NDE at its Extreme – Applications for Space Explorations

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Outline

- Introduction to The Aerospace Corporation (Aerospace)
- Presenting 4 Case studies for challenging NDE tasks

Case 1:

Determine and predict degradation in rubber based on testing and operational conditions

Case 2:

Find fiber composite fiber dimples in thickness transition area of sandwich structure under bonded cork

Case 3:

Kissing unbonds under 1.25” – 3” thick heatshield blocks

Case 4:

Find improperly seated small springs in satellite thrusters

The Aerospace Corporation

- Created in 1960 as a California nonprofit corporation
- Attract and retain high-quality engineers, scientists, and managers
- Governed by a Board of Trustees

The Aerospace Corporation

- Sponsored by government agencies (DOD, DOE, IRS, others)
- Provide objective advice and perform research and development activities in highly complex technological disciplines
- Work in the national interest
- Administered independently to ensure objectivity
- Dedicated to the success of their sponsors

FFRDCs

Aerospace Principal Functions

System Development and Engineering

Launch Certification

System of Systems Development

Technology Application

Process Implementation

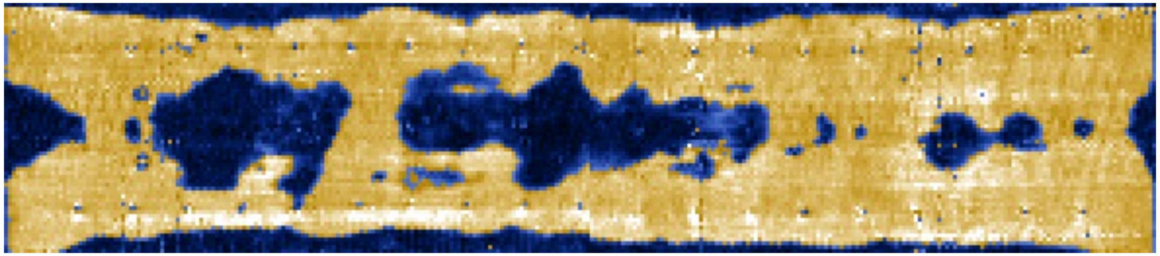
Engineering and Technology Group

Electronics and Sensors	Computers and Software	Communications and Cyber	Vehicle Systems	Systems Engineering	Physical Sciences Laboratories
Microelectronics	Computer technology	Cyber and IA	Guidance/control	Architecting	Electronics and photonics
Analog and digital electronics	Information science	Resiliency	Real-time simulation	Modeling & Sim	Mechanics
Power systems	Software engineering	Vulnerability and penetration testing	Flight/fluid mechanics	Mission performance	Materials
Parts, Materials and Processes	Software verification	Communication architectures and systems	Thermal control	Concept design	Space environment
Sensor engineering and exploitation	Software acquisition	Network systems	Structural/dynamics analysis	Cost and schedule engineering	Mission oriented research
Optical sensors	Ground systems	Spectrum Mgmt.	Test and evaluation	Acquisition and support analysis	Special sensor fabrication
Radar systems	Operations engineering	Digital implementation	Risk management	Resource allocation	Remote sensing signatures
	Cyber security	Communication electronics		Operability assessment	
		Antenna systems		Reliability and failure analysis	

Case 1

Task: Determine and predict degradation in rubber based on testing and operational conditions

Technique: Ultrasound

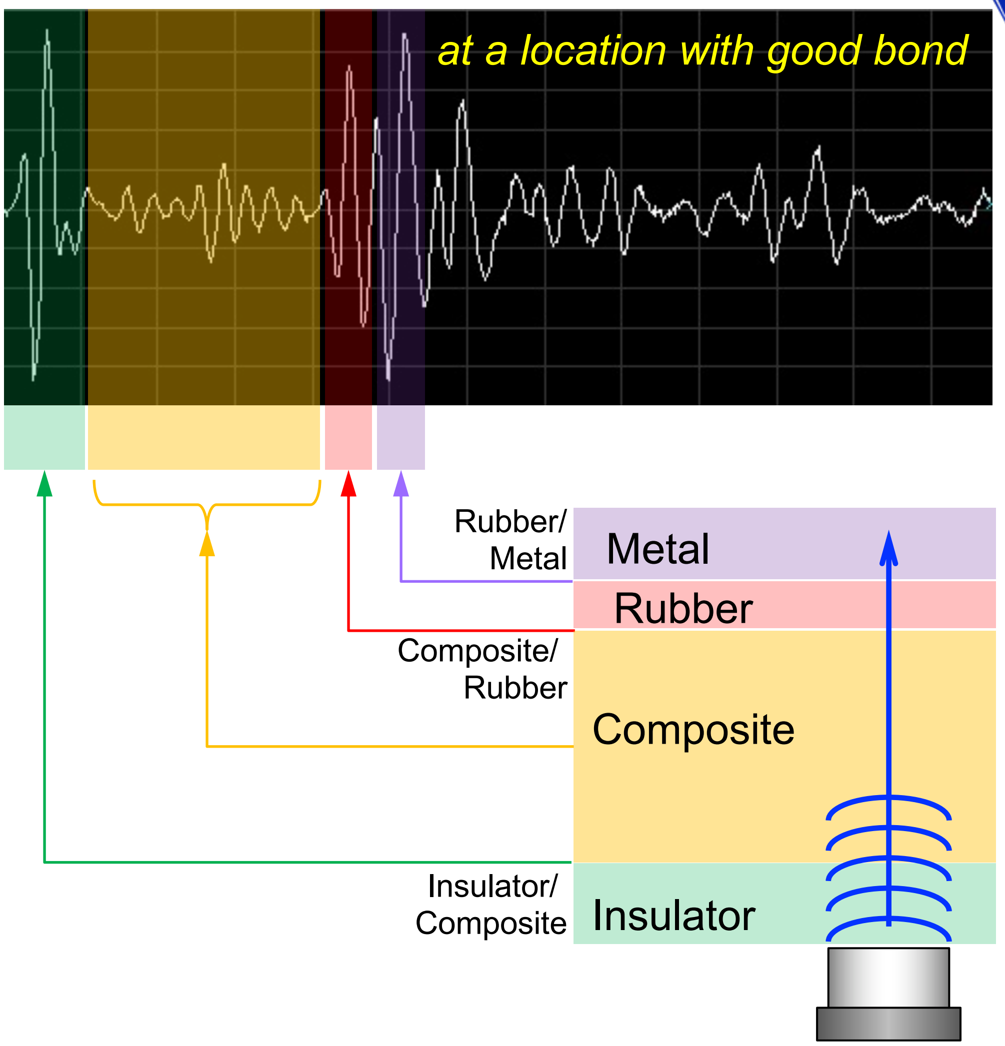


Background

- Project involving NASA mission
- Joint investigation between Aerospace, NASA, and contractors concluded that UT attenuation was indicative of cavitation or porosity in a rubber layer on a spacecraft.
- Cavitation is a damage mechanism in elastomers due to sudden expansion of microdefects into macroscopic voids
- The size and amount of these voids cause attenuation in the UT signal
- Variability in as-manufactured properties and geometry, and low compaction pressure during cure, believed to contribute to variability between different parts.
- Extent of UT attenuation and area of attenuated signal can be used to compare amount of cavitation in as-built parts.

UT-scan : Signal Processing Steps

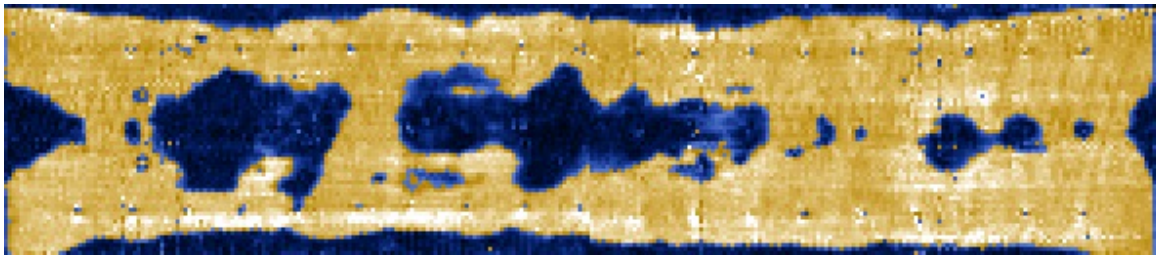
1. **Time Alignment** to make TOF of echoes consistent.
2. **Normalize echoes** by Insulator/ Composite echo to make later amplitudes comparable by removing surface artifacts and coupling issues.
3. **Hilbert transform** and waveform **phase rotation** to allow a clear phase-sensitive-peak mapping based on the echo shape.
4. **Evaluation of amplitudes** under very tight Δt time resolution to produce a new C-scan image.
5. **Integrating scans** of same structure from multiple occasions. Voids in rubber can be hidden under compression.

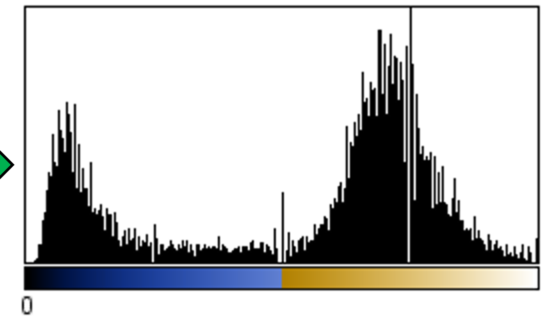


Comparative Scan Index (CSI)

$$\boldsymbol{CSI} = \frac{Average\ of\ all\ pixel}{Average\ of\ "gold"\ pixel}$$

Wellness Indicator

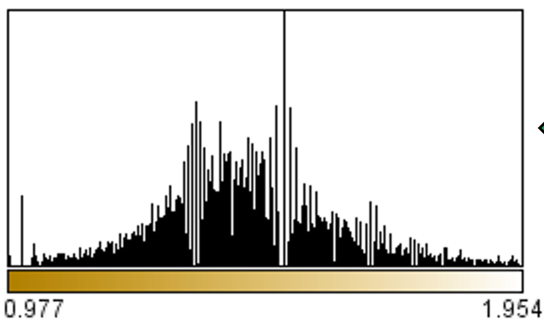




Count: 18692
Mean: 1.074
StdDev: 0.557
Bins: 256

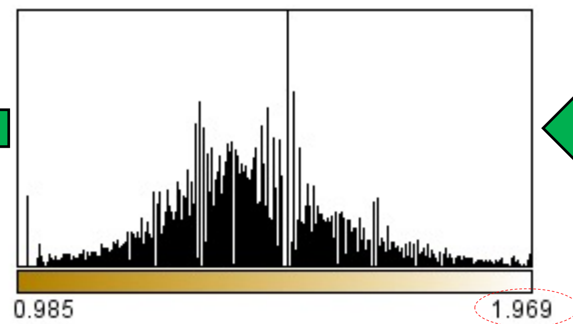
Min: 0.0270
Max: 2
Mode: 1.504 (335)
Bin Width: 0.00781

$$CSI = \frac{\mathbf{1.074}}{\mathbf{1.432}} = \mathbf{0.750}$$



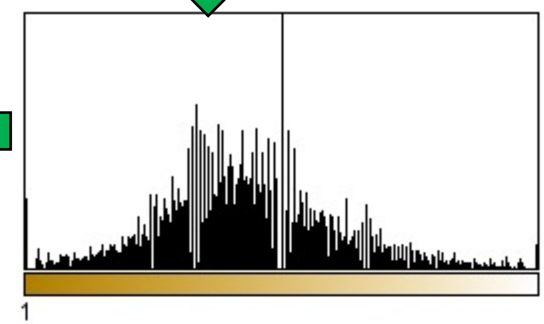
Count: 12517
Mean: 1.432
StdDev: 0.174
Bins: 256

Min: 0.977
Max: 1.954
Mode: 1.502 (335)
Bin Width: 0.00382



Count: 12531
Mean: 1.433
StdDev: 0.175
Bins: 256

Min: 0.985
Max: 1.969
Mode: 1.502 (335)
Bin Width: 0.00385



Count: 12573
Mean: 1.435
StdDev: 0.178
Bins: 256

Min: 1
Max: 2
Mode: 1.502 (335)
Bin Width: 0.00391

After several iterations

$$1.435 + (3\times 0.178) = 1.969$$

Growth Model

- Growth model is proposed, a simple power law fit to CSI data, suggesting that growth is only determined by current state and conditions of the next test

$$\boldsymbol{CSI_n = CSI_0 - Dn^{\alpha}}$$

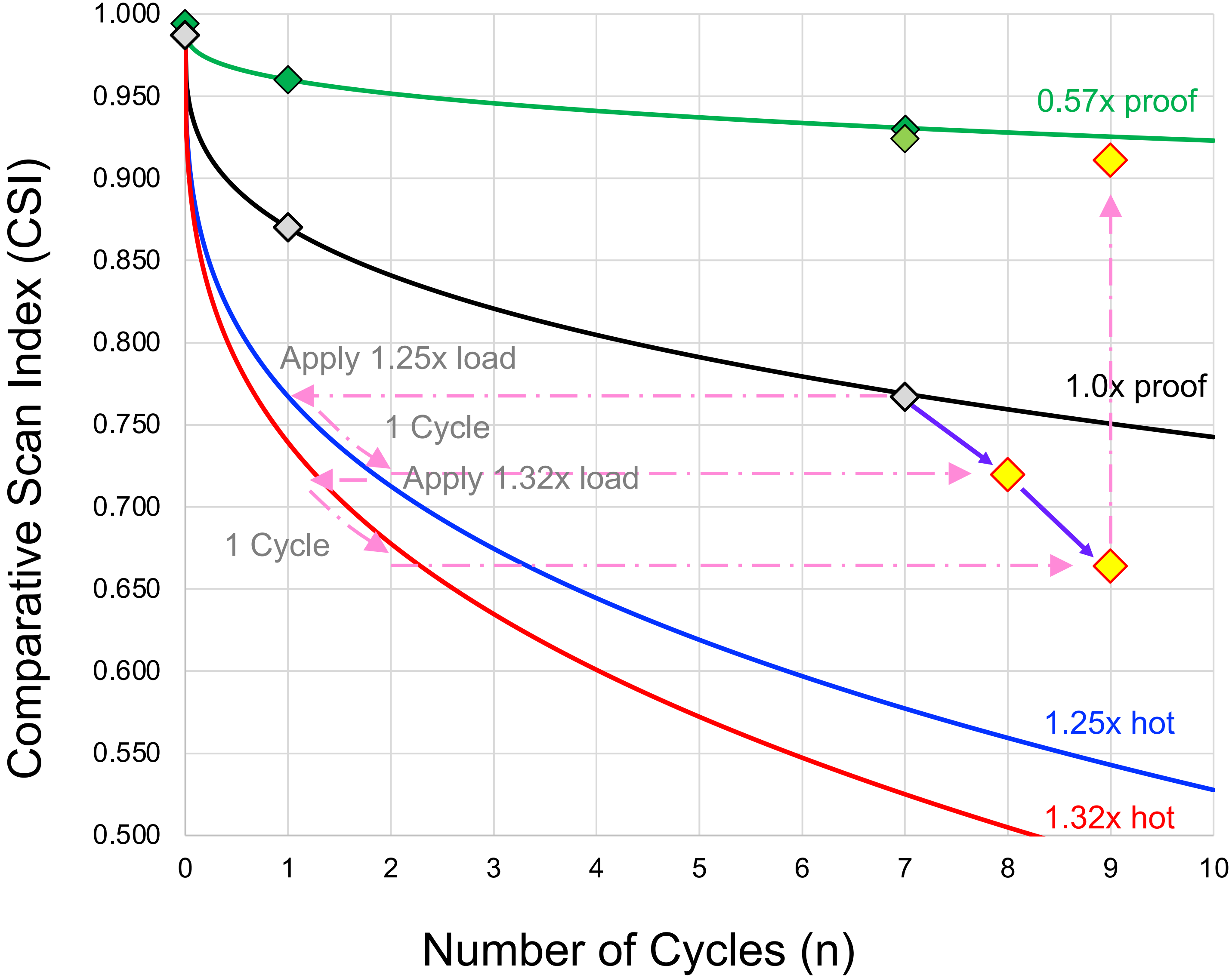
$$\boldsymbol{D_{(M,L,T)} = M \times \gamma_{(T)} \times L^{\beta}}$$

n = number of cycles
α = Cycle-related growth coefficient
M = Material constant
γ = Temperature effect constant
L = Load factor (ratio wrt a select original scan)
β = Load-related growth coefficient

- Estimate β … From loading conditions of different parts
  - *Load factors approximated by ratio of Rt, which is the primary load factor*
  - *Note that other loads (and pressure) do have an effect on cavitation, but primary influence is believed to be Rt.*

- Estimate γ … From before/after qual CSI

- Estimate M … From first hydroproof loading



Worst case CSI is selected experimentally.
The previous load/cycle setting is then selected as the safe limit.

Growth Model

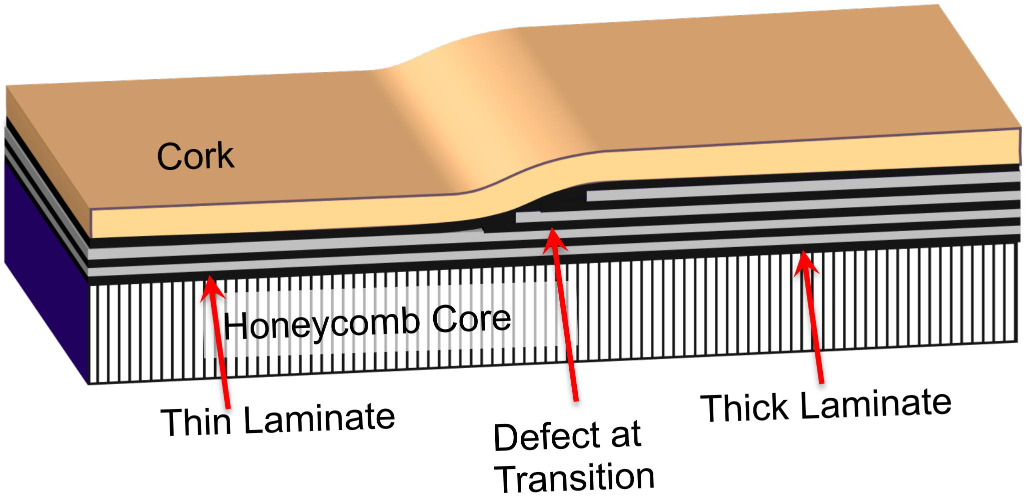
Margin Evaluation

- Using data of one part, as an example
  - *CSI prior to qual is 0.702*
  - *CSI after qual (including repeat tests) is 0.543*
- Strength margin of 1.25x loads were comparable to 1.57x load factor.
- In another case
  - *CSI after seven cycles = 0.724*
  - *Factor of safety on single hot cycle to get to 0.543 CSI = 1.58 (on load)*

Case 2

Task: Find fiber composite fiber dimples in thickness transition area of sandwich structure under bonded cork

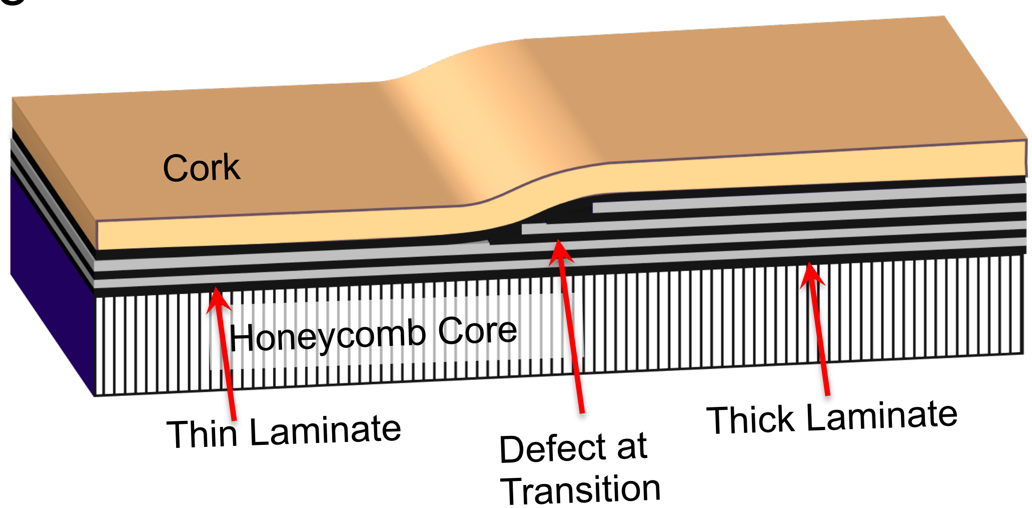
Technique: Eddy Current



Introduction

Composite facesheet contour deviation

- Measurements were needed to characterize known surface contour deviations in a composite
- Structure consisted of a composite sandwich panel with a carbon/epoxy facesheet and aluminum honeycomb core with cork bonded on outer surface
- Abrupt transition between two facesheet thicknesses was known to be associated with the contour deviations on the outer surface



Introduction

Composite facesheet contour deviation

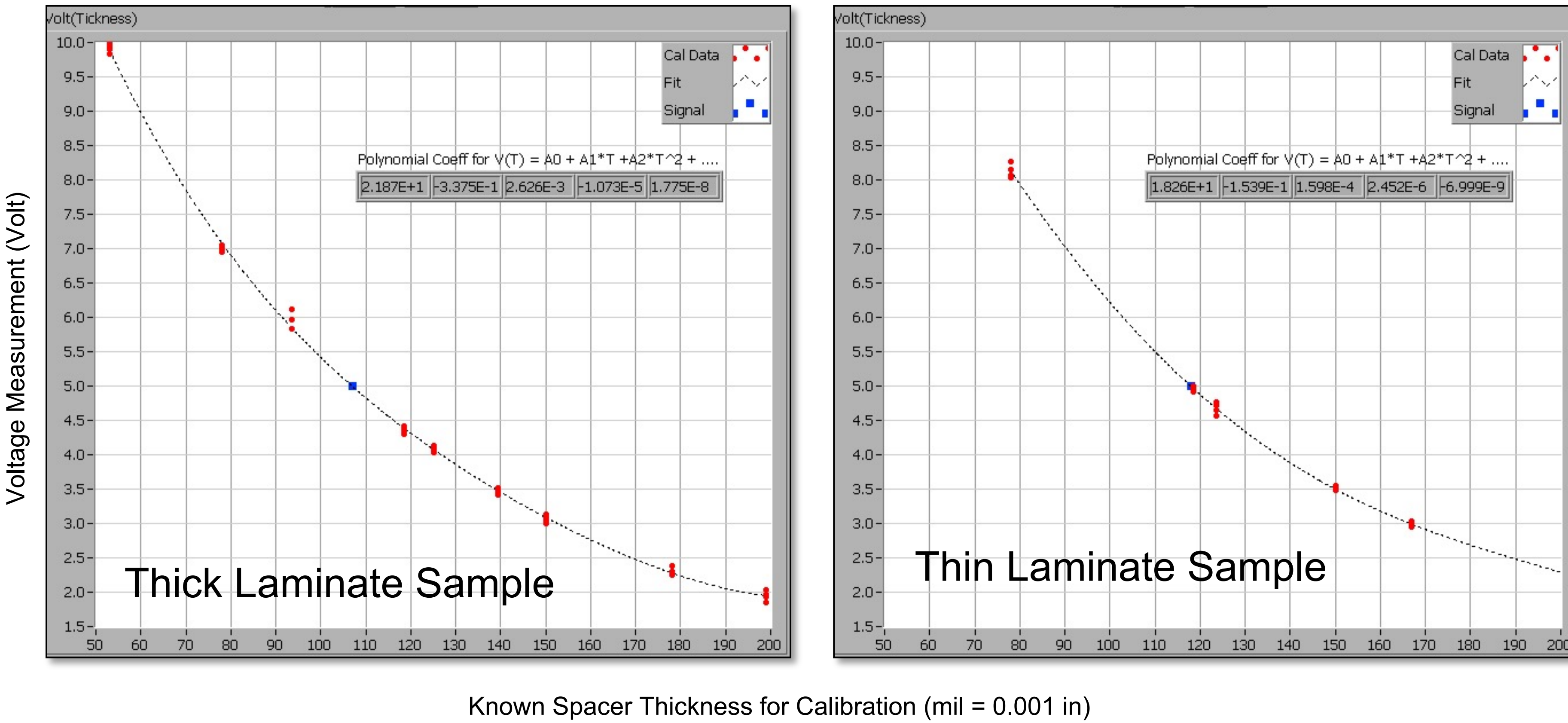
- Bonded cork on the outer surface prevented direct measurement of surface flatness
  - *Cork removal is time consuming, costly and poses risk to hardware.*
  - *Residual adhesive would affect measurement confidence*

- An eddy current technique was therefore developed to measure the surface contour of the carbon/epoxy facesheet beneath the cork

Calibration of Technique

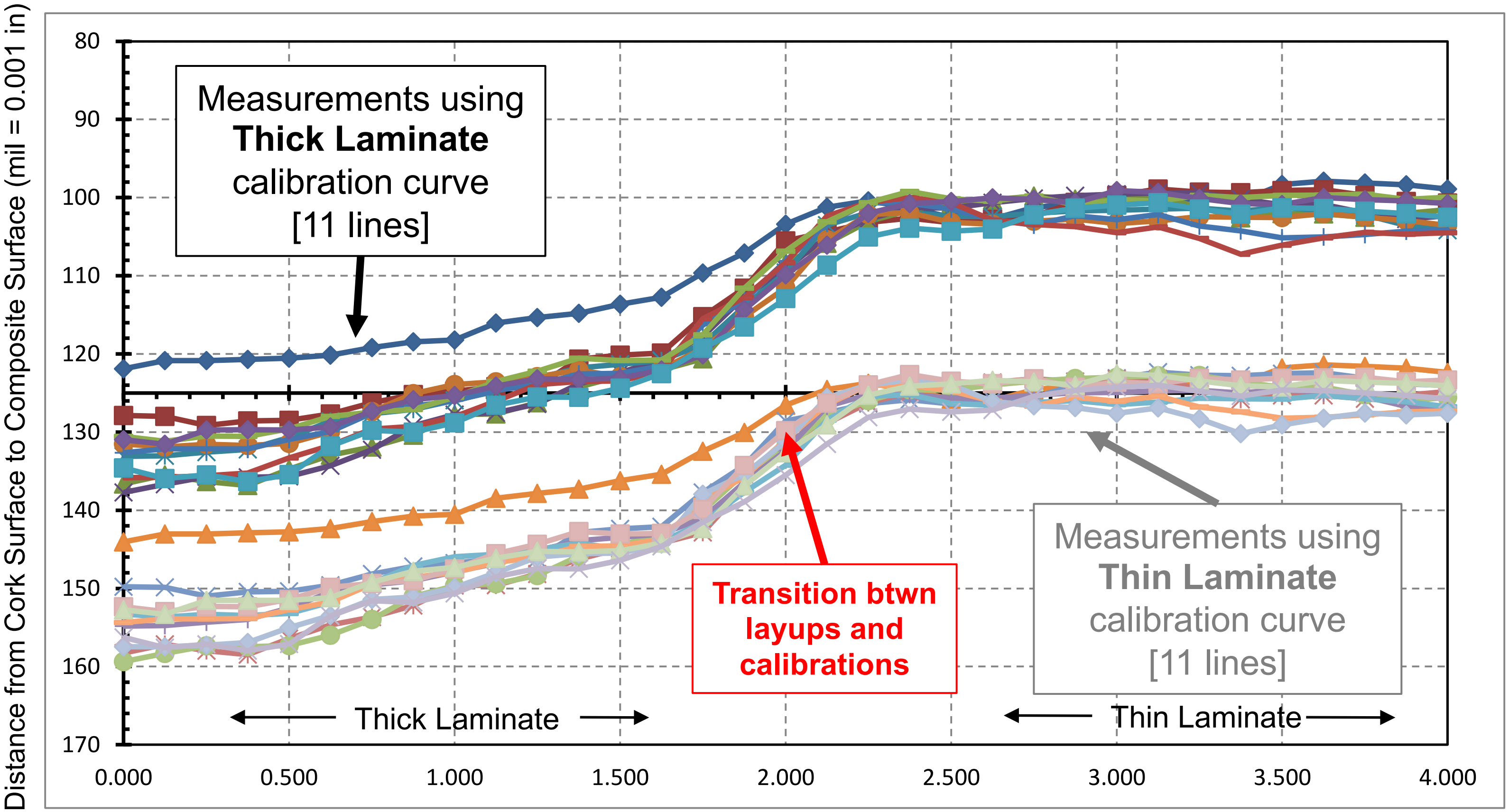
Transitional area between thin and thick laminates

- Calibration curves were developed away the from transition region
  - *Polynomial fit used to convert signal voltage to material thickness*



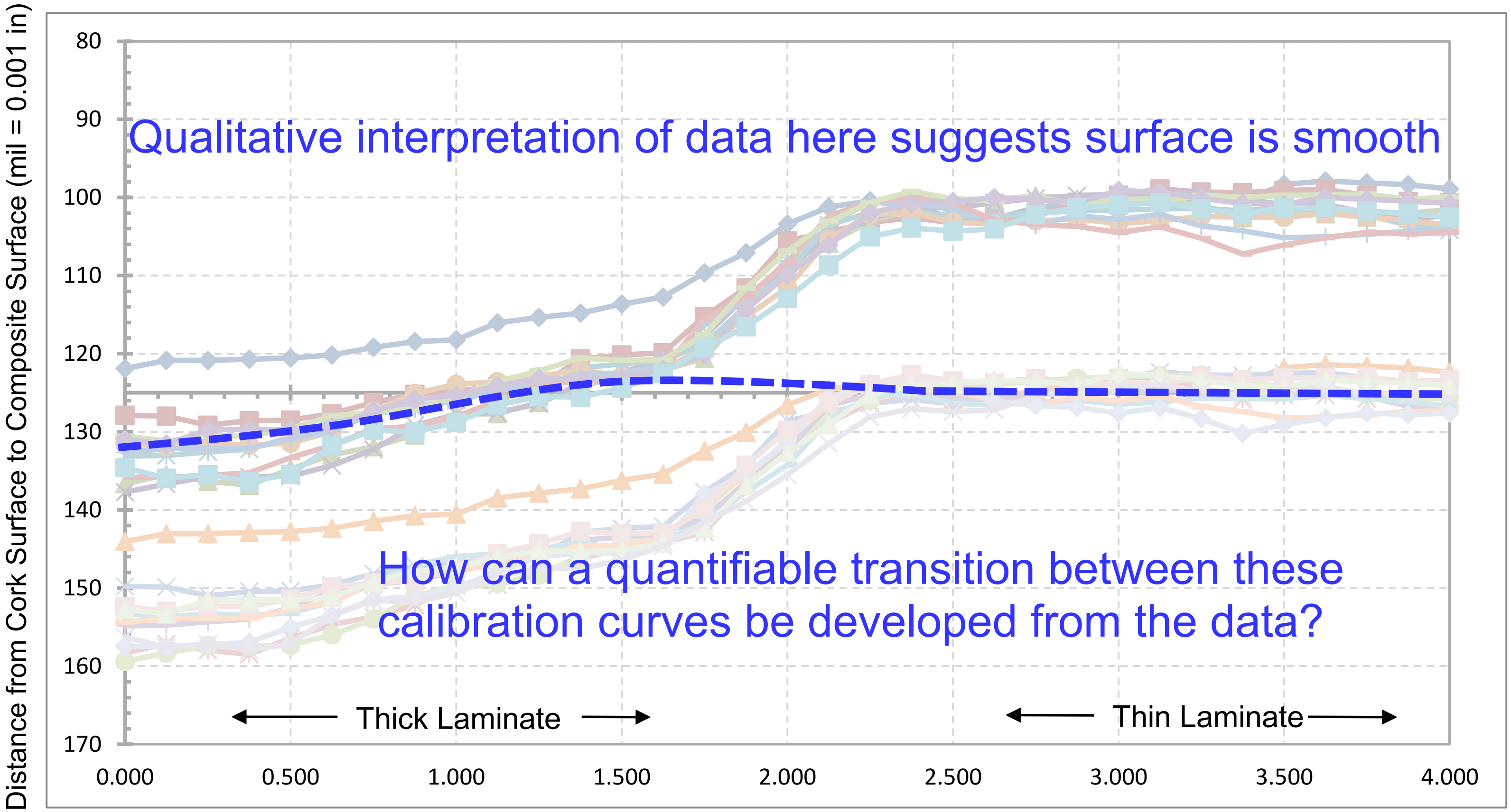
Calibration of Technique

Transitional area between thin and thick laminates



Calibration of Technique

Transitional area between thin and thick laminates



Margins of Error

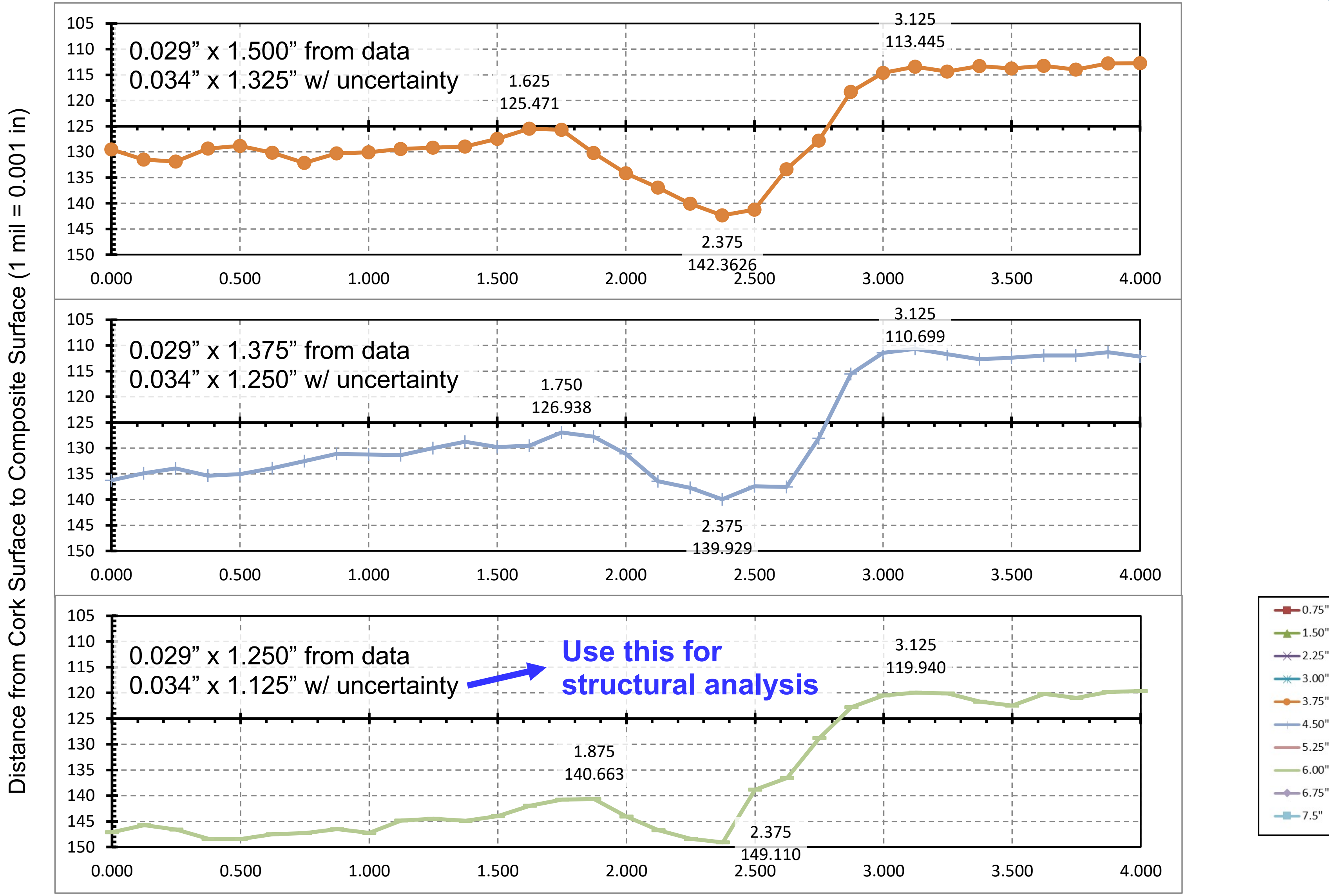
Using margins toward deeper and narrower dimples

Measurement error must be understood and considered in the evaluation process.

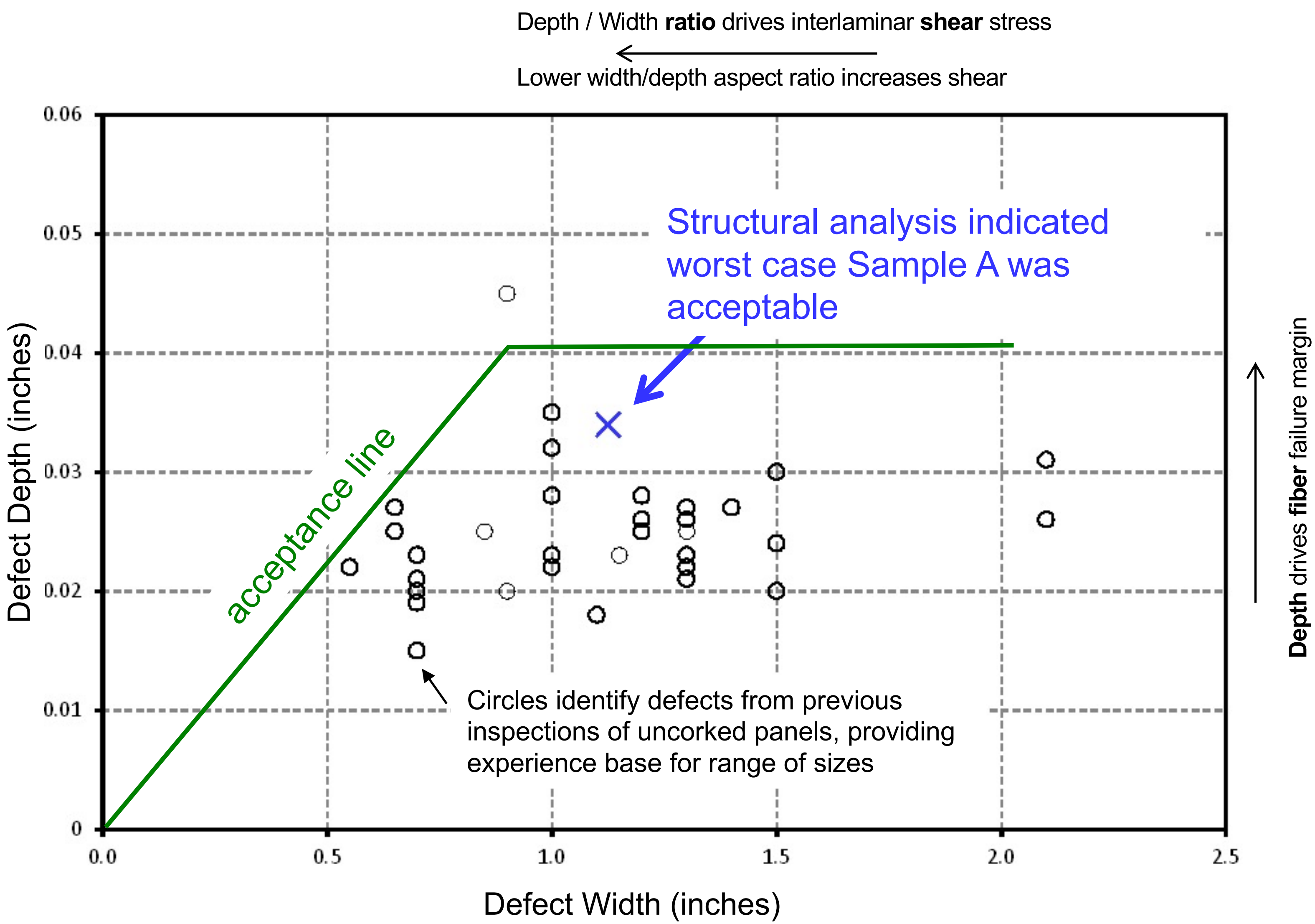
- Several sources of 0.005” error for depth measurement
  - *Intrinsic material variability (surface roughness, local curvature, underlying structure)*
  - *Electronic drift of instrument*
  - *Consistency of probe placement by operator*
  - *Calibration process also vulnerable to these contributors*
- 0.125” uncertainty in width measurement

Therefore, a 0.007”x1.125” indication can translate to a 0.012”x1.000” defect.

Measurements



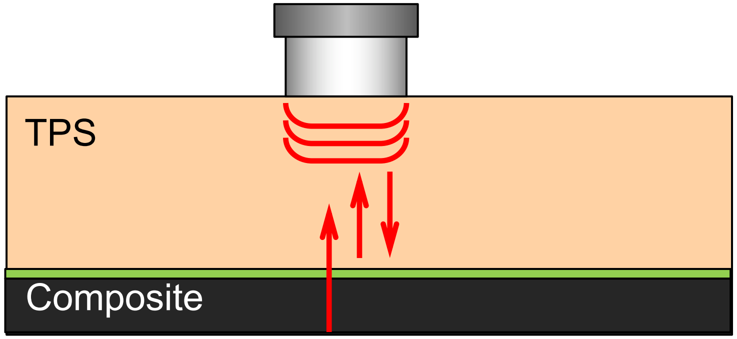
Margins of Safety



Case 3

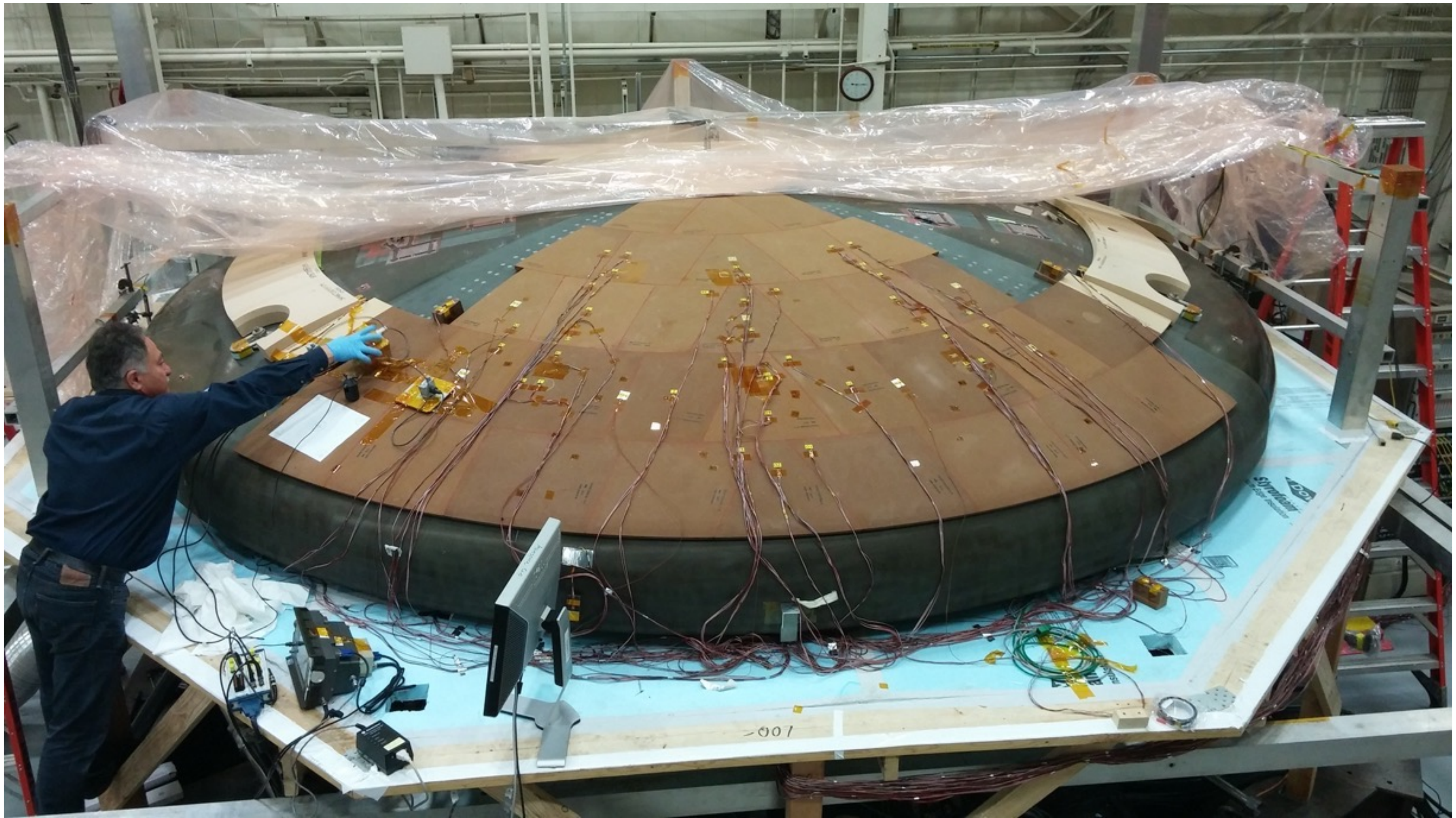
Task: Kissing unbonds under 1.25” – 3” thick heatshield blocks

Technique: Ultrasound



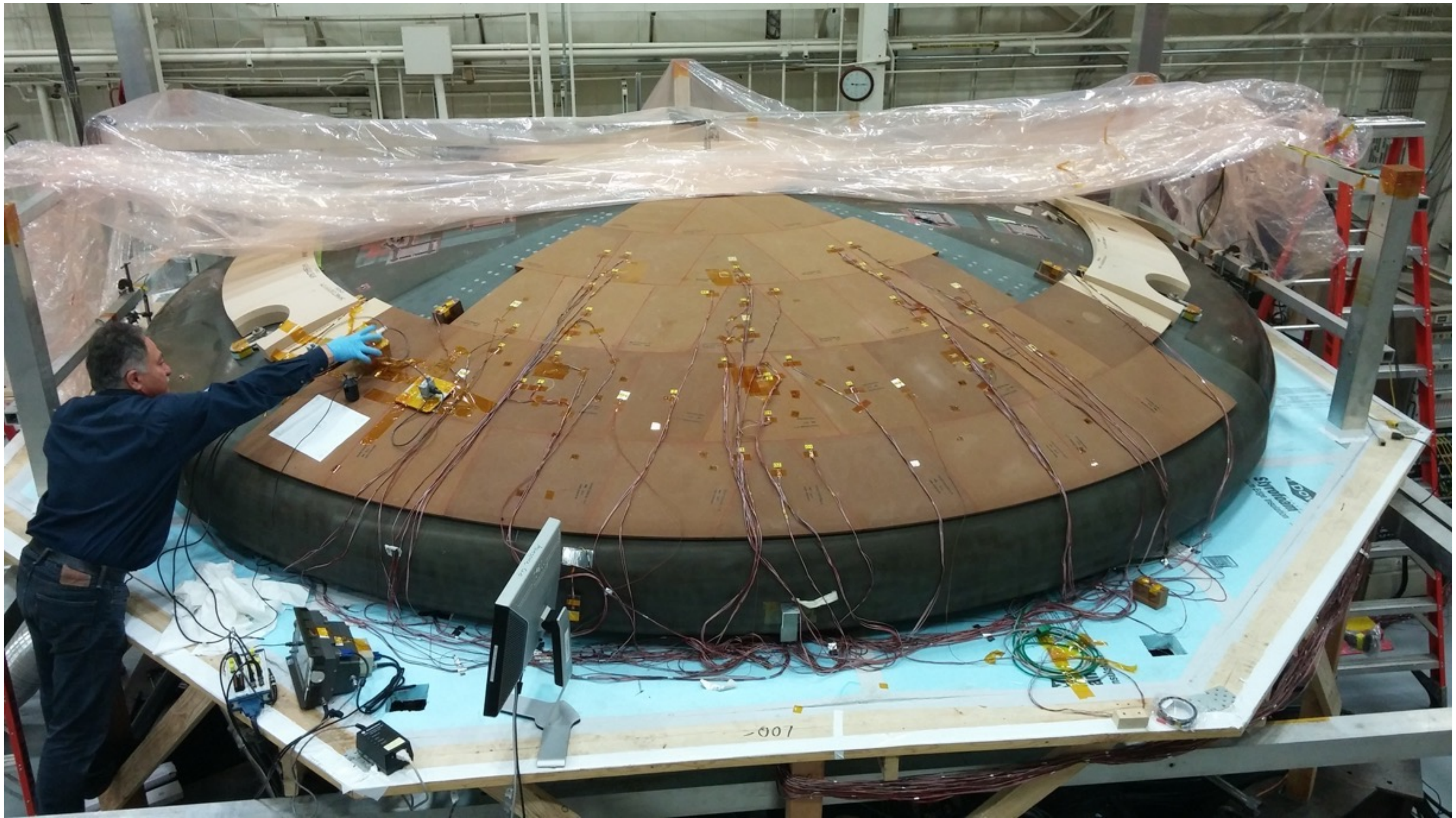
Background

- The Thermal Protection System (TPS) of a NASA spacecraft comprises heat shield blocks that are designed to survive high temperatures upon reentry.
- An effort is underway to develop an inspection method for the heat shield blocks that are bonded to a composite substrate.



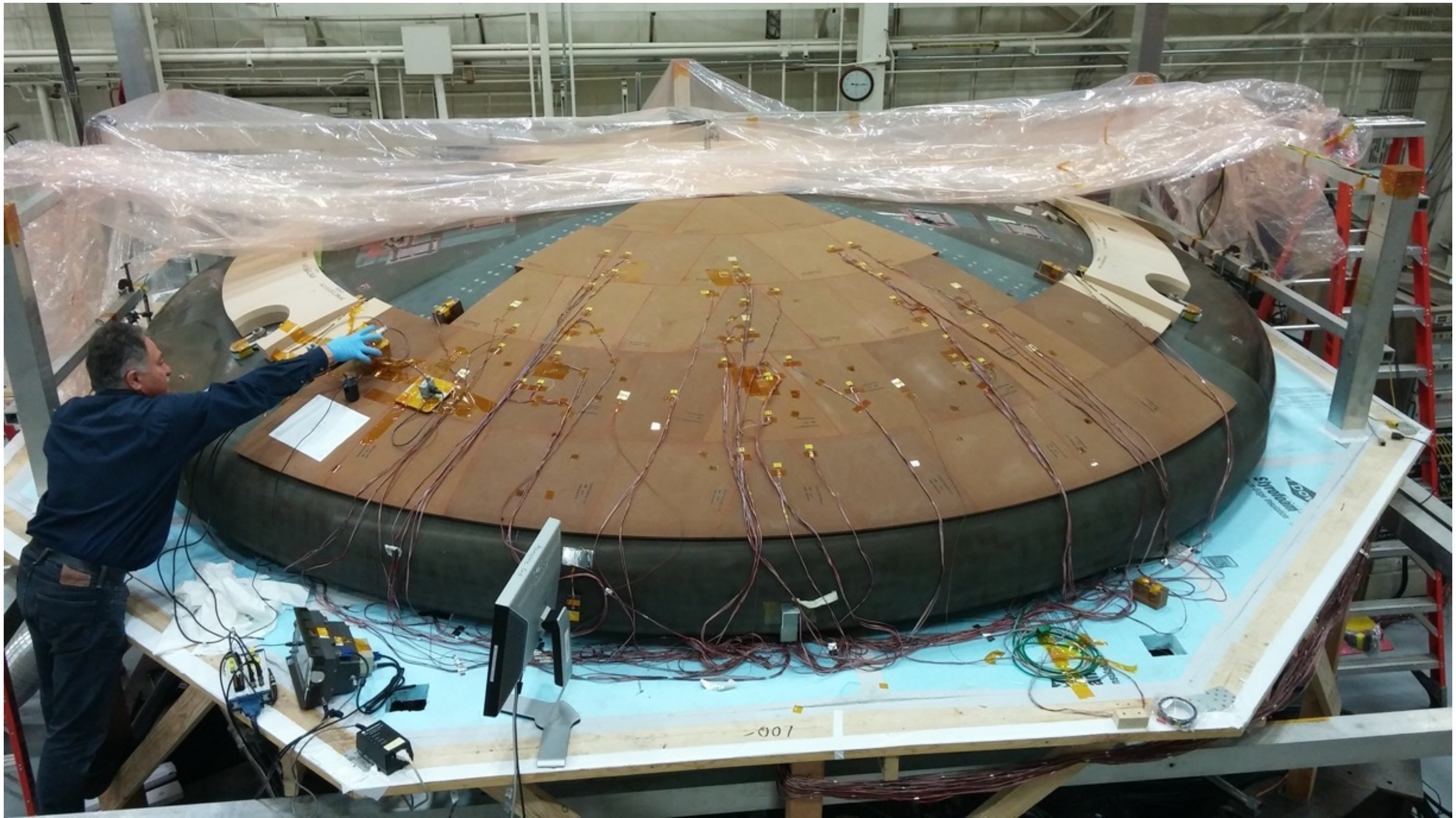
Background

- The application requires a one-sided inspection technique applied from the outer surface of the TPS.
- This proved to be very difficult because the the TPS material is:
  - *Inhomogeneous*
  - *highly attenuating and scattering to ultrasonic waves by nature*



Background

- An extended effort was expended to inspect heat shields and detect kissing unbonds, that involved several institutions and facilities.
- They scanned specimens using various ultrasonic techniques, microwave, Terahertz, radiography, and shearography and resulted in limited success in the end.
- Kissing unbonds remained undetectable.



Background

- For the initial effort, one of the samples made available contained manufactured flaws:
    - 2.5” circular kissing bond (no air gap)
    - 1”x 2.5” disbond (air gap) created using a pull-tab

- When performing a one sided inspection from the outer surface of the TPS, all the different techniques had partial success in the detectability of the flawed regions and uncertainties in the good regions.

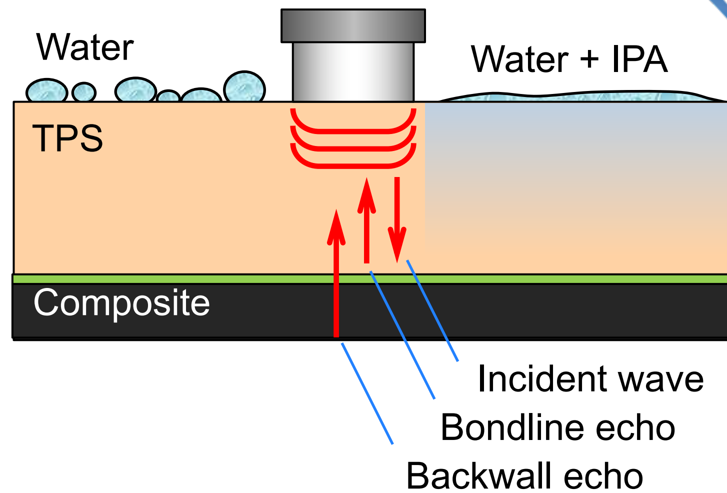
- Most promising was THz
    - *THz can detect change in material, such as air gaps, but cannot discern between bond and unbond conditions when an air gap is missing.*

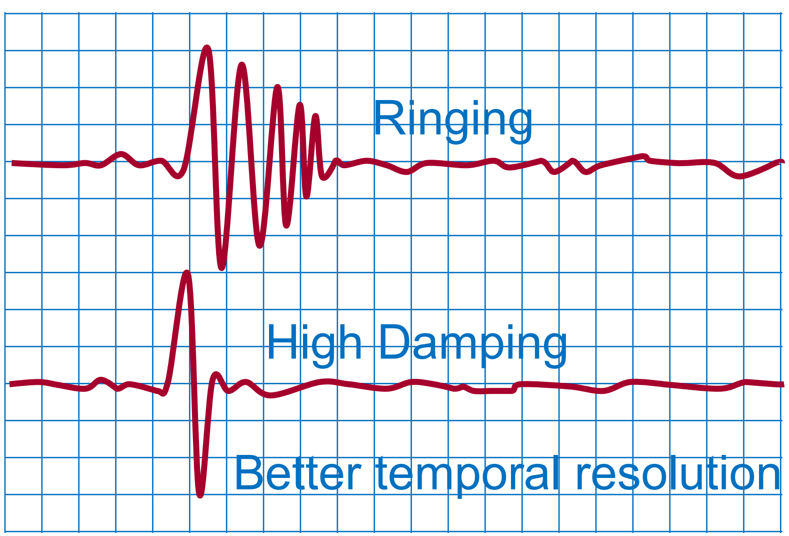
Ultrasonic Inspection Plan

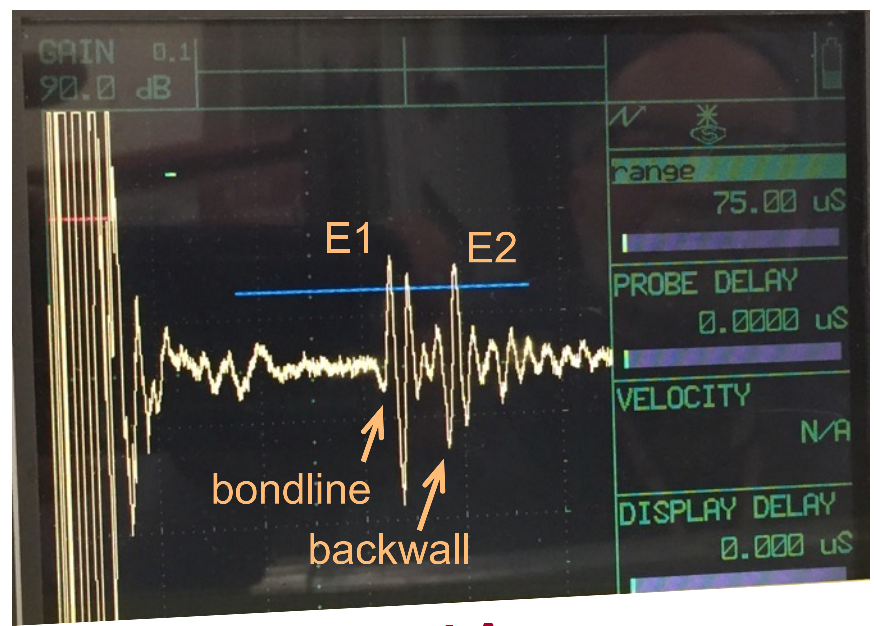
- Bond condition can be interrogated with ultrasound (mechanical wave) rather than THz (electromagnetic wave)
- Ultrasound became the prime approach.
- It was quickly discovered that this inspection would pose a number of challenges. These challenges were addressed in the development of a scanning methodology and applied to a number of signal processing techniques that proved to be very useful.
- The steps taken toward providing reasonably successful scans are:
  - *Step 1: Transducer choice*
  - *Step 2: Coupling*
  - *Step 3: Amplitude ratio scan*
  - *Step 4: Phase*
  - *Step 5: Phase polarity*
  - *Step 6: Weighted phase scan*
  - *Step 7: SAFT*

Transducer Choice

- A 1" diameter, **High Damping** 0.5 MHz transducer was used. This allows low frequency signals to be transmitted with little ringing.
- IPA added to water for better wetting and provide impedance matching gradient.



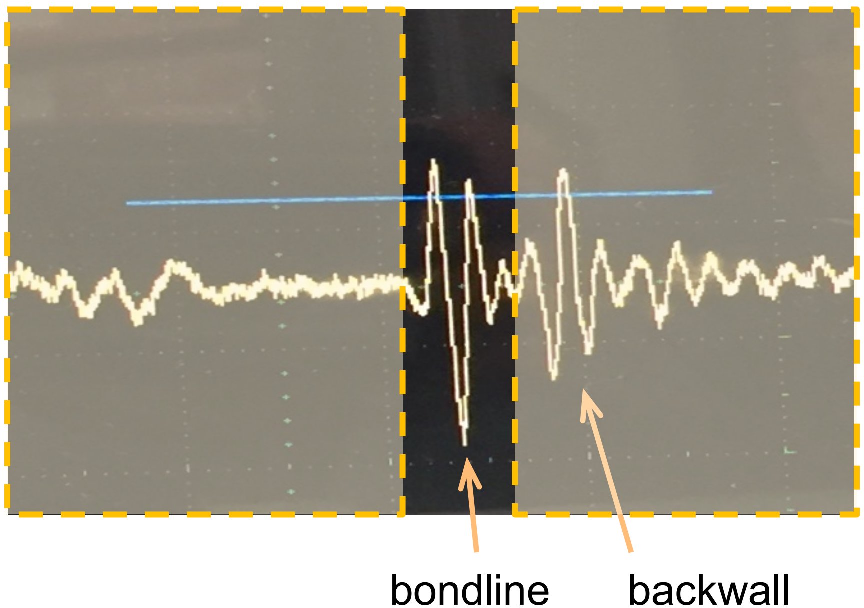




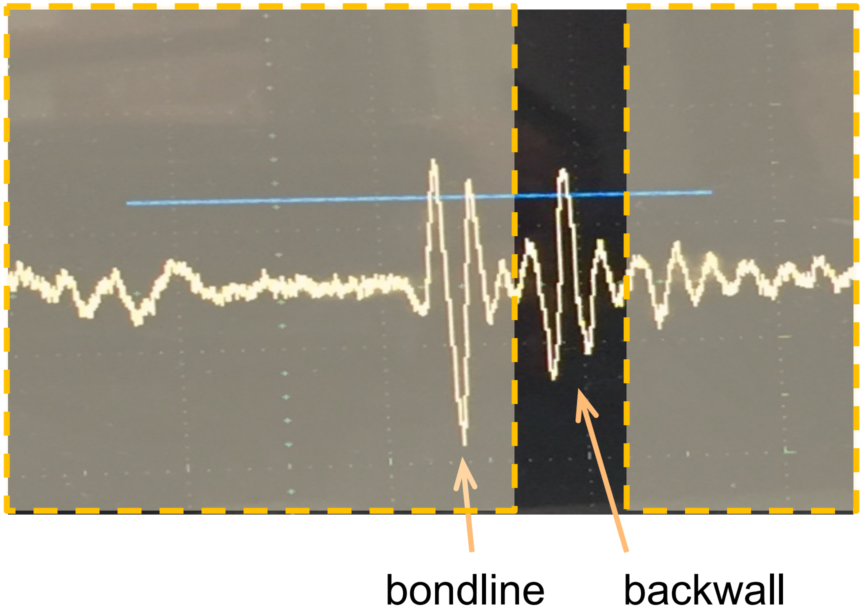
Good Area

Raw Scans

Sample 1 = Kissing Unbond + Pull Tab



Time Gate at Bondline



Time Gate at Backwall

Key Words: Time Gate or Window

Raw Scans

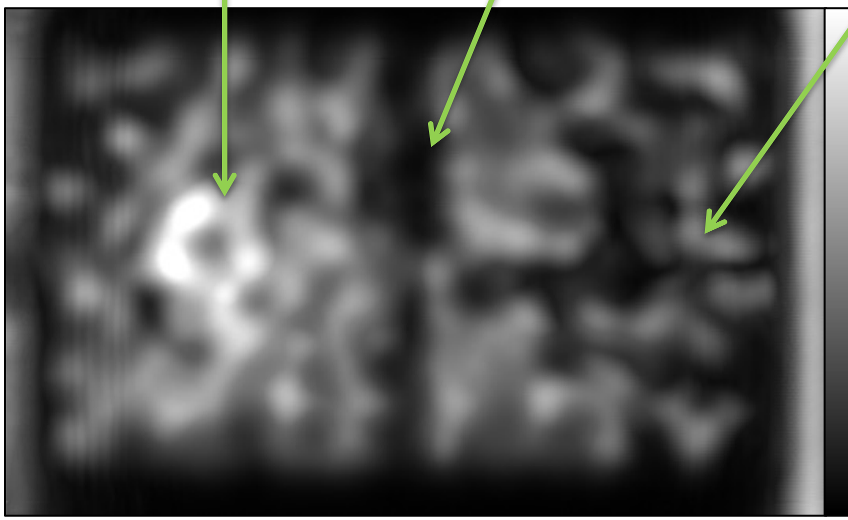
Sample 1 = Kissing Unbond + Pull Tab

kissing unbond

joint line

pull tab not visible

The cloudy background
is highly repeatable



Magnitude of bondline echo (M1)
the grey scale has a 0 to 2400 range

Magnitude of backwall echo (M2)
the grey scale has a 0 to 800 range

The amplitude of the bondline echo is typically 3 times stronger that the backwall echo, which is the reason behind the 3:1 range grey scale selected.

Key Words: Time Gate or Window

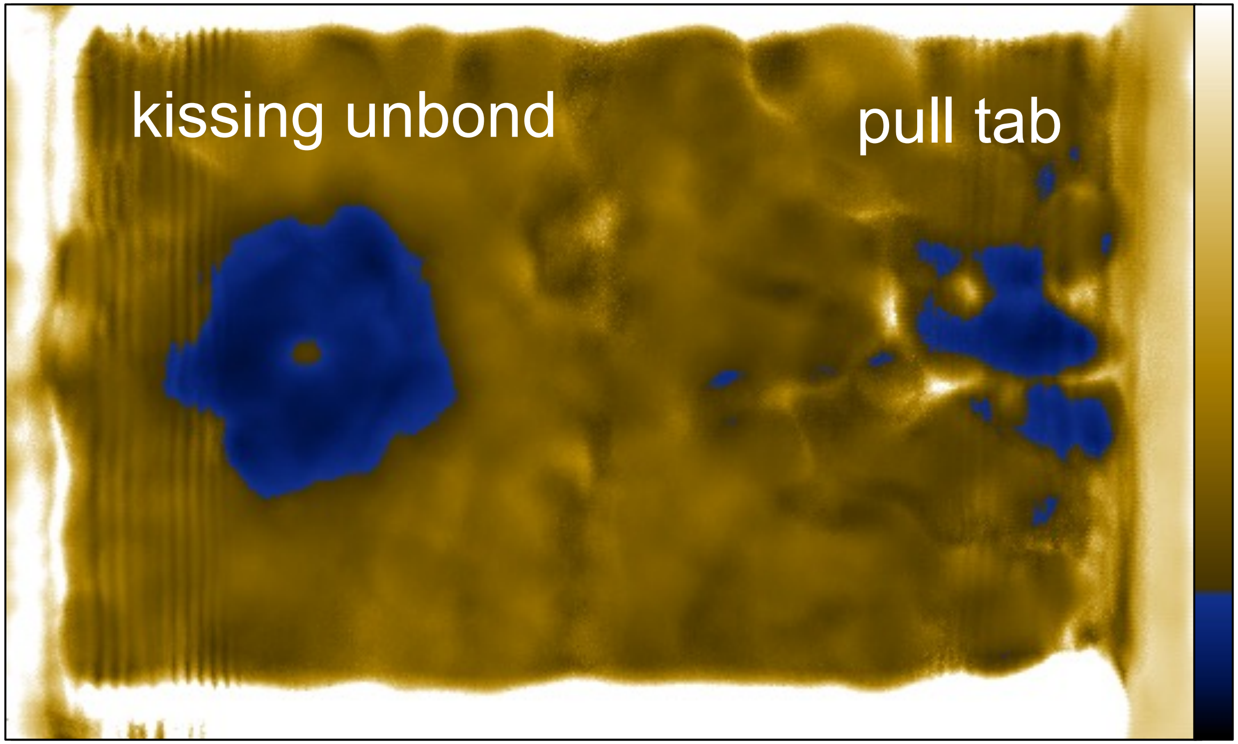
Amplitude Ratio

Sample 1

Backwall to bondline ratio of magnitudes (M2/M1)

A 30% ratio reflects a good bondline, a 20% threshold is selected for flaws.

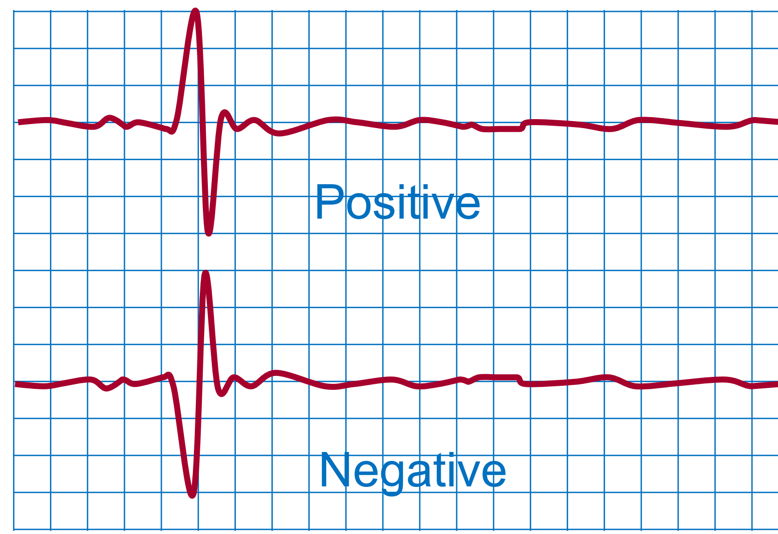
A custom color scale was designed here so the scale is preserved when converted to a grey.



Coefficient of Reflection

The coefficients of Reflection (R) is determined from the impedance mismatch between the the two media at any given interface.

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2}$$



Suppose

Z_{Comp} = 6 kg/m²s

Z_{Foam} = 2 kg/m²s

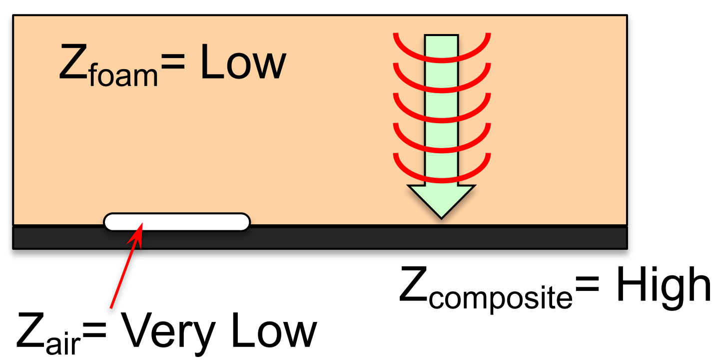
Z_{Air} = 0 kg/m²s

Then

Foam to Comp R = (6-2)/(6+2) = +0.5

Comp to Foam R = (2-6)/(2+6) = – 0.5

Foam to Air R = (0-2)/(2+0) = – 1



Key Words: Impedance Mismatch

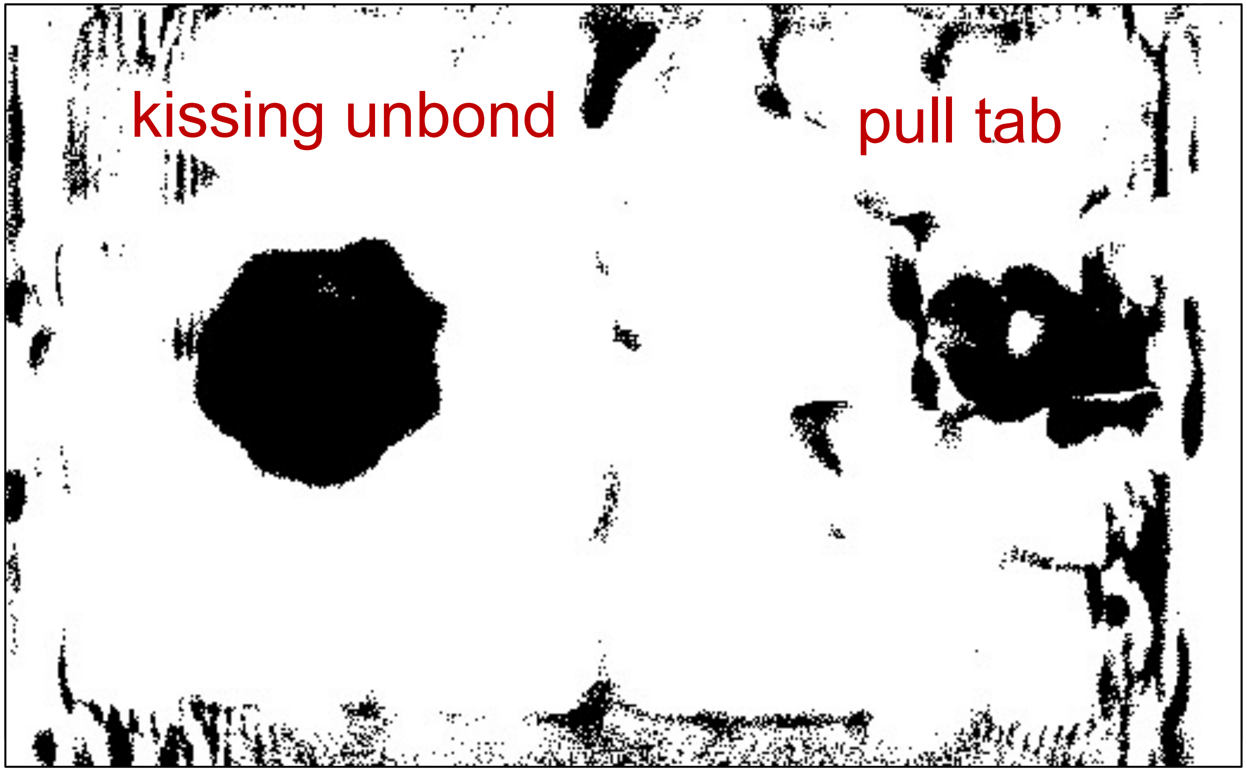
Phase Scan

Sample 1

Phase cosine of bondline echo (CosP1)

Cos P1

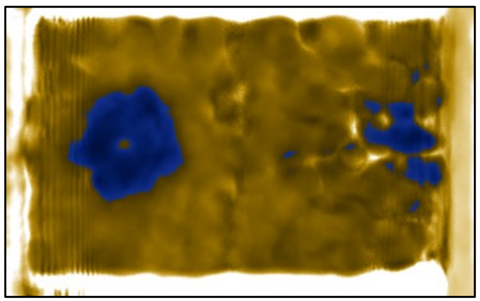
By taking the cosine of the phase map, values were converted to a -1 to +1 range. Setting a threshold at 0, converts the phase map to a black and white representation of the reversed versus preserved phase.



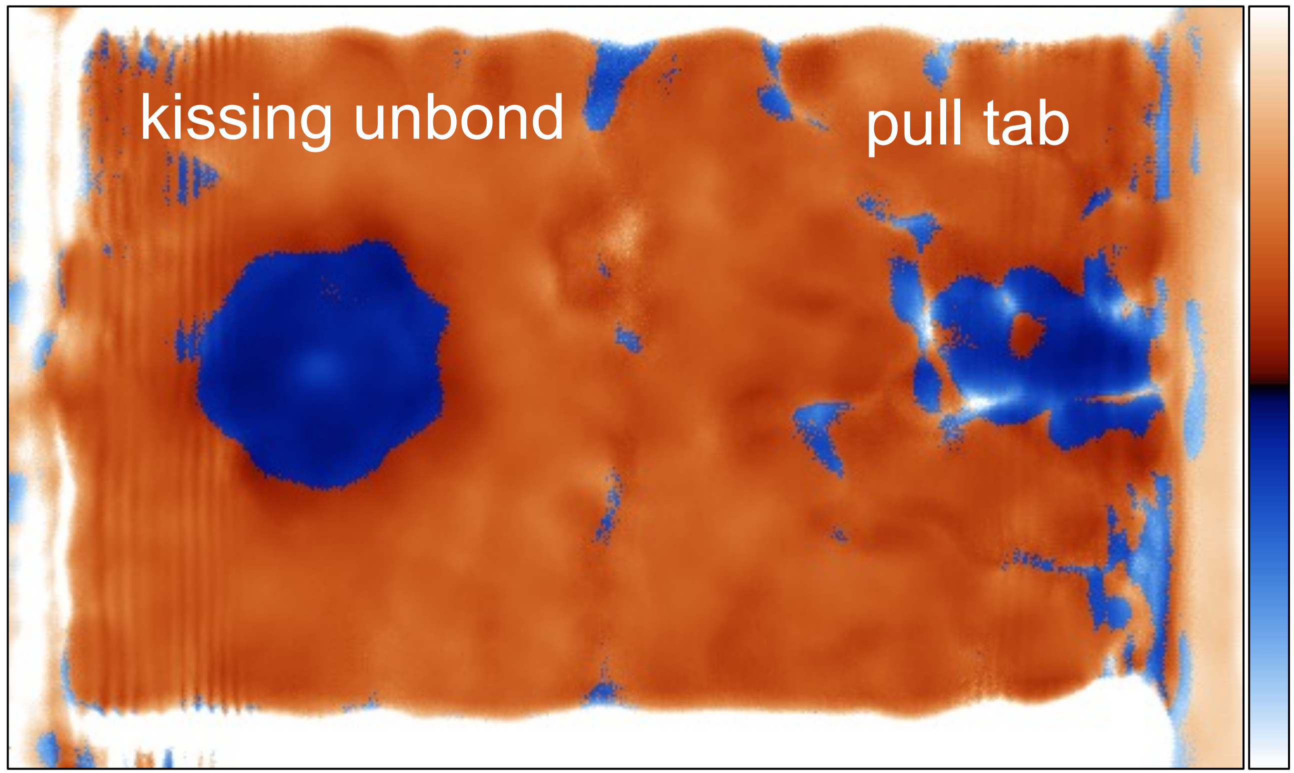
Weighted Phase Scan

Sample 1

Weighted phase by ratio of amplitudes (M2/M1)(CosP1)

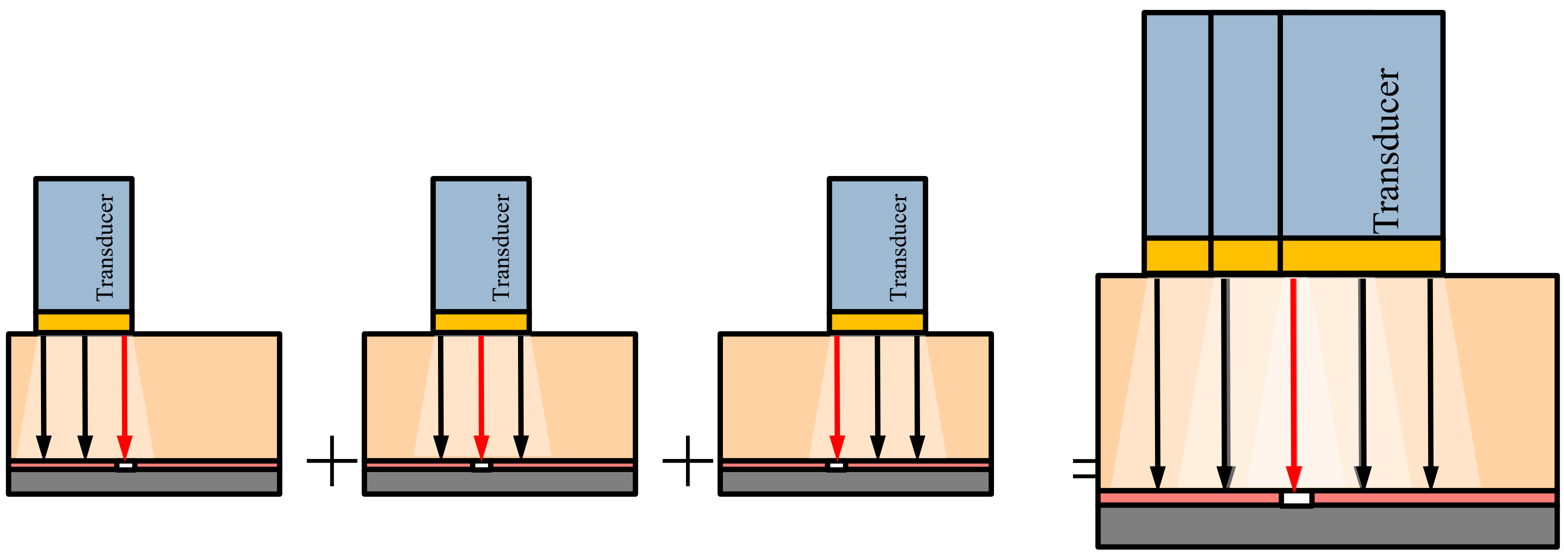


X



SAFT

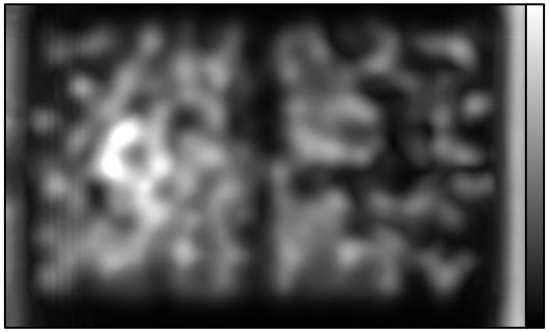
- The Synthetic Aperture Focusing Technique (SAFT) was applied in hopes to better refine the definition of the flawed regions.
- Due to the large footprint of the transducer and beam spread (both characteristic of low frequency waves), the ultrasonic beam can detect a feature from multiple locations as it traverses over the surface.
- These positions can be back-calculated into a focusing law that will sharpen the original image.



Key Words: Synthetic Aperture Focusing

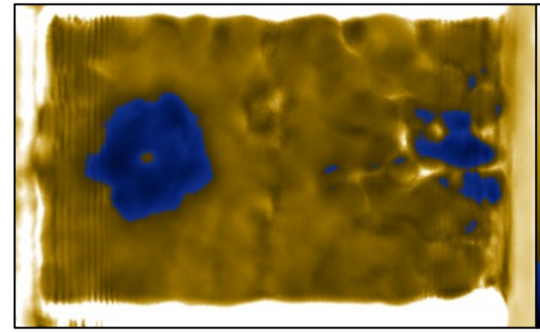
Summary of test results

Sample 1: Before SAFT

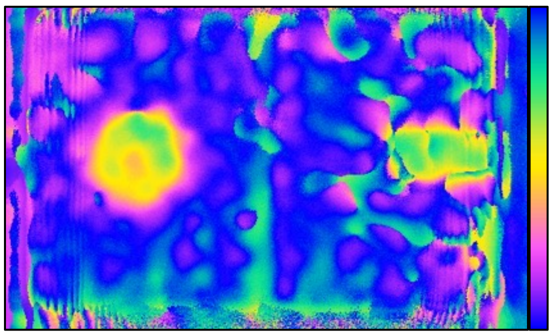


M1

M2

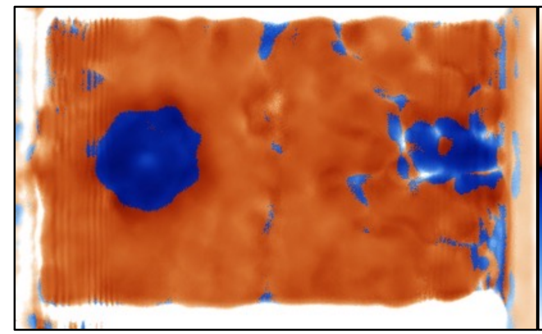


M2/M1

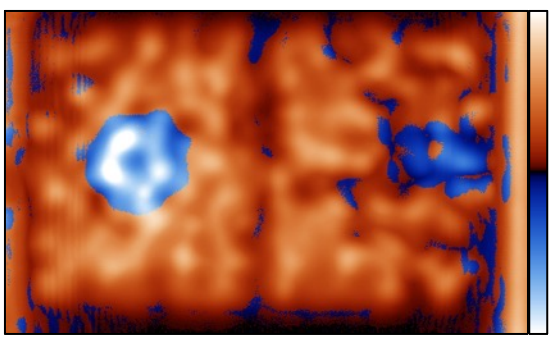


P1

H = (Cos(P1) Threshold)

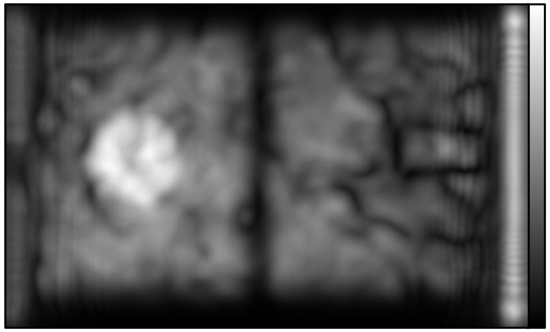


(M2/M1) x H

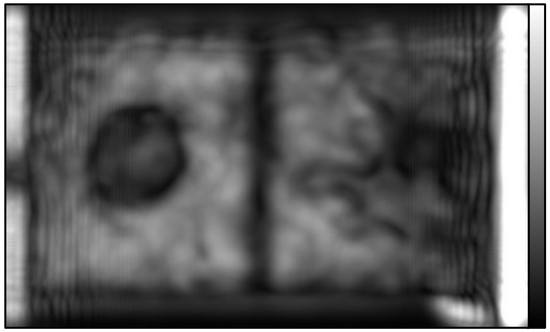


(M1) x H

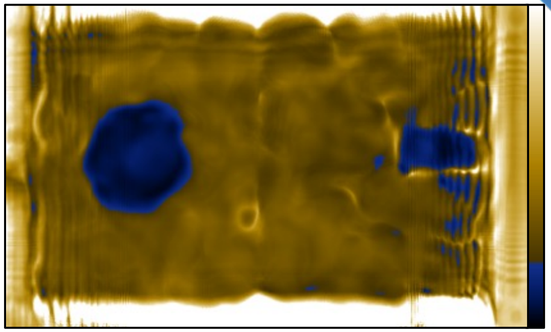
Sample 1: After SAFT



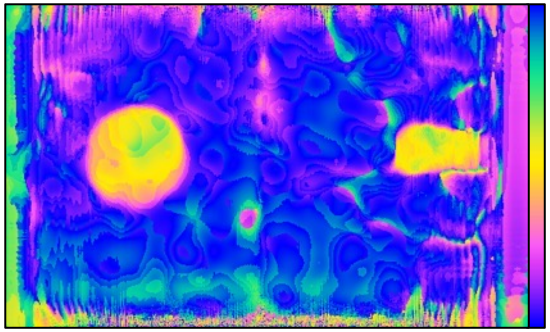
M1



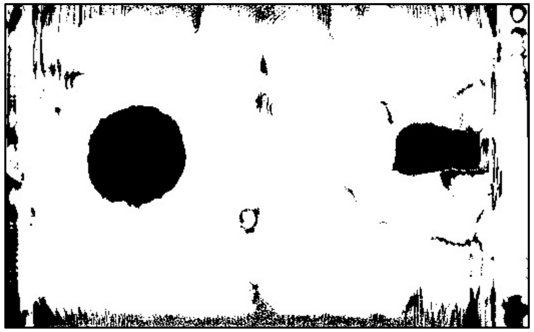
M2



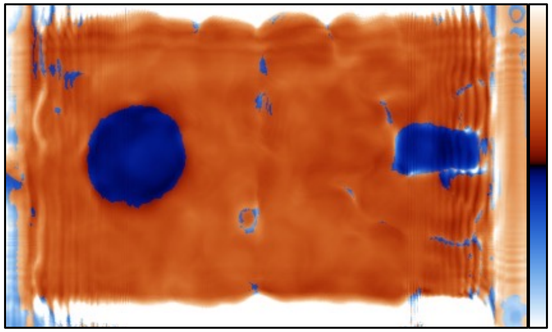
M2/M1



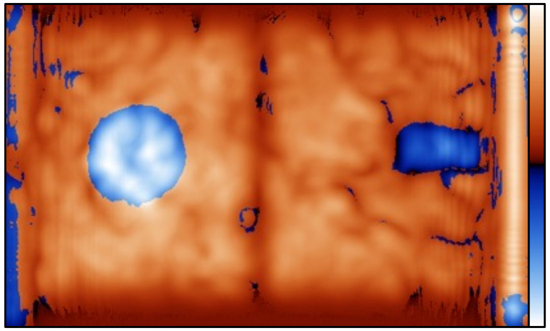
P1



H = (Cos(P1) Threshold)



(M2/M1) x H



(M1) x H

Publications

This work was published in a special issue of Materials Evaluation, Vol 77(1), Jan 2019, dedicated to the ORION inspection

Shant Kenderian, Joseph T. Case, and Yong Kim, "Orion Heat Shield Bond Quality Inspection: Developing a Technique", Materials Evaluation, vol. 77(1), Jan 2019, pp. 83-93.
Outstanding Paper Award

Joseph T. Case and Shant Kenderian, "Orion Heat Shield Bond Quality Inspection: Engineering a Technique", Materials Evaluation, vol. 77(1), Jan 2019, pp. 94-101.

Joseph T. Case and Shant Kenderian, "Orion Heat Shield Bond Quality Inspection: Complete Inspection System", Materials Evaluation, vol. 77(1), Jan 2019, pp. 102-110.

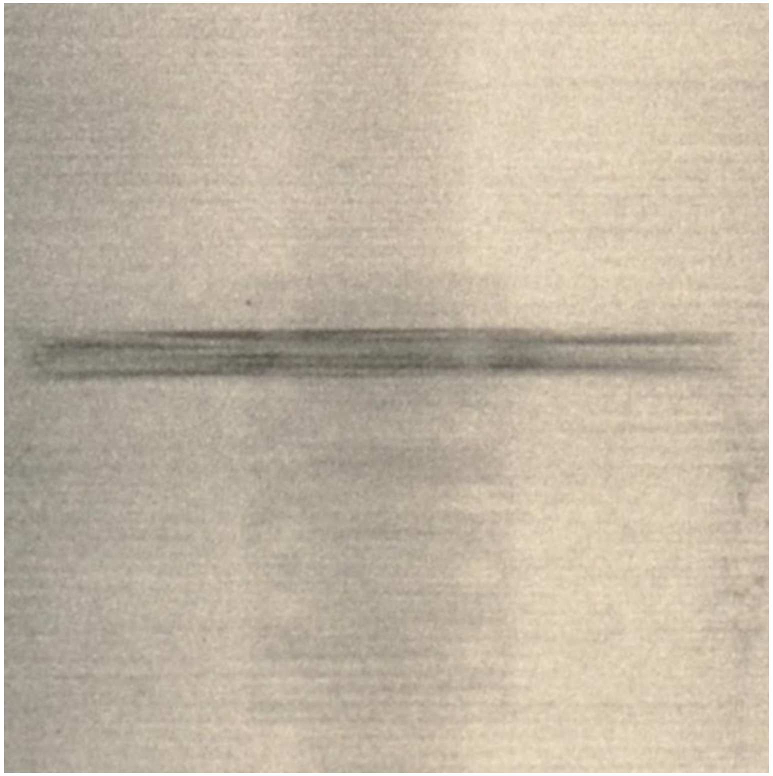
US Patent Application: 10,495,609 B2 / Apr 19, 2018

Ultrasonic Inspection Technique To Assess Bond Quality in Composite Structures

Case 4

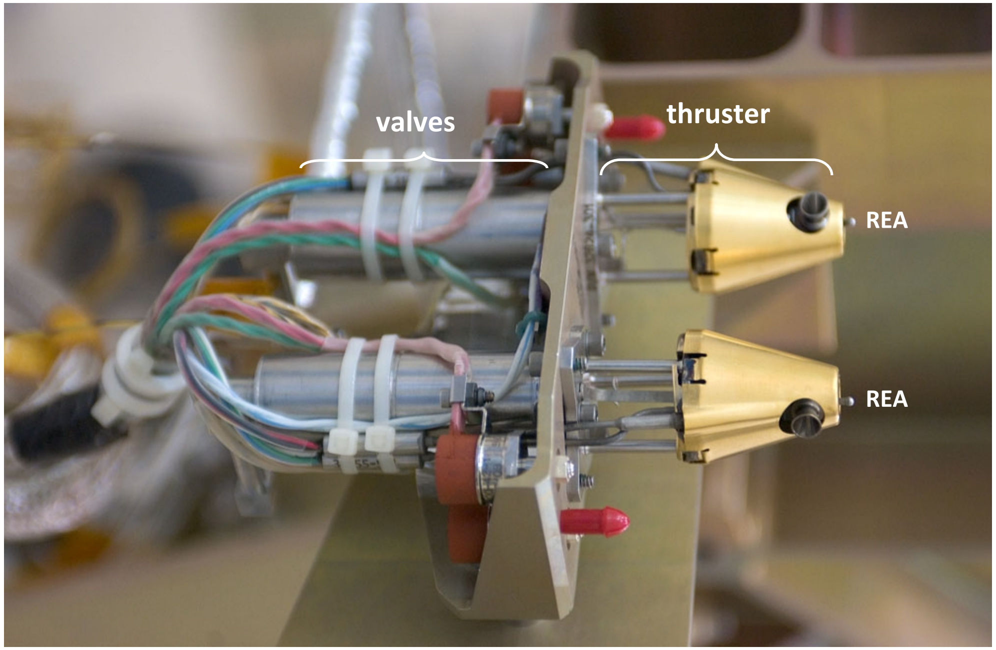
Task: Determine is small spring is seated appropriately in thrusters for satellite

Technique: X-ray



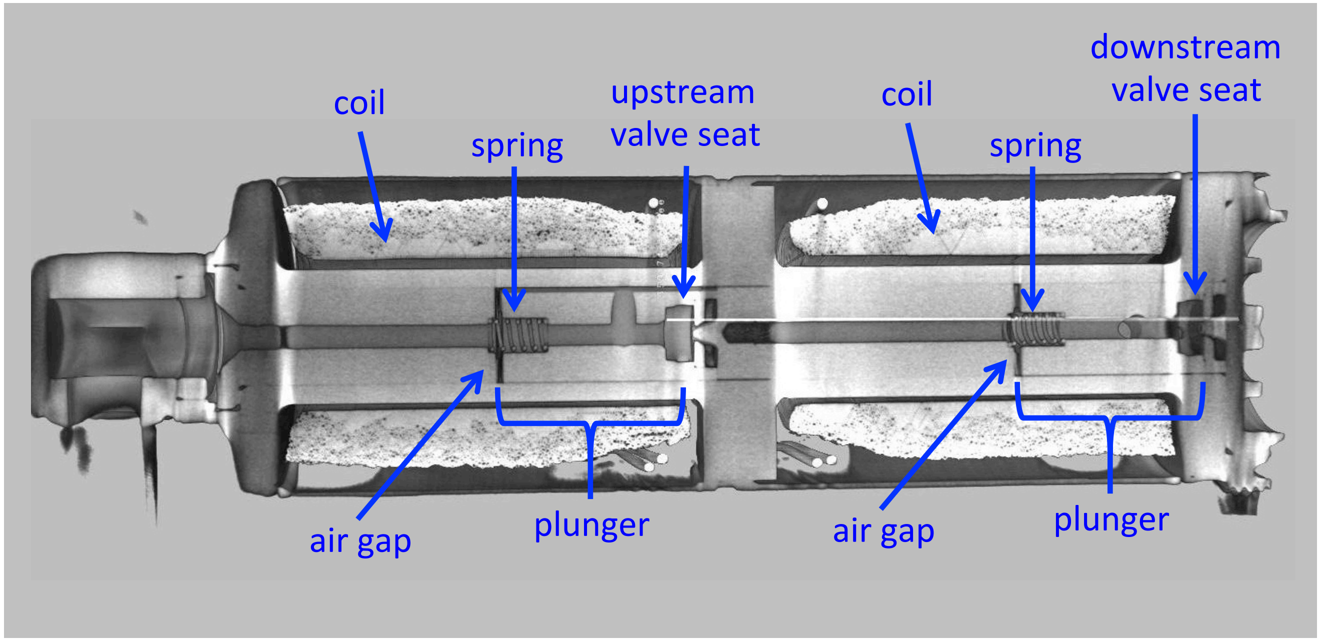
Background

- Rocket Engine Modules (REMs) like the one pictured below are attached to spacecraft for velocity adjustment and translational and attitude control.
- This REM includes two right angle, monopropellant Rocket Engine Assemblies (REAs); also referred to as thrusters.
- One of these thrusters failed to open during acceptance testing. An ensuing failure investigation concluded with the root cause assigned to improper seating of a small spring in the valve.
- The discovery of this failure mode had significant implications as thrusters and/or oxygen generators incorporating the same valve design were already installed on numerous spacecraft in various stages of build for a variety of space programs.



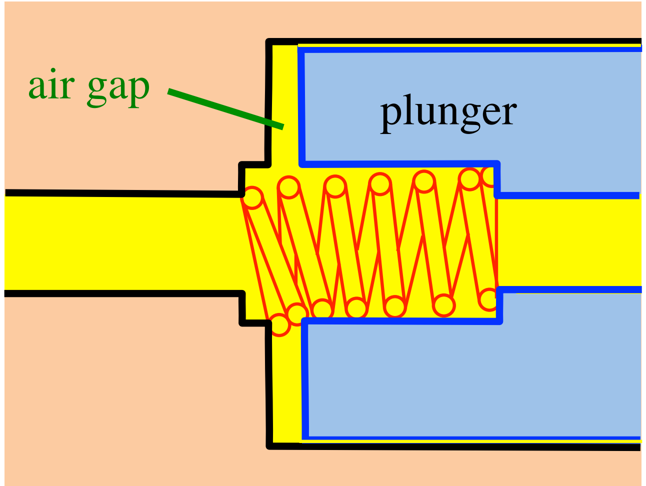
CT Image of Valve Assembly

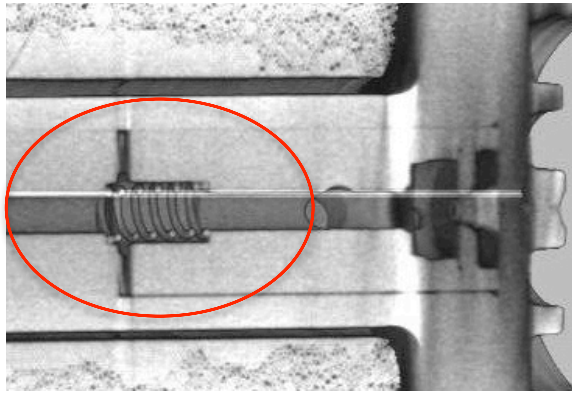
- The thruster valve springs are clearly resolved in the CT image below. There is a small air gap near the left end of the spring. When the coils surrounding each valve are energized, magnetic forces move the plunger to the left into the air gap, opening the valve.
- The springs are comprised of ~ 10 mil (0.25 mm) diameter wire with a free length of less than 0.2 inch (5 mm) and outside diameter less than 0.1 inch (2.5 mm).



Failure Mode

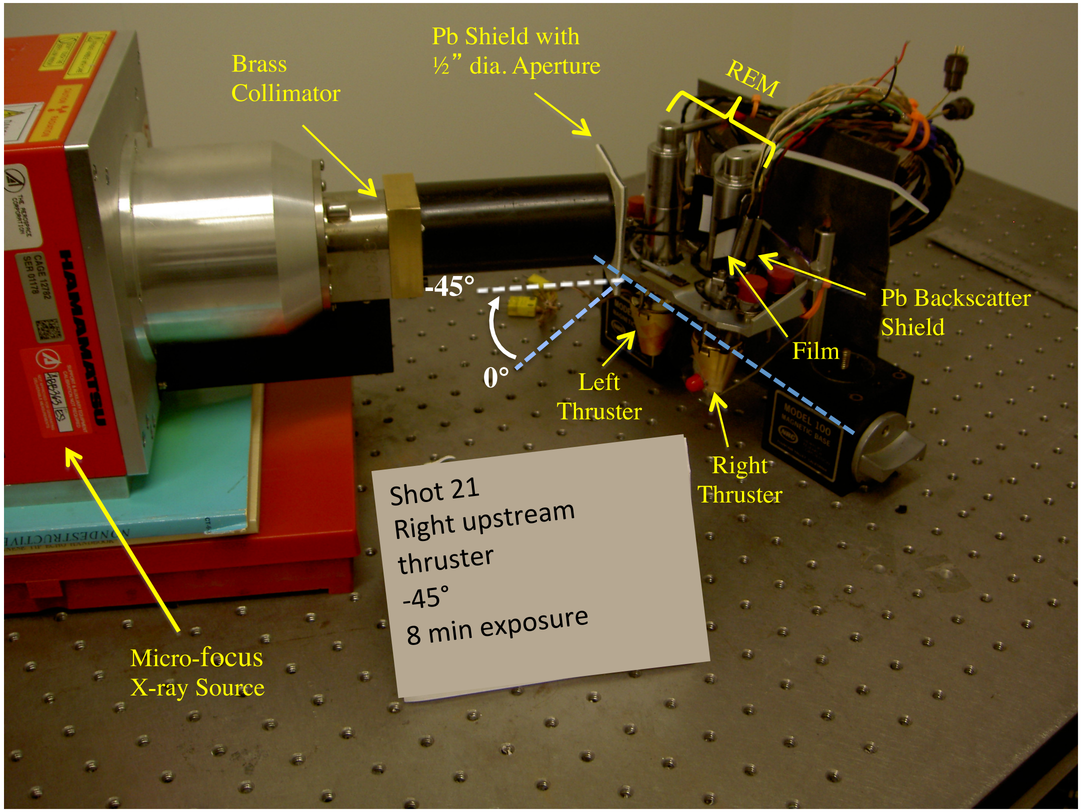
- Some of the springs were supplied with an end that was out-of-tolerance with respect to angularity and surface finish.
- The out-of-tolerance springs were susceptible to a condition where the spring end gets caught on the edge of the air gap as shown below.
- Upon repeated valve operation, the “caught” end of such a spring can eventually become wedged in the gap and interfere with movement of the plunger, preventing the valve from opening.
- Because the plunger visually obscures the spring, this would not have been noticed during assembly of the valve.





Technique Development

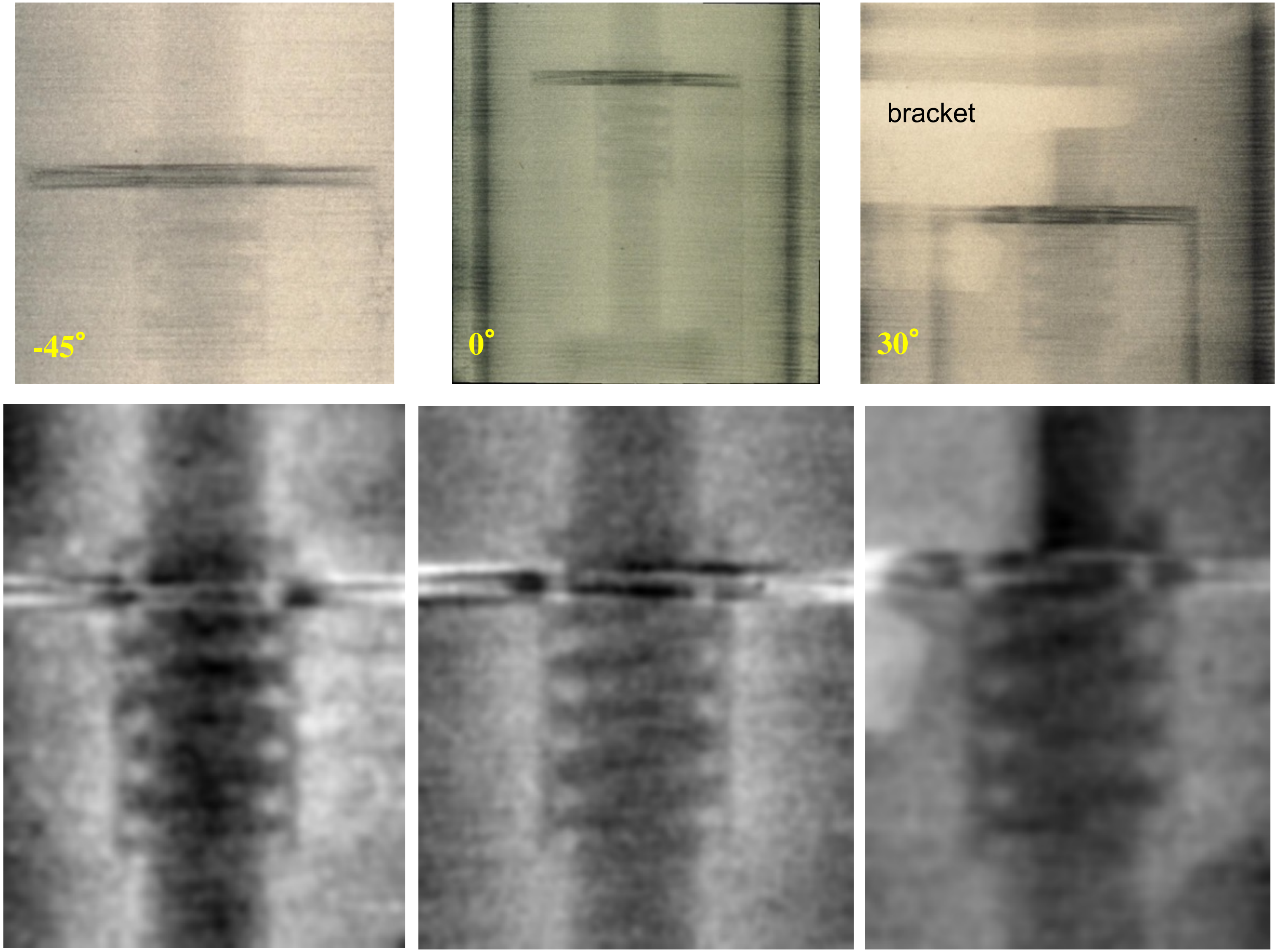
- Steps were taken to minimize the effects of X-ray scatter:
  - The beam exits the source as a 45° cone. A 2.0" long brass collimator with a ¾ inch bore was added to the front of the source.
  - To further restrict the beam, a plastic extension tube with a with ½ inch lead aperture at the end was then placed over this collimator.
  - A 1/32-inch thick sheet of Pb foil was placed behind the Pb-pack film to further reduce the effects of backscatter.



Technique Development (cont.)

- The source was positioned 6.5 inches from the thruster.
- A fixture was designed to center an alignment laser in the collimator bore to target the air gap in the thruster.
- The CT study revealed that at some viewing angles an improperly seated spring would not be evident. It was concluded that shots at three equally space angles spanning at least 90° would comprise a complete inspection.
- An 8 min exposure was found to produce a reasonable image.
- The films were developed and then photographed under illumination using a digital camera and macro lens.
- To aid in film evaluation, each digital image was processed using an FFT bandpass algorithm set to filter out large structures down to 300 pixels and small structures up to 12 pixels.

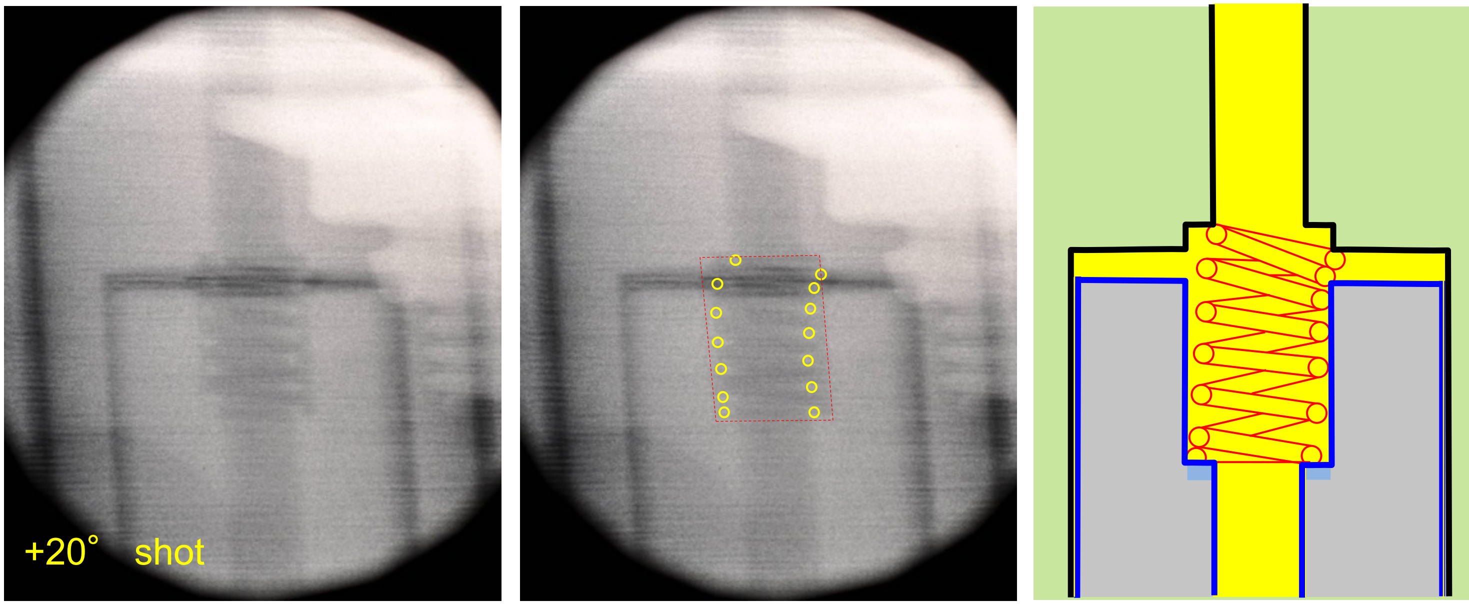
Results



Left Downstream Thruster Valve – Improperly Seated Spring

(30° view obscured by bracket)

Results



Left Downstream Thruster Valve – Improperly Seated Spring

(12 min exposure - bracket blockage avoided)

Technique Application

- The results provided proof-of-concept that an *in-situ* radiographic inspection could be performed to check for improper seating of the REM valve springs.
- Upon notice that the intent was to go forward with the inspection of a number of flight articles, adjustments were made and effort was directed toward determining optimum exposure parameters.
  - The contractor was able to provide a mobile/hydraulic mount to facilitate positioning of the source for each radiograph. An adaptor was machined to interface the source to this mount.
  - The number of units to be inspected was large enough to motivate a study to strike the right balance between improving the image contrast and reducing the time for the overall inspection. A 12 min exposure time for a 6.5-inch source to thruster distance was deemed optimal. This time was reduced or increased according to an inverse square law in distance depending on how close one could get the source to each thruster.
  - The plastic extension tube in the laboratory setup was replaced with a shorter aluminum extension tube (covered with lead). This further reduced the forward beam scatter and allowed for closer positioning of the source to the thrusters.

Acknowledgement

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Thank You