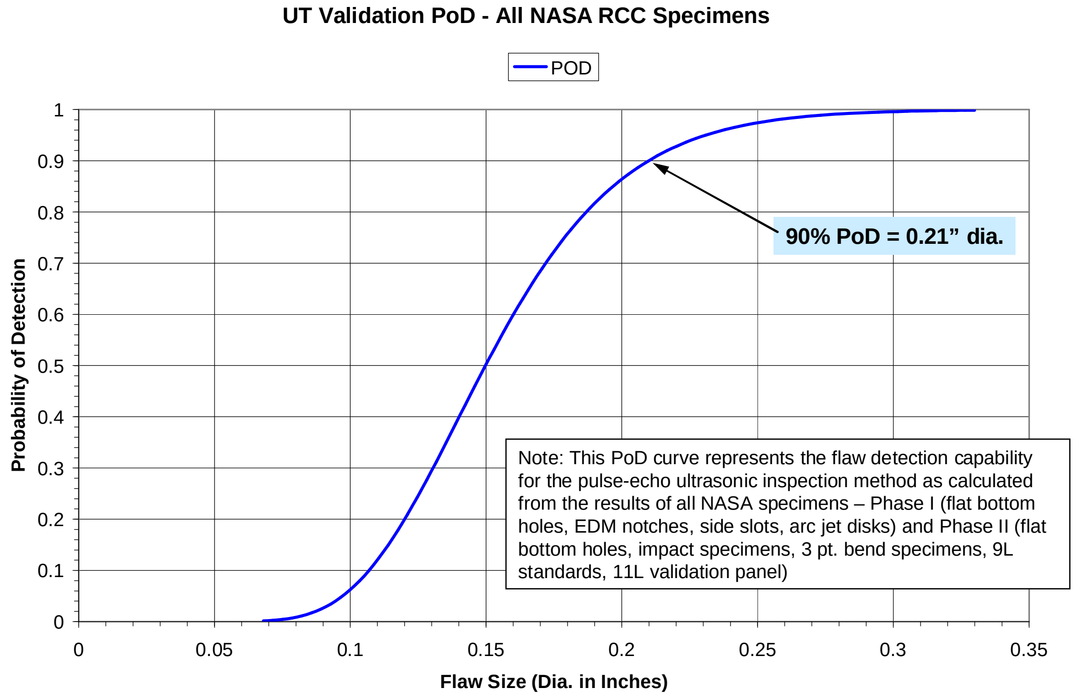
Flaw Detection Summary for All Flaws in RCC Tee Seal 12L

Detection Flaws in RCC Tee Seal 12L				
Flaw Size	**Flaw Size and Location**		**Detection by Pulse-Echo UT**	
	Lock Side (11L)	**Slip Side (12L)**	**Yes**	**No**
1/8" diameter	#2 (Zone 1)		X	
1/8" diameter		#6 (Zone 1)		X
1/8" diameter	#2 (Zone 2)			X
1/8" diameter		#6 (Zone 2)		X
1/8" diameter	#2 (Zone 3)		X	
1/8" diameter		#6 (Zone 3)		X
1/4" diameter	#1 (Zone 1)		X	
1/4" diameter		#5 (Zone 1)	X	
1/4" diameter	#1 (Zone 2)			X
1/4" diameter		#5 (Zone 2)		X
1/4" diameter	#1 (Zone 3)		X	
1/4" diameter		#5 (Zone 3)		X
3/8" diameter	#3 (Zone 1)		X	
3/8" diameter		#7 (Zone 1)	X	
3/8" diameter	#3 (Zone 2)		X	
3/8" diameter		#7 (Zone 2)	X	
3/8" diameter	#3 (Zone 3)		X	
3/8" diameter		#7 (Zone 3)		X
1/2" diameter	#4 (Zone 1)		X	
1/2" diameter		#8 (Zone 1)	X	
1/2" diameter	#4 (Zone 2)		X	
1/2" diameter		#8 (Zone 2)	X	
1/2" diameter	#4 (Zone 3)		X	
1/2" diameter		#8 (Zone 3)	X	

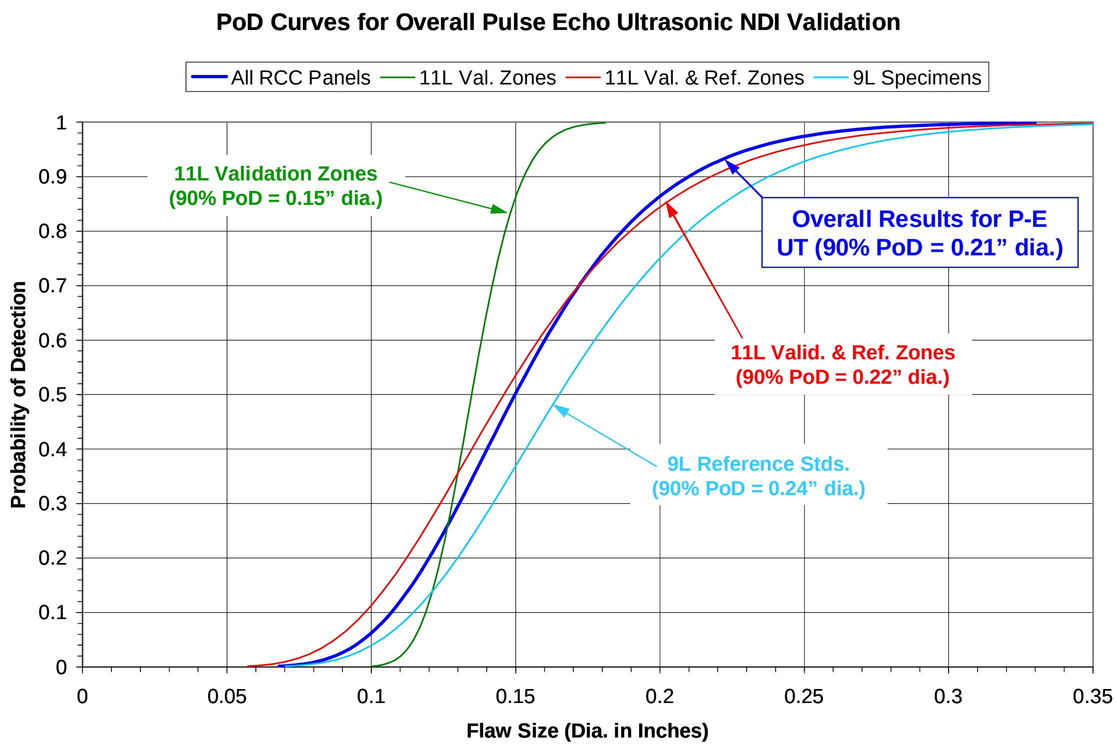
Probability of Detection Curve for Pulse-Echo UT Flaw Detection in Panel 12L Tee Seal



Probability of Detection Curve for Pulse-Echo UT Flaw Detection in
All NASA RCC Test Specimens (Phase I & Phase II)



Probability of Detection Curves for Pulse-Echo UT Flaw Detection in
Various NASA RCC Test Specimen Sets



Summary of UT Flaw Detection Evaluation in 11L & 12L

UT Pulse Echo Flaw Detection Summary

- 11L Panel Reference Zones: 29 detected, 5 undetected, 0 mislocated, 2 ambiguous and 0 false

  (Reference Zone Misses = five 1/8" flaws; all flaws larger than 1/8" dia. were detected with no false calls)

- 11L Panel Validation Zones: 35 detected, 7 undetected, 0 mislocated, 0 ambiguous and 0 false

  (Validation Zone Misses = *seven 1/8" flaws; all flaws larger than 1/8" dia. were detected with no false calls)*

- 12L Tee Seal Validation Zones: 16 detected, 8 undetected, 0 mislocated, 0 ambiguous and 0 false

  (Validation Zones Misses = four 1/8" dia. flaws, one 3/8" dia. flaw, & three 1/4" dia. flaws; all flaws larger than 3/8" dia. were detected with no false calls)

- 12L Tee Seal EDM Notches: 0 detected, 12 undetected, 0 mislocated, 0 ambiguous and 0 false

  (EDM notches located 0.6" below surface & 0.30" below skin-to-vertical flange interface; notches are below depth of penetration for UT)

Final Conclusions on Pulse-Echo Ultrasonic Inspection Method for In-Situ Orbiter Health Monitoring

- **18 month test series for UT system certification was completed in March 2005; tests utilized 46 specimens containing 306 flaws**
- **306 flaws → 257 hits, 49 misses; 45 of the misses (92%) were 1/8" dia.; 98% of flaws larger than 1/8" dia. were detected**
- **Pulse-Echo Ultrasonics is able to locate flaws through the entire RCC thickness**
- **Pulse-Echo UT sensitivity ≈ 1/4" dia. flaw in <u>RCC LE panels</u>;**

  90% PoD level = 0.21" dia. flaw
- **Pulse-Echo UT sensitivity ≈ 3/8" dia. flaw in <u>RCC Tee seals</u>;**

  90% PoD level = 0.38" dia. flaw

APPENDIX A

RCC Life Cycle Wear Study - Effect of UT/EC Scanner System on Surface of RCC Panels

RCC Life Cycle Wear Study - Effect of UT/EC Scanner System on Surface of RCC Panels

Reference: RCC NDE Wear Test Plan (Document Number - KSC-5600-7096)

Background

The Orbiter RCC In-Situ NDE System will be used during Orbiter turnaround flow to perform inspections of the entry critical RCC panels of the leading edge structural subsystem. Design and fabrication of the complete RCC In-situ NDE systems are underway at various organizations. The complete NDE system will be comprised of flash Thermography, Pulse echo ultrasonic subsystem, and eddy current. During implementation of these inspection tools, caution will be required to protect the RCC from further damage.

Objective

The objective of this test was to perform a wear study on flat panel RCC using the pulse echo ultrasonic system to determine if any degradation of the RCC coating material could occur during inspections. The test was carried out based on the likelihood that a certain area of the RCC will be inspected a finite number of times over the remaining life of the vehicle. The data from these tests was used for certification of the equipment. Therefore, the data integrity had Quality oversight.

Test Article

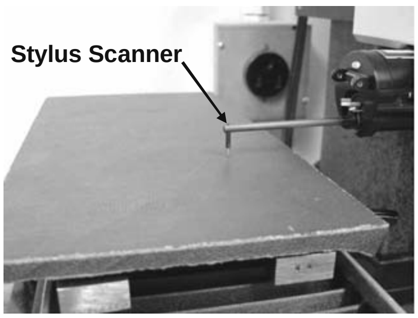
The test article was an 8.5" L x 4.5" H piece of flight hardware RCC material that was cut from the lower surface of Panel 9L.

Test Description

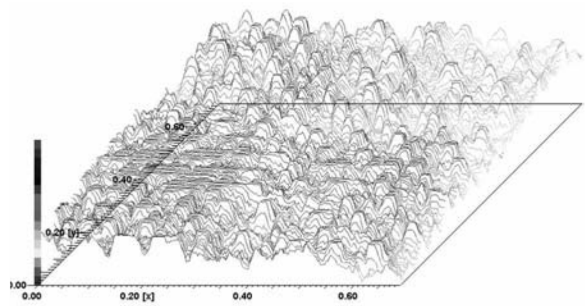
The test article was pre-scanned using Eddy Current Si-C thickness measurement at NASA Langley. A pre-scan flaw profile assessment with Thermography was performed at NASA Langley. Sandia labs performed pre- and post scan mechanical testing. The ultrasonic scans on the RCC test article were performed at Sandia labs using the same equipment that will be used during actual shuttle RCC inspections. Once the wear test was completed, Eddy Current and Thermography post-scans were performed at NASA Langley.

RCC Life Cycle Wear Study - UT/EC Scanner System

- **Wear specimen - RCC specimen of sufficient size to include a scan area with adjacent un-scanned area**
- **Conduct pre-scan surface characterization – EC Si-C thickness measurement; IR baseline; mechanical thickness measurement; surface profilometry; microscopic cleanliness baseline**
- **Scan the surface using NASA linear spring with Sandia probe, probe housing, and weeper couplant system (60 cycles)**
- **Conduct mid- and post-scan surface characterization**



Surface Texture/Profile Measurement



Sample Three Dimensional Surface Topography Map

NDE RCC UT Wear Study Test Plan

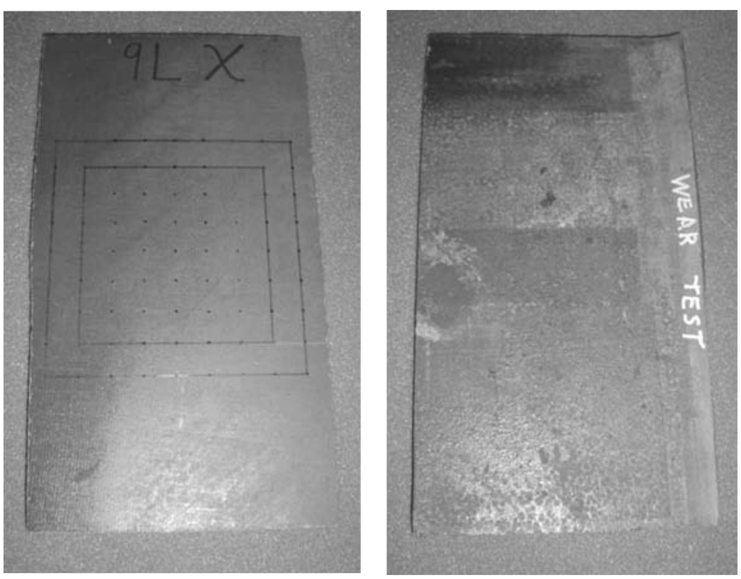
1. **Obtain flat RCC specimen of sufficient size to include a scan area with adjacent un-scanned area (e.g. 3” x 3” scan on the interior of a 4” x 4” specimen)**
2. **Conduct pre-scan surface characterization**
   a) **Eddy current Si-C thickness measurement**
   b) **Perform infrared flash Thermography**
   c) **Perform mechanical thickness measurement (1/2” grid over entire surface)**
   d) **Perform mechanical and / or optical surface profilometry**
   e) **Visually scan the sample surface with a 10x to 30x microscope to check for traces of Delrin housing or urethane membrane material. (Initially for part cleanliness verification only)**
   f) **Measure the thickness of UT fixture contact area using appropriate micrometer**
3. **Scan the surface using NASA linear spring with Sandia probe housing / transducer**
   a) **Scan at max spring load to be used on orbiter**
   b) **Perform <u>60</u> scans over the same area per the following reasoning:**
      i. **Max orbiter remaining flights = 15**
      ii. **Estimate 2 possible scans to the same area after any flight (based on possible re-scan needed**
      iii. **Use a factor of safety of 2**
      iv. **So 15 flights x 2 scans x 2 safety factor = 60 possible scans over one location during the orbiters remaining flights**
4. **Conduct surface characterizations identical to Step 2 above after the 30th scan and final characterization after the 60th scan (IR and ET to be performed pre-test and after 60th scan only)**
5. **Section RCC panel in a minimum of 3 locations after final characterizations to observe the surface at scanned areas as well as un scanned (must assure that the Si-C layer can not be smeared by the cutting process**
6. **Record and report all results**

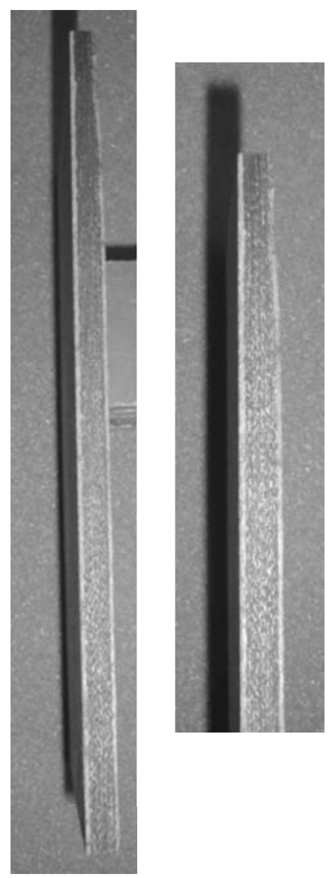
NDE RCC UT Wear Study and Normal/Shear Load Measurement Test Plan

<u>Quality Assurance Checks</u>

- Ø **Use a Sandia Quality Assurance to sign off on activities at predetermined steps in the testing. Suggested steps are:**
- Ø **Verify surface characterization at 0 cycles**
- Ø **Check test set-up prior to wear testing and sign off on scanning operation**
- Ø **Verify surface characterization performed after 30 cycles**
- Ø **Verify surface characterization performed after 60 cycles**
- Ø **Verify shear stress plan operations are completed per test plan**
- Ø **Verify normal stress measurement operations are completed per test plan**
- Ø **Utilize a USA and / or NASA Quality Assurance inspector as needed to verify the entire test plan is completed as written**

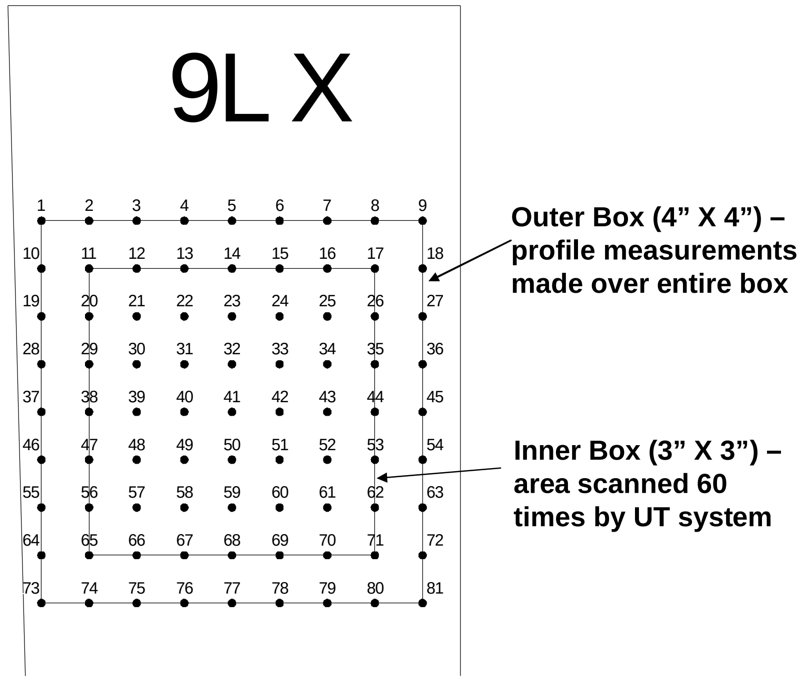
Wear Test Panel Cut from RCC Panel 9L



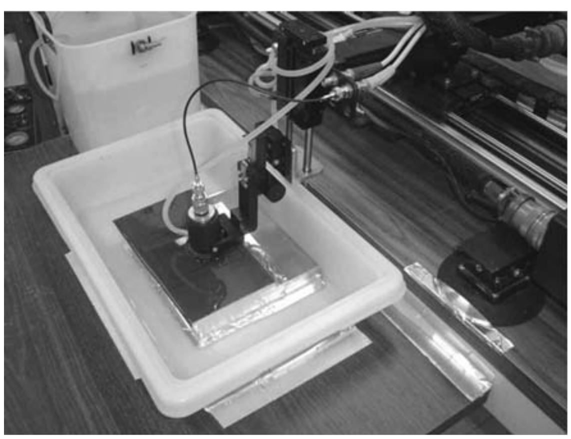


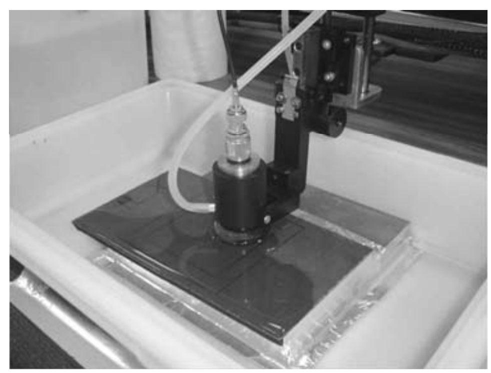
Wear Test to Assess Potential Wear of RCC Surface Caused by Ultrasonic Sanning System

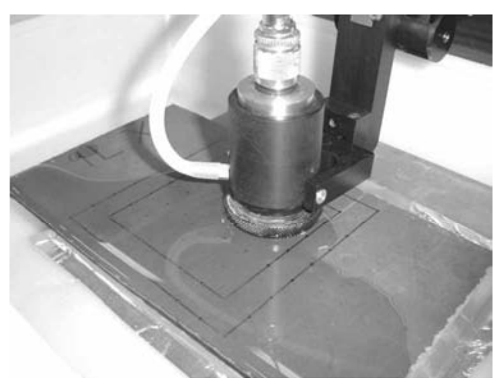
Grid Points Layout on Wear Test Specimen for Data Logging



Scanning Wear Test Panel with Ultrasonic System

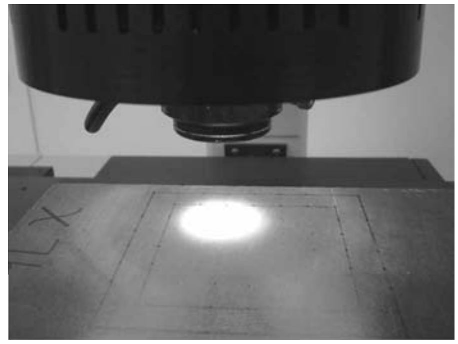


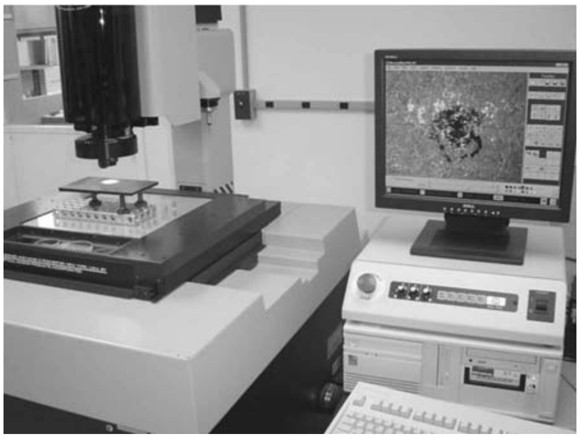


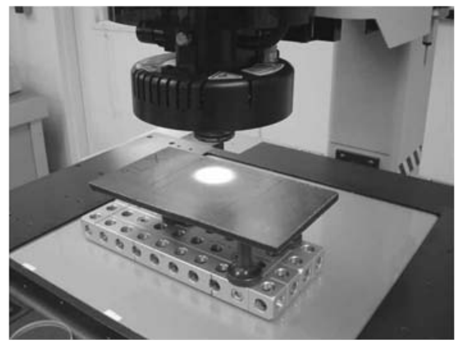


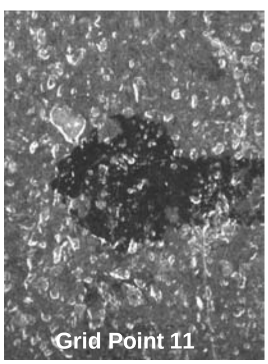
Microscopic Surface Assessment - Avant 300 Optical Inspection System

Microscopic photography of RCC panel was performed to determine if any materials from the probe housing (delrin or plastic membrane) are deposited on the surface during UT scanning – photos on following pages indicate that there are no deposits on the surface following 30 and 60 scans with the UT probe housing

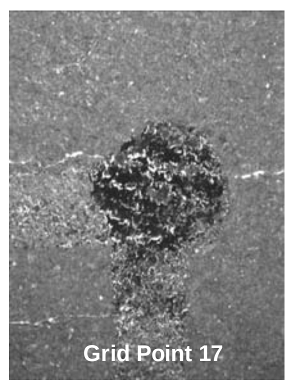


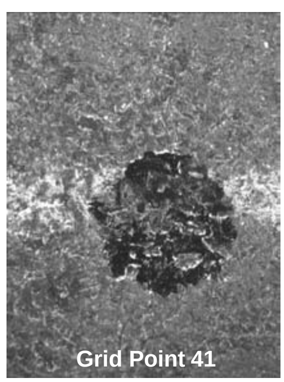


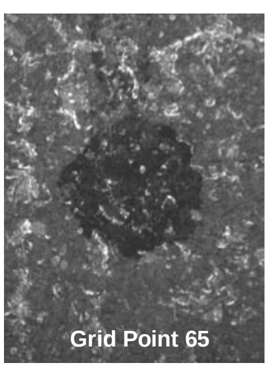



Grid Point 11

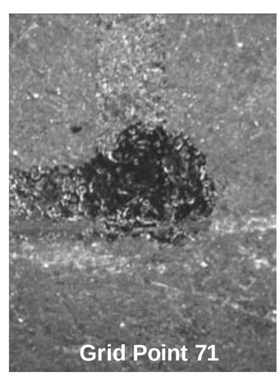
O.G.P. AVANT Photo Microscope with a 71X magnification

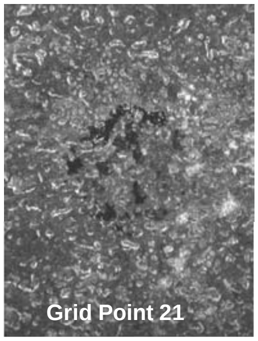

Grid Point 17


Grid Point 41

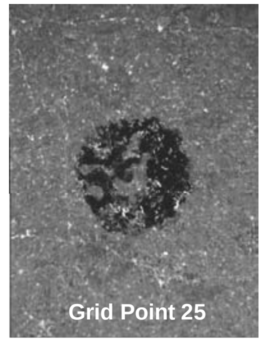

Grid Point 65

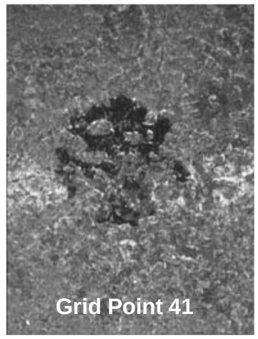
0 Scan Cycles (pre-UT scans)

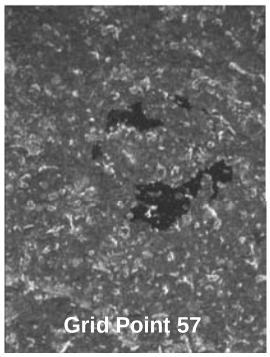

Grid Point 71

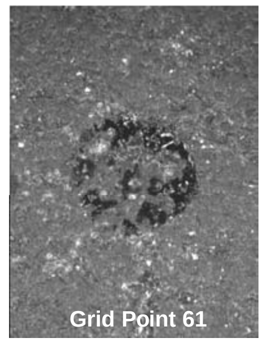

Grid Point 21

O.G.P. AVANT Photo Microscope with a 71X magnification

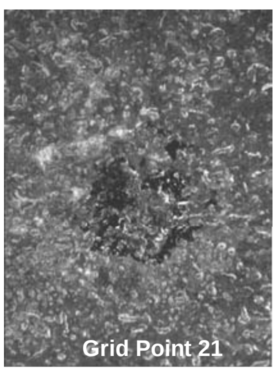

Grid Point 25


Grid Point 41

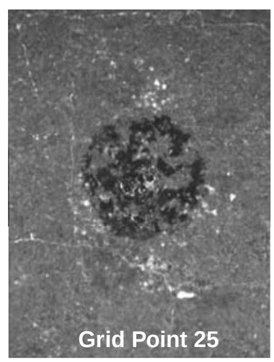

Grid Point 57


Grid Point 61

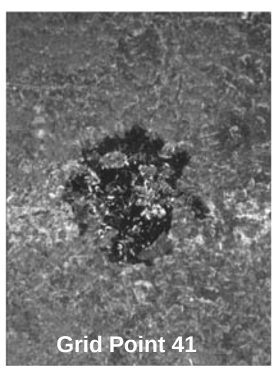
After 30 UT Scan Cycles

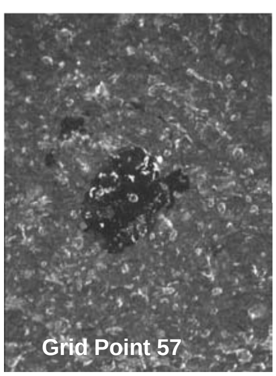

Grid Point 21

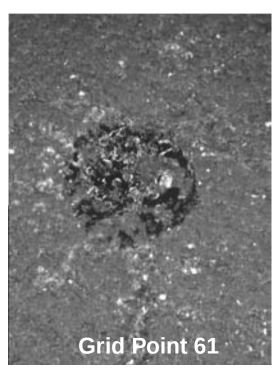
O.G.P. AVANT Photo Microscope with a 71X magnification


Grid Point 25

Note: Grid dots reinstalled with sharpie after 30 scans so shape of black grid pts. are different


Grid Point 41

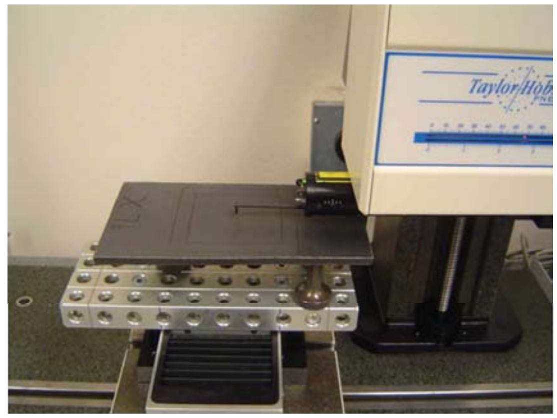

Grid Point 57

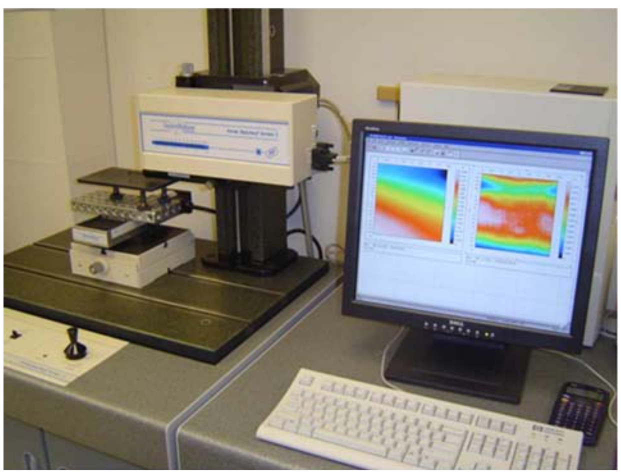

Grid Point 61

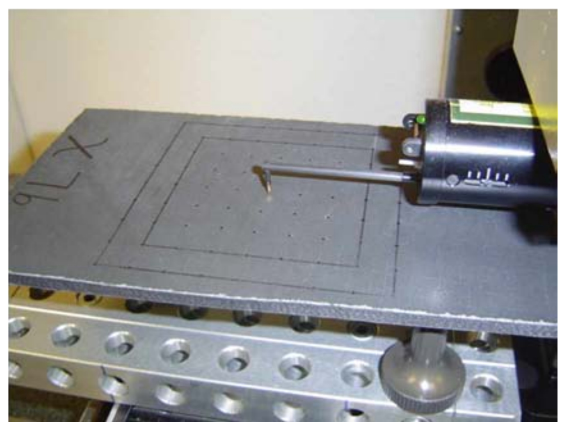
After 60 UT Scan Cycles

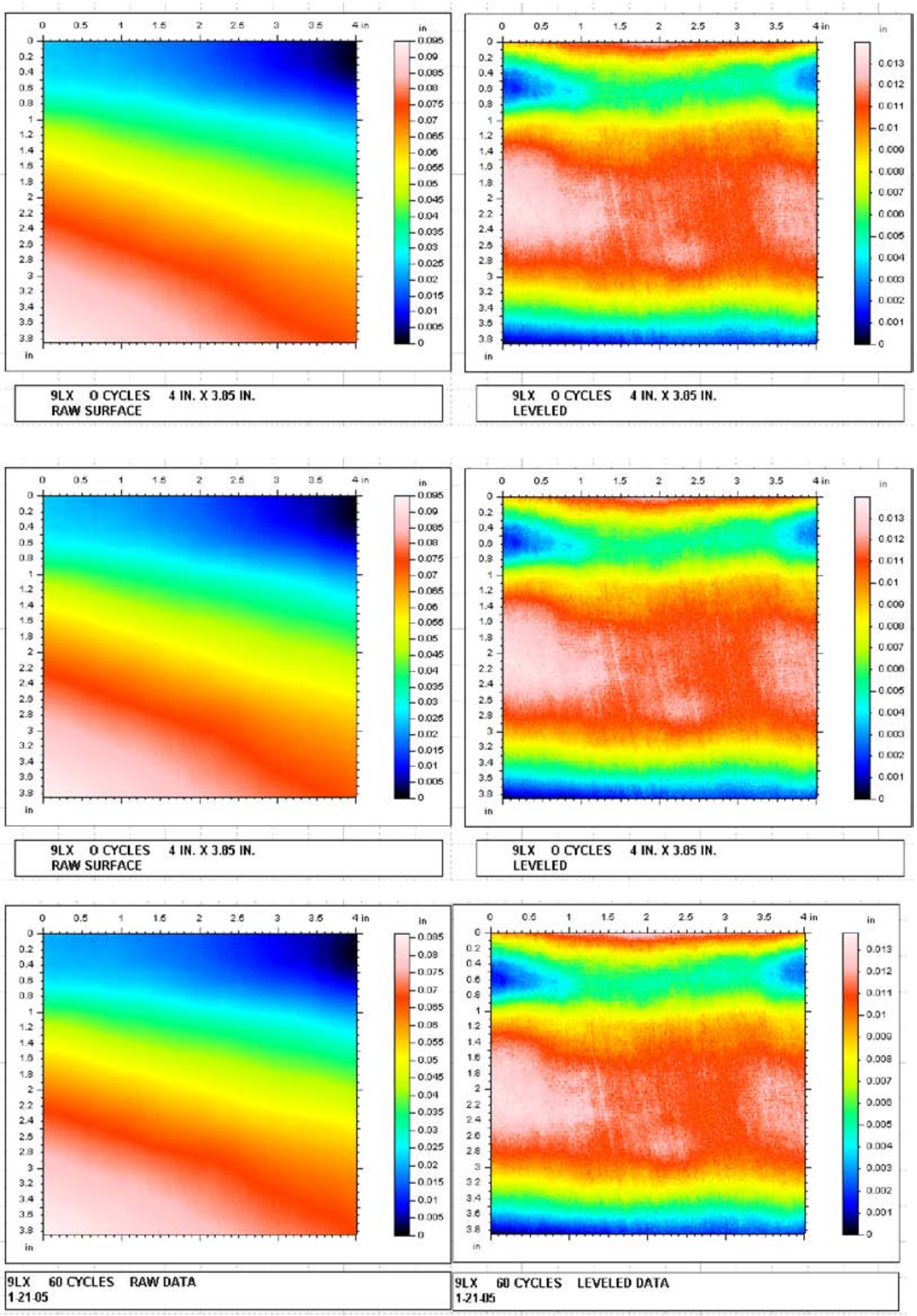
Surface Profilometry - Taylor/Hobson Pneumo (TalySurf Series 2)

Mechanical profilometry (resolution of 1 μin.) was used to determine if the UT scans produced any wear in the RCC Si-C coating – profile data on the following pages show that the surface was unchanged by the UT probe housing after 60 scans over the same area









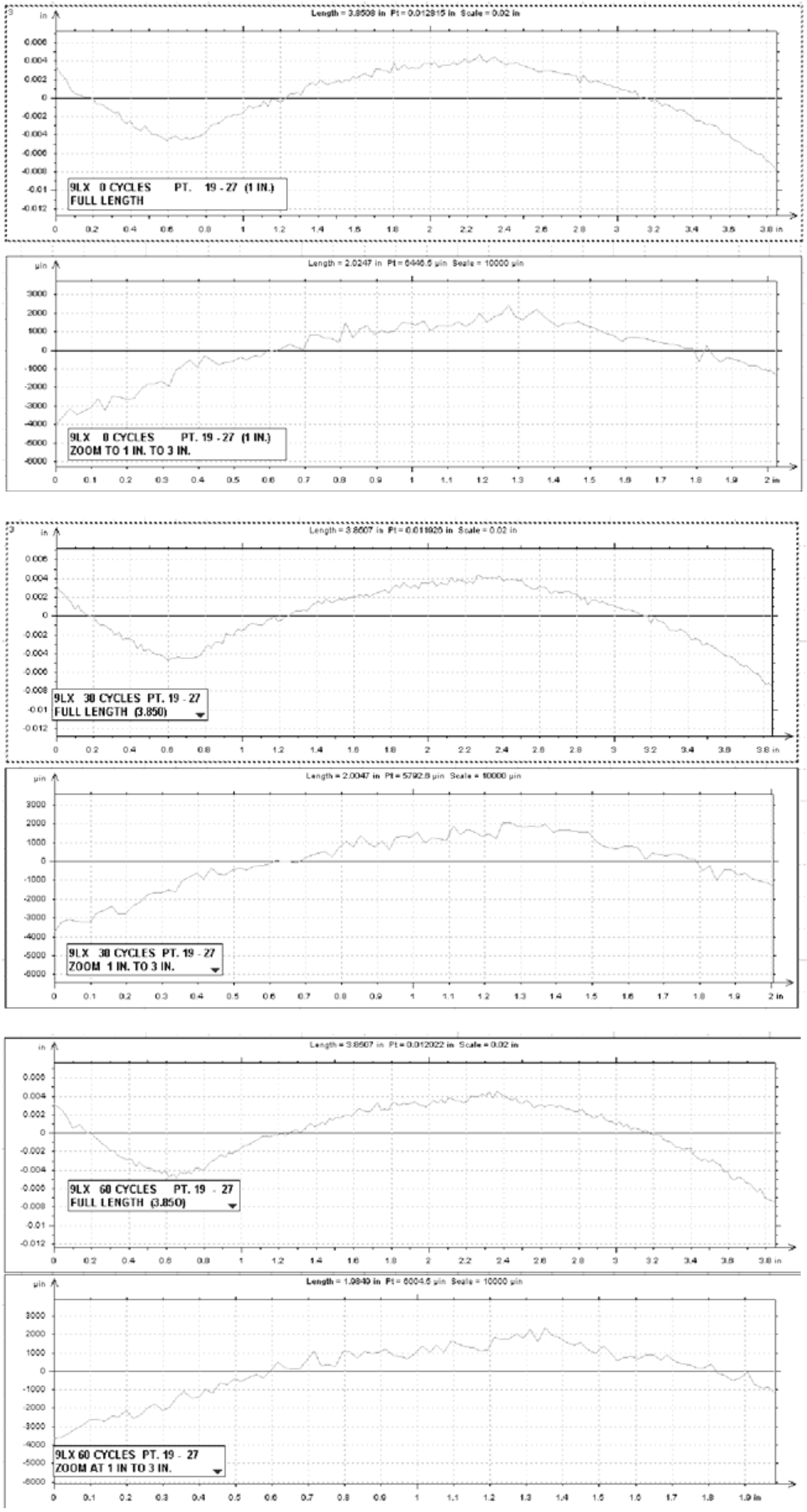
O CYCLES

30 CYCLES

60 CYCLES

Surface Contour Plots of Entire Specimen Before and After UT Scanning - No Removal of RCC Material Measured

Grid Row 19 - 27



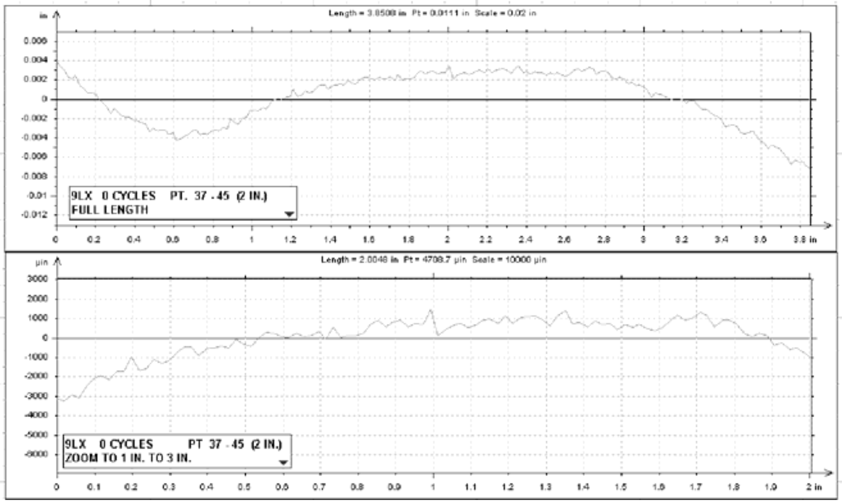
0 Cycles

30 Cycles

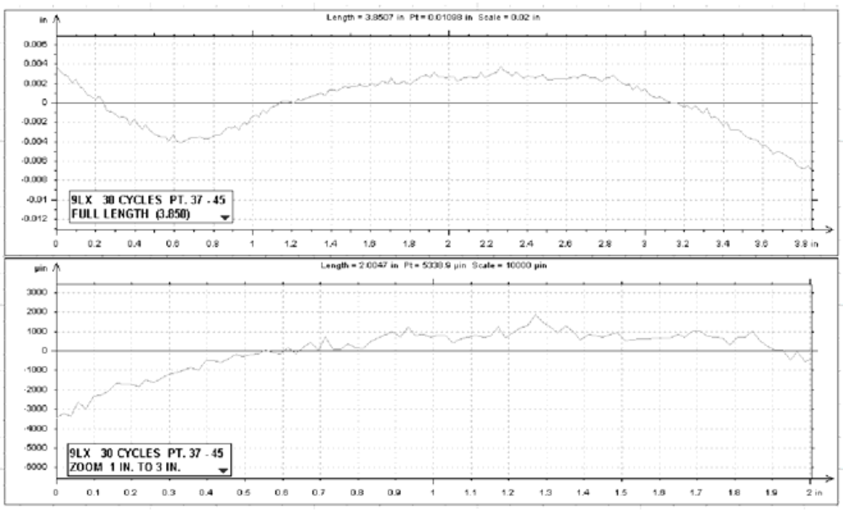
60 Cycles

Contour Plots Across Grid Line 19-27 Before and After UT Scanning – No Removal of RCC Material Measured

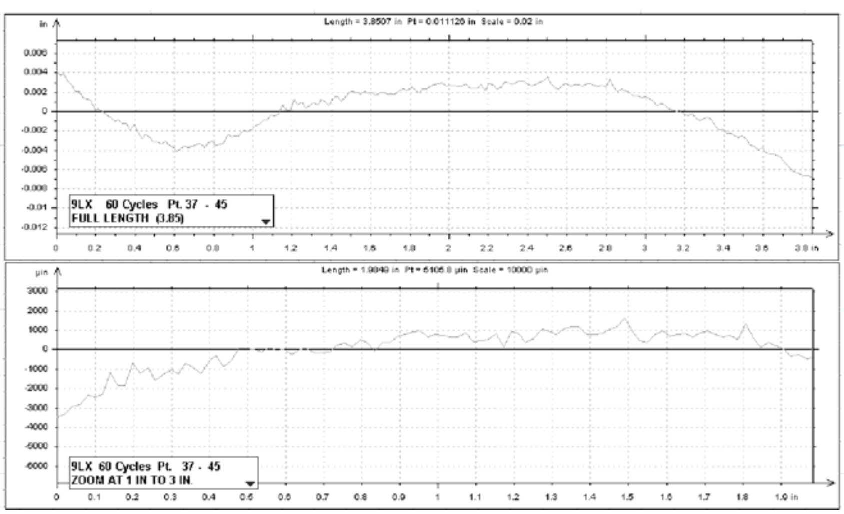
Grid Row 37 - 45



0 Cycles



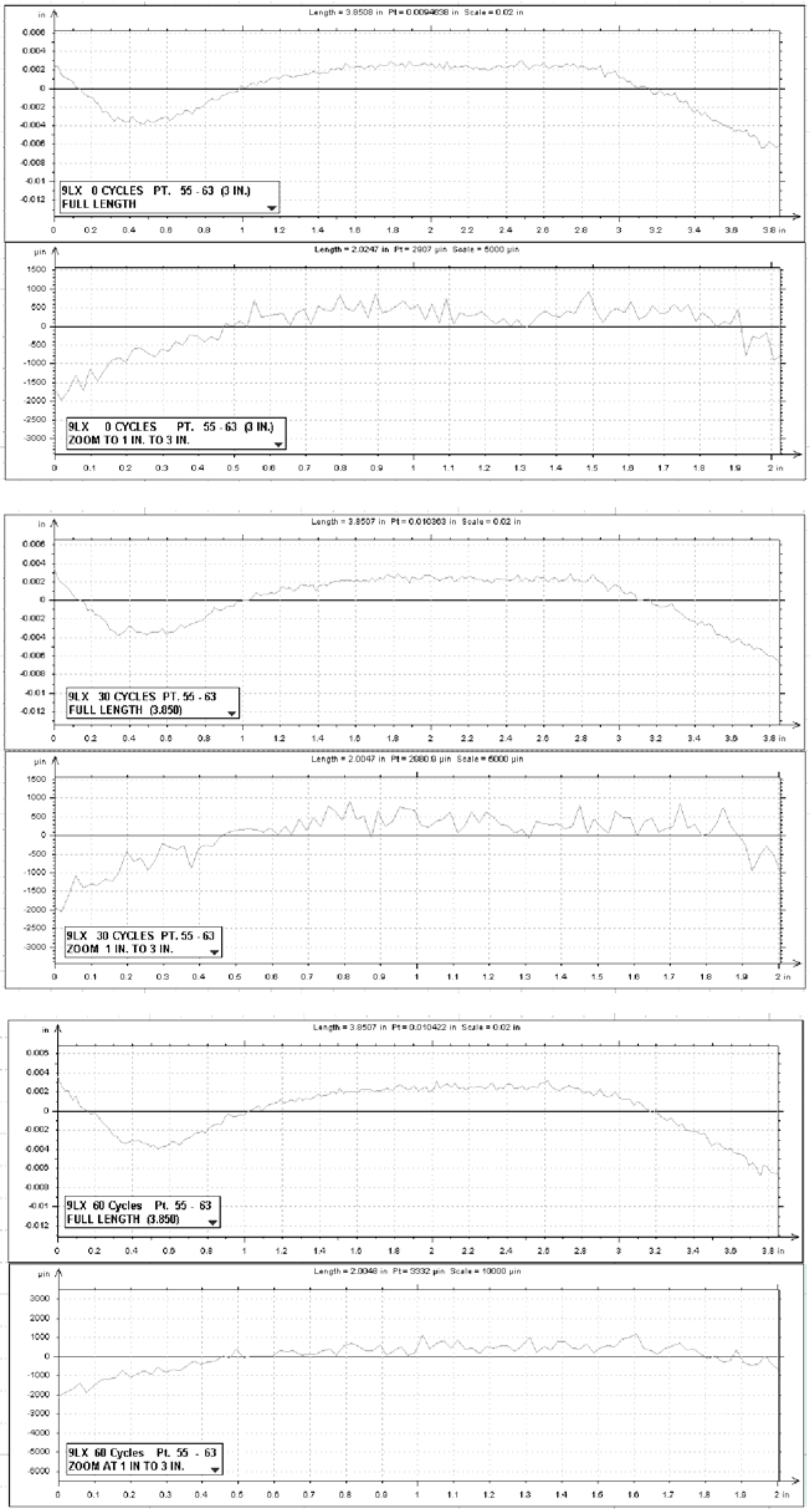
30 Cycles



60 Cycles

Contour Plots Across Grid Line 37-45 Before and After UT Scanning – No Removal of RCC Material Measured

Grid Row 55 - 63



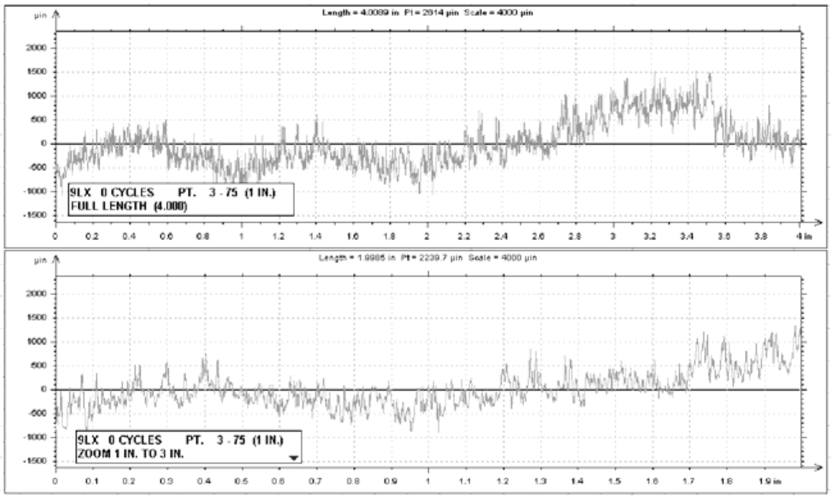
0 Cycles

30 Cycles

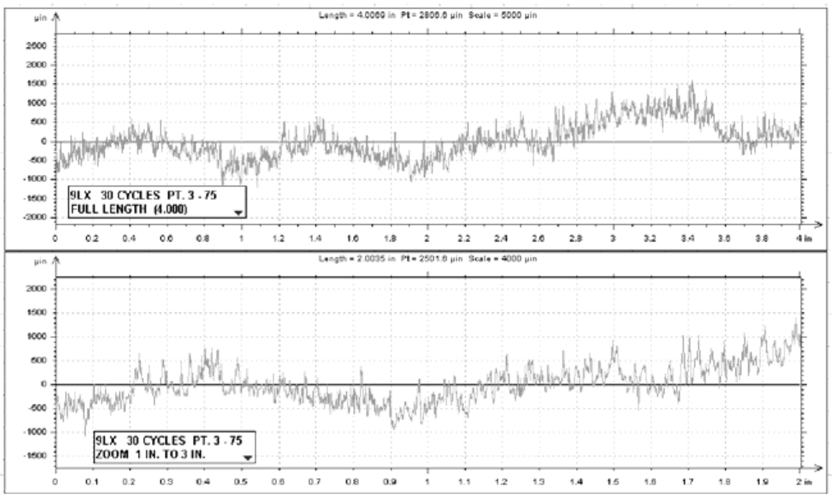
60 Cycles

Contour Plots Across Grid Line 55-63 Before and After UT Scanning – No Removal of RCC Material Measured

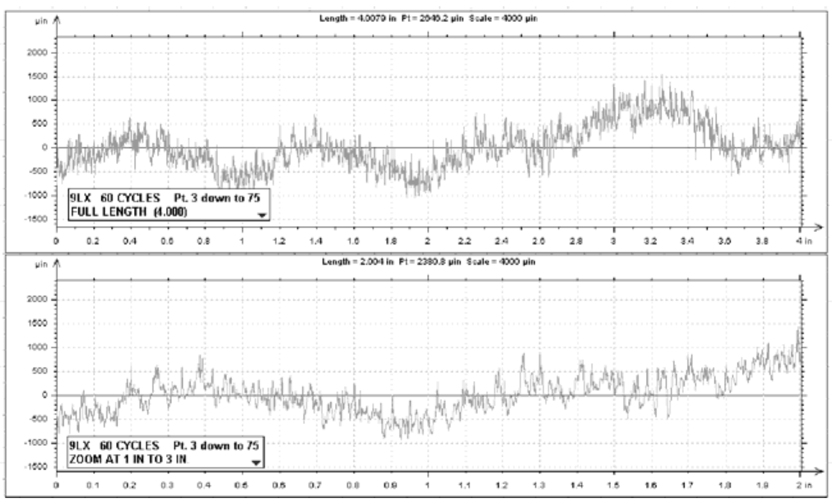
Grid Row 3 down to 75



0 Cycles



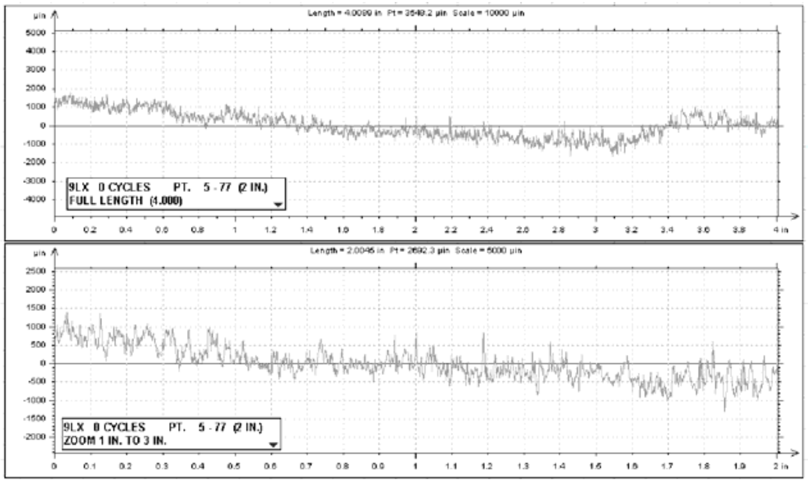
30 Cycles



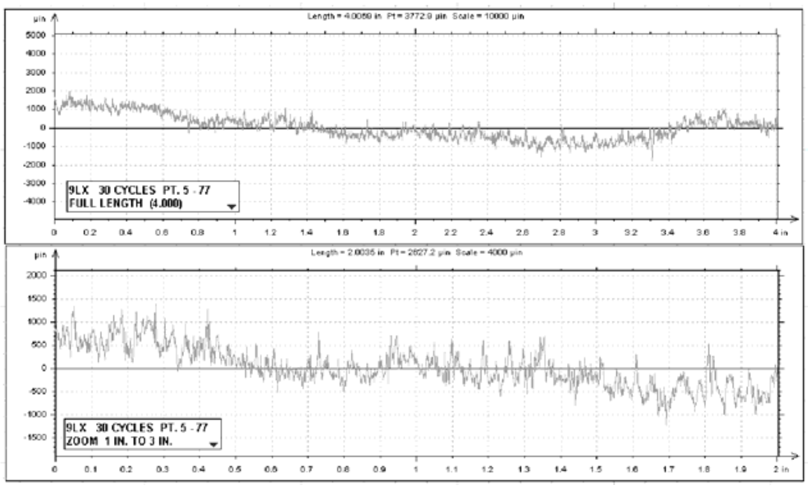
60 Cycles

Contour Plots Across Grid Line 3 to 75 Before and After UT Scanning – No Removal of RCC Material Measured

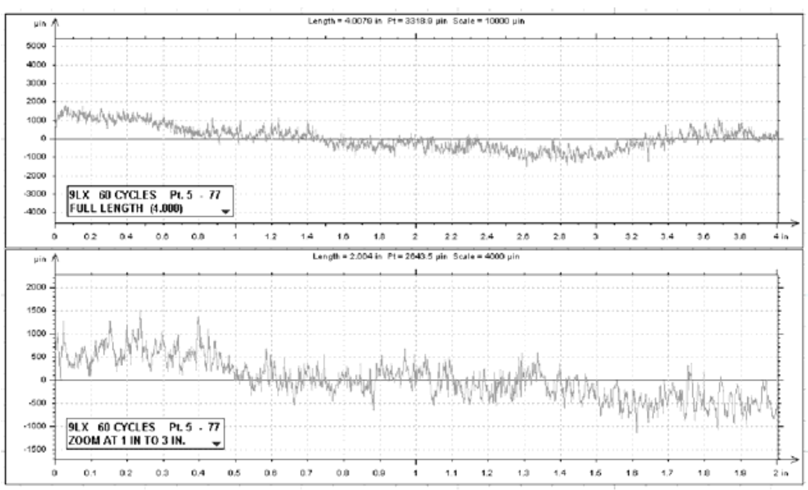
Grid Row 5 down to 77



0 Cycles



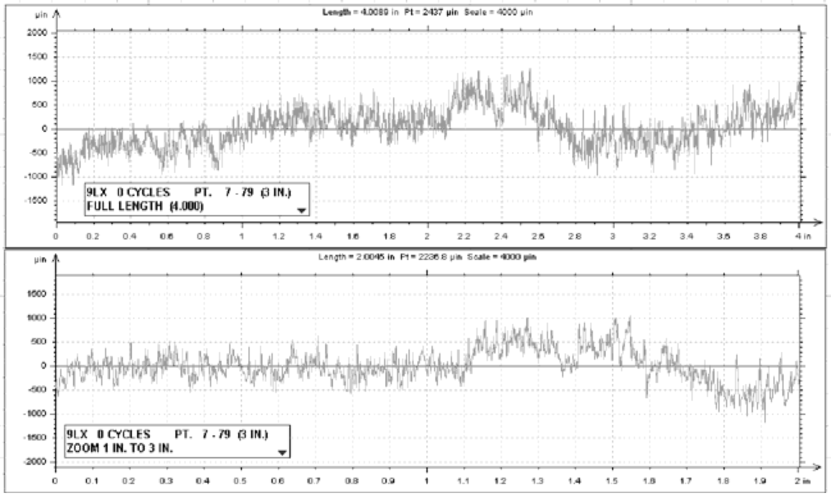
30 Cycles



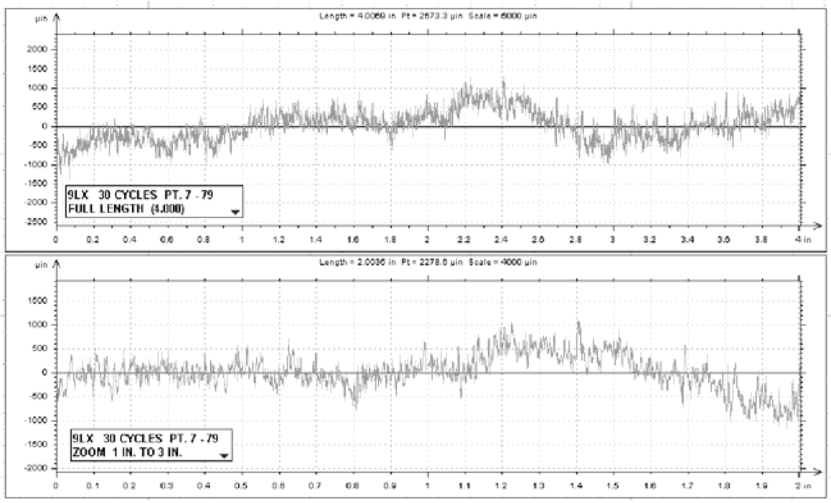
60 Cycles

Contour Plots Across Grid Line 5 to 77 Before and After UT Scanning – No Removal of RCC Material Measured

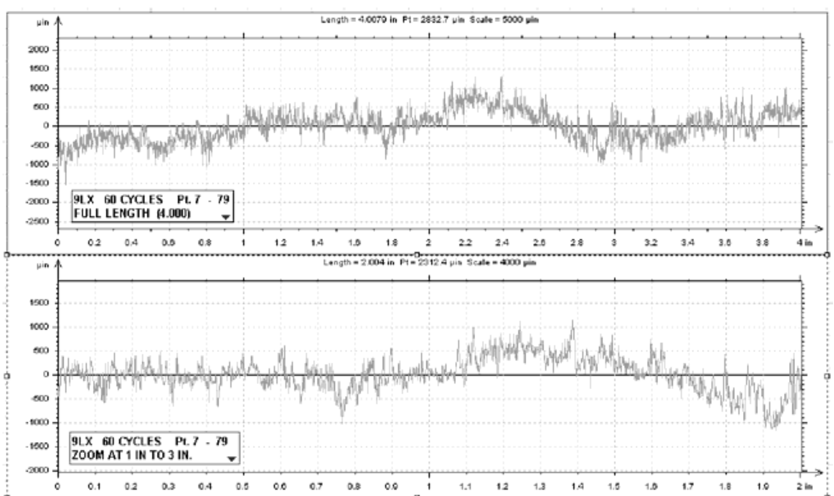
Grid Row 7 down to 79



0 Cycles

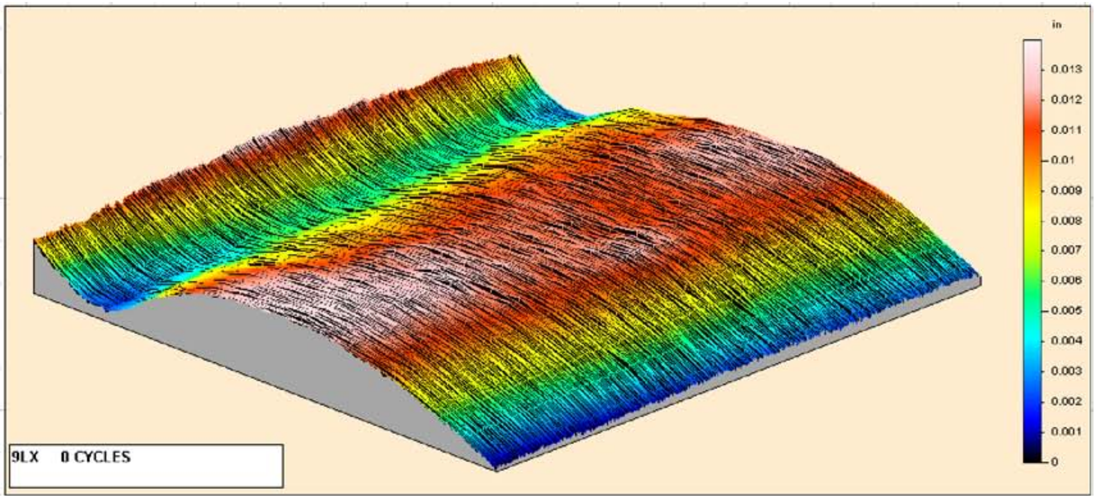


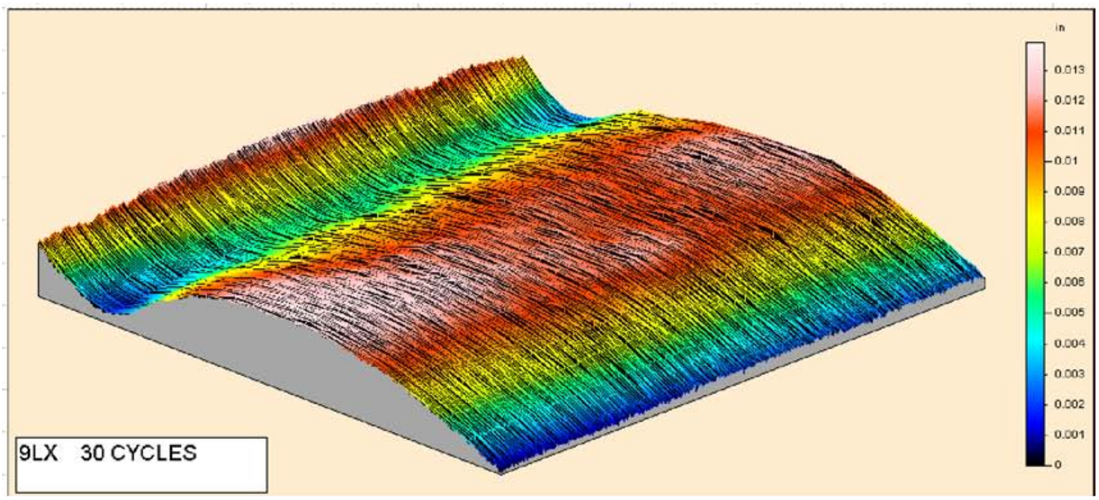
30 Cycles

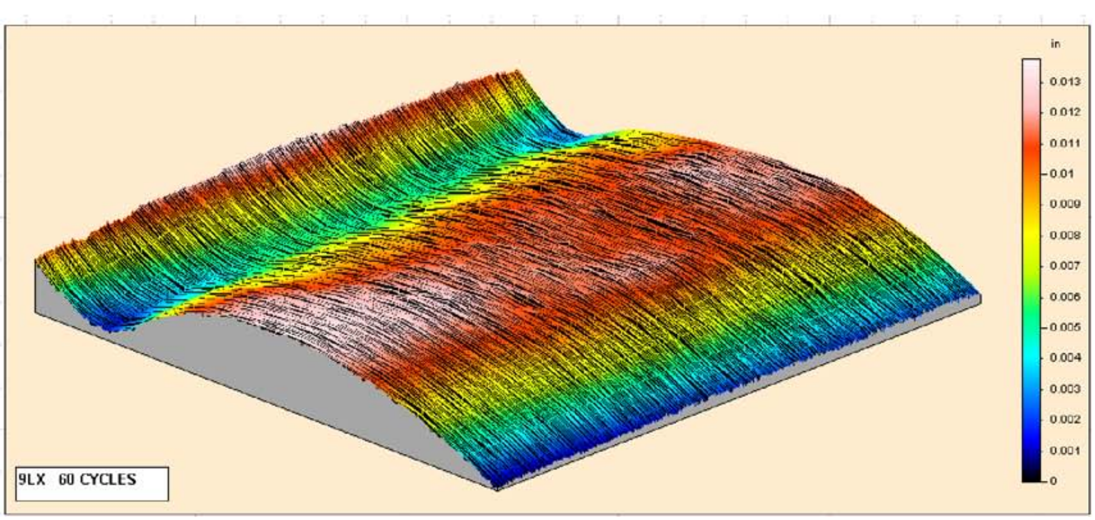


60 Cycles

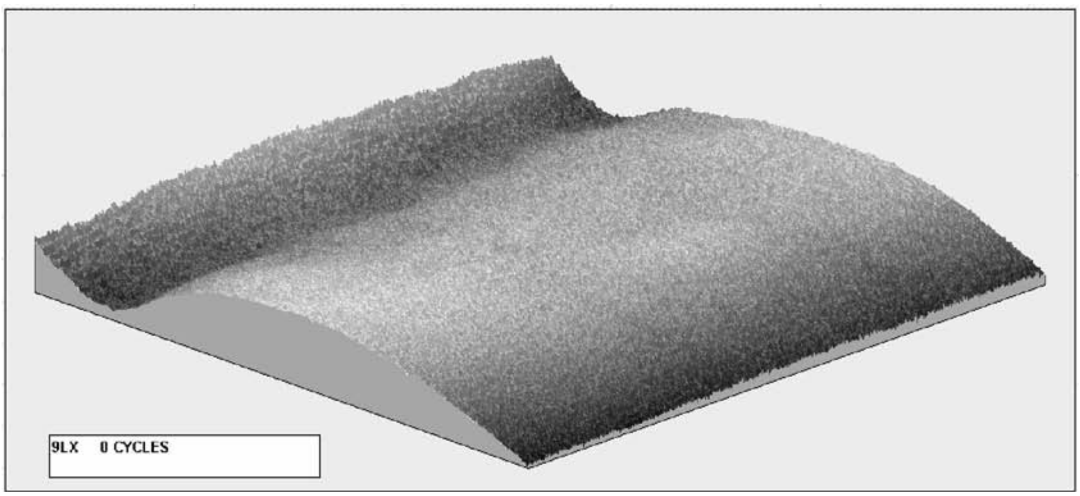
Contour Plots Across Grid Line 7 to 79 Before and After UT Scanning – No Removal of RCC Material Measured

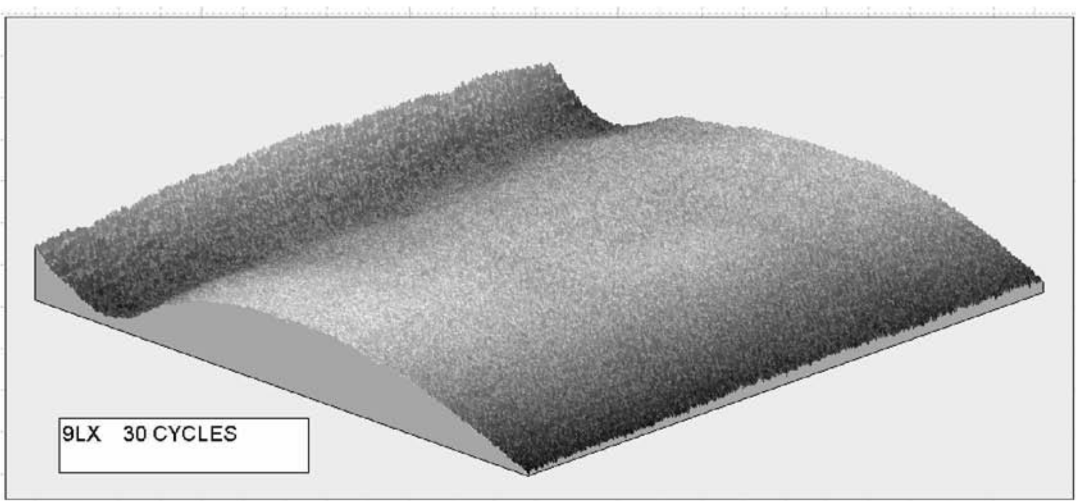


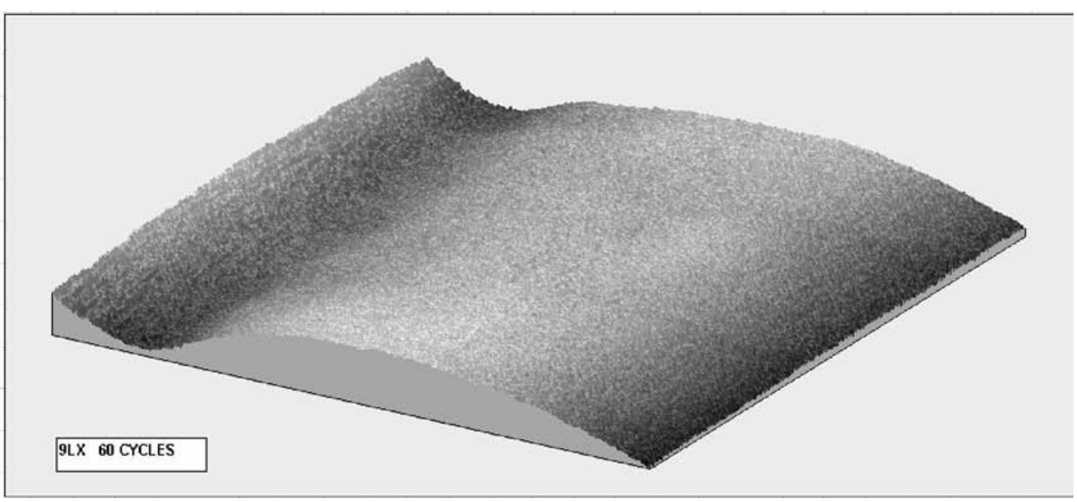




Three Dimensional Contour Plots of Entire Specimen Before and After UT Scanning - No Removal of RCC Material Measured

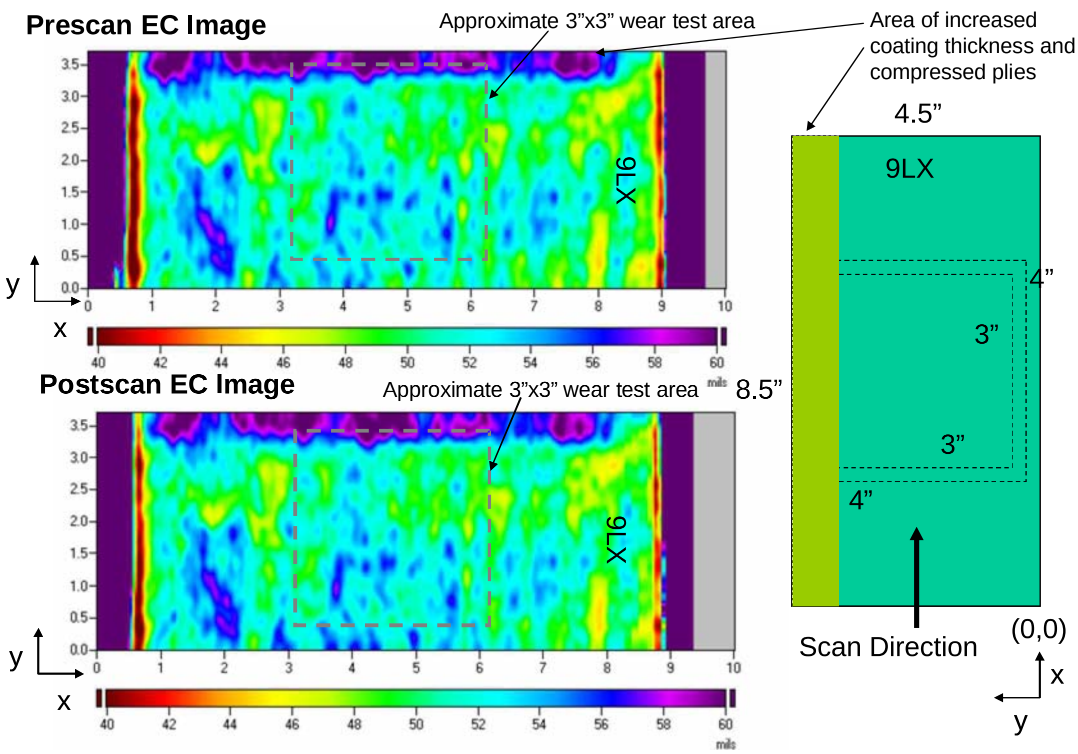




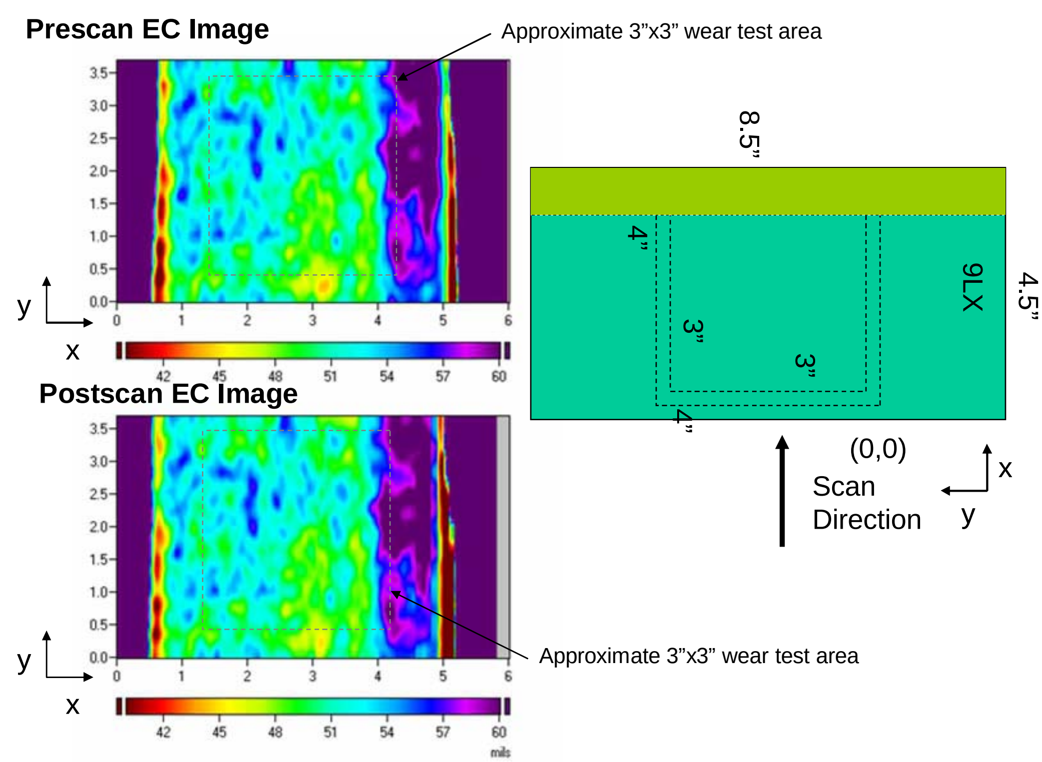


Three Dimensional Contour Plots of Entire Specimen Before and After UT Scanning - No Removal of RCC Material Measured

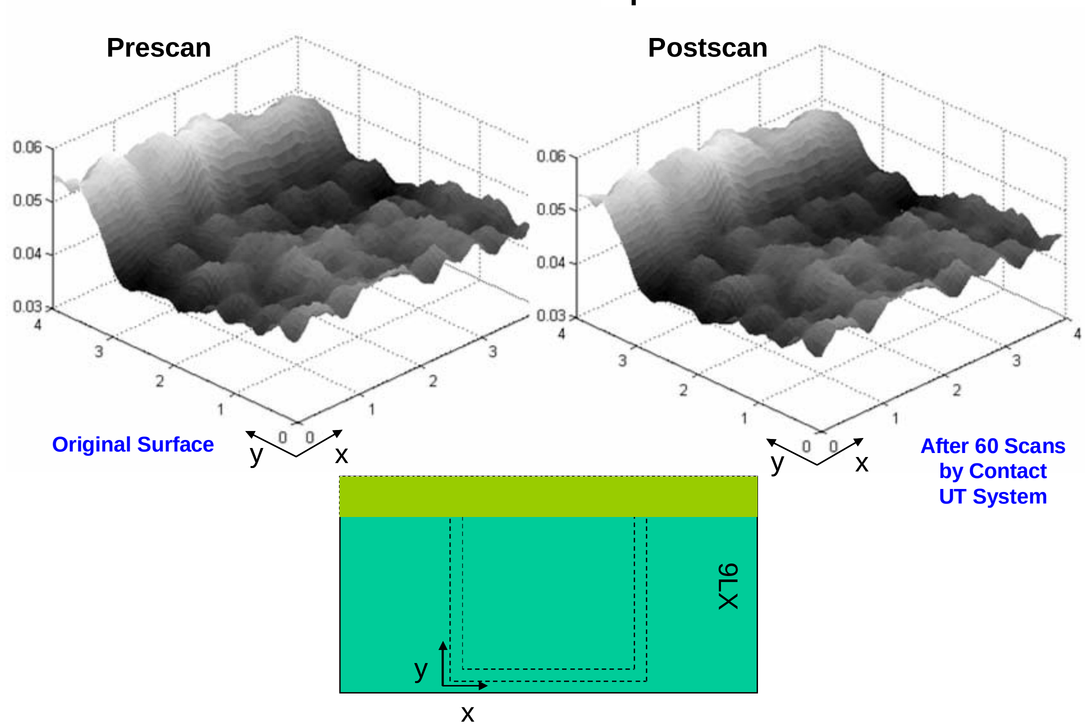
Eddy Current Results - 9LX Wear Test, MWM Scan Direction 1



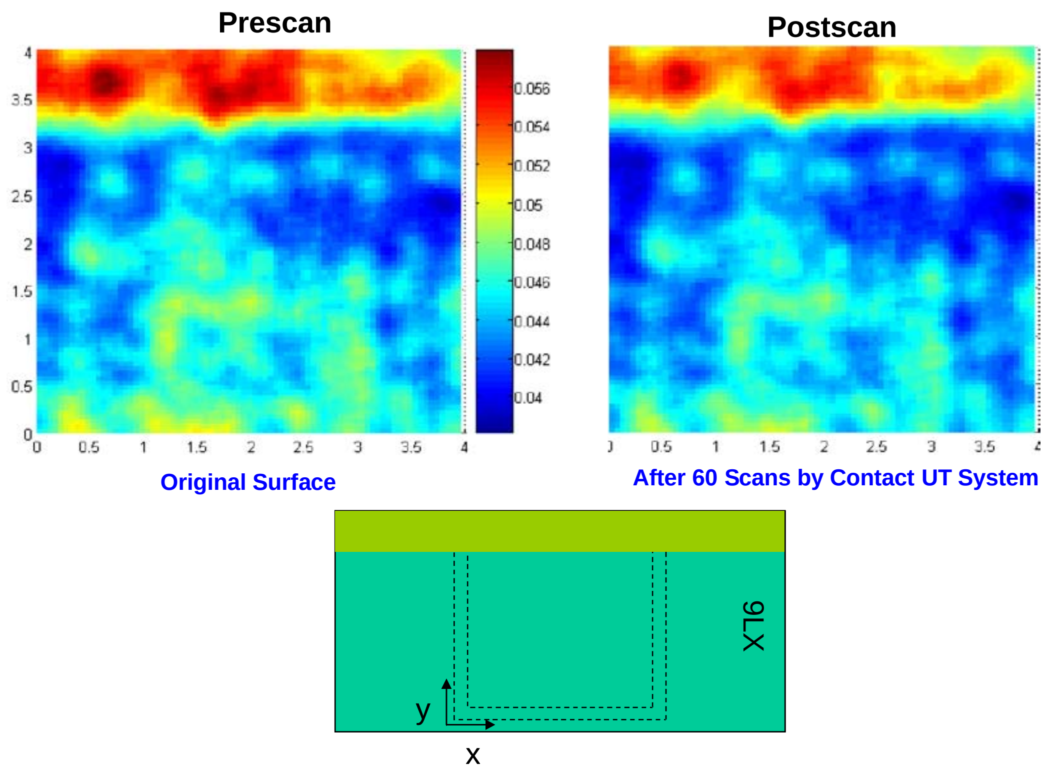
Eddy Current Results - 9LX Wear Test, MWM Scan Direction 2



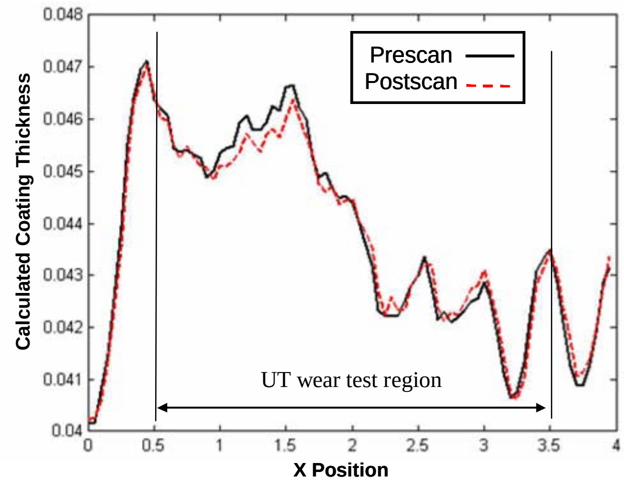
Eddv Current Results - 9LX Wear Test. Spot Probe Data

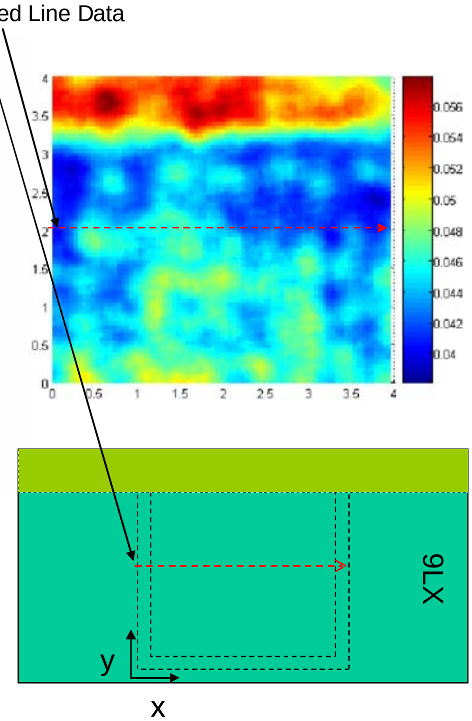


Eddy Current Results - 9LX Wear Test, Spot Probe Data



Eddy Current Results - 9LX Wear Test, Spot Probe Data





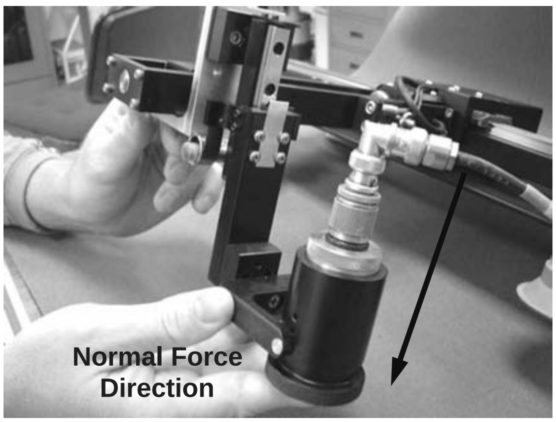
Postscan data shows a global shift of approximately 0.0005", most likely due to a calibration artifact. The global shift in the calculated lift-off could not be caused by the UT wear test scans, as the shift also extends beyond the wear test region into the unscanned area.

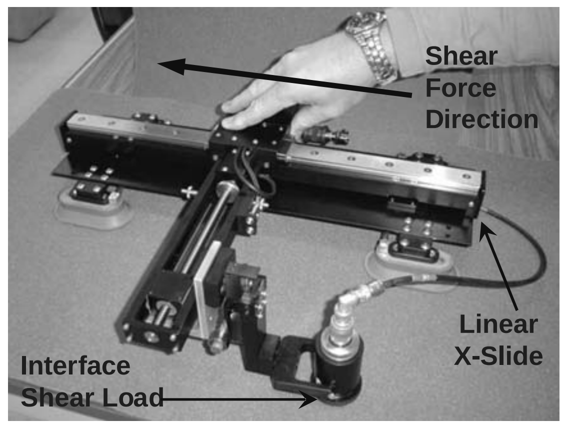
Conclusions from RCC Life Cycle Wear Study

- **Contact ultrasonic scanning system was applied to an RCC panel**
- **60 scans were completed to conservatively assess any RCC wear or degradation stemming from repeated exposure to the ultrasonic transducer housing**
- **Series of inspections were performed on the RCC panel before and after scanning to assess any changes in the surface**
- **Surface profilometry (resolution of 1 µin.) determined that the UT scans did not produce any wear in the RCC Si-C coating; profile data showed that the surface profile was unchanged by the UT probe housing after 60 scans over the same area**
- **Eddy current thickness mapping showed that there was no change in the thickness of the Si-C coating after 60 scans nor was there any change in the EC inspection images**
- **Microscopic photography of RCC panel determined that there were no materials from the probe housing (delrin or plastic membrane) deposited on the surface during UT scanning**

RCC Normal and Shear Loads Assessment

- **Measure Normal Loads - force needed to actuate the vertical, surface-follower springs in the linear spring, probe holder device**
- **Measure Shear Loads – A force transducer will be used to measure the force needed to actuate the scanner arm (determine the friction load at the transducer-RCC interface)**





RCC Contact Loads

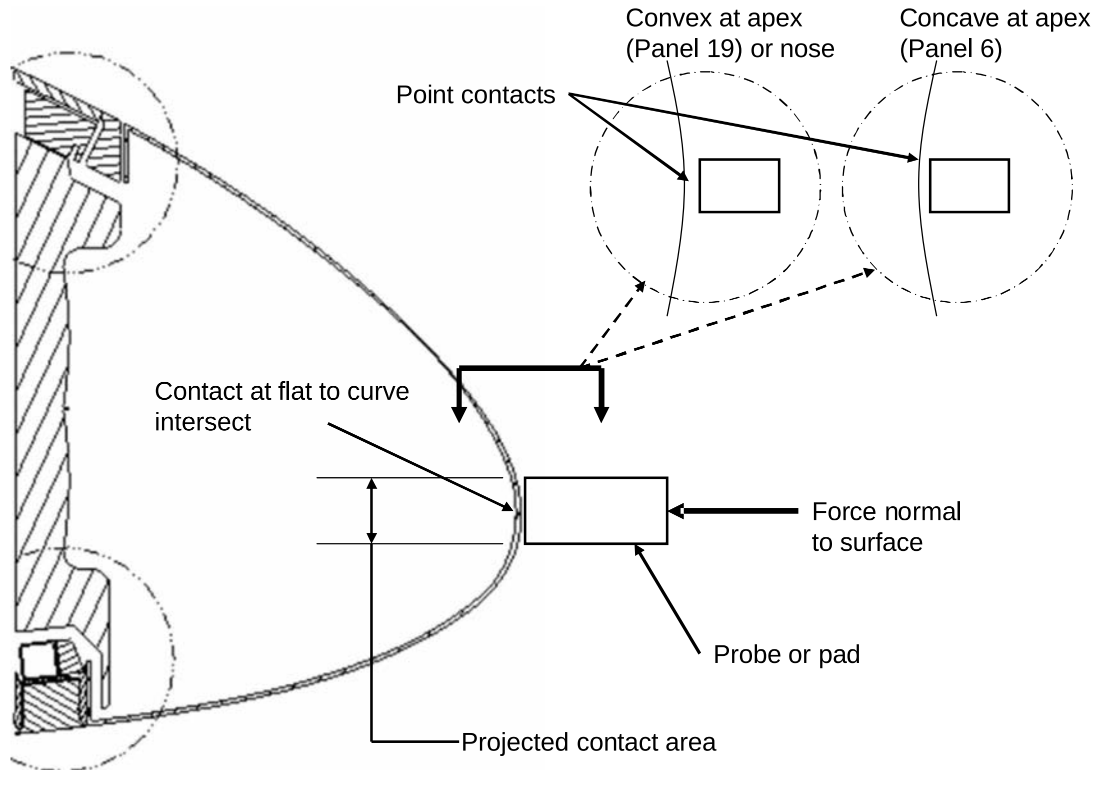
Scope

- These contact definitions prescribe the loads allowed to be applied to the RCC by NDE devices and define the allowed materials for devices applying loads to RCC
- These contact definitions are for the RCC NDE devices including
  - Flash Thermography hood
  - Eddy Current probe
  - Eddy Current MWM conformal array probe
  - Pulse Echo Ultrasound probe with weeper
  - Marking system templates

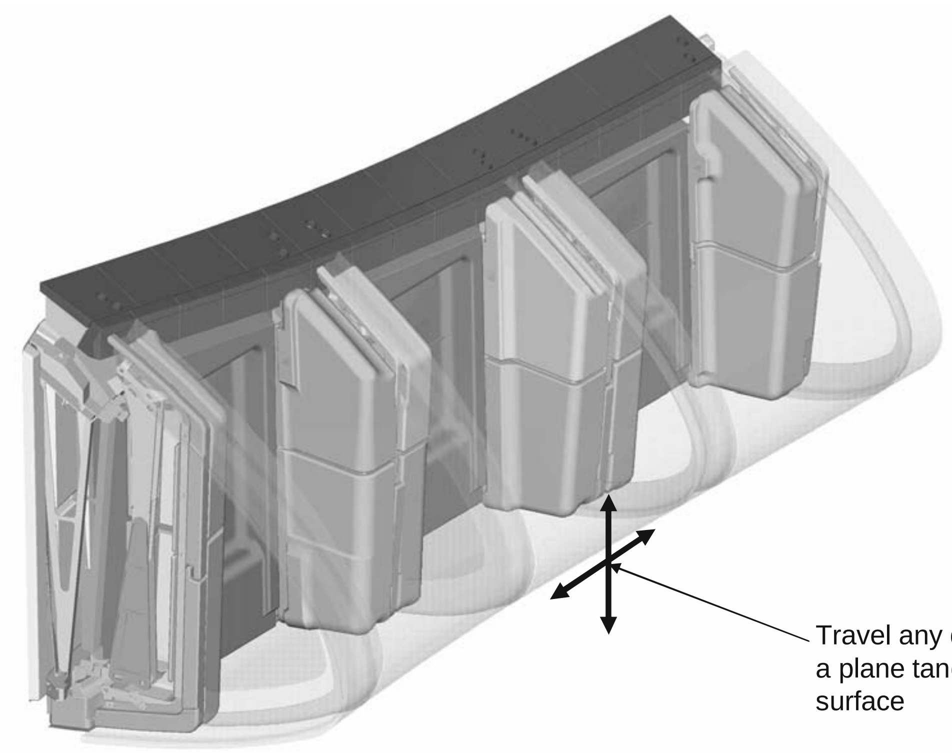
RCC Contact Loads Allowables

- Contact materials for this interface
  - Ensolite, Nylon, Delrin, Kapton, Mylar, urethane, phenolics, Mystic 7000/7001 tape
- Force applied is from the maximum allowed operator or equipment induced load
- Load applied normal to RCC surface with conforming contact
  - not to exceed 6 psi
  - not to exceed 30 lb total per panel (WLE, nose, chin) or gap seal
- Load applied normal to RCC surface with flat or nonconforming contact
  - projected contact area not to exceed 3 sq. inches
  - not to exceed 3 psi averaged over projected area
- Shear load not to exceed 3 psi

Flat or Nonconformal Contact



RCC Contact Configuration



NDE RCC UT Normal and Shear Load Measurement Test Plan

1. **Shear Stress Measurement (max 3 psi allowable)**
   a) **Use a force transducer to measure the force needed to move the scanner arm when the transducer is in the air (not conacting surface);** Linear Slide Resistance in Air = **R1**
   b) **Use a force transducer to measure the force needed to move the entire scanner arm so that the UT transducer moves across the RCC surface at maximum load.** Friction Shear Load + Slide Resistance = **R2**
   c) **Calculate friction force at RCC surface.** Friction Force at RCC Surface = **R2 – R1**
   d) **Divide this force by the projected surface area in contact with the RCC to determine shear stress.**
2. **Normal Stress Measurement (max 6 psi allowable; 3 psi for projected area)**
   a) **Use a force transducer to measure the force needed to actuate the vertical, surface-follower springs.**
   b) **Divide this force by the projected surface area in contact with the RCC to determine normal stress.**

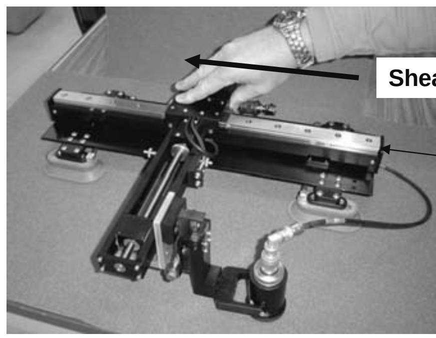
Assessment of Shear Forces on RCC

Measurement Device: Quantrol Advanced Force Gage 100N (resolution = 0.1 oz.)

<u>Shear Loads</u>

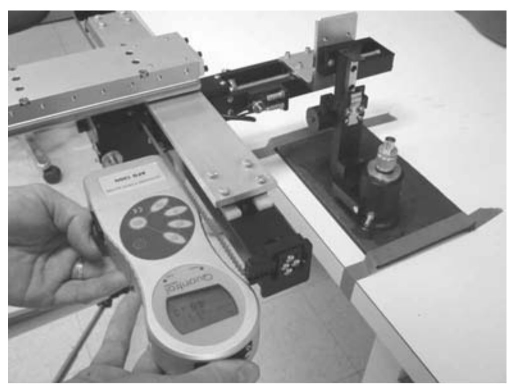
A force transducer will be used to measure the force needed to actuate the scanner arm as shown below. One measurement will be made without the transducer in place. This will determine the amount of force needed to move the scanner arm along the rail (resistance in the linear slide scanner arm). This is called the linear slide resistance force (R1). A second measurement will be made with the transducer mounted and an RCC panel in place under the transducer. In the second measurement, the UT transducer will move across the RCC surface. This second measurement will determine the friction load at the transducer-RCC interface as well as the resistance in the linear slide (scanner arm). This is called the friction shear load plus the linear slide resistance force (R2). The first force measurement will be subtracted from the second to determine the friction shear load on the RCC (R3). This friction shear load on the RCC (R3) will be divided by the surface area in contact with the RCC to determine the shear stress on the RCC panel. The shear stress shall not exceed 3 psi.

R2 – R1 = R3
(friction shear load on RCC)



Determining Shear Forces on RCC

<u>Average Three Measurements</u>



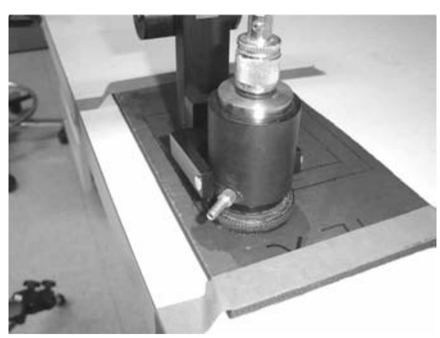
Linear Slide Resistance in Air = 31 oz., 31.5 oz., 30 oz.
R1 = 1.93 lbs. (30.8 oz.)

Friction Shear Load + Slide Resistance = 52.7 oz., 54 oz., 56 oz.
R2 = 3.39 lbs. (54.2 oz.)

Friction at RCC Surface = R2 – R1 = 1.46 lbs.

Surface Shear Stress = Friction at RCC/Surface area

Surface Shear Stress = 0.61 psi (min) to 1.88 psi (max)



Allowable shear stress on RCC panel is 3 psi

(membrane dia. = 1.0" for min contact area)
(delrin housing dia. = 1.75" for max contact area)

Assessment of Normal Forces on RCC

Measurement Device: Quantrol Advanced Force Gage 100N (resolution = 0.1 oz.)

<u>Normal Loads</u>

A force transducer will be used to measure the force needed to actuate the vertical, surface-follower springs in the NASA linear spring, probe holder device. The measured force will be divided by the surface area in contact with the RCC to determine the normal stress on the RCC panel. The normal stress shall not exceed 6 psi. The force will be measured at the base of the probe housing and in the direction shown below

Determining Normal Forces on RCC

<u>Average Three Measurements</u>

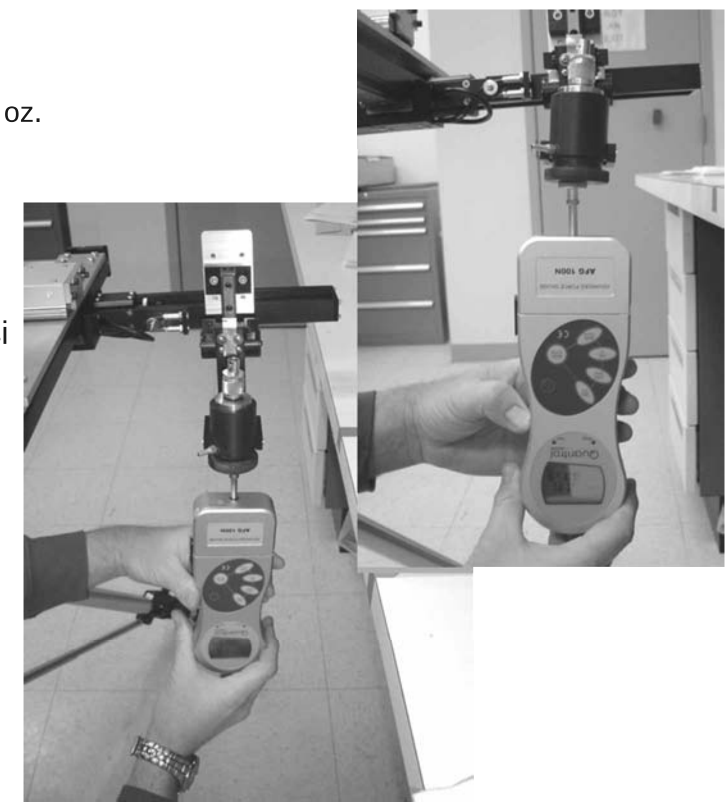
Normal Force = 49.5 oz., 50.5 oz., 50 oz.
F_n = 3.13 lbs. (50.0 oz.)

Normal Surface Stress = Normal Force at RCC/Surface area

Normal Surface Stress = 1.30 psi

Allowable normal stress on RCC panel is 3 psi if projected contact area is used

(delrin housing dia. = 1.75” for projected contact area A= 2.4 in.^{2})



APPENDIX B

PULSE-ECHO ULTRASONIC INSPECTION PROCEDURE for SPACE SHUTTLE SILICON CARBIDE COATED REINFORCED CARBON-CARBON (RCC) HEAT SHIELD PANELS

PULSE-ECHO ULTRASONIC INSPECTION PROCEDURE for SILICON CARBIDE COATED REINFORCED CARBON-CARBON (RCC) HEAT SHIELD PANELS USED ON THE SPACE SHUTTLE

April 2005
Phil Walkington and Dennis Roach
Sandia National Laboratories - Albuquerque, NM

Prepared for NASA

1.0 SCOPE

This procedure describes the criteria and procedure for ultrasonic (UT) inspection of silicon carbide coated reinforced carbon-carbon (RCC).

2.0 REFERENCES

2.1 SAIC Ultra Image International
Operation Manual UltraSpect-MP

3.0 REQUIREMENTS

3.1 Inspection Equipment

3.1.1 Ultra Image Low Profile 2-Axis Manual Scanner (LPS-100) per Figure 1 & 2

3.1.2 UltraSpect-MP Data Acquisition System per Figure 3

3.1.3 Sony laptop computer with SAIC Ultraspect software

3.1.4 Ultrasonic Probe (GE Inspection Technologies / Krautkramer 1 MHZ; 1.0 inch diameter; 2.0 inch SPH Focus part # 389-058-620) per Figure 4

3.1.5 Testech Weeper per Figure 5 & 6

3.1.6 Ultrasonic Calibration Standards

3.1.7 Bogen Tripod: manual scanner positioning mechanism (Model # 3058) per Figure 2

3.2 Supplemental Equipment and Materials

3.2.1 Ultrasonic Couplant - Distilled Water

3.2.2 Mystic Tape – approved for placement on RCC surface

3.2.3 120 V AC power

3.2.4 Personnel stand/ladder to allow access to points 76" from floor

3.2.5 Mylar film (0.001" thick)

3.3 Personnel

It is recommended that the inspector using this procedure be experienced and knowledgeable in the fundamentals of ultrasonic testing. Inspectors should fully possess the qualification of ultrasonic testing personnel as defined in Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive testing, available from ASNT (American Society for Nondestructive Testing), ATA 105 or other approved certification standard. It is recommended that the inspector has taken the SAIC Ultra Image International UltraSpect-MP Scanner Course so that they are familiar with all system software and controls.

4.0 PROCEDURES

Refer to the referenced operation manuals for the description of the software as needed. A brief overview of the System setup and Calibration Icons are shown in Figure 7.

4.1 Instrument Set-Up

4.1.1 Connect the cables between the laptop PC and data acquisition system (DAS) as shown in Figure 3. Setup the tripod and attach the manual scanner as shown in Figure 2. Attach the probe holding fixture (linear spring) to the manual scanner and then attach the WEEPER body to the yoke on the linear spring as shown in Figure 2. Place the ultrasonic (UT) probe into the WEEPER body and connect the water line to the weeper body from the water distribution system as shown in Figure 2. Finalize the cable connections from the DAS, manual scanner and ultrasonic probe as shown in Figure 3.

4.1.2 Position the manual scanner system over the UT Calibration Standard. Position the tripod with the manual scanner so that the linear spring which holds the Weeper body is in contact with the RCC surface. The linear spring should be at middle range of travel so that the Weeper body can follow gradual contour changes and move smoothly across the surface. Position the UT probe on the appropriate UT Calibration Standard at an unflawed area. Turn the power on to the recirculation pump in the water distribution system and set the recirculation valve to open. Next, adjust the water flow to the WEEPER body and clear out any air bubbles in the water column by turning the weeper end cap up so that any air can escape from the holes in the membrane. The UT Calibration Standard contains a series of flat bottom holes (FBH) at various depths from the front surface. These FBH locations are referenced in the following inspection procedure and can be used to interpret the inspection results.

4.1.2.1 During inspection of the calibration standard, the scanner and ultrasonic probe should be in the same orientation as they will be deployed in subsequent RCC inspections. The cal standard inspection can be completed on an adjacent work surface or by placing the calibration standard over the region of interest on the RCC panel. If necessary, Mylar film can be placed between the cal standard and the RCC surface. By looking at the resulting flaw pattern on the C-scan and comparing it to the known flaw layout in the calibration standard, this process will allow the inspector to determine the orientation of the C-scans produced by the system. This will ensure that any flaw indications found during the actual inspection will be accurately located on the RCC panel.

4.1.3 Turn the power on to the laptop PC. Once the laptop computer has booted up, go to the SYSTEM UTILITIES Icon and select which scanner will be used for this inspection (manual or automatic). The manual scanner can be selected in 'Defaults' at "Custom 1" as shown in Figure 8. The manual scanner can now be set up to perform an ultrasonic inspection. Turn the power on to the DAS. Now right click the red A icon in the lower right corner of the screen and then left click 'Status' for the System Status window to appear. In approximately 30 seconds to three minutes, the DAS Subsystem will indicate 'Online' as shown in Figure 9.

4.1.4 Now the ultrasonic test parameters can be set up by selecting the UT CALIBRATION Icon and selecting the 'OMASTER.tiff' file as shown in Figure 10. Once the 'OMASTER.tiff' file is open, go to 'File' and do a 'Save As' (example PE03482). The file is now unlocked so new setup parameters can be entered. Now go to 'Channel' and select "Channel 1" and then go to 'Settings' to select 'Select Ch/Gt' as shown in Figure 11. Four gates have been selected in this example. The ultrasonic transducer information can be documented in the 'Transducer' section (Figure 12).

4.1.5 Select "Pulser Preamp" and set PULSER TYPE to Sq. Wave and the WIDTH to 700 nanoseconds. Adjust the DAMPING to 100 ohms, GAIN to 35 dB, and VOLTAGE to 300 volts. Set the LP FILTER to off and the HP FILTER to 0.25 MHz.

4.1.6 Set the correct focus of the UT probe in the Weeper body in order to image the BS of the RCC material. Right now, the time base for the A-trace display is set to show the first twenty microseconds with the main bang on the left side as shown in Figure13. Go to "Gate Adjust", set the A-DELAY and A-WIDTH for 40 microseconds each and the C-DELAY for 45 microseconds and the C-WIDTH for 12 microseconds. Set the PEAK MODE to Max so that the highest peak in the gate is recorded. The A-trace display now displays a flat A-trace on the screen (Figure 14) because the back surface (BS) is later in time and could be viewed by changing the time base. As the inspector pushes the UT probe into the Weeper body an echo will appear in the A-trace display (Figure 15). Now the inspector needs to adjust the time base for the A-trace display for a viewing window of 44 to 60 microseconds and push the UT probe into the Weeper body until the large negative peak is at approximately 47 to 48 microseconds as shown in Figure16. The A-trace signal on the screen from left to right shows: (A) echo from the WEEPER membrane / front surface (FS) echo, (B) region between front and back surface, and (C) the back surface (BS) echo of the RCC material. The BS echo is approximately 5 microseconds from the FS (time base 53 microseconds). Due to the inspection frequency of 1 MHz there is a long ring down which makes it difficult to image flaws close to the FS. The signal variations between (B) and (C) are used to detect flaws in the RCC material.

4.1.7 Move the transducer around the RCC surface with the manual scanner X-Y Controls and adjust the "Pulser Preamp" GAIN until the amplitude of the echo from the back surface (BS) of the RCC reads approximately +80% Full Screen Height (FSH). These settings can vary from probe to probe and are somewhat dependent on operator preferences.

4.1.8 Set up the necessary parameters to do a full wave capture of the ultrasonic signals between the front surface (FS) and back surface (BS) of the RCC specimen. In the "Acquisition" menu, set the VIDEO MODE to collect "Full" wave (positive and negative peaks) data acquisition as shown in Figure17. Set the 'A/D Rate' to 50 Msps. Select "Signal Processing" and set the I-Gate from Off to SW (software gate) (Figure 18) and in the 'Gate' menu select the Interface Gate (Figure 19). Now the SURFACE FOLLOWER is on. The surface follower threshold can be set to approximately 50% by going to 'File' and unlocking this file. This selection should give a consistent signal display with the A-trace screen display triggering on the front surface echo signal (A) as shown in Figure 20.

4.1.9 To detect flaws in the RCC material, a series of gates will be positioned in the data acquisition system. The gates are set in order to control the acquisition of appropriate UT information. User specified depth gates allow only those echo signals that are received within a limited range of delay times following the front surface (FS) echo to be in the C-scan plot.

4.1.9.1 Now the inspector is ready to select "Gate Adjust" while the Interface Gate is still selected. The operator can set the V-DELAY to 45 microseconds, V-WIDTH to 20 microseconds for the full wave signal capture interval (green color on the A-trace display) and the I-DELAY to 46 microseconds, I-WIDTH to 12 microseconds for the C-scan plot (red color on the A-trace display) as shown in Figure 20. The full wave capture will allow the operator to re-adjust gate delays and widths after the RCC material has been scanned and generate new C-scan plots. The position and number of gates will determine the C-scan data plotted. The operator can select up to four separate gates consisting of either positive, negative, or both signal amplitudes or time of flight intervals. The gates can be positioned by selecting 'GATE' and selecting either Gate 1, 2, 3 or 4 in the menu (Figure 21 and 22).

4.1.9.2 By employing a series of gates in one scan, it is possible to display data over a wide range of depths. Once 'Gate 1' has been selected, the operator can set the I-DELAY and I-WIDTH for each of the four gates to display C-scan information. Repeat the gate selection process for each of the four gates.

4.1.9.3 Set-up information will be saved for this file upon exit. It is important to understand that once a file is unlocked, any changes will be saved upon exit. To recall a particular setup, just go back to the UT CALIBRATION icon and select that FILE (example PE03482) and go to 'File' and do a 'Save As' (example PE03482x). By opening this file, all the old scanning parameters are called in and will be saved under a new test name. This way the original file won't be altered.

4.1.10 Complete the calibration standard inspection.

4.1.10.1 Position the UT probe over the reference standard that represents the inspection zone to be scanned and adjust the water flow to the weeper body to ensure optimum UT coupling with the RCC surface.

4.1.10.2 Use engineered flaws on the reference standard to check equipment operation and data acquisition gate settings. Use this set-up and standard to adjust the position (focus) of the UT probe in its housing so that an optimal back surface signal is produced.

4.1.10.3 Adjust the gain until the amplitude of the echo from the back surface of the RCC is approximately 80% of full screen height over a non-flawed area and record the gain level used.

4.1.10.4 Establish scan boundaries to cover the region of interest, set the step size for data acquisition in the X and Y direction to 0.040" increments, and complete a scan of the reference standard.

4.1.10.5 Save the recorded data to the computer hard disk

4.2 Inspection Procedure

4.2.1 Position the tripod with the manual scanner so that the linear spring which holds the Weeper body is in contact with the silicon carbide coated reinforced carbon-carbon (RCC) surface. The linear spring should be at middle range of travel so that the Weeper body can follow gradual contour changes and move smoothly across the surface. Turn the power on to the recirculation pump in the water distribution system and set the recirculation valve to open. Next adjust the water flow to the WEEPER body and clear out any air bubbles in the water column by turning the weeper end cap up so that any air can escape from the holes in the membrane. Now the ultrasonic test parameters can be set up by selecting the EXAM icon and selecting the current test name (example 'PE03482.tiff') file. After this file is opened, go to 'Scanner' and select "Exam Setup/Position" as shown in Figure 23. Then enter the X-Y scanning dimensions and the interval for the X-Y data collection in the "Exam Setup/Scanner Position" menu as shown in Figure 24.

4.2.2 Establish the scan boundaries to cover the region of interest and set the step size for data acquisition in the X and Y direction to 0.040" increments.

4.1.2.1 Prior to initiating the inspection scan, place a piece of Mystic tape on the RCC panel such that it is inside the edge of the scan boundary but not over any inspection area of interest. When the UT probe encounters the tape, a distinct signal – and thus a distinct image – will be produced in the C-scan. This unique portion of the C-scan will allow the inspector to determine the orientation of the C-scans produced by the system. This will ensure that any flaw indications found during the actual inspection will be accurately located on the RCC panel.

4.2.3 Adjust the water flow to the weeper body to ensure optimum UT coupling with the inspection surface.

4.2.4 Move the UT transducer to at least three different locations within the inspection area of interest. Adjust the gain until the amplitude of the echo from the back surface of the RCC is approximately 80% of full screen height over a non-flawed area and record the gain level used. Gain adjustments from the levels set using the calibration standard will not exceed ± 4 dB and may not be changed during a scan. The difference between the reference standard gain and the inspection zone gain used is referred to as the transfer gain.

4.2.5 Complete the UT inspection by using the manual scanner to move the UT transducer over the prescribed region of interest. The probe can now be indexed to the starting position and the "Zero Position" selected so that each axis is set to zero (Figure 24). The scanning parameters are:

Index Axis: Y

Scan Axis: X

X & Y Resolution	EXAMPLE	0.04 inches
Y-Scan Length	EXAMPLE	6 inches
X-Scan Length	EXAMPLE	6 inches
Y-Scan Exam Vel	EXAMPLE	1.0 (Manual)
X-Scan Exam Vel	EXAMPLE	1.0(Manual)

Finally, the inspector can check all the Scan Setup Parameters and, if satisfied, the scan can be started by selecting "Scan" (Figure 25). At the end of the scan, the operator can STOP and then save the data (Figure26). The engineered flaws are clearly visible when viewed side-by-side with adjacent, unflawed material.

4.2.6 To RESCAN a specific region within the scan area before the scan is saved, just use the X-Y controls to go back over an area and the new data will be rewritten.

4.2.7 Save the recorded data to the computer hard disk.

4.2.8 Data analysis: utilize the "Amplitude" and "Time of Flight" C-scan images, along with select A-scan waveforms from critical regions to determine the presence of flaws in the material.

4.2.9 To SCAN a new area, go to the UT CALIBRATION Icon and select the "test.tiff" file that has the right scanning test parameter. Once the "test.tiff' file is open, go to 'File' and do a 'Save As' (example PE03482x). Now the inspector has the new test file ready. The file is now unlocked so new setup parameters can be entered if needed. Next the ultrasonic test scan parameters can be set up by selecting the EXAM icon and selecting the new test name (example ‘PE03482x.tiff’) file. Once this file is open, go to ‘Scanner’ and check the X-Y scanning dimensions and the interval for the X-Y data collection. The probe can now be indexed to the starting position and the “Zero Position” selected so that each axis is set to zero. Then select “Scan” to start the data collection for the new test.

5.0 EVALUATION

5.1 Once the digitized A-scan waveforms are recorded during the ultrasonic pulse-echo inspection of the RCC material, the amplitude, dB (attenuation), and time of fight peak signals can be displayed as a C-scan image and analyzed to determine if a flaw exist within the material. The reflected beam from the back surface of the RCC material can be used as the starting point for this analysis. The pseudo colored C-scan image can reveal several variations within the RCC material. The peak amplitude from the back surface is affected by the attenuation within the material and will be displayed in the pseudo colored C-scan image. Any large amplitude change (>12db) in the C-scan image shall be reported. Depending upon the geometry of a flaw and location within the RCC material, the amplitude might not appear very different than that of the surrounding back surface. This is where the time of flight C-scan image can show a slight shift in the pseudo color of the back surface. By analyzing all pseudo colored images (amplitude, dB, and time of flight) and the A-scan waveforms, the inspector can determine if a flaw exists within the RCC material. The time of flight C-scan image also shows thickness variations or the taper along the edges of the RCC panel. Figure 27 is a photo of an RCC test specimen containing flat bottom holes on the backside. Inspections were completed from the opposite (unflawed) side and the resulting C-scan image is shown in Figure 28. The flaws are detected by the UT system and clearly imaged in the color-coded scans.

6.0 INSPECTION RESULTS

6.1 Report all flaws greater than 0.25 inches in diameter and any large amplitude changes (greater than 12 dB) that appear in the C-scan image to the appropriate engineering personnel on site for further evaluation / action.

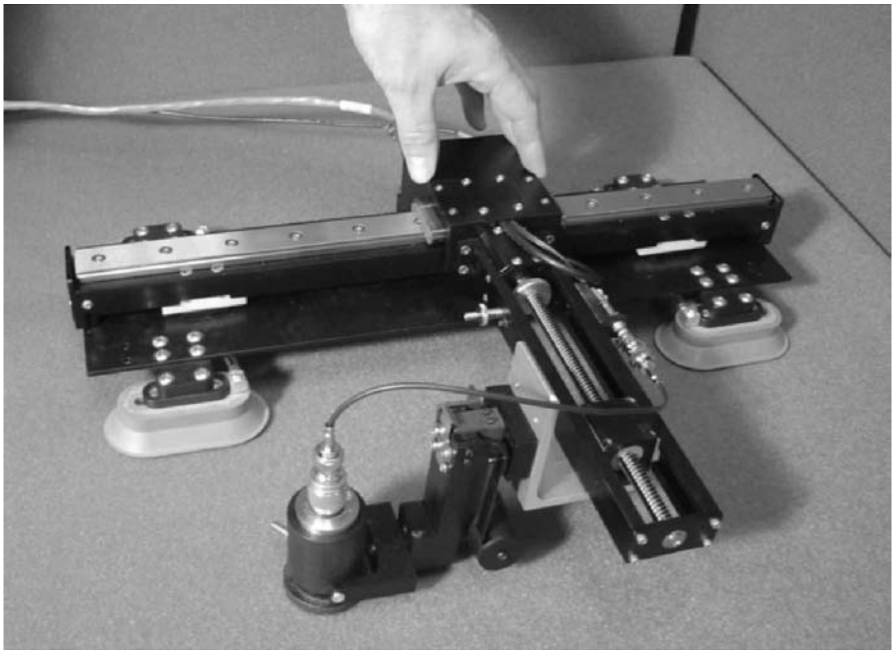


Figure 1: Ultra Image Low Profile 2-Axis Manual Scanner

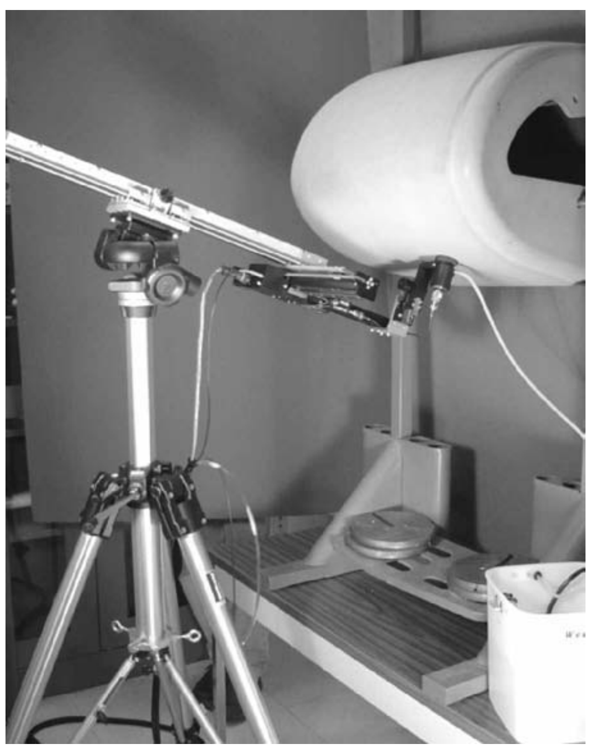
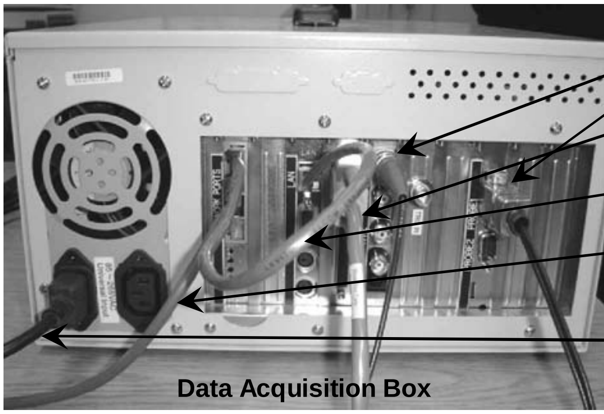


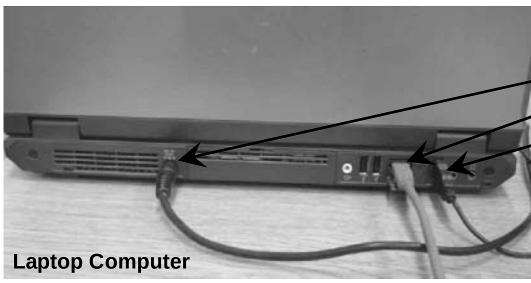
Figure 2: Manual Scanner Mounted on Tripod with Weeper

UT and EC Scanner System Hook-Up



Connections on Back of DAS Box:

- **UT transducer ⇒ T/R1 (BNC connector)**
- **EC transducer ⇒ Probe 1 (9 pin, male)**
- **Scanner position encoders ⇒ 9 pin female connector**
- **Network jumper (blue cable) ⇒ connect LAN to top Network Port**
- **DAS-to-computer (orange cable) ⇒ second port on Network Ports card**



Connections on Back of Laptop:

- **Power supply to computer**
- **Computer-to-DAS (orange cable)**

Figure 3: Cable Connections Between Laptop, DAS, Manual Scanner and UT Probe

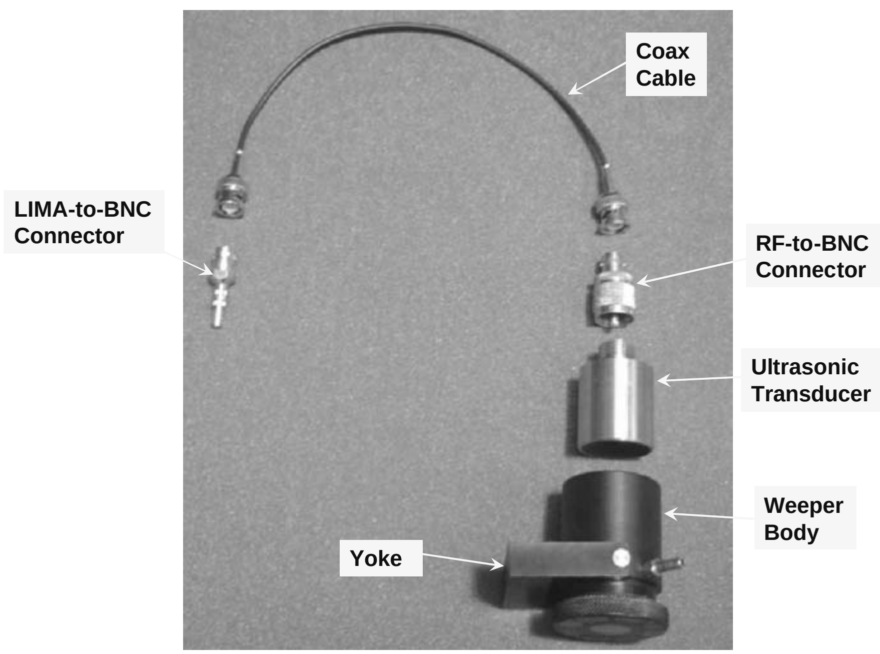


Figure 4: Individual View of Weeper Body, Ultrasonic Transducer Connectors and Coax Cable

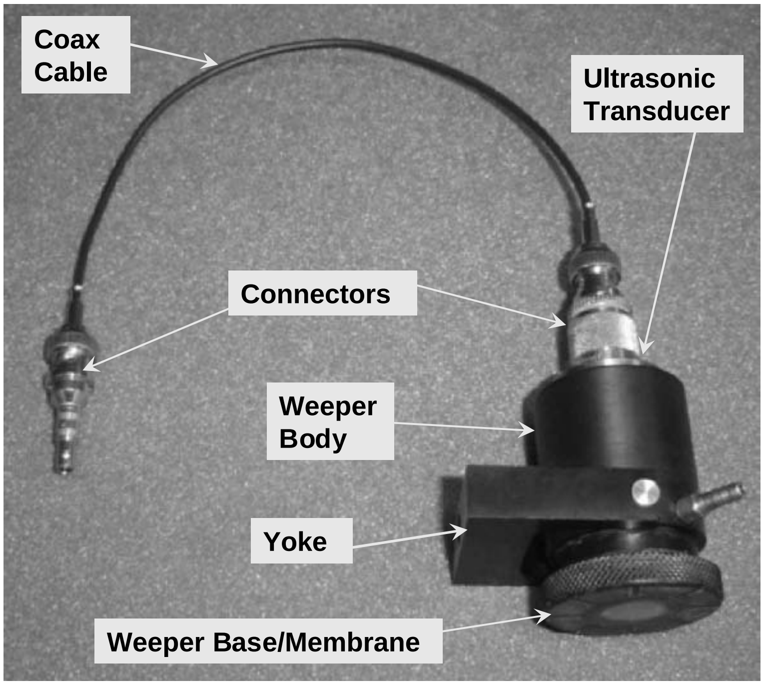


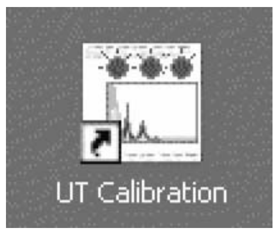
Figure 5: Assembled View of Weeper Body, Ultrasonic Transducer, Connectors and Coax Cable

Figure 6: Testech Weeper Water Supply

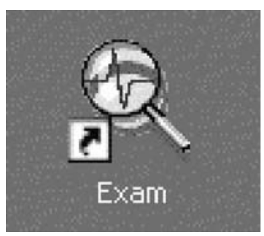
System Setup and Calibration

As with all inspection processes, Calibration file selection is the first step to setting up the instrument for data acquisition. Double clicking the calibration icon (shown below) will bring up the file selection window as shown on the next page. The other system icons and a brief explanation of their function are also given.

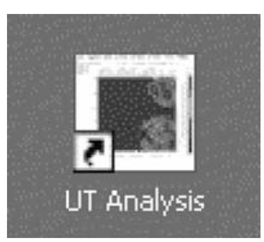
UT Calibration: Ultrasonic parameters setup and calibration module. Setup files may be selected or created; UT calibrations are performed in this module.



Exam: Data acquisition module. All scanner functions and data collection parameters are controlled from this module. Motion control for jogging and positioning scanner head can be performed here.



Analysis: All data analysis and report functions are performed in this module.



Scanner Position: Contains the same motion control for jogging and positioning as found in Exam but does not require an Exam file to be opened.

System Utilities: Scanner selection, Motion enable and other functions are found in this module.

Figure 7: System Setup and Calibration Icons

Figure 8: System Utilities Menu

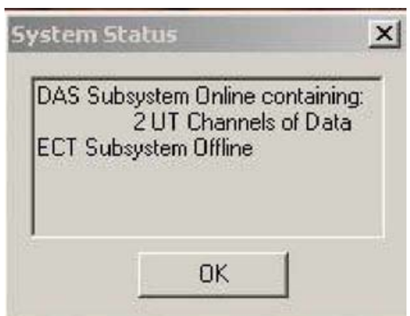


Figure 9: System Status

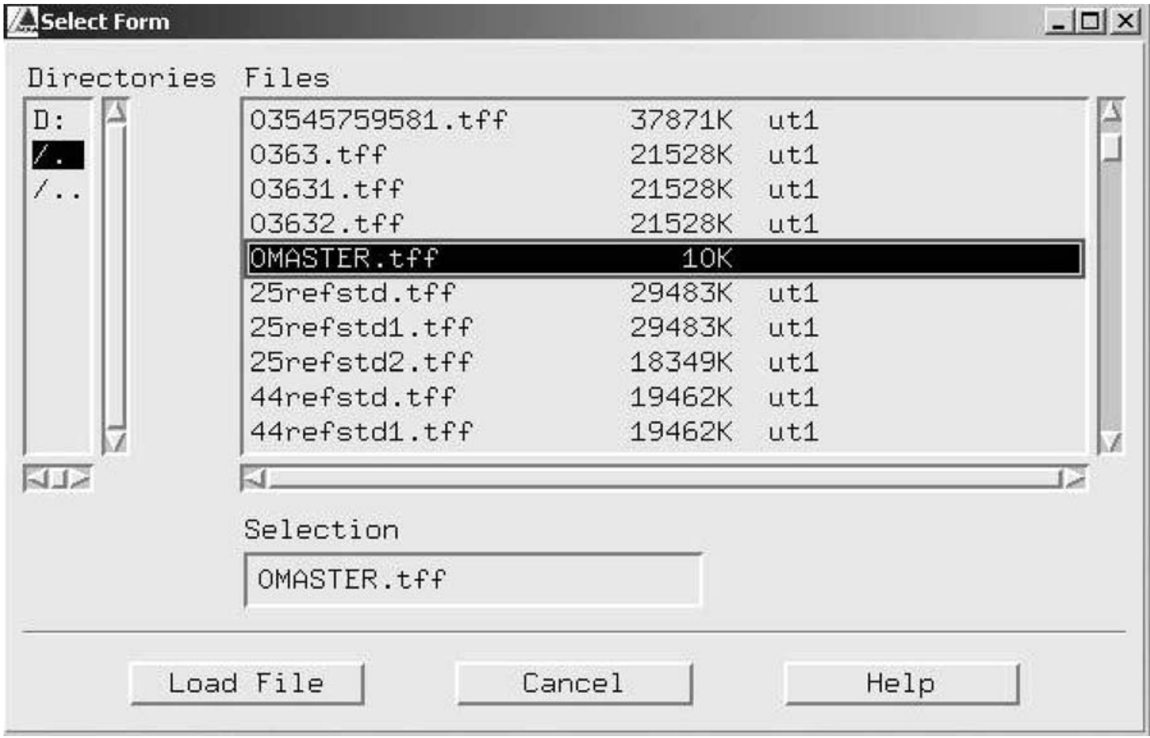


Figure 10: UT File Selection

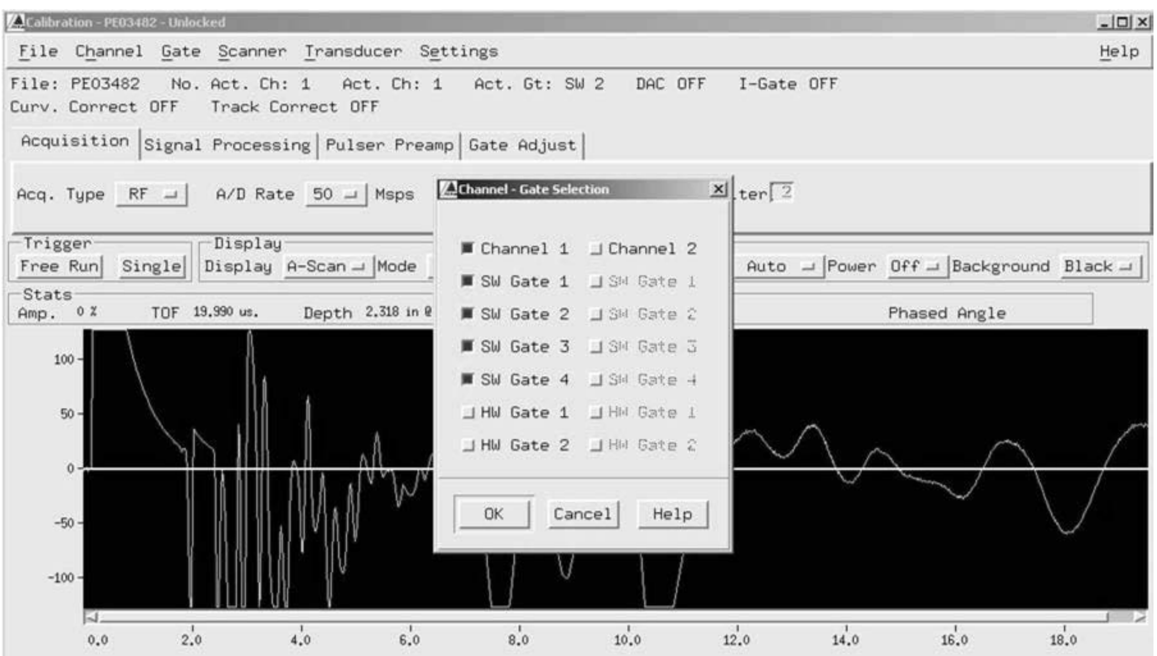


Figure 11: Channel 1 Gate Selection

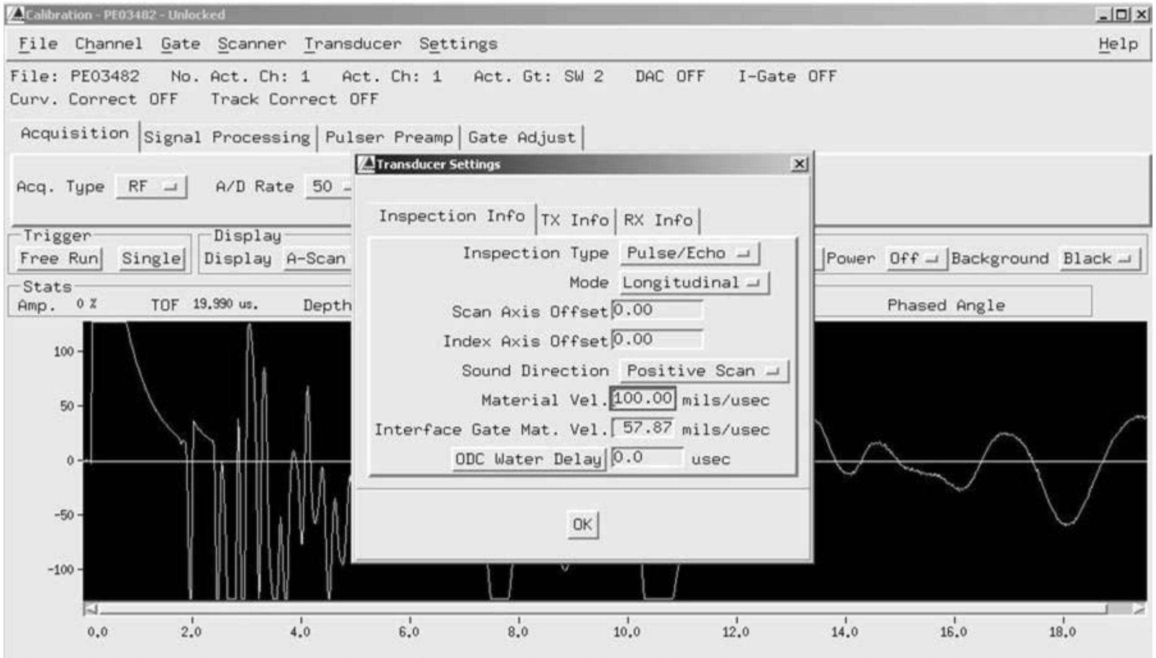


Figure 12: Transducer Settings

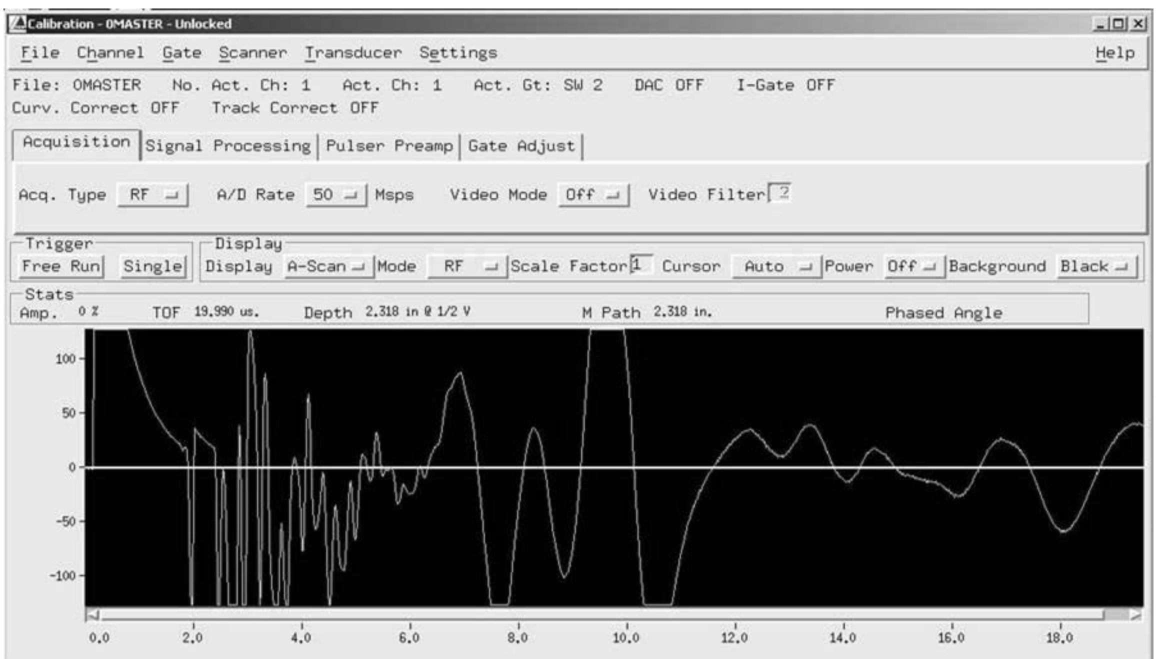


Figure 13: UT Main Bang Signal on A-trace Display

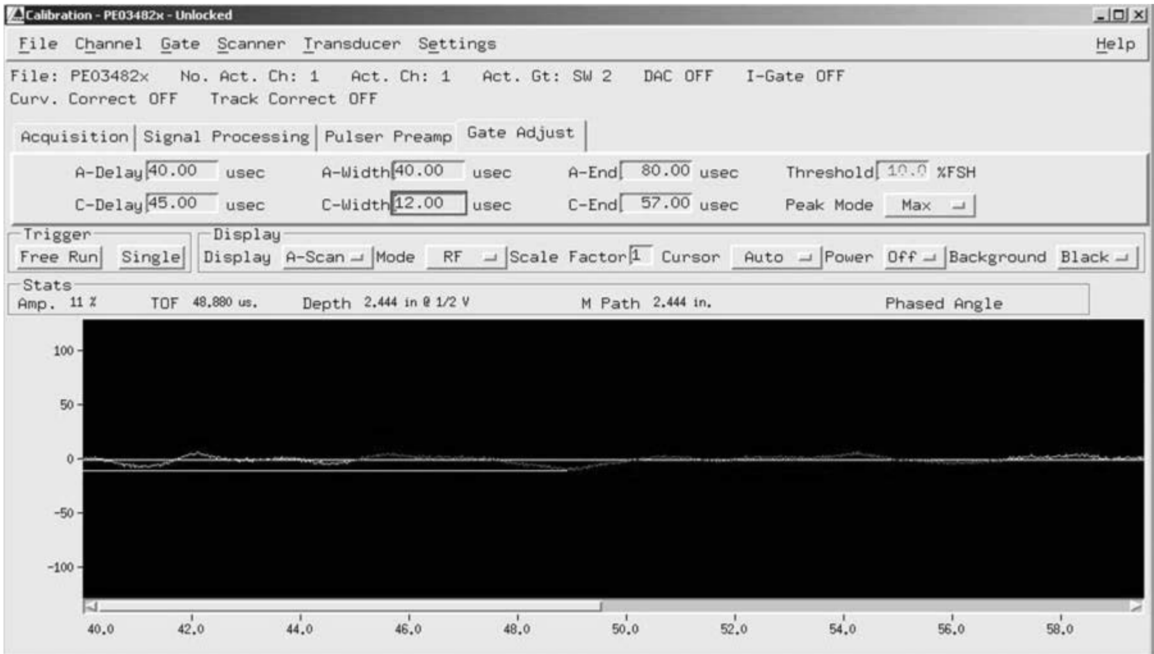


Figure 14: UT signal on A-trace Display during Weeper/probe adjust

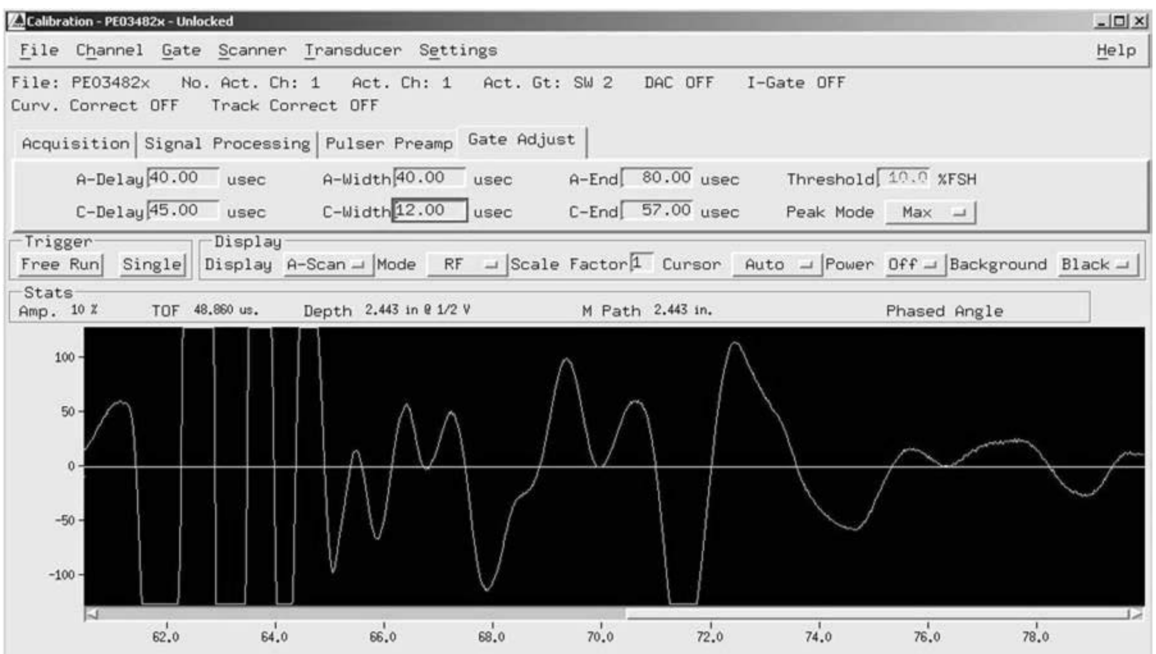


Figure 15: UT signal on A-trace Display during Weeper/probe adjust

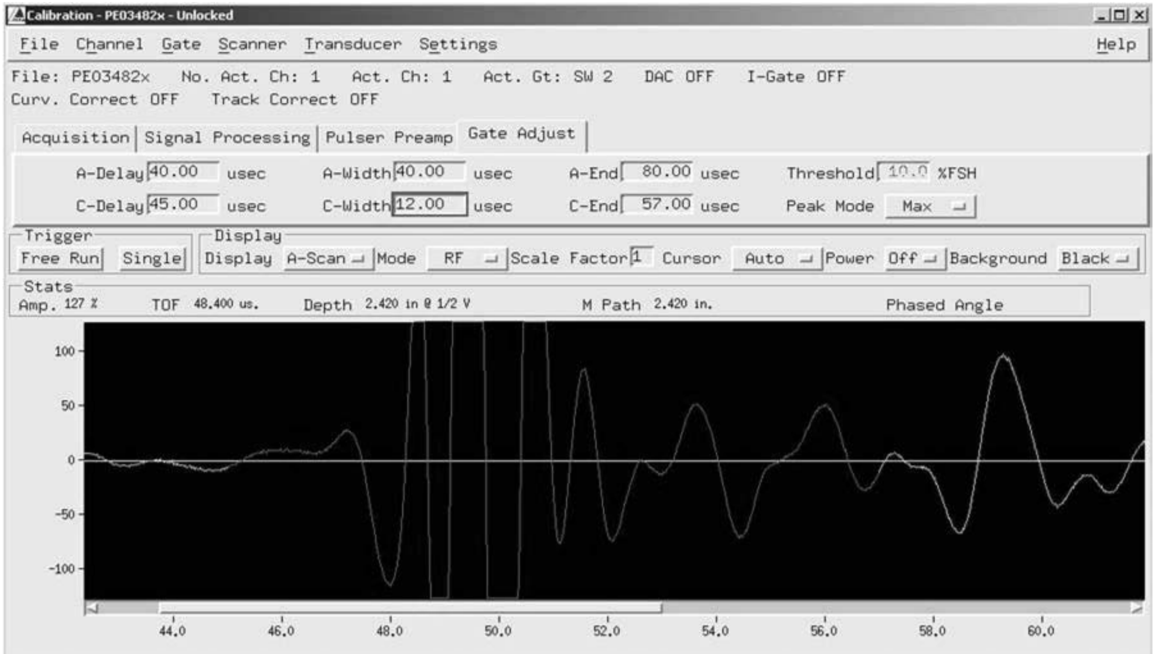


Figure 16: UT signal on A-trace Display at Inspection Focus

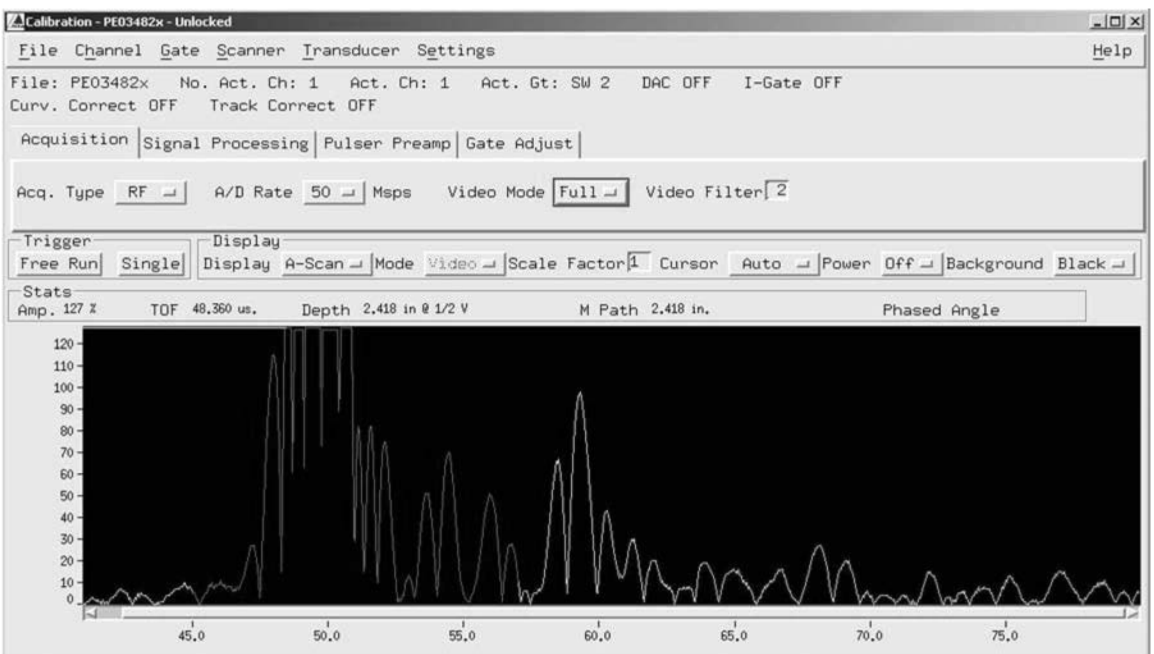


Figure 17: Acquisition Menu/Video Mode set to Full wave capture

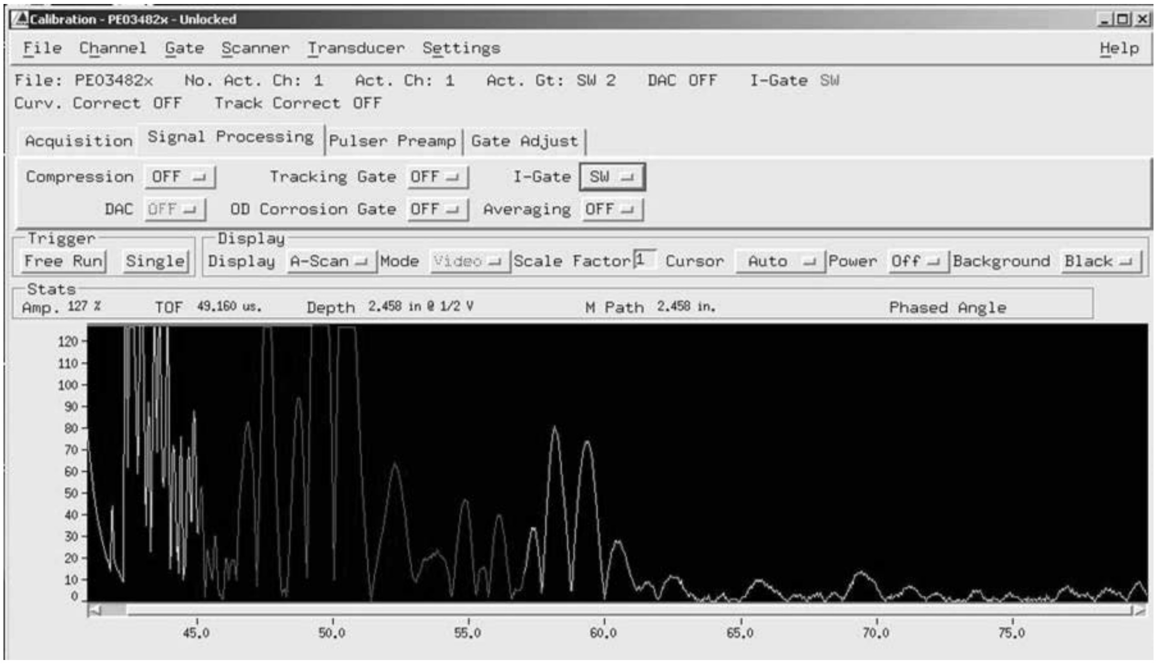


Figure 18: Signal Processing Menu/SW Gate selected

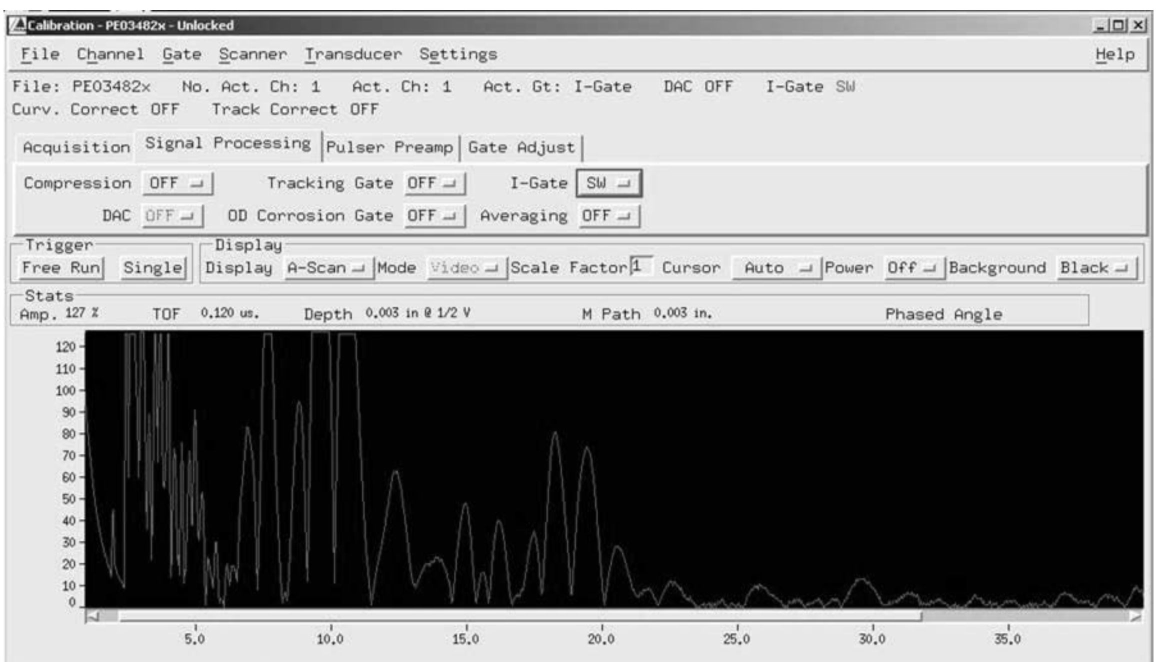


Figure 19: Gate Menu/Interface Gate selected

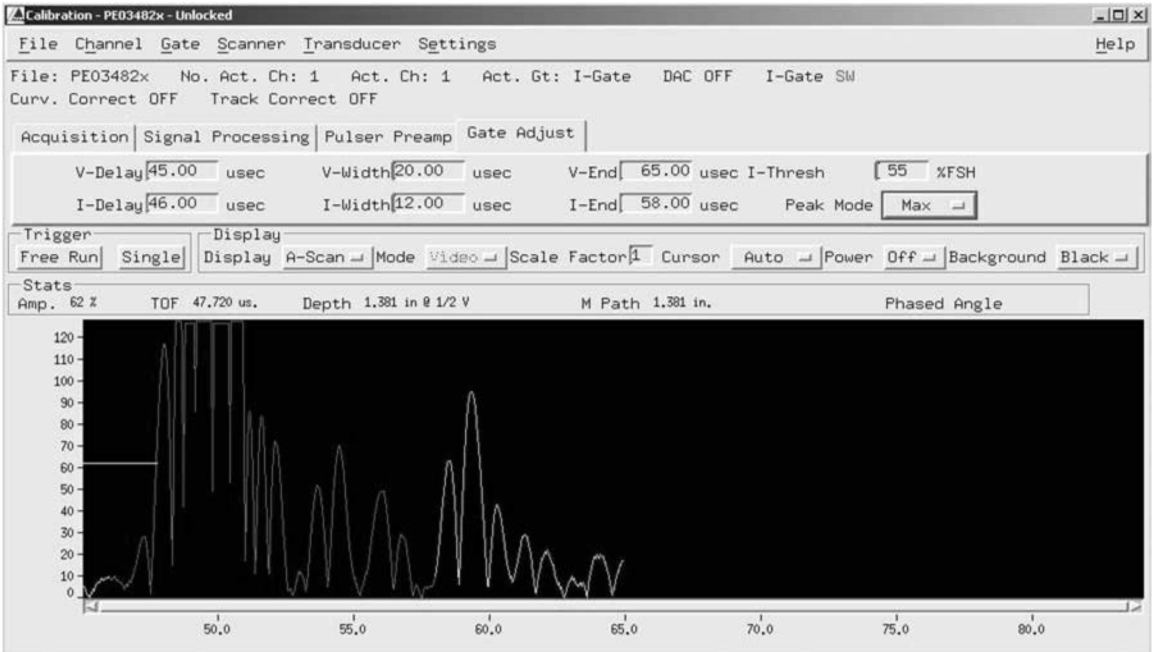


Figure 20: Surface Follower Threshold set to 50% FSH

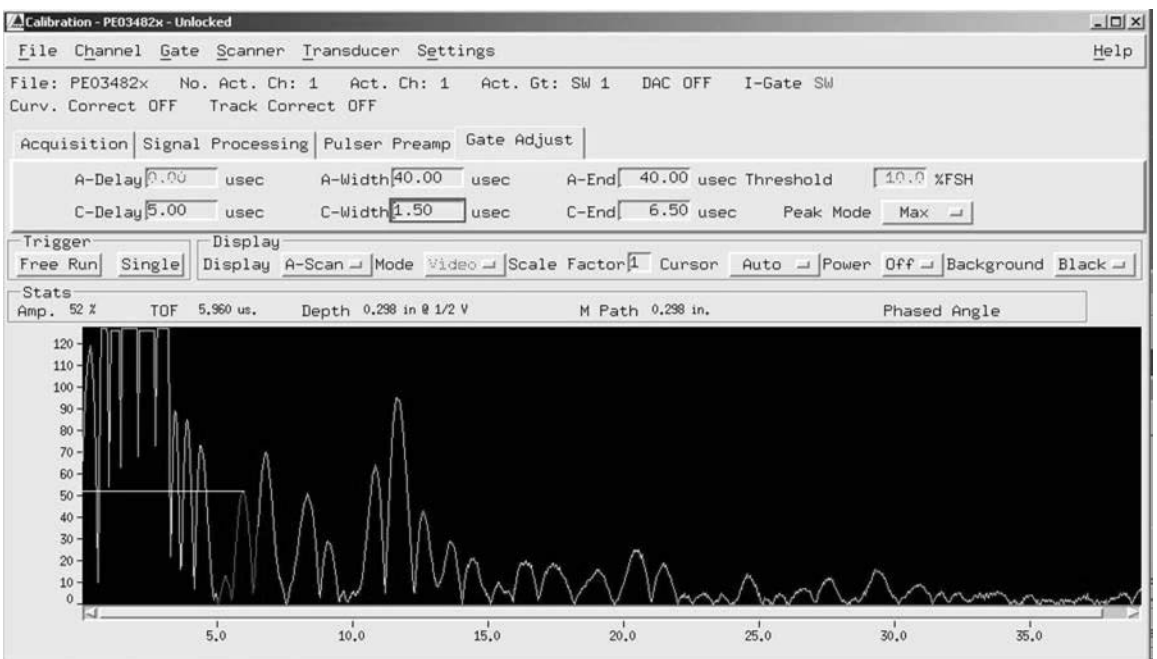


Figure 21: Gate 1 setup to display data at C-Delay of 5 microseconds

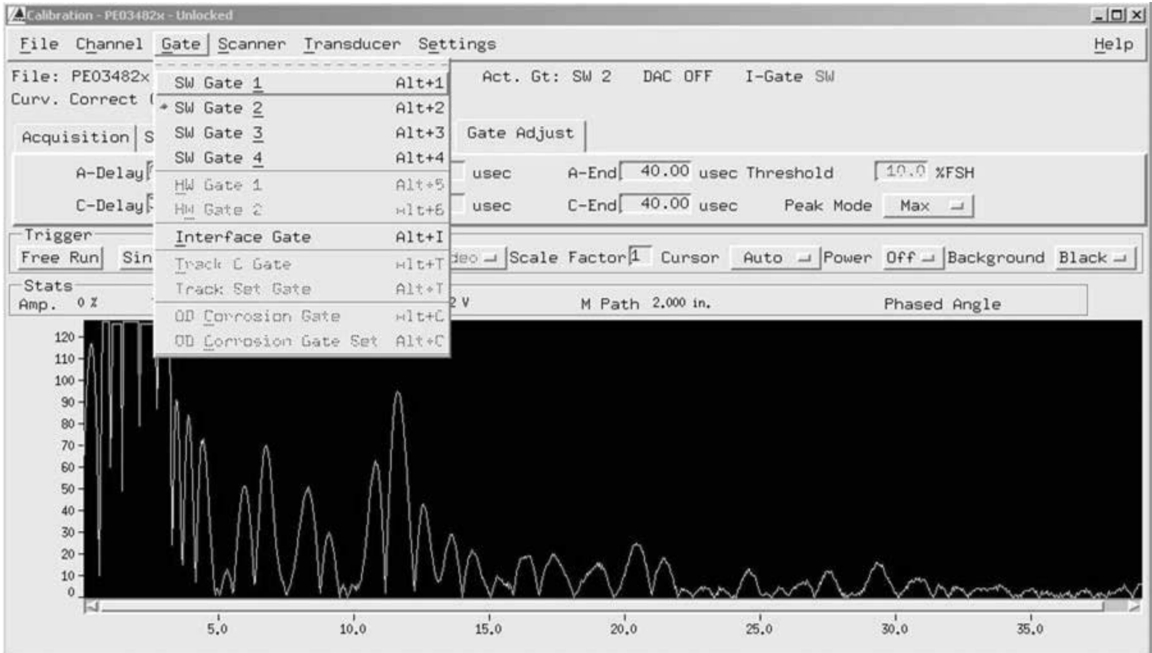


Figure 22: Gate Menu with Gate 2 selected

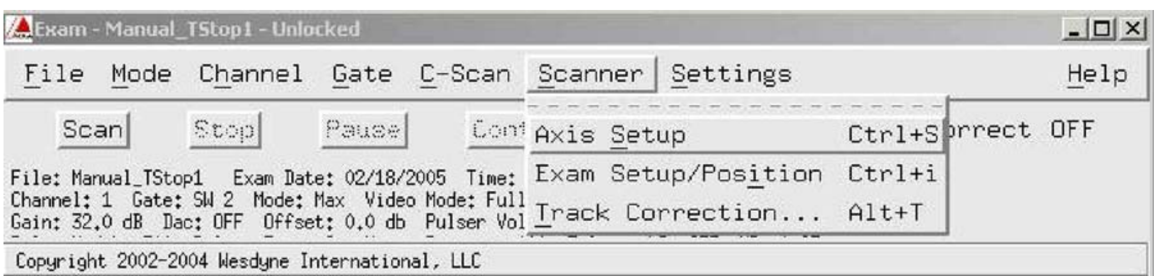


Figure 23: Exam Setup/Position Menu

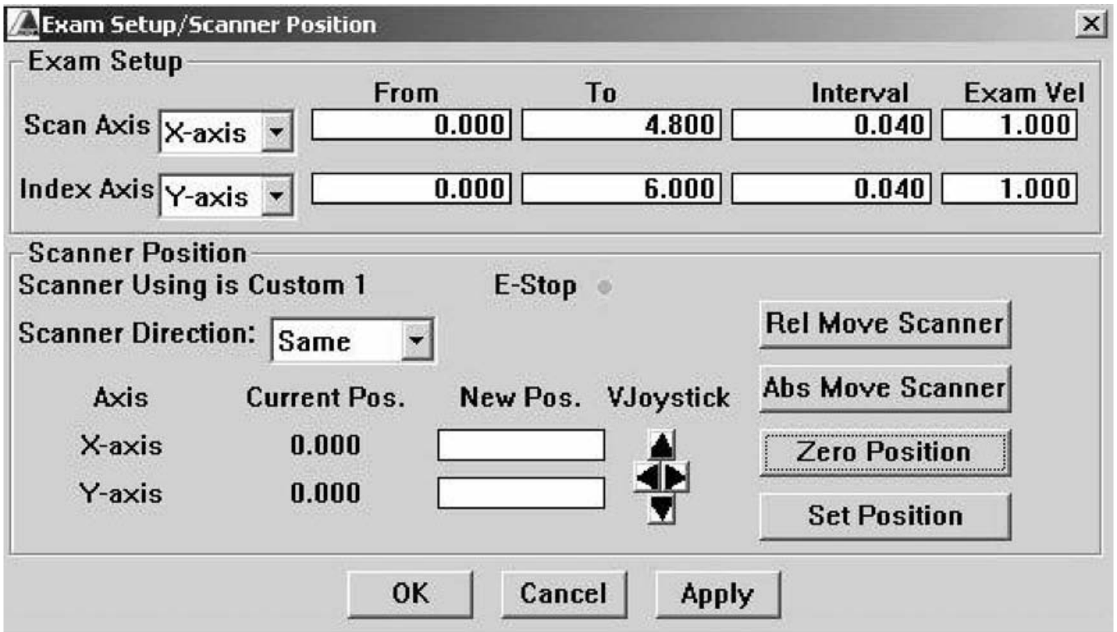


Figure 24: Exam Setup/Scanner Position

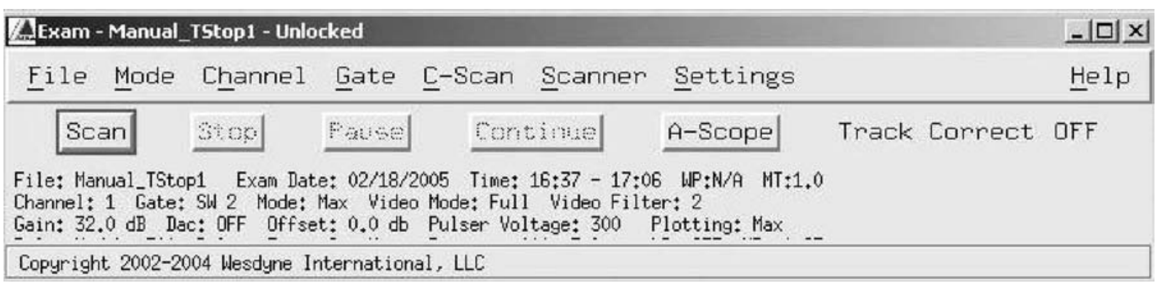


Figure 25: Exam Scan Start

Figure 26: Exam Stopped

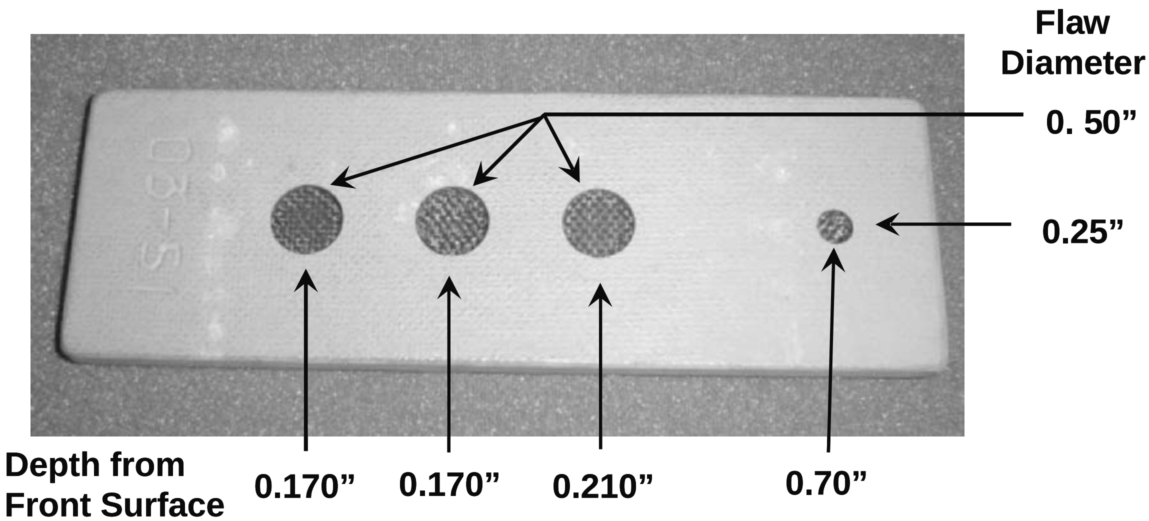


Figure 27: Photo of RCC Specimen 03-51 Containing Simulated Flaws

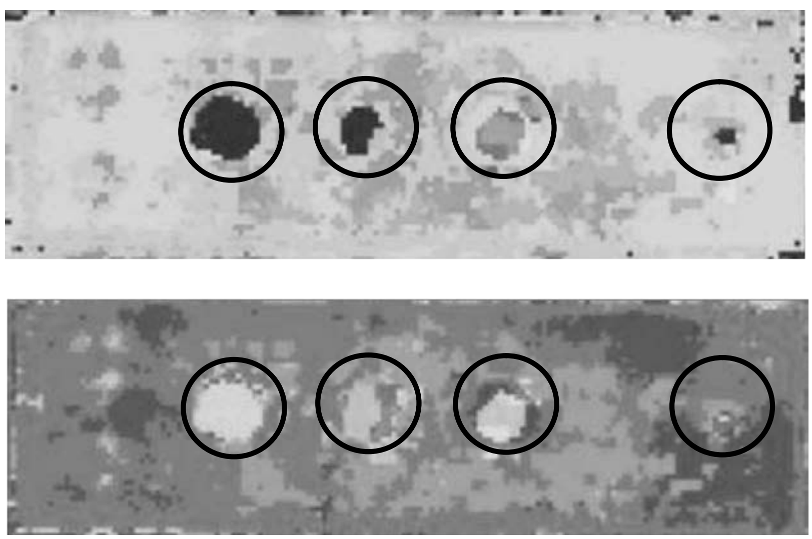


Figure 28: Amplitude and Time-of-Flight C-scan Images Showing Flaws in RCC Test Specimen

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