14th International Symposium on Nondestructive Characterization of Materials

Composite Overwrapped Pressure Vessel (COPV) Liner and Thin Wall Metallic Pressure Vessel Inspection Scanner Development and Assessment

Regor Saulsberry

William Prosser

June 25, 2015: 12:35

Presentation Overview

Presenter
Regor Saulsberry
Date
June 25, 2015

- Background
- Assessment Team Membership
- System Developmental Overview
- System Description
- Current System Performance and Data Review
- Backup (get with me off-line)
  - Coupon Flaw Growth Status and Data Review
  - POD Plan
  - Other developmental details

Background

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- Following a Commercial Launch Vehicle On-Pad COPV failure, a request was received by the NESC June 14, 2014.
- An assessment was approved July 10, 2014, to develop and assess the capability of scanning eddy current (EC) nondestructive evaluation (NDE) methods for mapping thickness and inspection for flaws.
  - Current methods could not identify thickness reduction from necking and critical flaw detection was not possible with conventional dye penetrant (PT) methods, so sensitive EC scanning techniques were needed.
  - Developmental methods existed, but had not been fully developed, nor had the requisite capability assessment (i.e., a POD study) been performed.

Team Members

Presenter	Date
Regor Saulsberry	June 25, 2015

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Prior Supporting R&D

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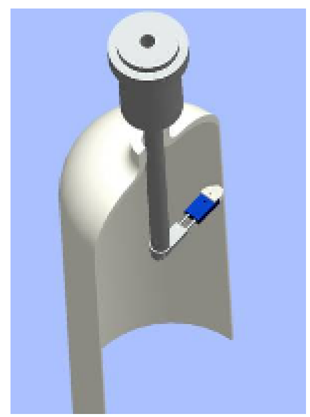
- The NASA-WSTF and NASA NDE Working Group (NNWG) demonstrated an ability to consistently detect fine defects using a desk-top liner internal and external scanning system; however, this technology needed further development and implementation into an existing WSTF full-scale scanning laser profilometer for typical flight vessel inspections.
  - The objective was to produce an inspection and analysis system that would help ensure reliable COPVs over their full design life and that would be feasible for use on both NASA and commercial spacecraft.

External EC added to desktop profilometry scanner

Articulated sensor developed for profilometry of domes



Internal EC added to desktop scanner

7' Nitrogen/Oxygen Recharge System (NORS) and Orion profilometry system developed, validated and used extensively by the ISS NORS Program

System Developmental Overview

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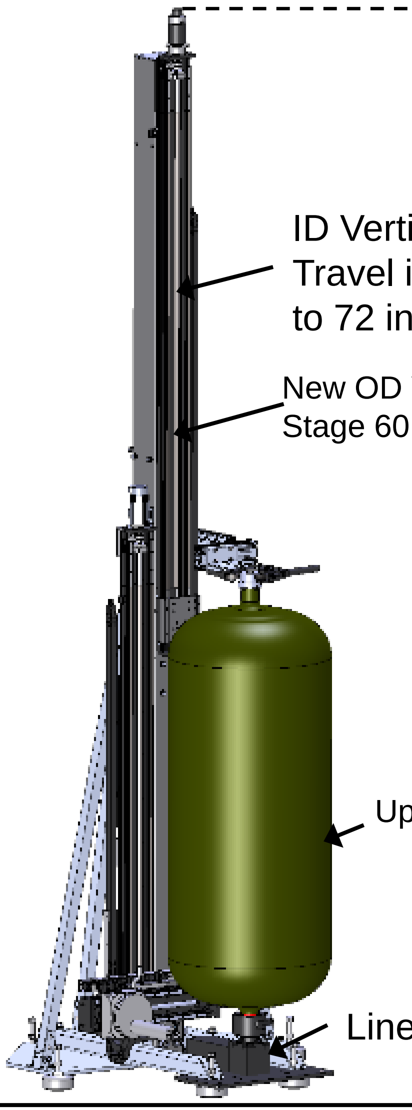
- Although further refinements are likely, the modifications are now complete and a true multi-purpose COPV NDE scanner has resulted.
  - New sensors were developed and integrated into the expanded laser profilometry delivery system.
  - This new inspection system is potentially a “game changer” for production of safer and more reliable COPVs.
    - Can scan COPV liners up to 22-in diameter and 48-in long and internally and externally map thickness variations, map surfaces, provide Laser Video™ and detect very fine defects.
    - Highly accurate and calibrated internal mapping allows mechanical response evaluation and provides high-resolution images of the vessel interior.
    - Allows flaw screening and analysis after wrapping and autofrettage addressing a long standing technical concern over potential flaw generation and liner thinning during this time of plastic deformation.



Ten System Configurations

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	Liner Diameter	
Sensor Type	**15-inch**	**22-inch**
EC Thickness	ID, OD	-
EC Flaw	ID, OD	ID, OD
Laser Profilometry	ID, OD	ID, OD

Each configuration has unique requirements for articulation, axis motion, and data acquisition.

Thickness/flaw EC sensors required new development

- Flaw sensors require simultaneous acquisition from two US-454A instruments
- Thickness sensors will require 2-frequency acquisition – requires digital acquisition

System ID (SID) used: with so many sensor variants, the design should limit the need for manual system configuration as much as possible.

Internal EC Sensor - Design

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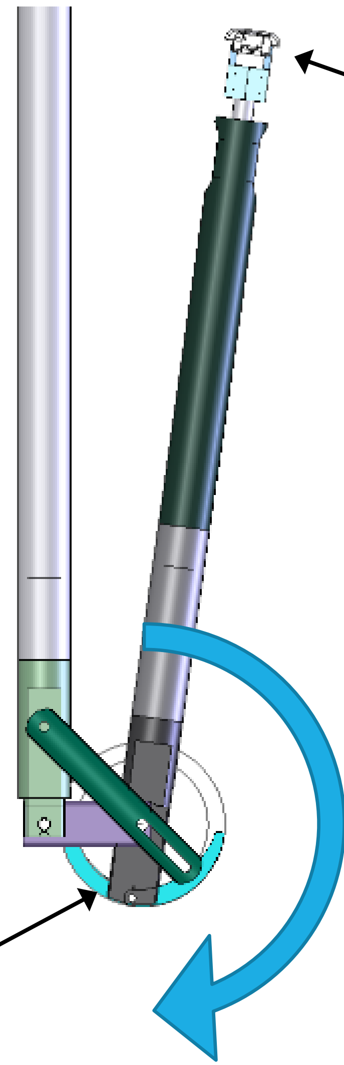
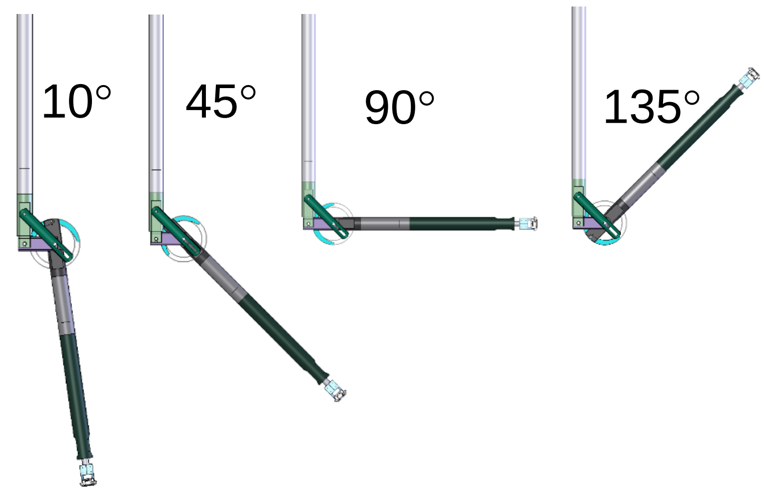
Double-joint mechanism enables single-scan for the full liner

0.65 Diameter shaft and sensor



Surface-riding mechanism & EC coil



Additional 90° elbow locks in place during scans

170° Max for full scans full liner

Outriggers pulled by cable provide stable rotation

Internal EC Sensor – liner Insertion

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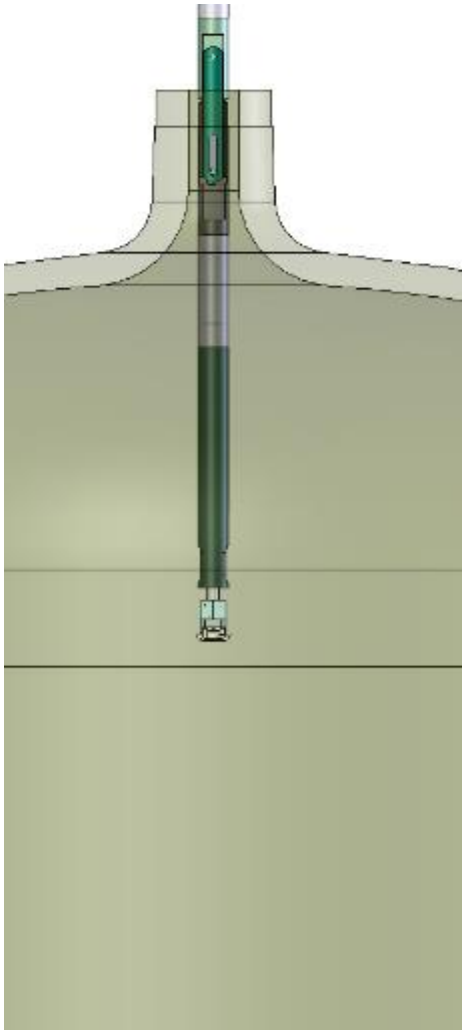
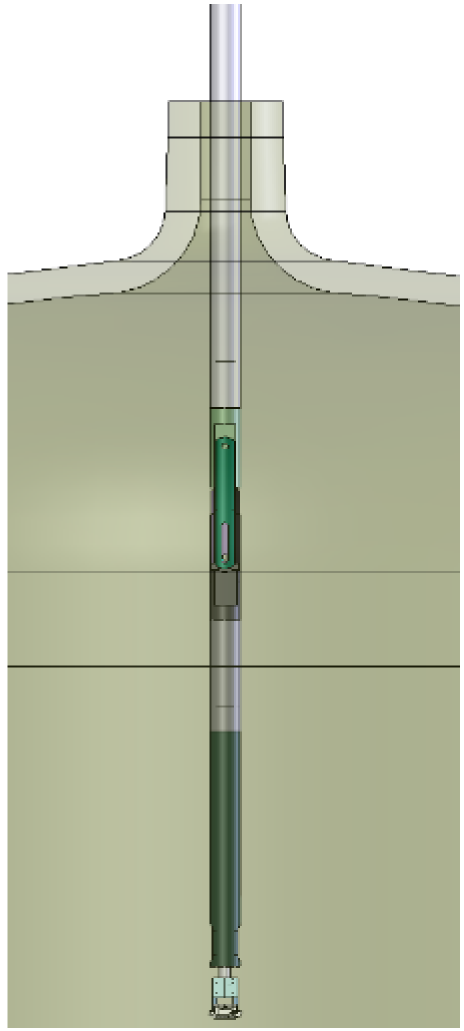
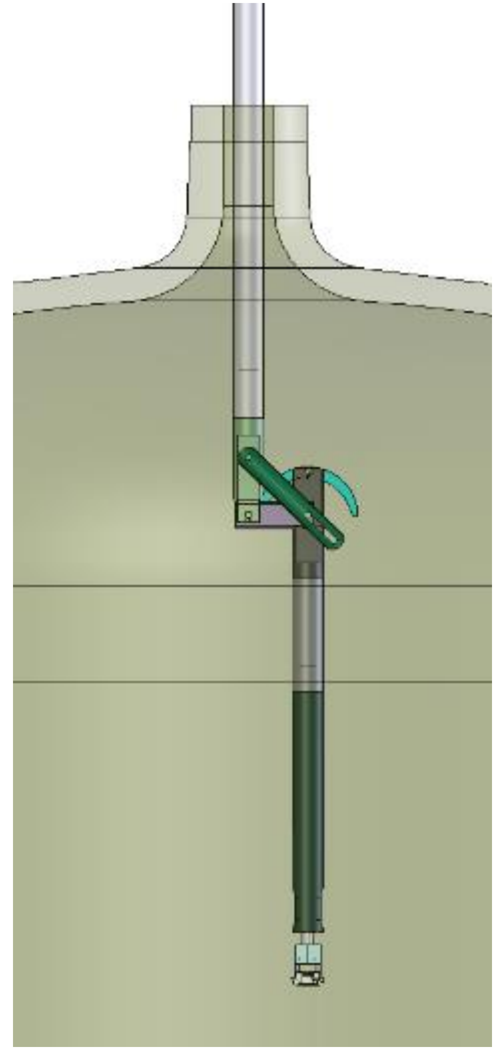

Inserting through port


Inside liner


90° elbow activated

EC ID End Effector Connector

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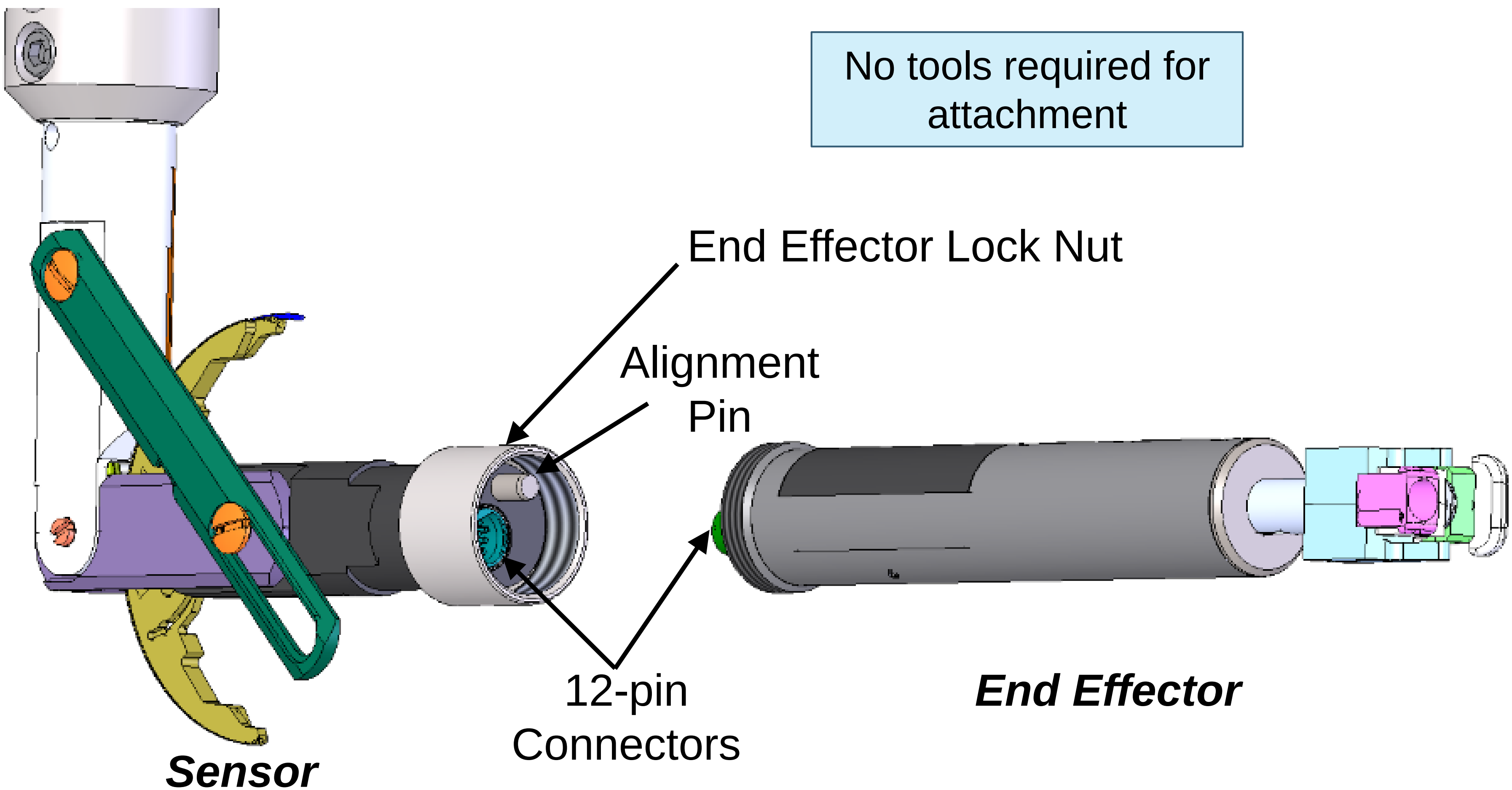
No tools required for attachment



EC Sensor – Surface-Riding Mechanism

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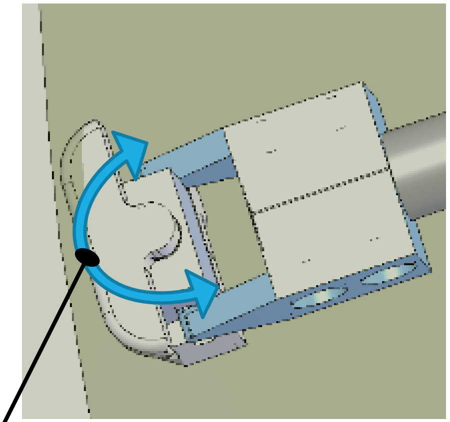
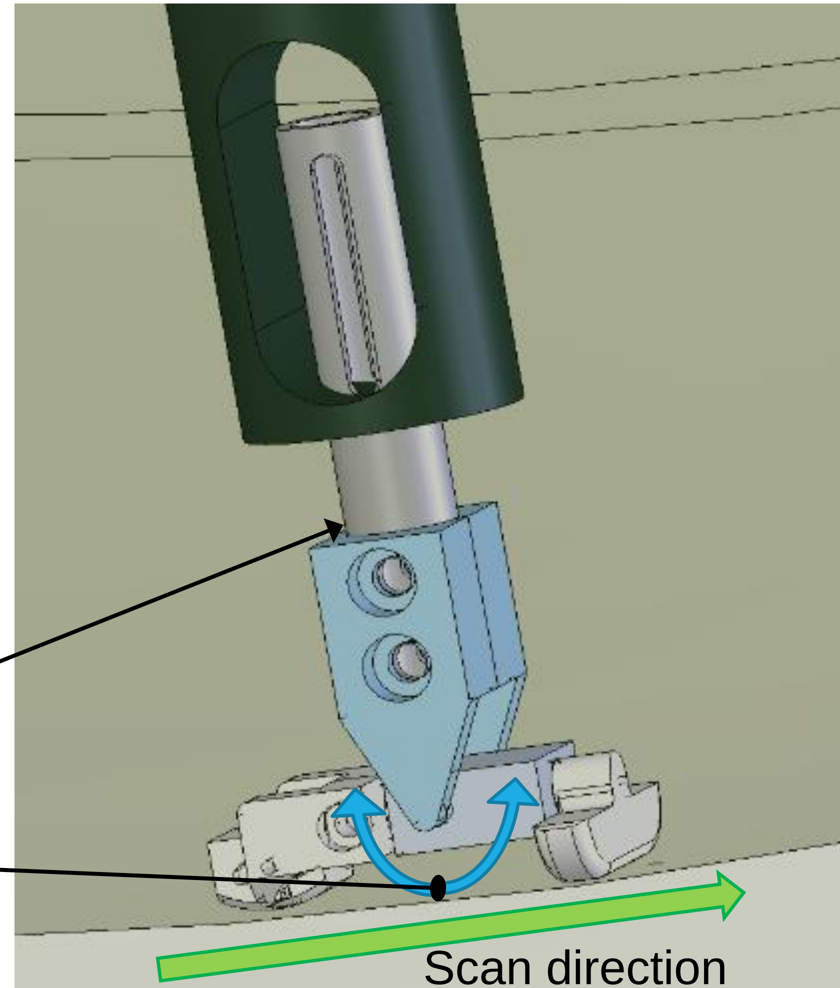


Surface-riding assembly pivots to maintain contact on domes

Spring-loaded shaft applies light force to keep EC coil on surface

Surface-riding assembly pivots to maintain contact during rotation



OD Thickness End Effector

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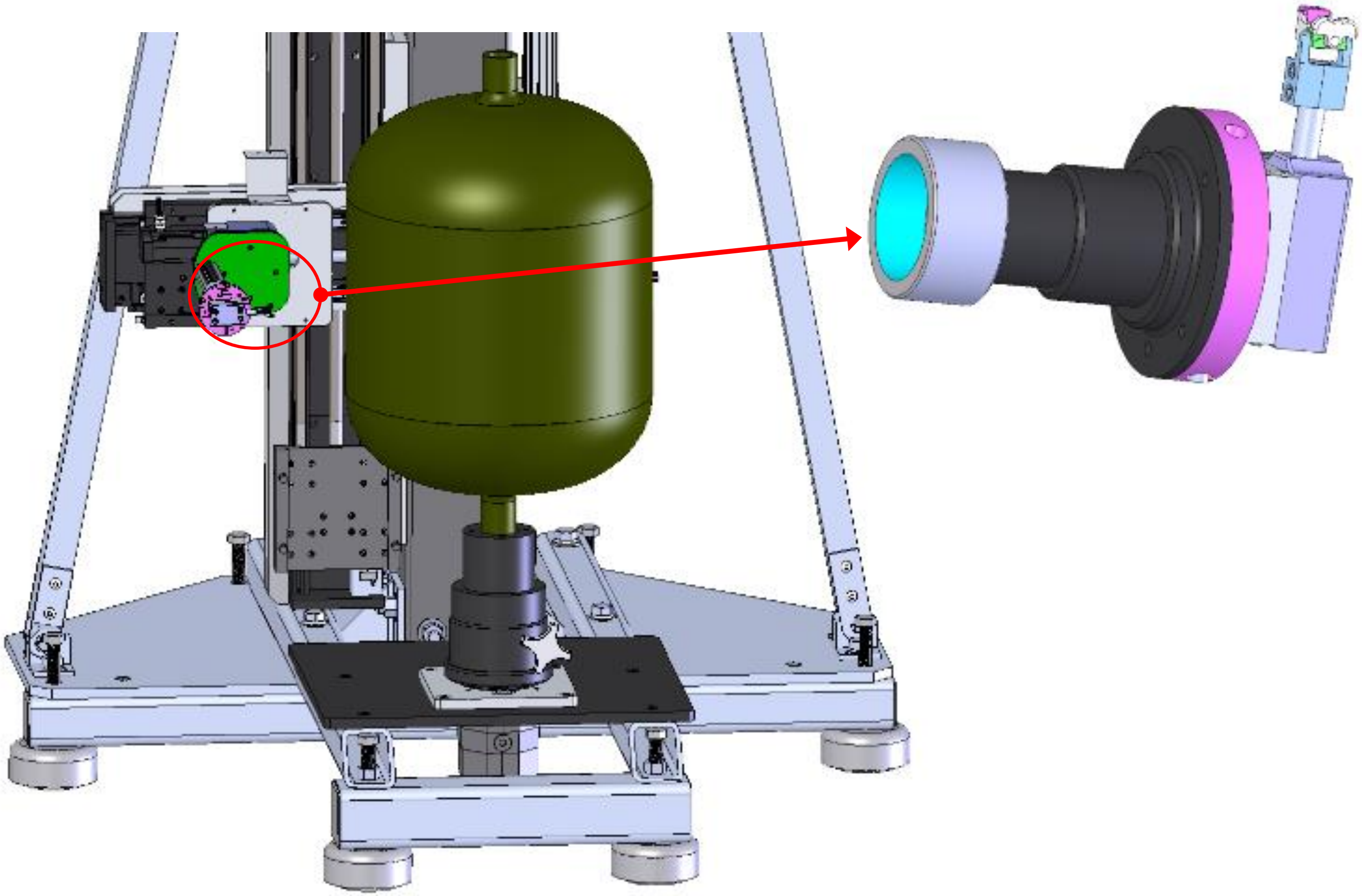
Same end effector used for both thickness and flaw detection sensors



OD Thickness EC Calibration Scan

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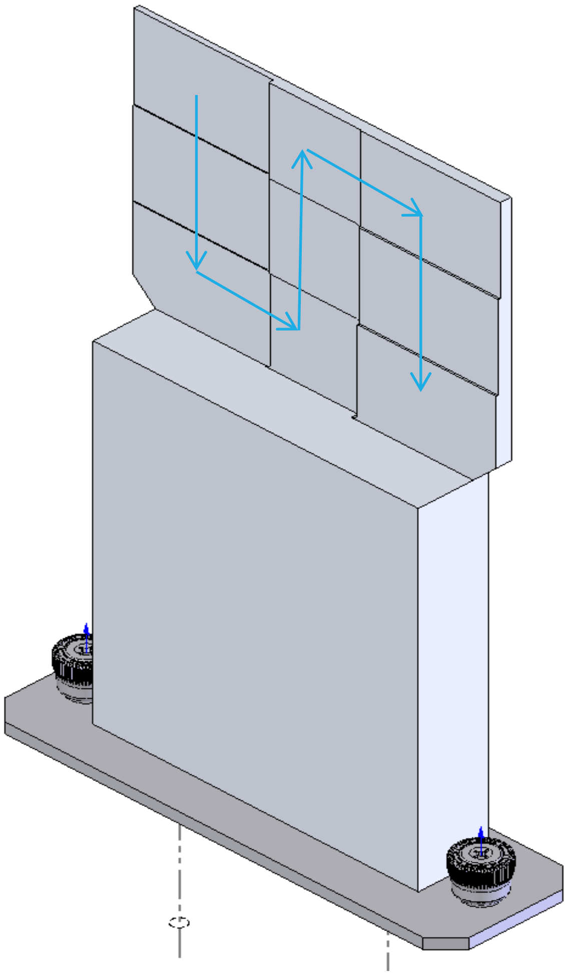

Calibration standards are NIST traceable

Flaw Detection Process

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Dual coils for optimum detection of flaws with different orientation

- For horizontal flaws there are two pickup coils spaced vertically, with the coil split along the horizontal axis.
- For vertically-oriented flaws the coils are rotated 90 degrees

Analysis Processors – optimized for each coil and flaw orientation

EC ID Sensor – End effectors

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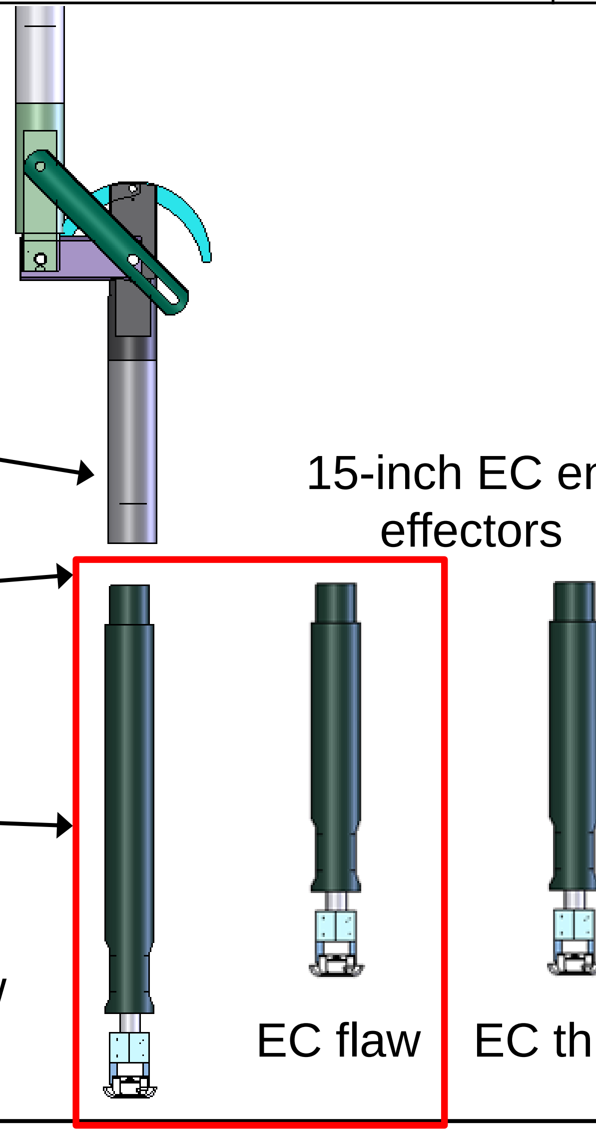

Laser Profilometry (LP)

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- Scanning of full liner OD and ID to near ports
- NIST traceable data to within 0.003 inch
- Produces high-resolution Laser Video™ Images

Articulated Laser Sensor

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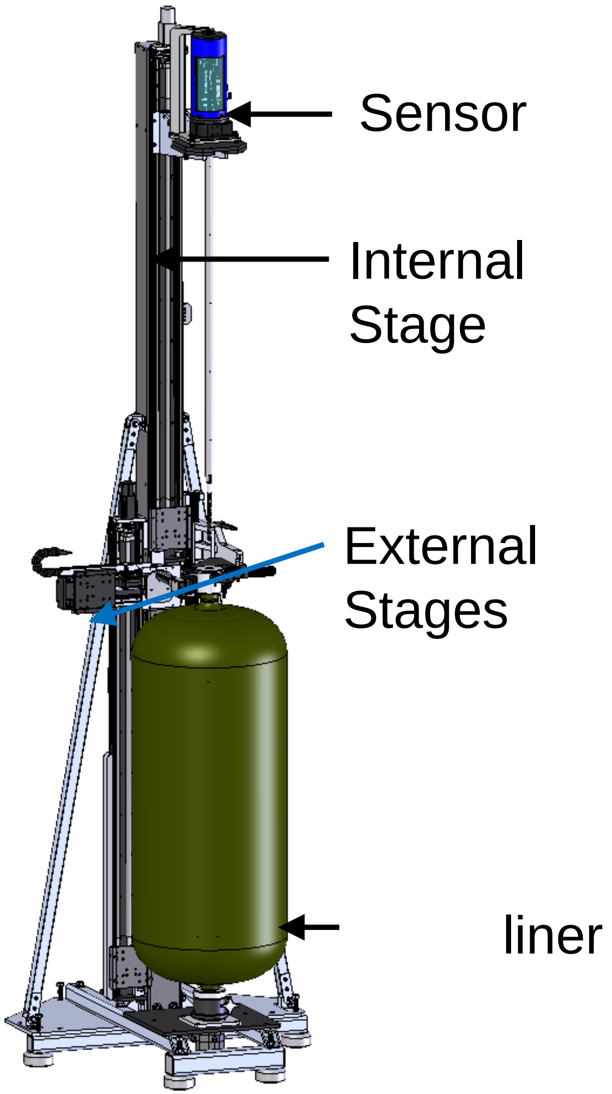

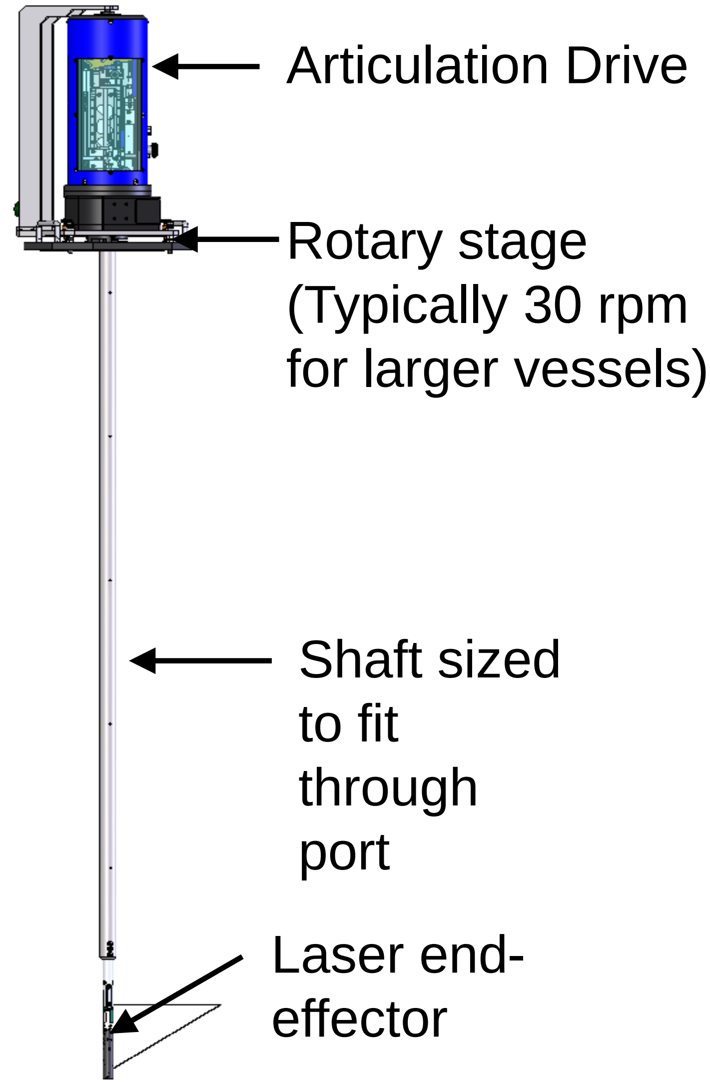

Laser Sensor in Shorty liner

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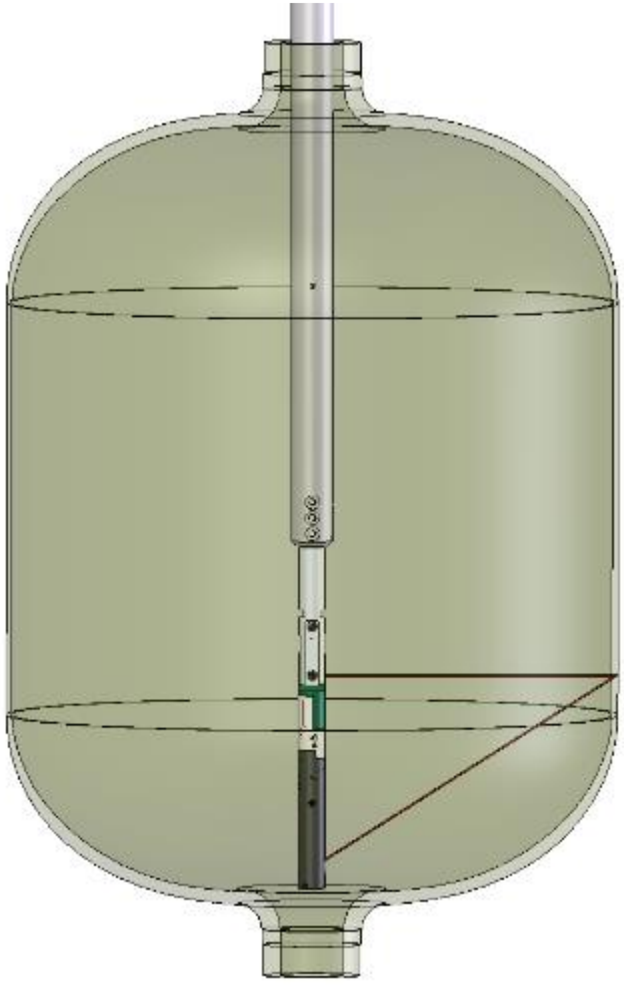

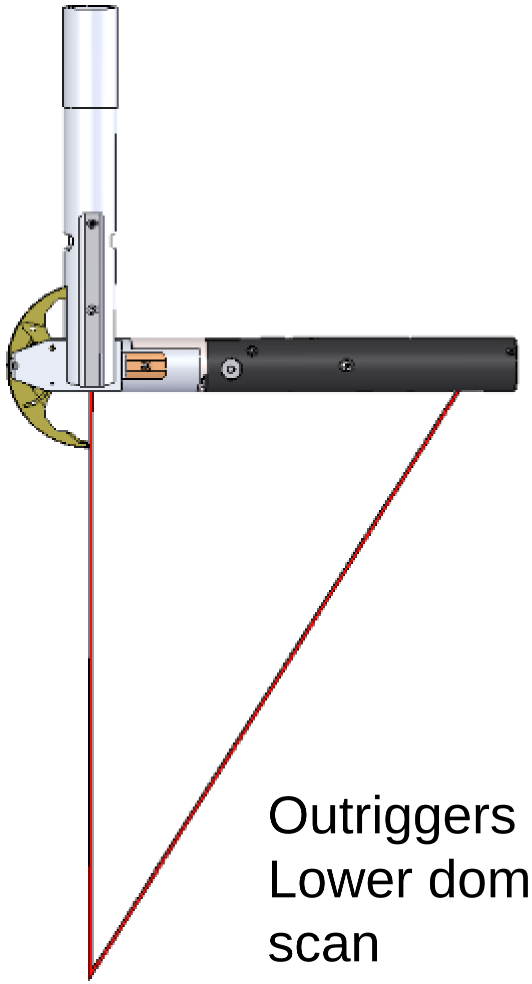

Outriggers open,
Lower dome
scan

NIST Traceable LP Calibration Setup

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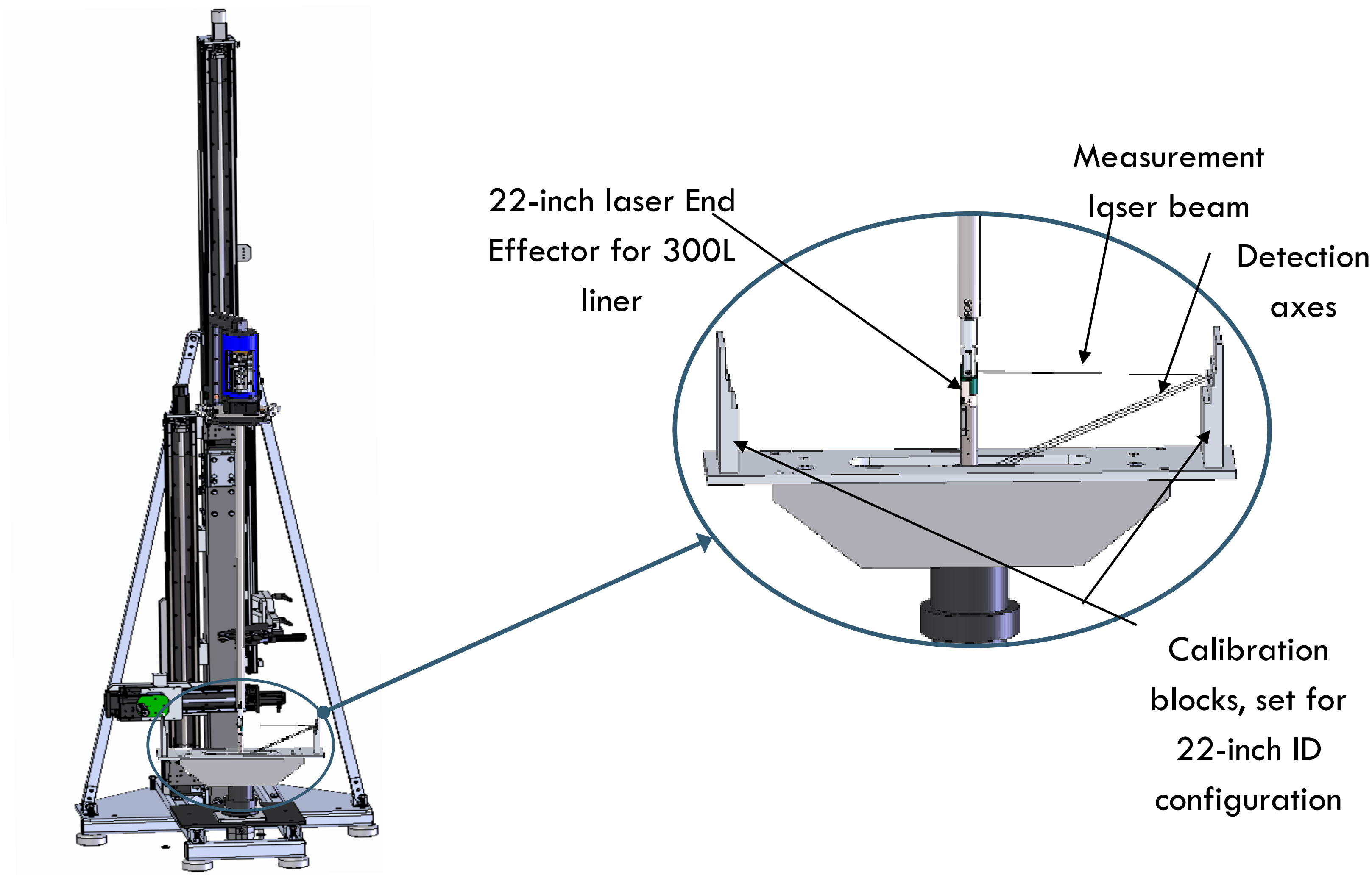

Data Review

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Regor Saulsberry

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June 25, 2015

1. Example data from the EC Thickness Mapping Acceptance Test
   a. Flaw Detection
   b. Laser Profilometry
2. Repeatability test data:
   a. Thickness Mapping (after improvements)
      - Refinement in technique applied during repeatability testing
   b. Flaw detection
3. Coupon Level Testing

Calibration Tooling Measurements

OD EC Thickness Sensor - After Auto-cal

Step	Actual (in)	Measured (in)	Difference (in)
1	0.060	0.0604	0.0004
2	0.070	0.0701	0.0001
3	0.080	0.0802	0.0002
4	0.090	0.0900	0.0000
5	0.100	0.0997	-0.0003
6	0.110	0.1098	-0.0002
7	0.120	0.1198	-0.0002
8	0.140	0.1404	0.0004
9	0.160	0.1658	0.0058

EC Thickness Mapping Acceptance Testing

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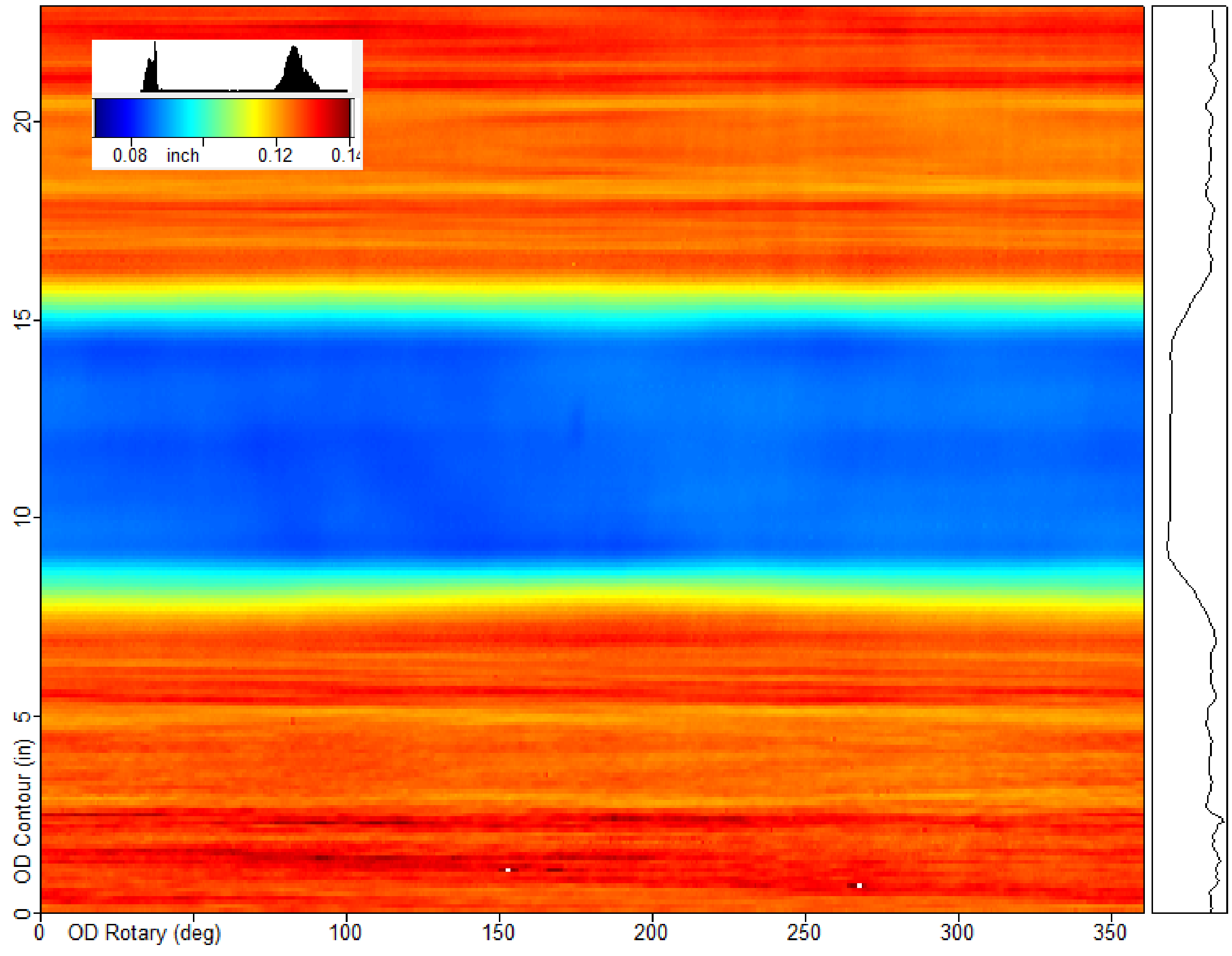
Date June 25, 2015

Calibrated Liner Scan – OD EC



EC Flaw Detection Acceptance Testing

Presenter	Date
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- OD Scans: 15-inch dia. Liner SN 005
  - 22-inch dia. 300L pending new flight like liners from a commercial spaceflight company
- Two groups of 3 flaws on upper dome

Group 1			
Notch Orientation	Actual Notch Dimensions (Measured)		
	Length	**Depth**	**Width**
Circ	0.016	0.007	0.004
Radial	0.016	0.007	0.003
45deg	0.017	0.007	0.003
Group 2			
Notch Orientation	Actual Notch Dimensions (Measured)		
	Length	**Depth**	**Width**
Circ	0.016	0.014	0.003
Radial	0.017	0.013	0.003
45deg	0.017	0.013	0.003

- All flaws clearly identified
  – Noise filtering and automated flaw detection

EC Flaw Detection Acceptance Testing

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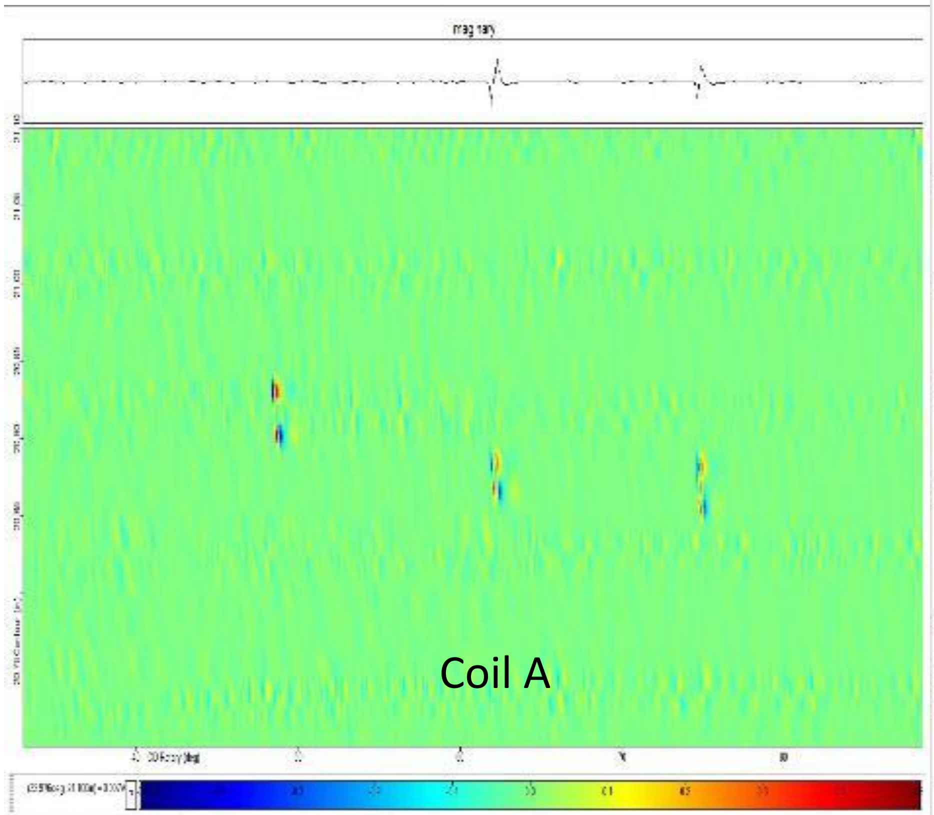
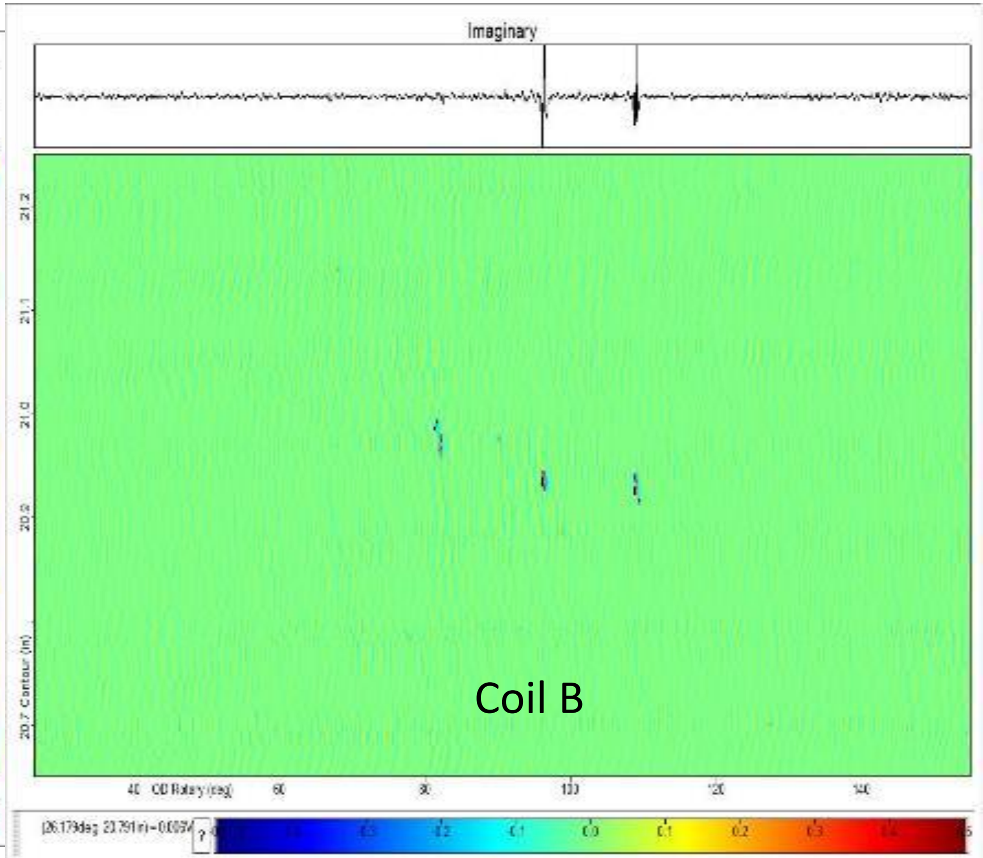
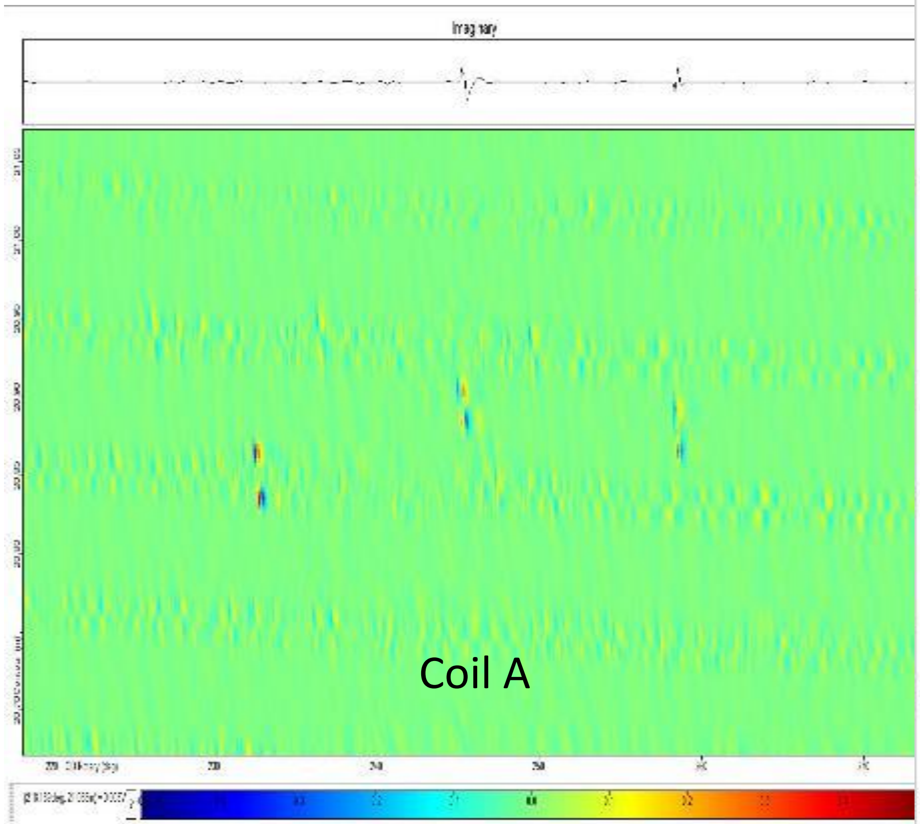
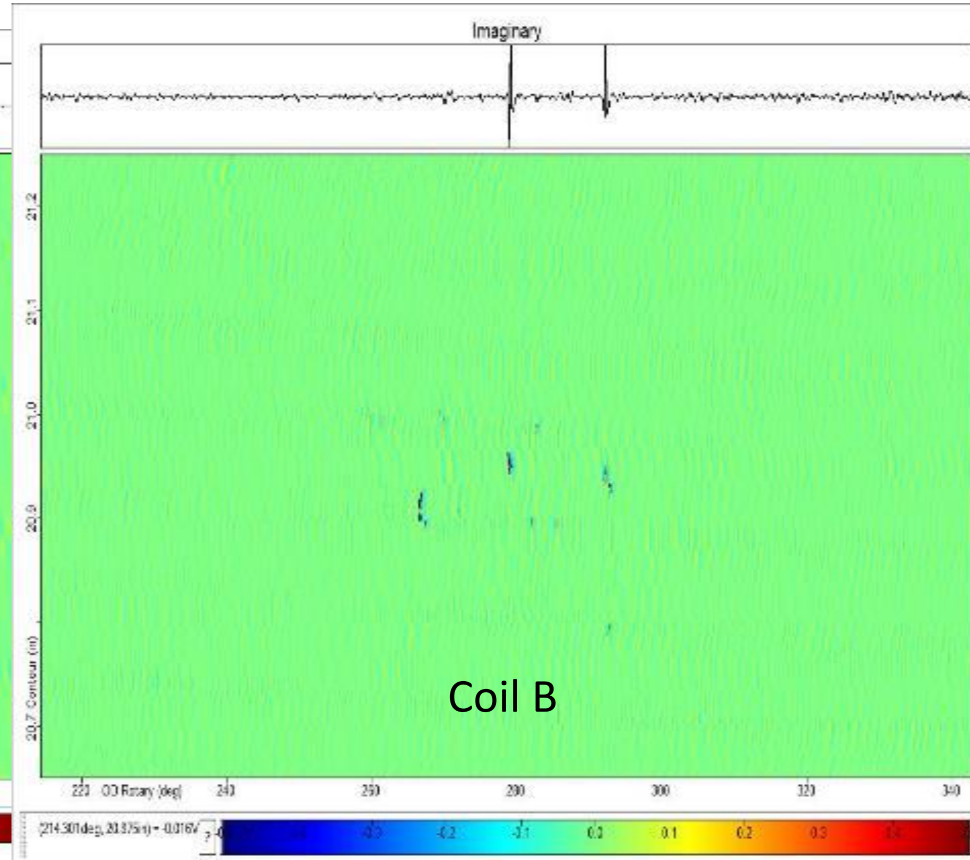
EC Flaw Testing – Shorty Liner OD Group 1, Upper Dome





EC Flaw Testing – Shorty Liner OD Group 2, Upper Dome





EC Flaw Detection Acceptance Testing

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- 4 groups of 3 fine ID Flaws (cylinder and dome):
  - Width: 0.0009-0.0011 inch
  - Depth: 0.0049-0.0055 inch
  - Length: 0.0123-0.0127 inch
- Flaws on cylindrical section were all found; however, noise was high on domes due to extreme roughness causing fine flaws not distinguished from noise in that area
  - To bound capability in that area, six new flaws 0.030 x 0.020 x 0.003 inch plus 0.049 x 0.021 x 0.003 inch Circumferential, Axial, and 45 degrees were later added and all were detected all after application of optimized noise filtering (slides in backup charts)
  - Recent data with the automated flaw detection software successfully identifying all scanned flaws with a signal to noise > 3 and no false positives (in backup).

Cylindrical Section Acceptance Testing

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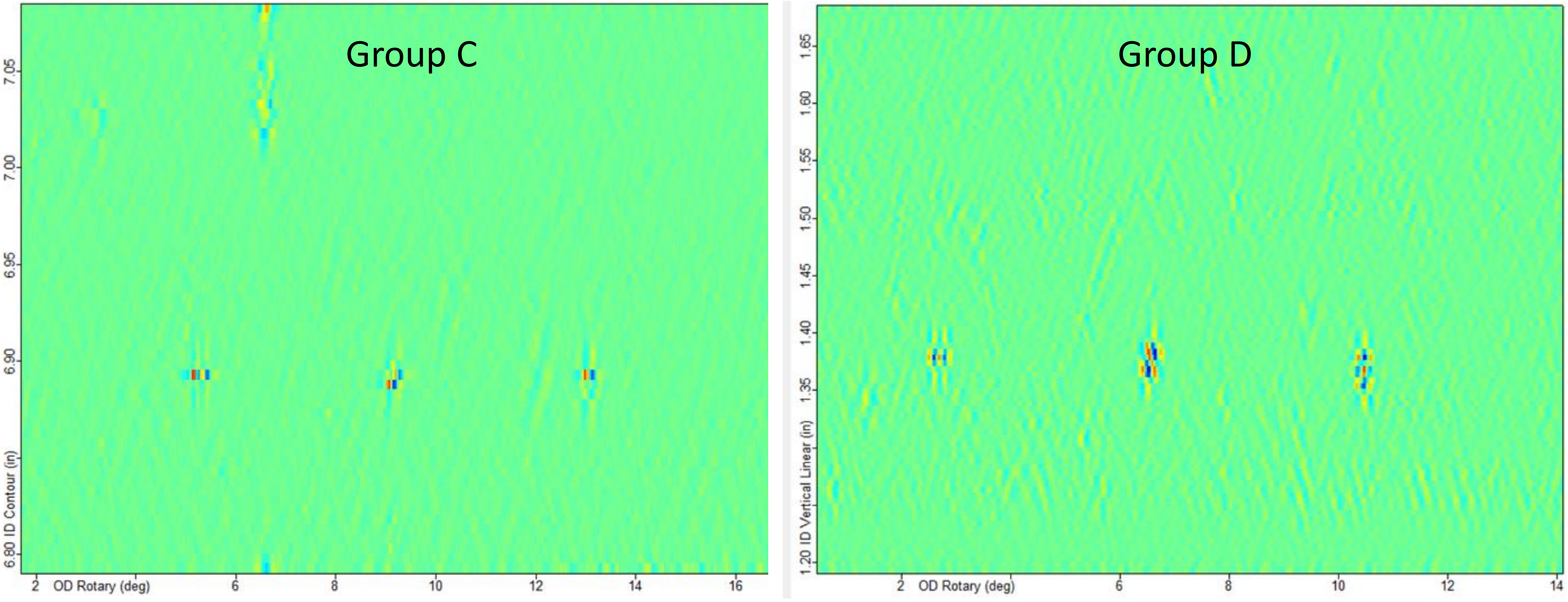


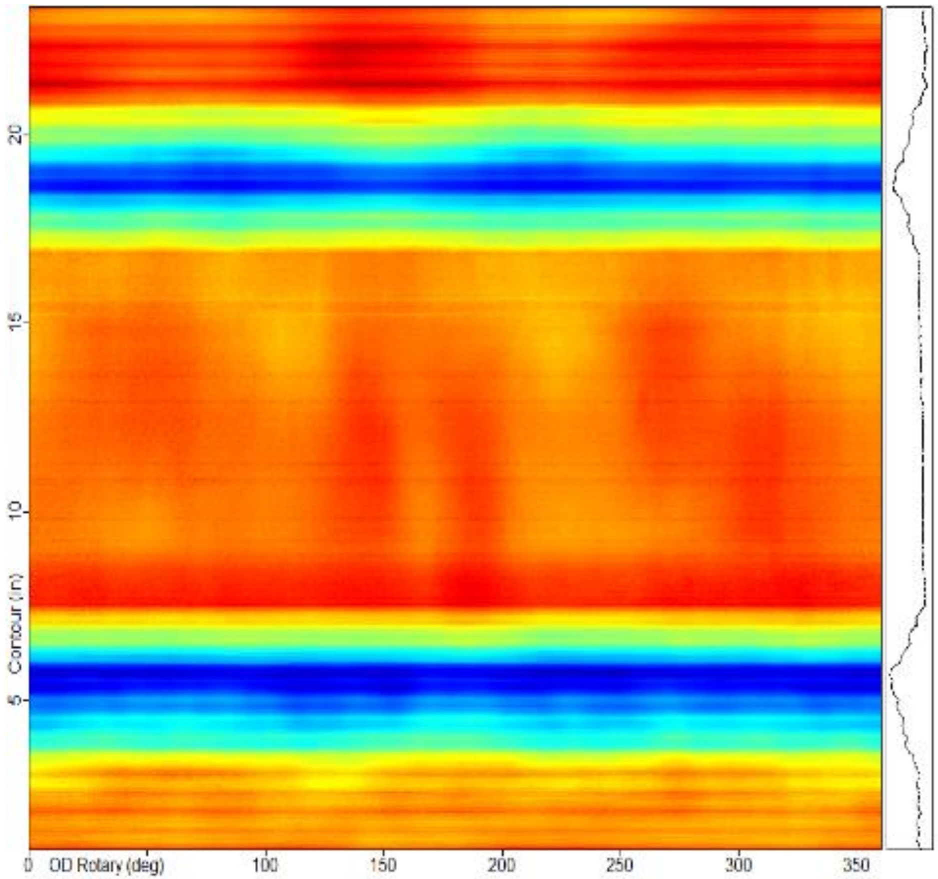
Laser Profilometry/Laser Video™ Acceptance Testing

Presenter
Regor Saulsberry

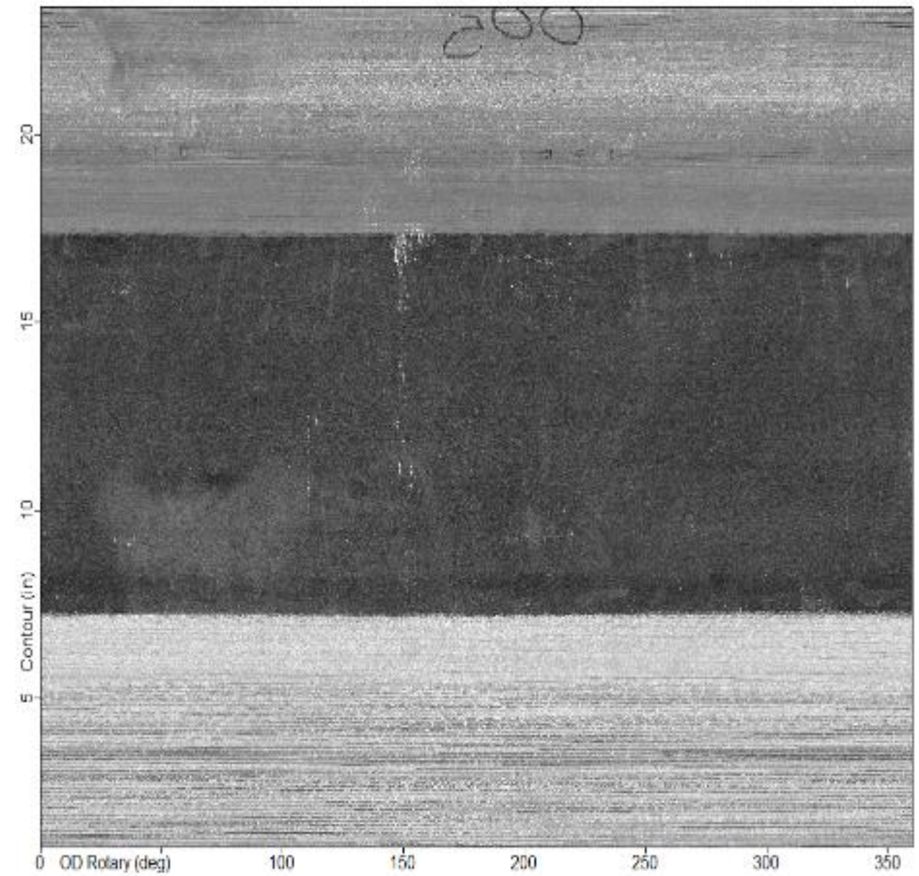
Date
June 25, 2015

OD Profile and Video Scans of “Shorty” Liner (ID Scans later)

Laser Profile



Laser Video™



Laser Profilometry/Laser Video™ Acceptance Testing

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Date
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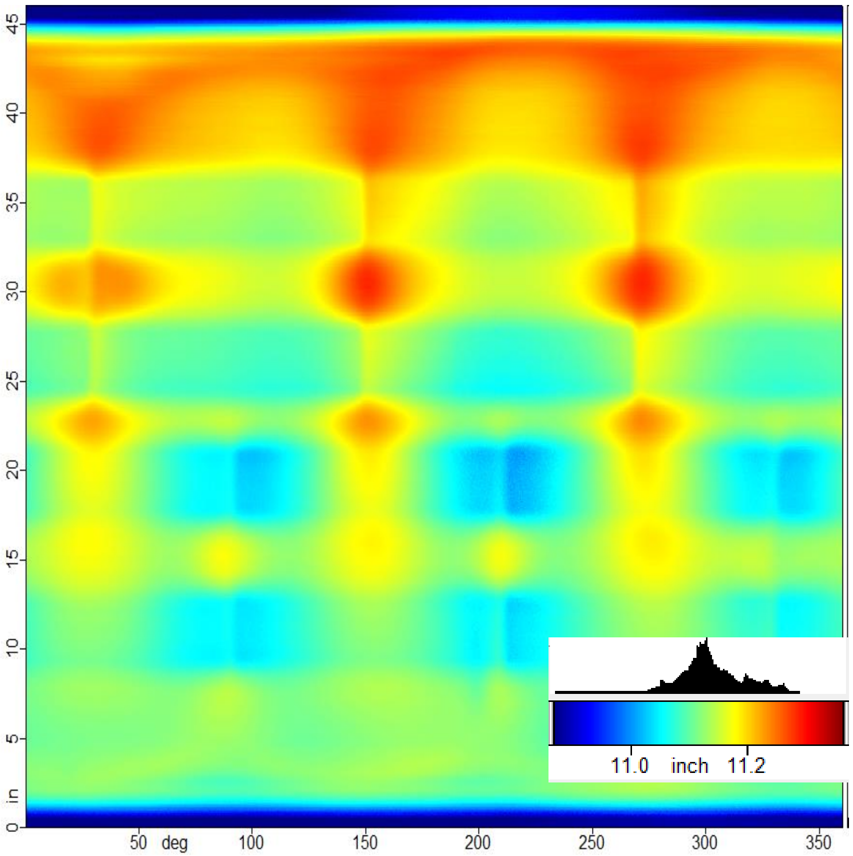
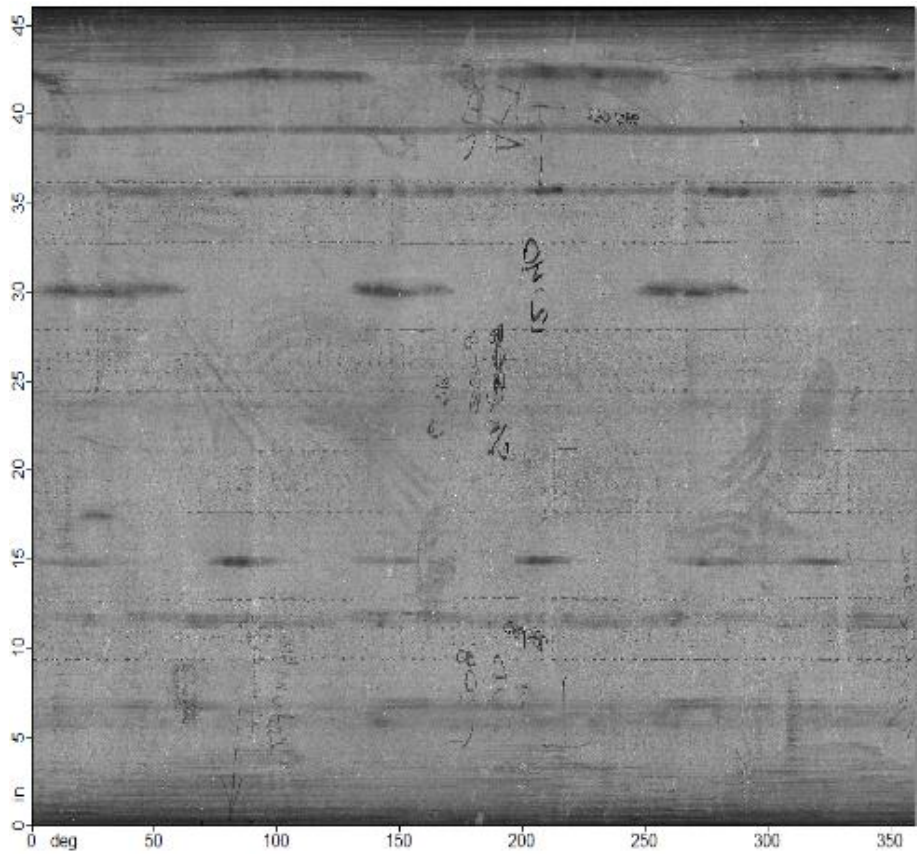
OD Profile and Video Scans of 300 Liter Liner

Laser Profile



Laser Video™



Repeatability Scan Testing

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Date	June 25, 2015

Task		Comments
Thickness Repeatability Shorty Liner SN005		Thickness completed with signal rotation and amplitude adjustments and 0.1 V offset applied
Thickness Repeatability Shorty Liner SN003		Thickness completed with signal rotation and amplitude adjustments and 0.1 V offset applied
Flaw Repeatability Shorty Liner SN 005 (OD)		All flaws found reliably in automatic flaw detection SW
Flaw Repeatability Shorty Liner SN 006 (ID)		All 6 new flaws found by reporting software

Example
Shorty Tank Thickness ID Repeatability-SN 003

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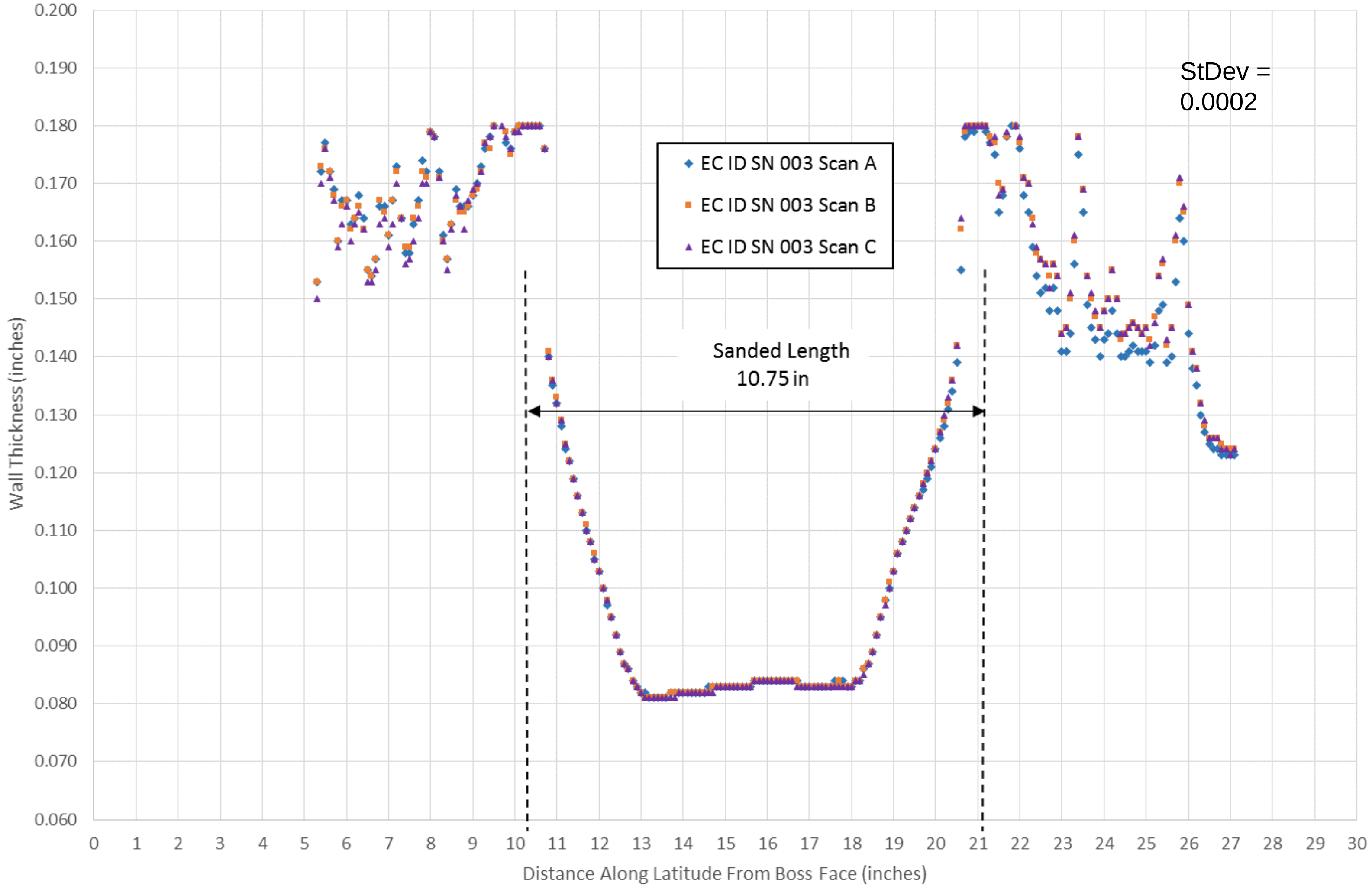

Example
Shorty Tank Thickness OD Repeatability-SN 005

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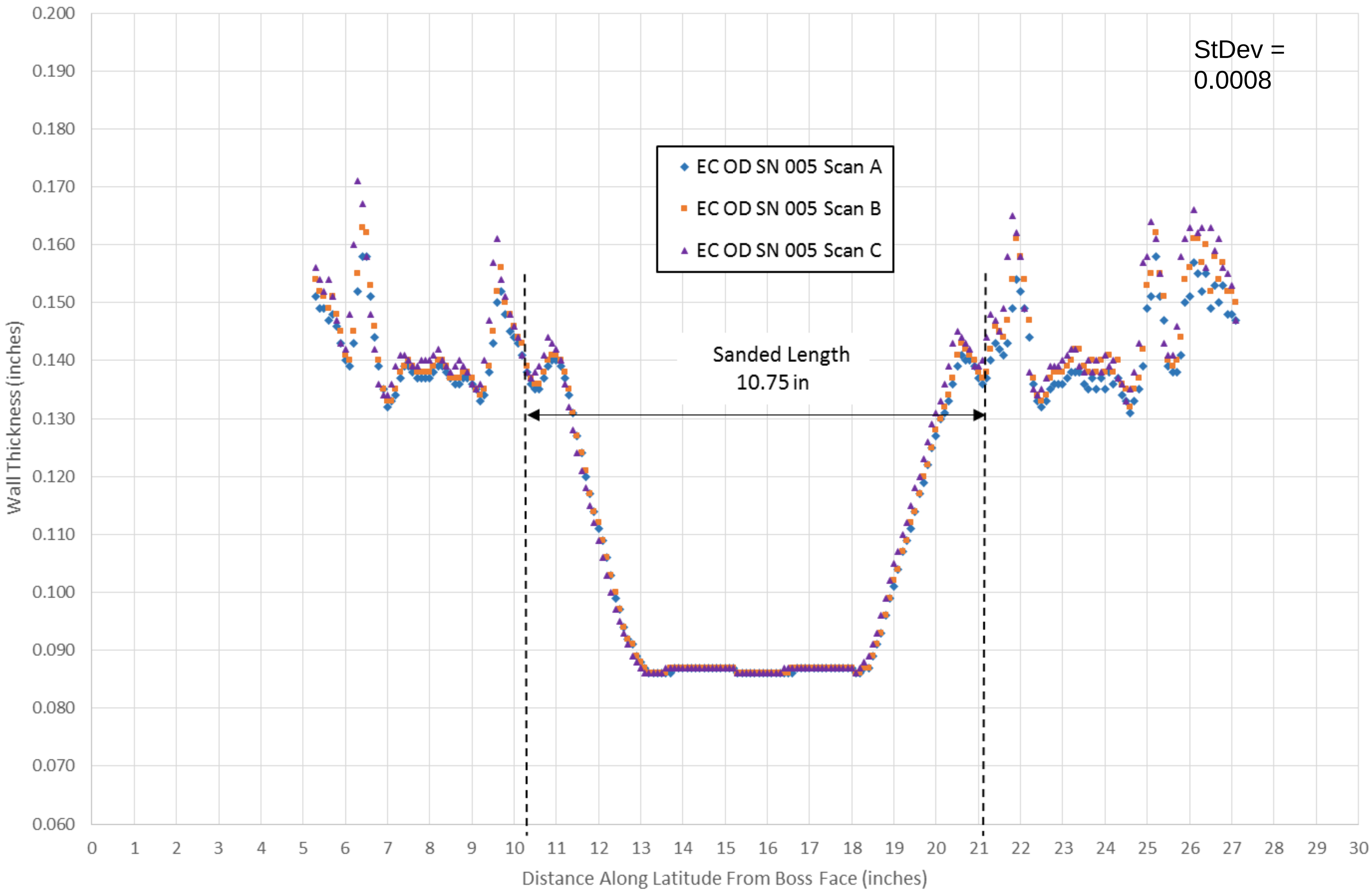

Shorty Tank Thickness ID Repeatability
Cross Section of SN 006 with Machined Grooves

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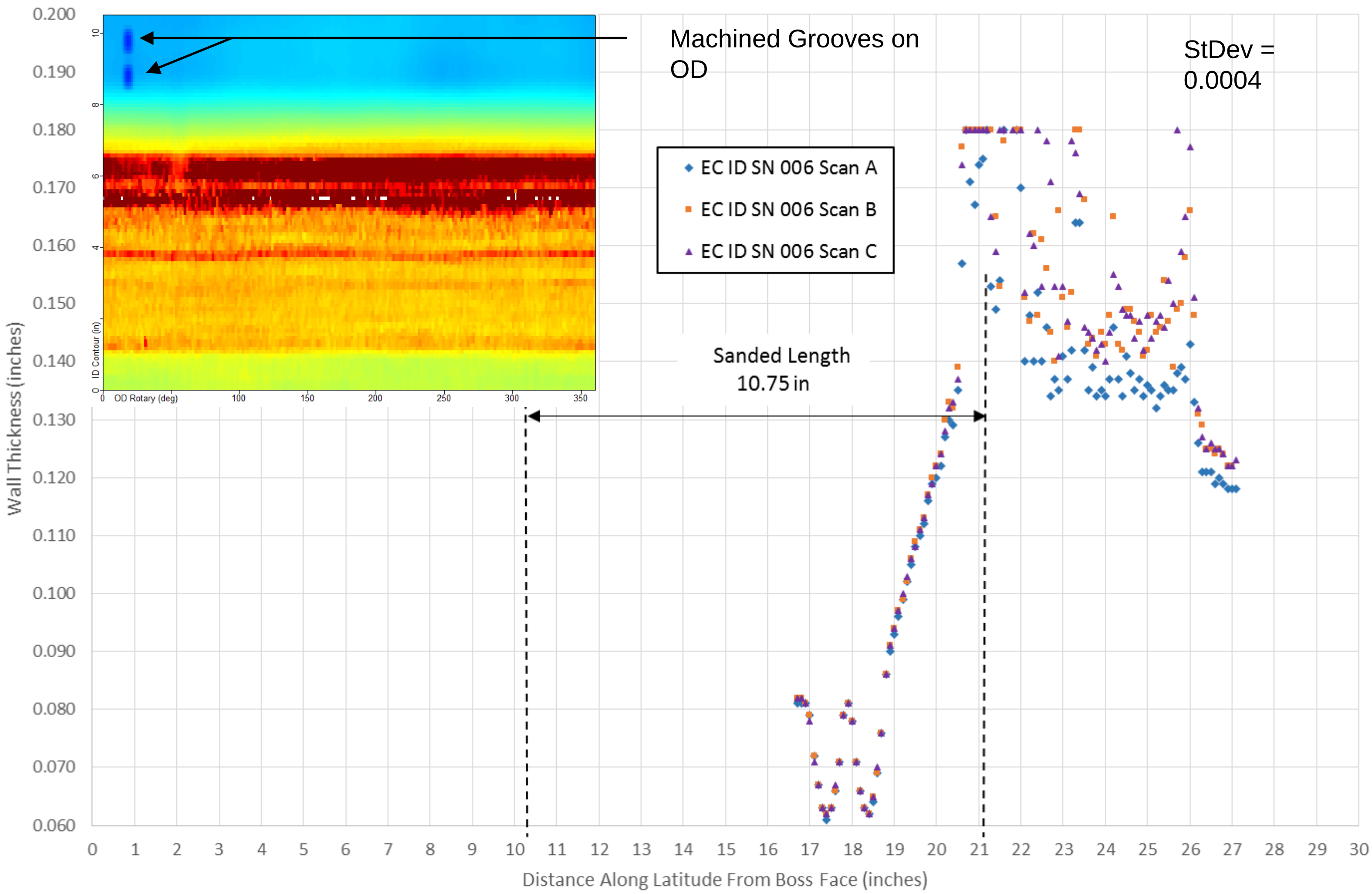

Comparison of OD Thickness to UT Shorty Liner SN 003

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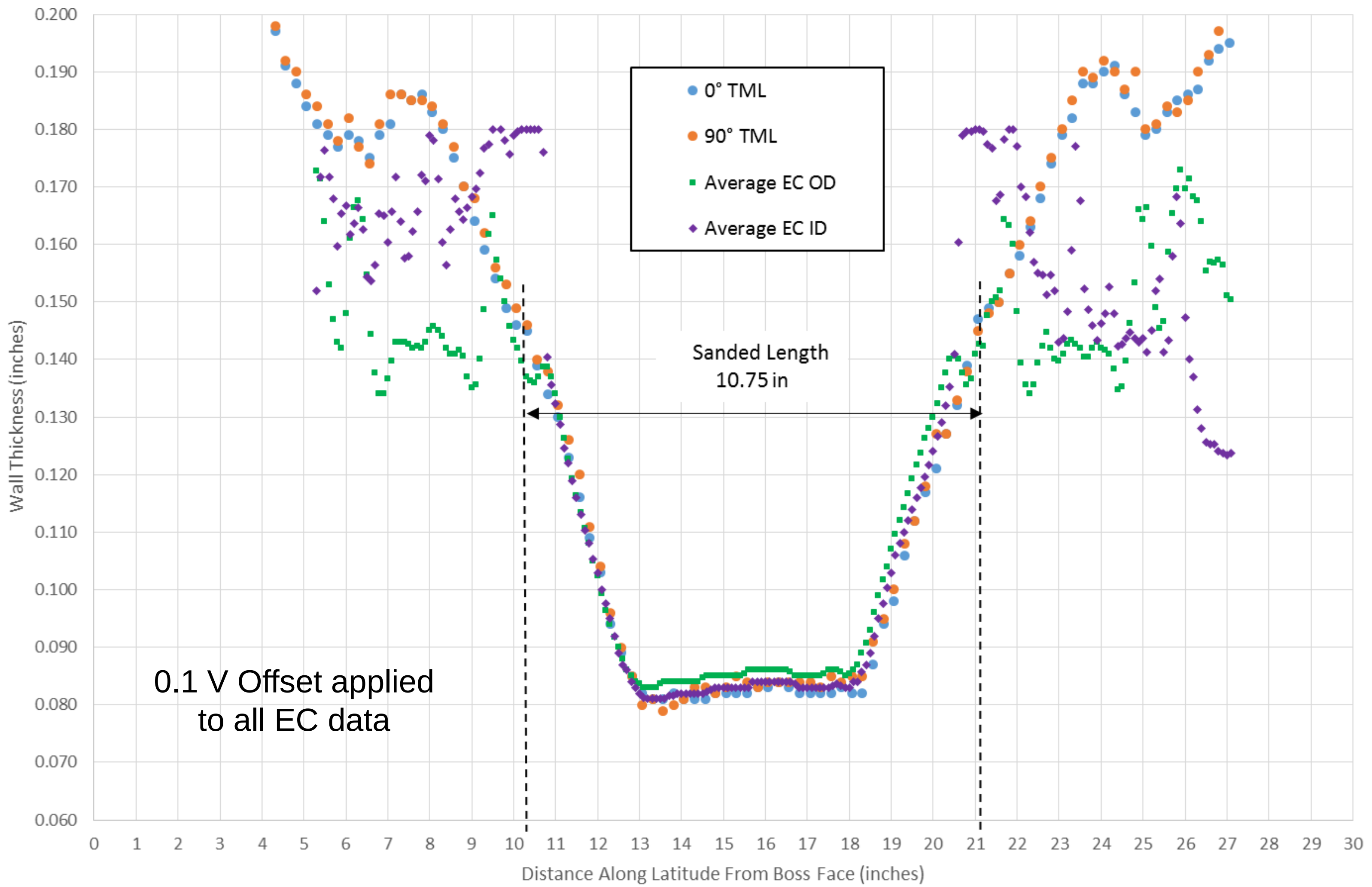

Conclusions

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Date	March 25, 2015

- Test System performance and Test Data to date is excellent; however, more comprehensive testing is planned at WSTF to wrap-up Phase I
- A Phase II POD plan has been developed and the coupon testing indicates that the approach is likely feasible
- The balance of the assessment has been scheduled to complete the task and provide a report around the end of 2015

Backup

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Date	June 25, 2015

Phase I Coupon Study Objectives
(Specific goals and parameters in later in backup charts)

Presenter
Regor Saulsberry
Date
June 25, 2015

1. Verify feasiblity of growing crack and controlling their depth in flat 6061-T6 coupons prior to growing cracks in vessels.
    - Same material as the commercial SK-1335B liners to be the subject of the POD Study
    - Coupon crack growth by tensile cycles
2. Identify size of starter notches and number of fatigue cycles needed to nucleate fatigue cracks and Validate the accuracy of EDM notch length and depth.
3. Evaluate EC response to various size cracks and develop capability to determine approximate crack size and depth from EC response.
4. Demonstrate feasiblity of machining and polishing away starter notches and leaving cracks.

Flaw Growth Approach

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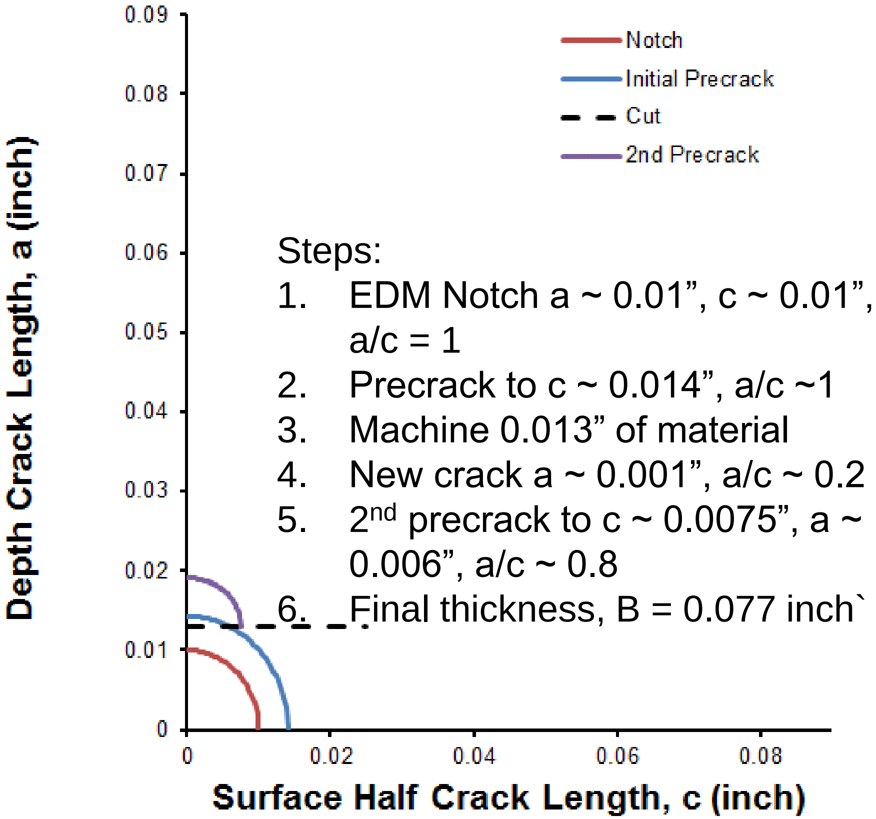
Regor Saulsberry

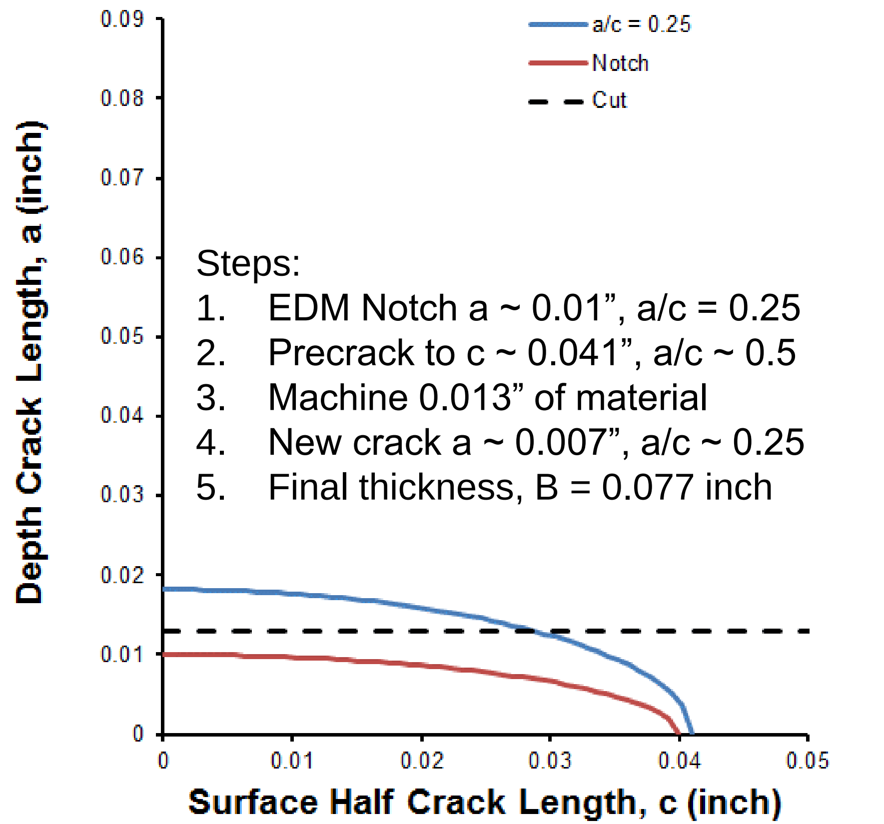
Date
March 25, 2015

Semi-circular Notch
Initial depth, a = 0.01 inch
Initial half length, c = 0.01 inch
Initial shape, a/c = 1



Steps:
1. EDM Notch a ~ 0.01”, c ~ 0.01”, a/c = 1
2. Precrack to c ~ 0.014”, a/c ~1
3. Machine 0.013” of material
4. New crack a ~ 0.001”, a/c ~ 0.2
5. 2nd precrack to c ~ 0.0075”, a ~ 0.006”, a/c ~ 0.8
6. Final thickness, B = 0.077 inch`

Long, Shallow Notch
Initial depth, a = 0.01 inch
Initial half length, c = 0.04 inch
Initial shape, a/c = 0.25



Steps:
1. EDM Notch a ~ 0.01”, a/c = 0.25
2. Precrack to c ~ 0.041”, a/c ~ 0.5
3. Machine 0.013” of material
4. New crack a ~ 0.007”, a/c ~ 0.25
5. Final thickness, B = 0.077 inch

Cracks from Long Shallow Notches

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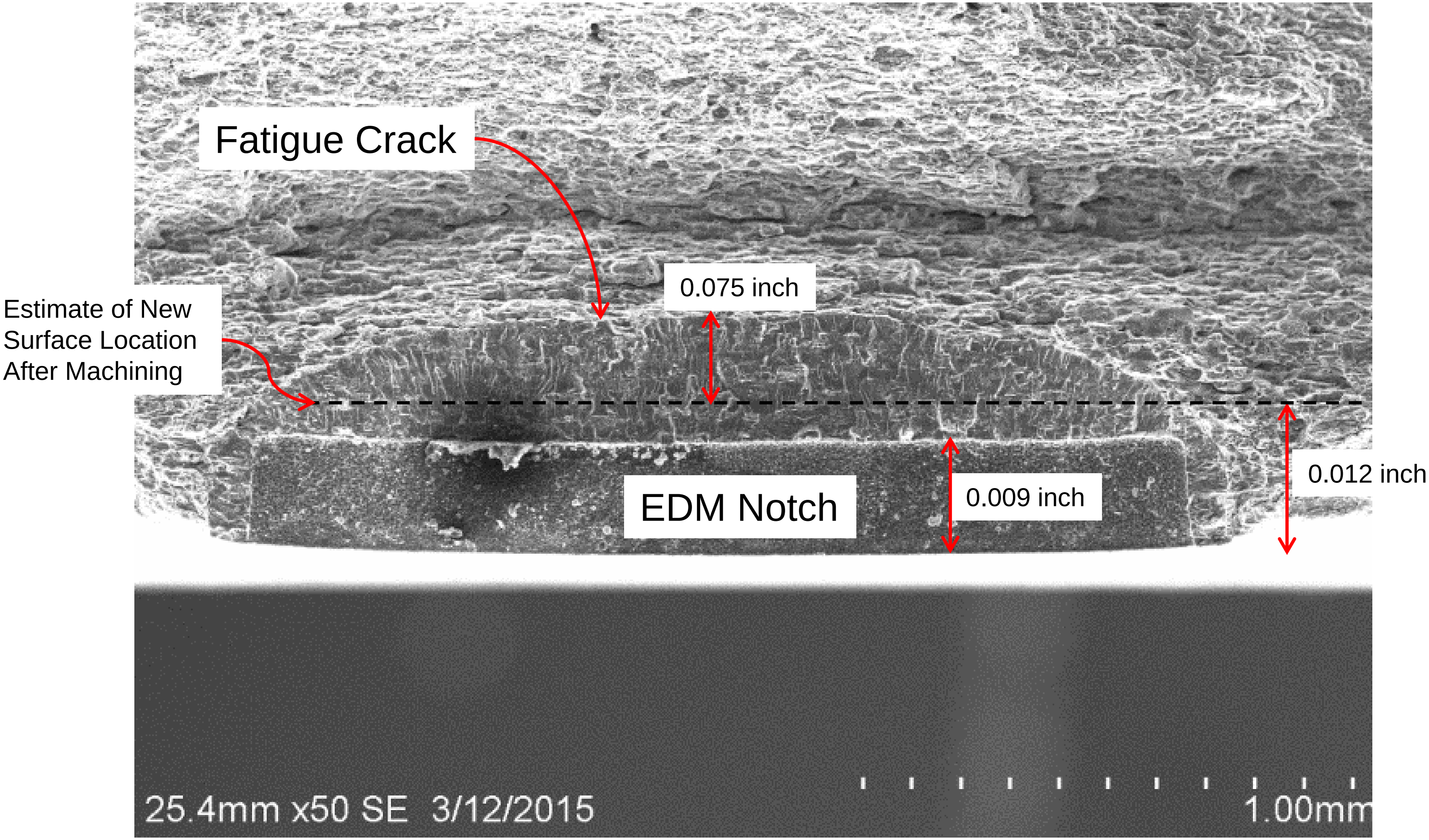
June 25, 2015

Crack nucleation required ~ 3,500 cycles



Cracks from Semi-Circular Notches

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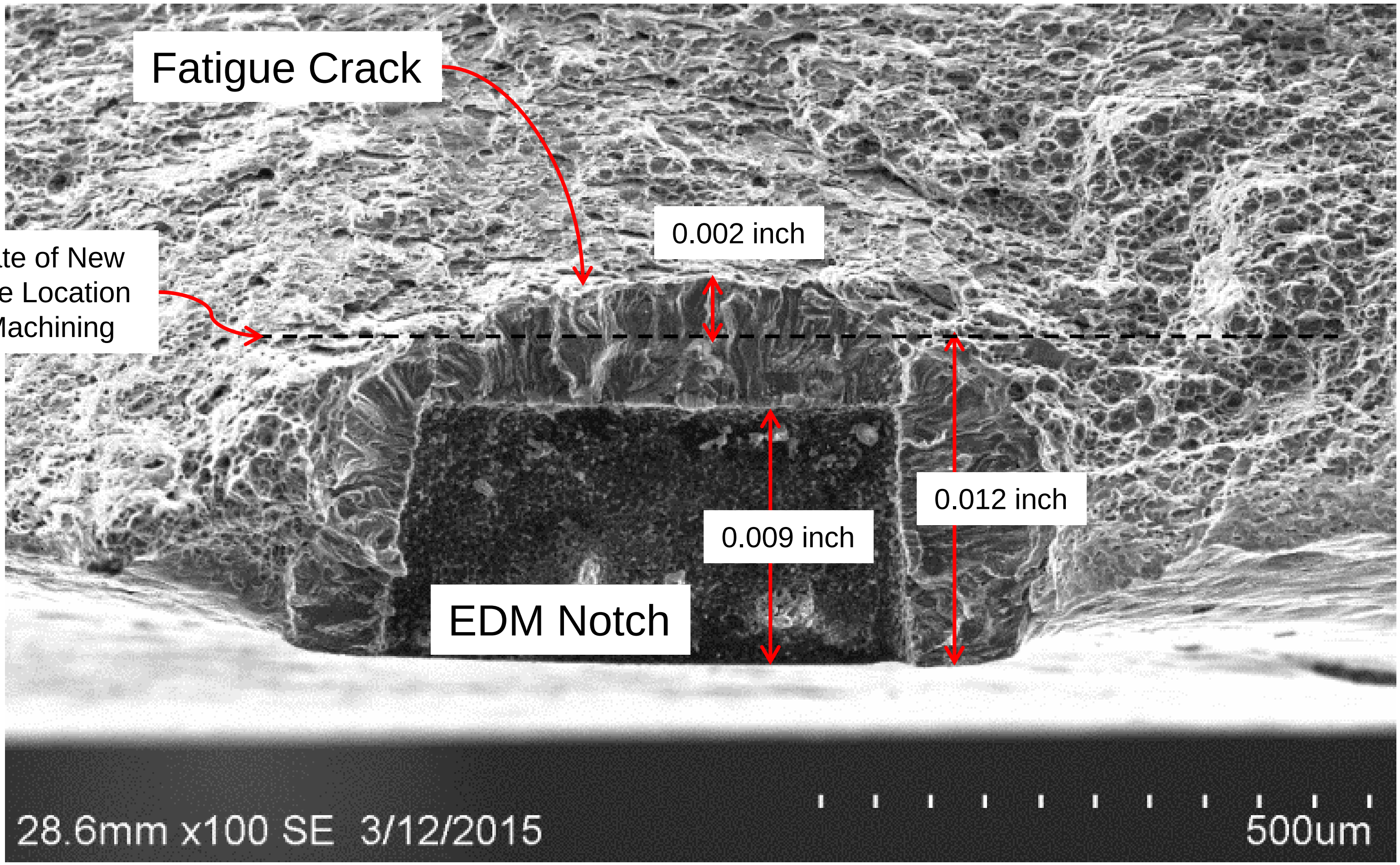
Crack nucleation required ~ 14,000 cycles

Estimate of New Surface Location After Machining



Long-Shallow Notch Post-Machining

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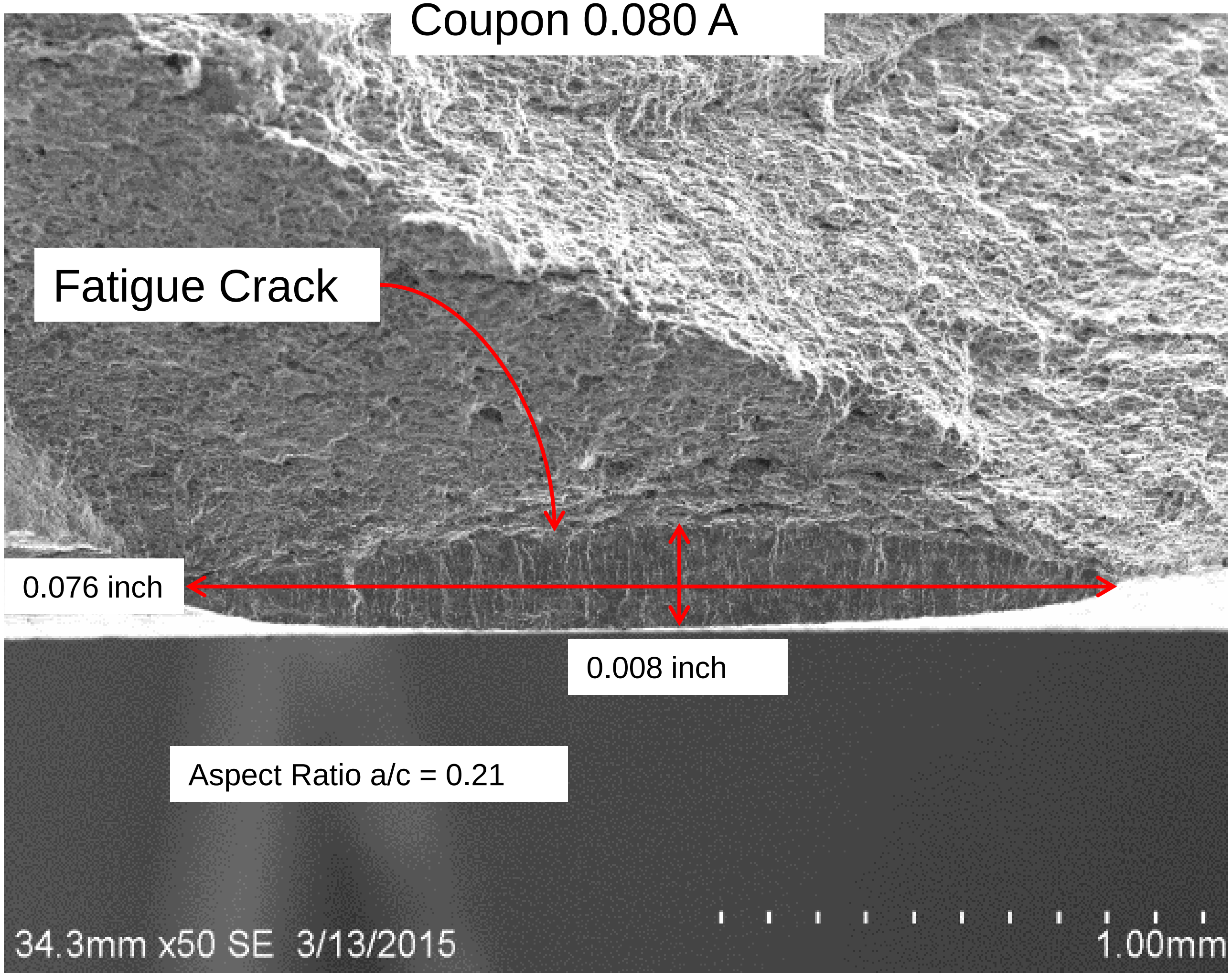
Date	June 25, 2015

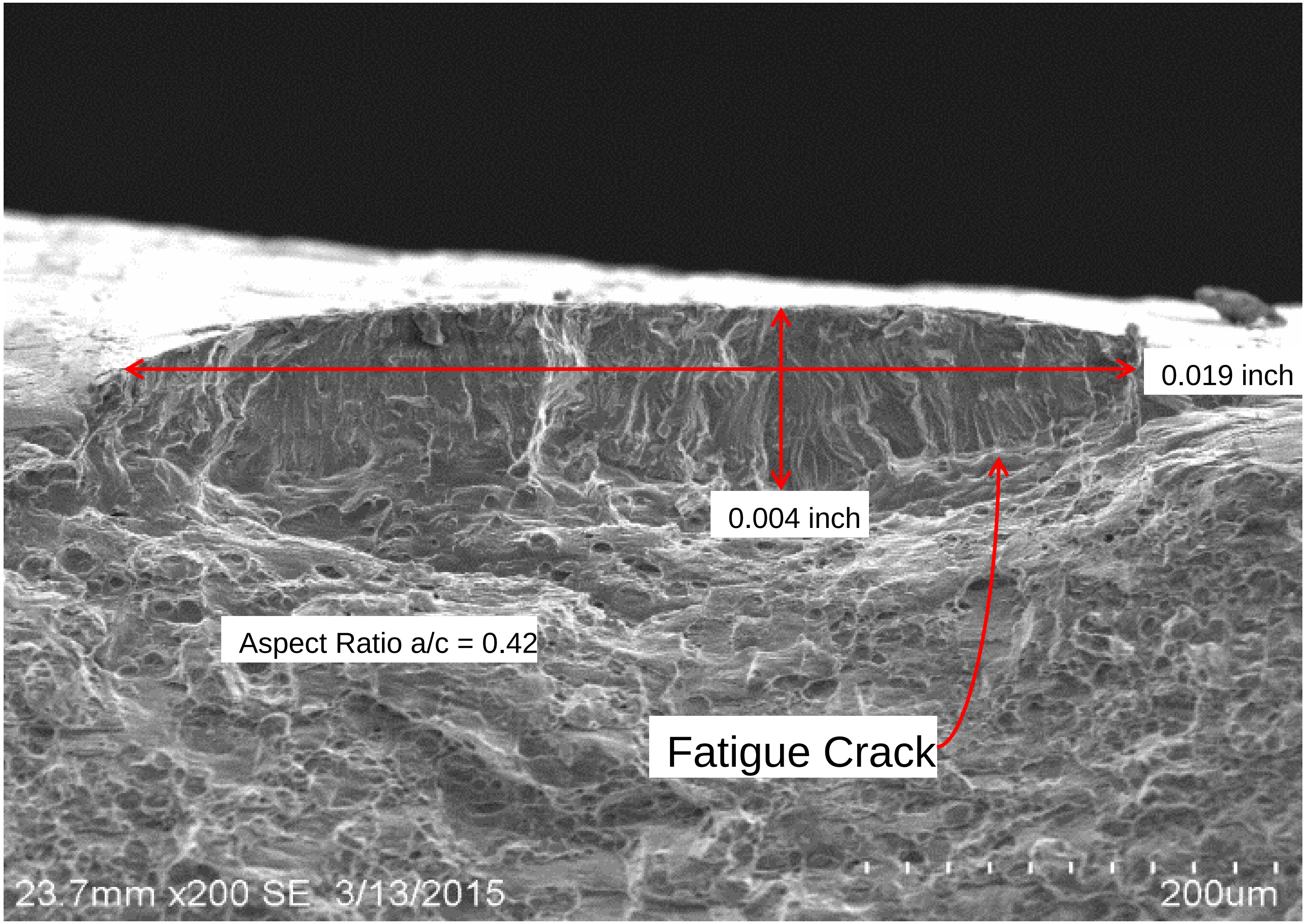
Coupon 0.080 A



Semi-Circular Notch Post-Machining

Presenter	Date
Regor Saulsberry	June 25, 2015

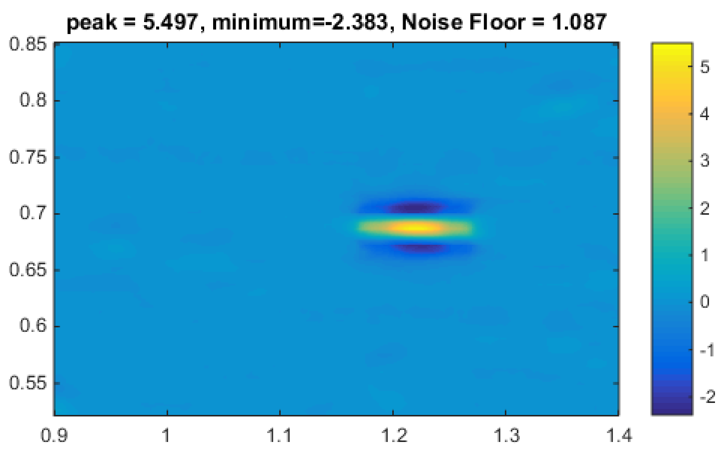
Coupon 0.020 A



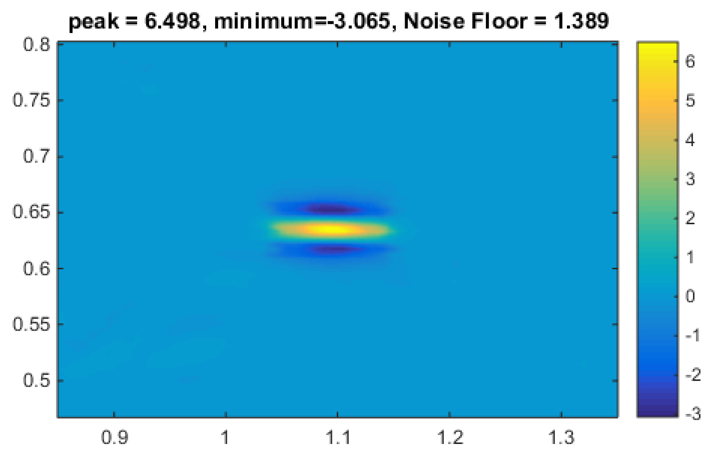
EC Response from 0.08" Starter Notch Sample UniWest ETC-2446 Probe, 4MHz, Differential Filter

Presenter	Date
Regor Saulsberry	June 25, 2015

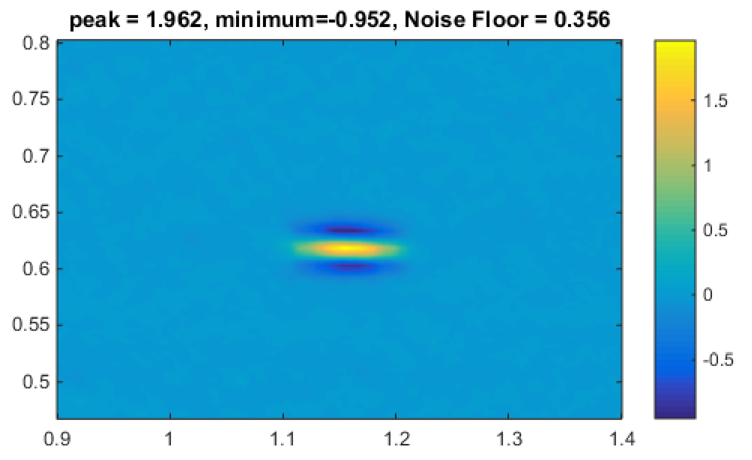
S#10 Notch Only



S#10 Notch + Crack

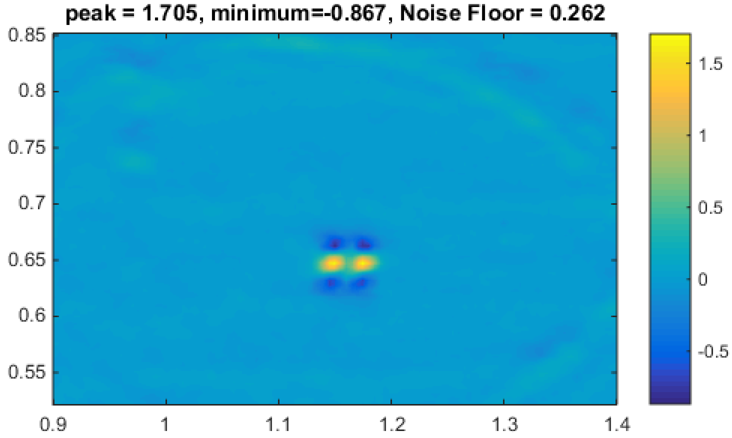


Sample A Crack Only

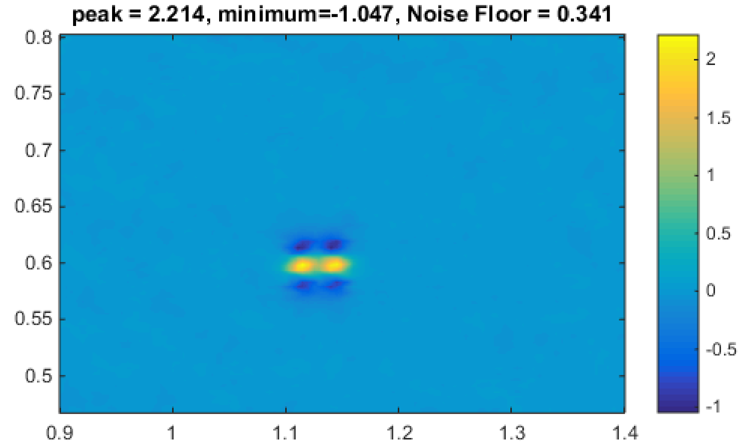


EC Response from 0.02” Starter Notch Sample UniWest ETC-2446 Probe, 4MHz, Differential Filter	Presenter Regor Saulsberry Date June 25, 2015

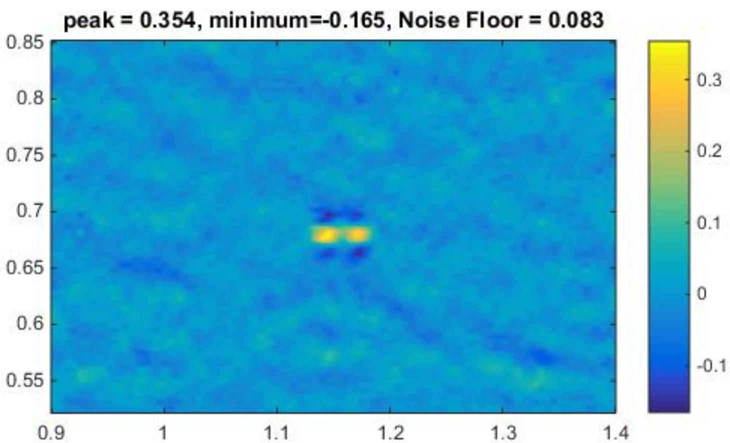
S#10 Notch Only



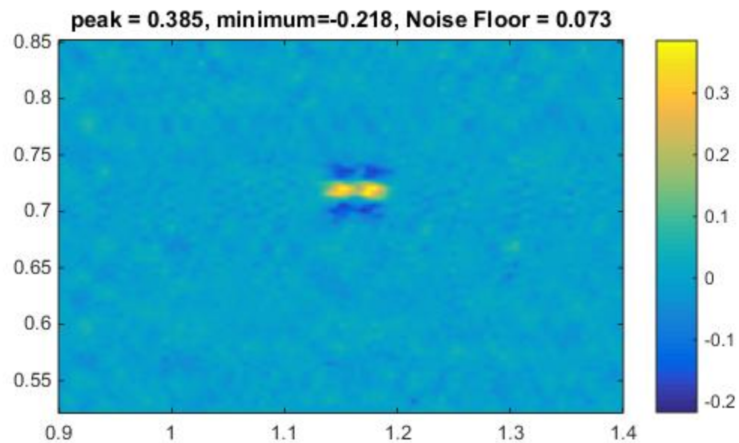
S#10 Notch + Crack



Sample A Crack Only



Sample B Crack Only



Coupon Testing Meets Objectives

Coupon testing to date indicates that the techniques applied are applicable to the “shorty” 100-liter vessels

- Crack growth appears predictable and controllable
- Starter notches were successfully machined away
- Chem. milling will uniformly remove material except for small masked areas minimizing machining
- Preliminary EC data correlation of signal response vs. notched and cracked samples size and length
- Final crack size met projections

EC Scanner POD Study Plan

Presenter	Date
Regor Saulsberry	March 25, 2015

Plan created by NDE TDT POD specialist, Floyd Spencer, and peer reviewed by the NNWG/Dr. Edward Generazio and this assessment team.

POD Study Plan

Presenter
Regor Saulsberry
Date
June 25, 2015

Approved and controlled work authorizing document will be used to control inspection procedures and order of presentation of liners to inspectors

MIL Standard 1823a POD estimations to be used

The EC system will be used to inspect 6 Samtech SK-1335B liners, OD and ID

- Cylinders and domes regions have differing critical flaw sizes due to different stress loads that roughly correspond to varying detection capability caused by surface noise levels

POD Flaws

Presenter	Regor Saulsberry
Date	June 25, 2015

"Natural" fatigue crack specimens used to characterize OD inspection of cylindrical region based on the Phase I Coupon Study results

- 2 different aspect ratios in 8 available liners (half-penny & long shallow)

Similarly sized EDM notches fabrication to characterize OD inspection of dome regions and ID inspection of cylindrical, transition, and dome regions

Two (2) tanks will be sacrificed after flaw growth in order to verify results of fabrication process

Target Fatigue Flaw Depths (6 cracks/liner)

Presenter
Regor Saulsberry

Date
June 25, 2015

		Flaw depth target			
Tank	a/c range	a=0.003	a=0.005	a=0.007	a=0.009
1	0.8 – 1.0	1	2	3	2
2	0.8 – 1.0	1	3	3	1
3	0.8 – 1.0	2	3	2	1
4	0.3 - 0.5	1	2	3	2
5	0.3 - 0.5	1	3	3	1
6	0.3 - 0.5	2	3	2	1
7 (sacrificial)	0.8 – 1.0	2	2	2	2
8 (sacrificial)	0.3 - 0.5	2	2	2	2

Notes:

- Target Range: 0.003 - 0.009 with emphasis on 0.005 - 0.007
- Uniformly placed along circumferential direction

OD & ID Inspection EDM Notches

Presenter	Regor Saulsberry
Date	June 25, 2015

ID notches will be placed on sectioned liner only (S/N 006)

OD notches will be placed on the same 6 liners with fatigue flaws

Will be placed in the three tank regions

- Cylinder
- Dome
- Transition

Various Sizes

- Target the two aspect ratios used in the fatigue flaws
- EDM notches are easier to detect, therefore lower range of target depths: 0.002, 0.003, 0.005, 0.007
  - Will be placed after fatigue flaw growth

Different numbers of flaws are placed in each liner to not create an expectation with the inspectors of having the same conditions within each liner

Inspectors

Presenter	Regor Saulsberry
Date	June 25, 2015

- Number of inspectors: 5
  - Will be trained to operate system according to developed procedures
  - Perform the inspections across all 6 liners
  - Liners will be presented to the inspectors in the following pre-defined order to not confound a possible liner effect with the effect of probe film wear
- Random ordering of tanks:
  - Inspector 1 – Tanks in order 6, 5, 1, 3, 2, 4
  - Inspector 2 – Tanks in order 3, 6, 2, 5, 4, 1
  - Inspector 3 – Tanks in order 1, 2, 5, 4, 3, 6
  - Inspector 4 – Tanks in order 2, 1, 4, 3, 6, 5
  - Inspector 5 – Tanks in order 5, 4, 3, 6, 1, 2

Analysis

- Estimate a POD function notches leading to two distinct POD curves represented by 2 separate equations
  - for cracks (cylinder region only)
  - for EDM A notch-to-flaw size transfer function will be used to estimate notch POD that can be compared to that for fatigue flaws
  - A noise floor parameter will also be added to the model which will lead to fewer false calls
- This makes notch POD curves available for transition and dome regions where fatigue flaw POD is not possible (transition and dome regions are significantly thicker)

Capability Objectives

Presenter
Regor Saulsberry
Date
June 25, 2015

Develop scan capabilities:

- EC thickness
- EC flaw (minimum detectible flaw size 0.030 x 0.015 inches)
- Laser Profilometry

For COPV sizes:

- 22 inch OD (300L)
- 15 inch OD (“Shorty”)

Including the following zones:

- Cylindrical section as well as the upper and lower domes
- Liner ID and OD

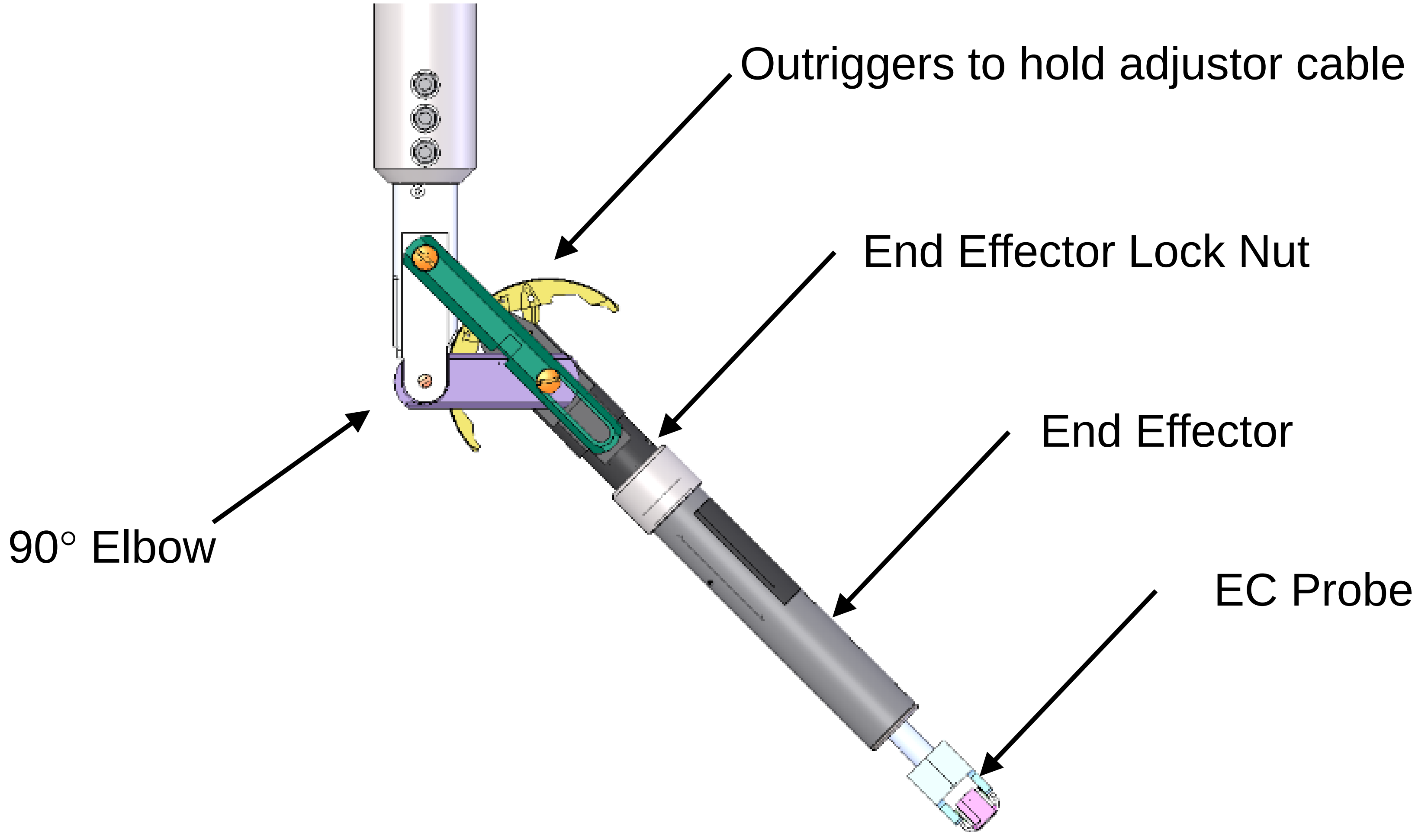
Implemented with:

- Modified existing WSTF COPV-scanning system (NORS)
- Newly developed additional sensors, stages, and software

Sensor assembly

Presenter	Date
Regor Saulsberry	June 25, 2015

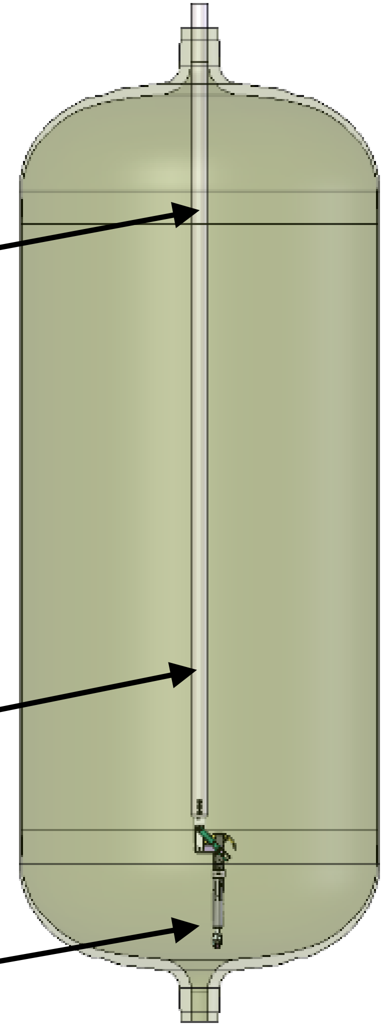
Shown with 15 inch (“Shorty”) end effector



EC ID Sensor

Presenter	Date
Regor Saulsberry	June 25, 2015

Shown with 22-inch liner



1” Delivery shaft for stability

0.650” Max OD for ¾” port compatibility

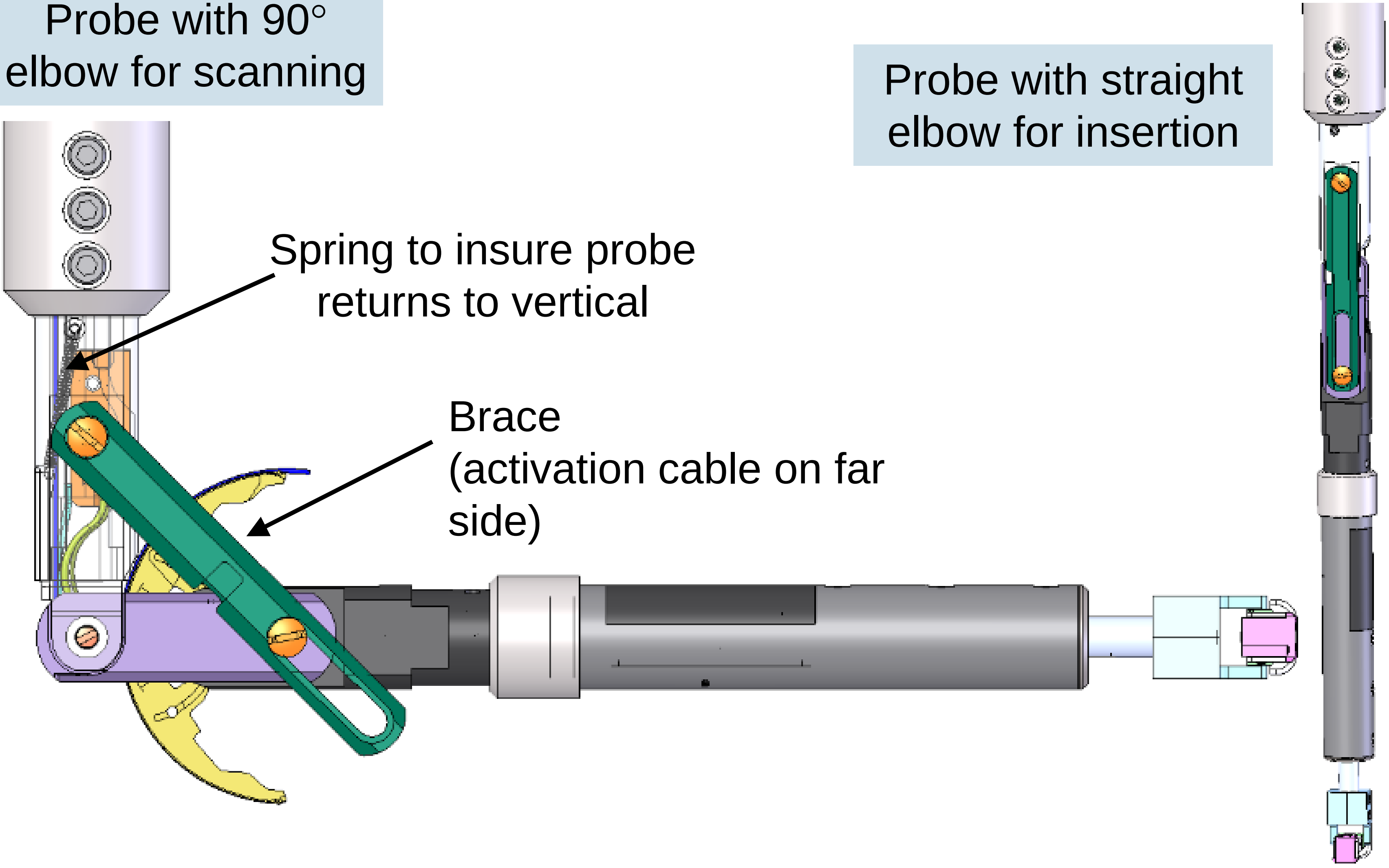
EC Probe

Elbow Mechanism

Presenter
Regor Saulsberry
Date
June 25, 2015

Probe with 90° elbow for scanning

Probe with straight elbow for insertion

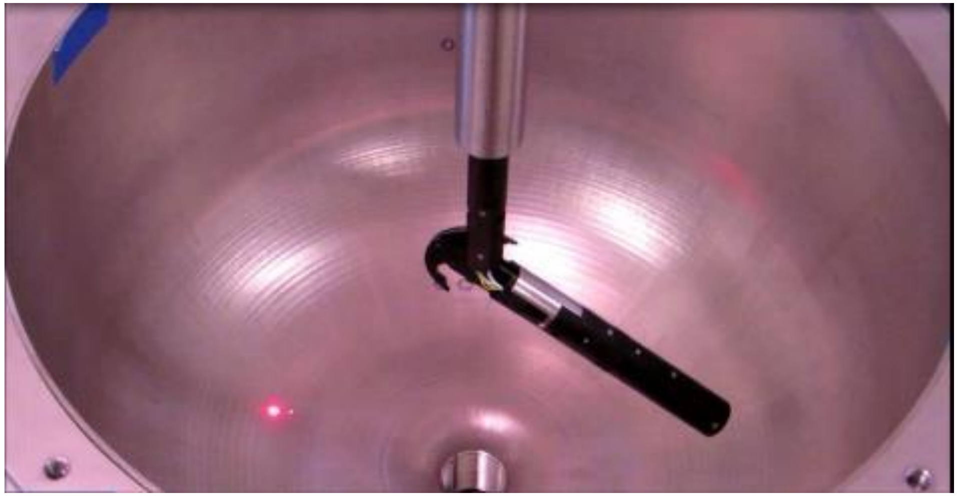


Spring to insure probe returns to vertical

Brace (activation cable on far side)

Videos of Laser Profilometry

Presenter
Regor Saulsberry
Date
June 25, 2015



Contour-following

Profilometry Scan

Flaw Summary – Liner S/N 006 ID

Presenter	Date
Regor Saulsberry	June 25, 2015

Uniwest EDM ID "Thumbnail" Flaws in Dome

Group	Flaw #	Rotary Position	Axial Position	Dimensions	Orientation
A	1	3.6°	4.06"	0.030 x 0.015 x 0.003"	Circumferential
	2	15.4°	4.06"	0.030 x 0.015 x 0.003"	Axial
	3	28.0°	4.06"	0.030 x 0.015 x 0.003"	45°
B	4	60.9°	3.73"	0.049 x 0.021 x 0.003"	Circumferential
	5	71.9°	3.73"	0.049 x 0.021 x 0.004"	Axial
	6	81.7	3.73"	0.049 x 0.021 x 0.003"	45°

Circumferential EC Coil

Feature Criteria

Boundary Threshold:	0.500	V
Minimum Peak:	0.700	V
Min. Size X:	0.050	deg
Min. Size Y:	0.010	in

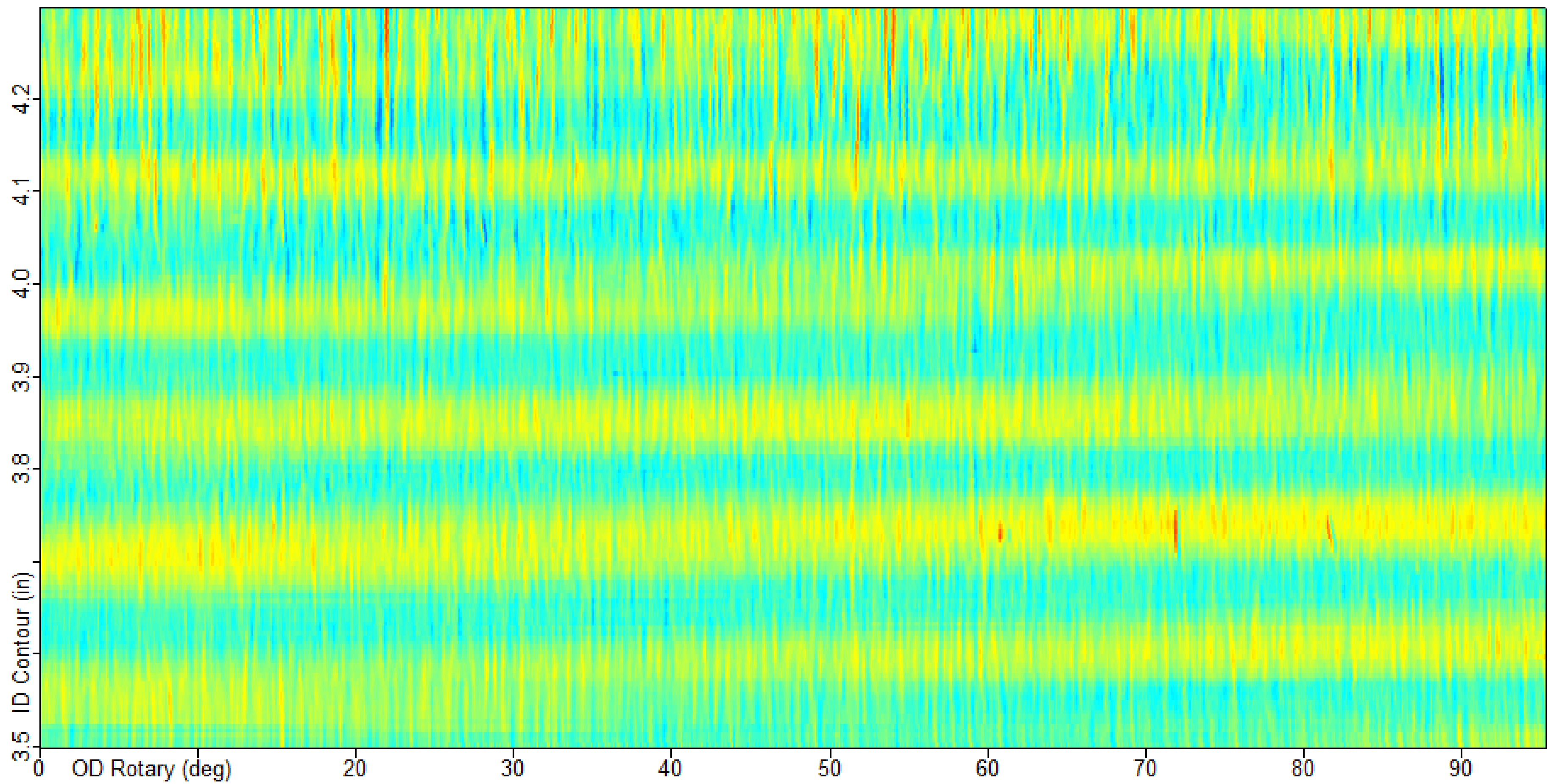
Axial EC Coil

Feature Criteria

Boundary Threshold:	1.000	V
Minimum Peak:	1.100	V
Min. Size X:	0.300	deg
Min. Size Y:	0.005	in

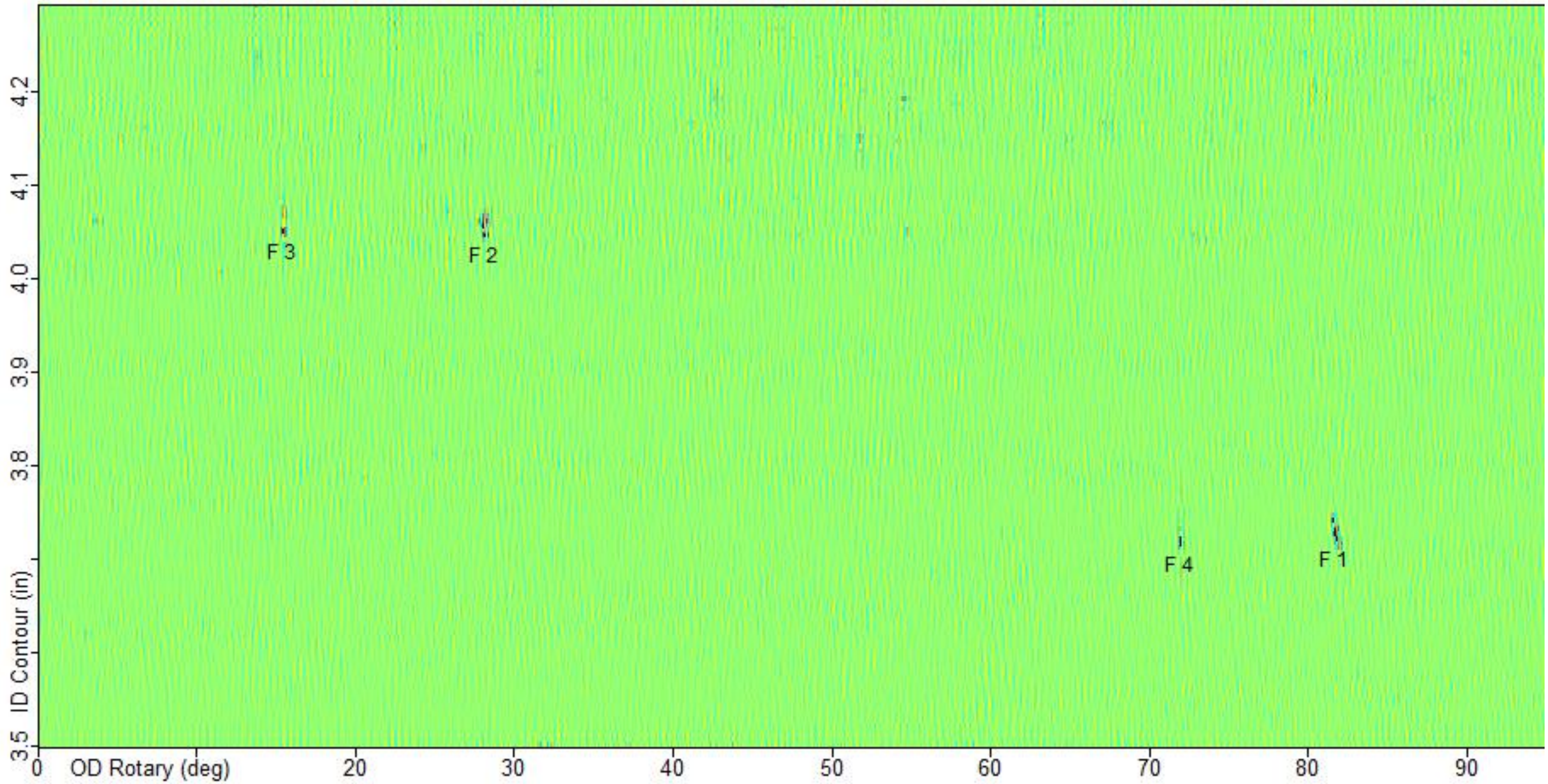
Flaw Detection – S/N 006 ID Dome Circumferential Coil - Pre-processing

Presenter	Regor Saulsberry
Date	June 25, 2015



Flaw Detection – S/N 006 ID Dome Circumferential EC Coil - After Processing

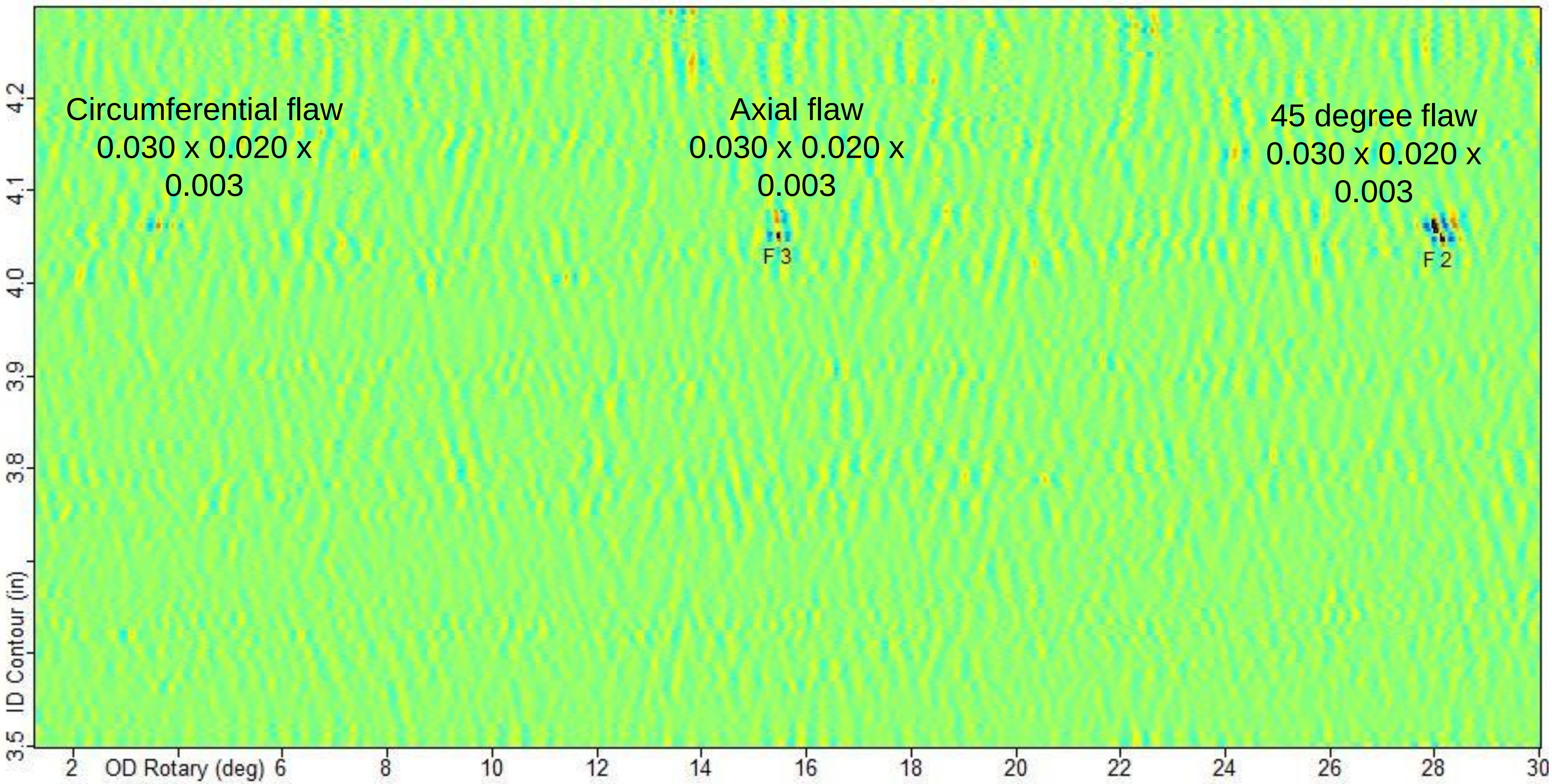
Presenter	Regor Saulsberry
Date	June 25, 2015



Rotary FIR filter applied - optimized for axial flaws

Flaw Detection – S/N 006 ID Dome
0.030 inch Long Flaws – Circumferential Coil

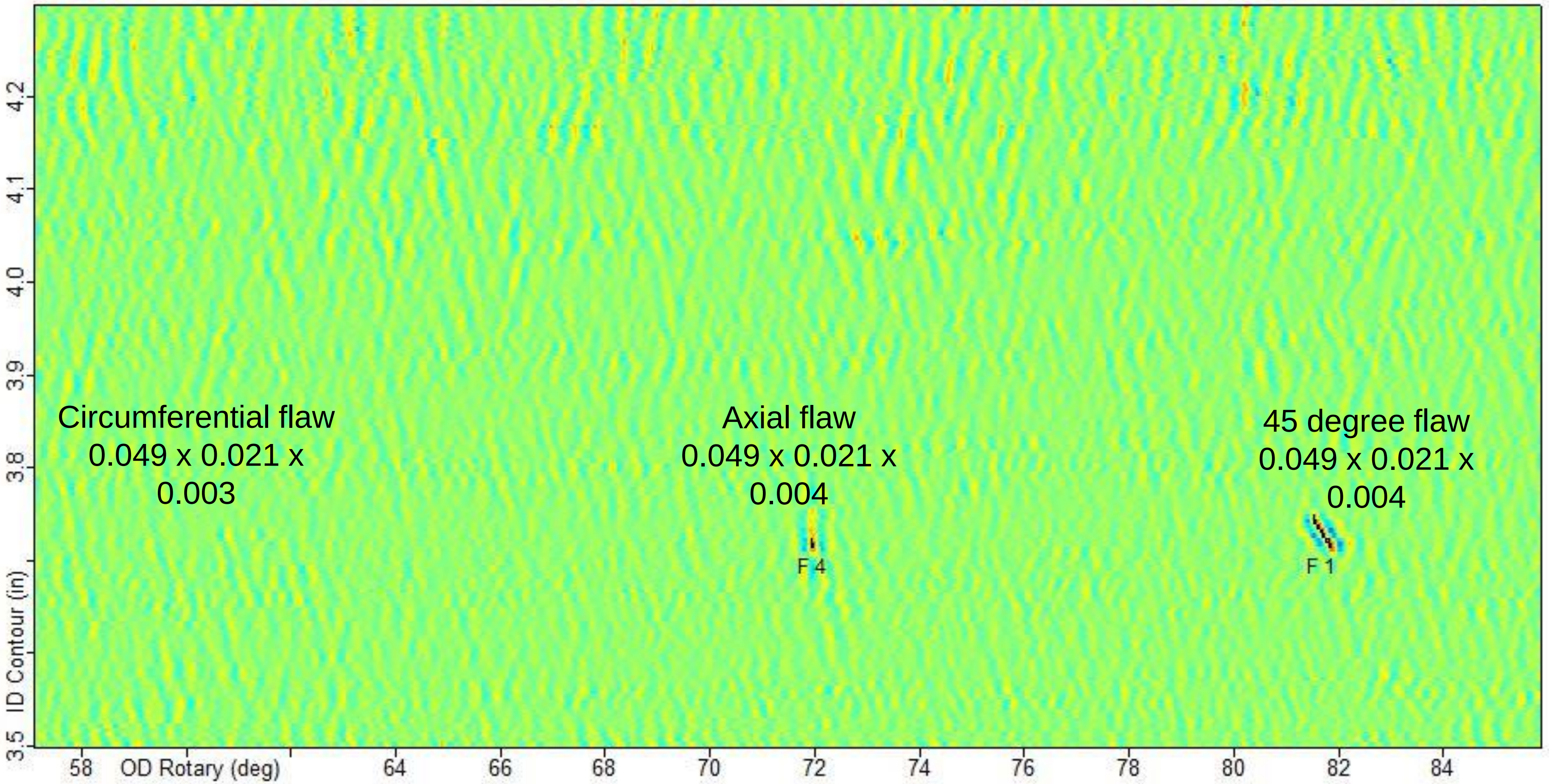
Presenter	Date
Regor Saulsberry	June 25, 2015



Rotary FIR filter applied - optimized for axial flaws

Flaw Detection – S/N 006 ID Dome 0.049 inch Long Flaws – Circumferential Coil

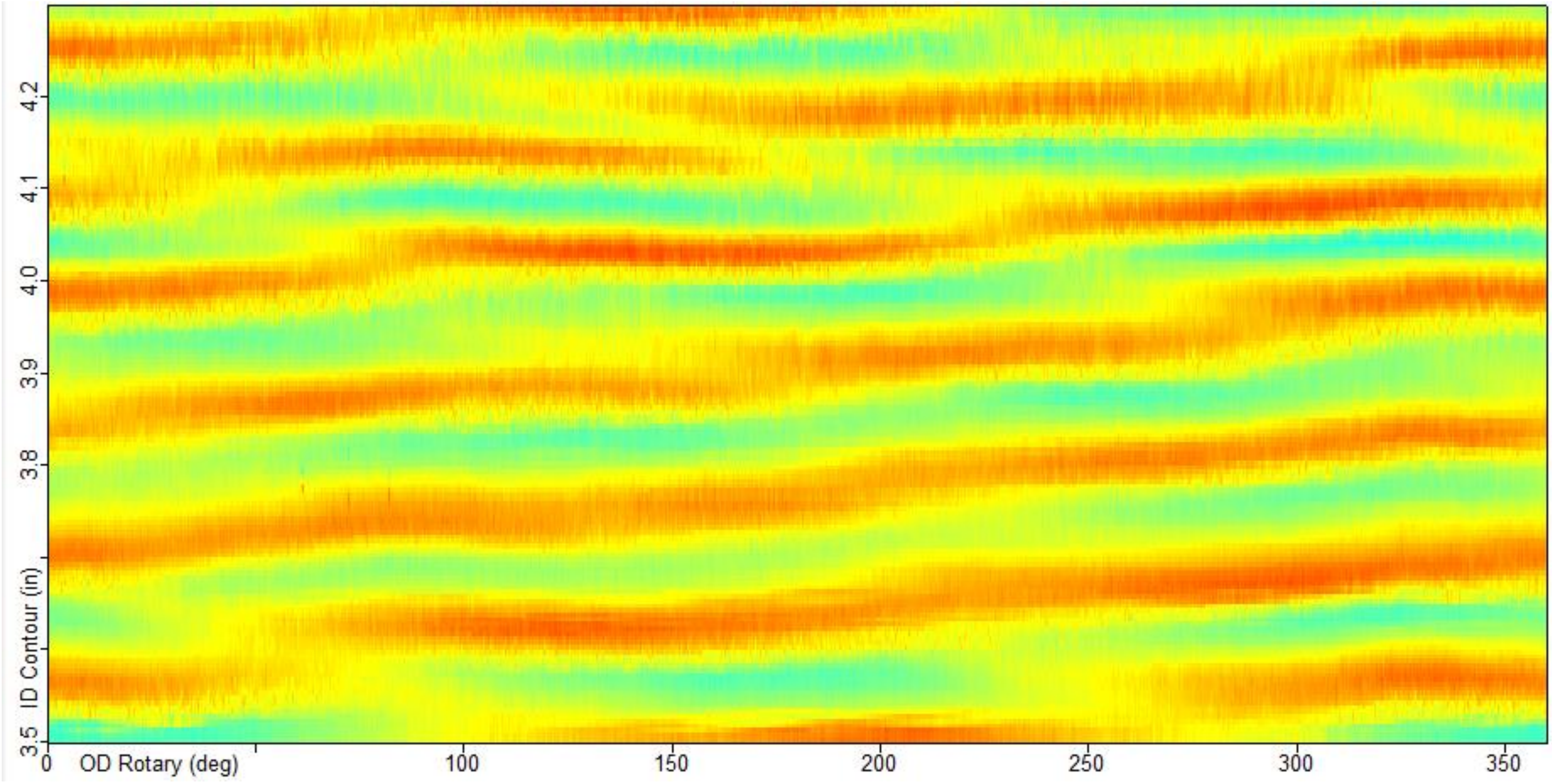
Presenter	Regor Saulsberry
Date	June 25, 2015



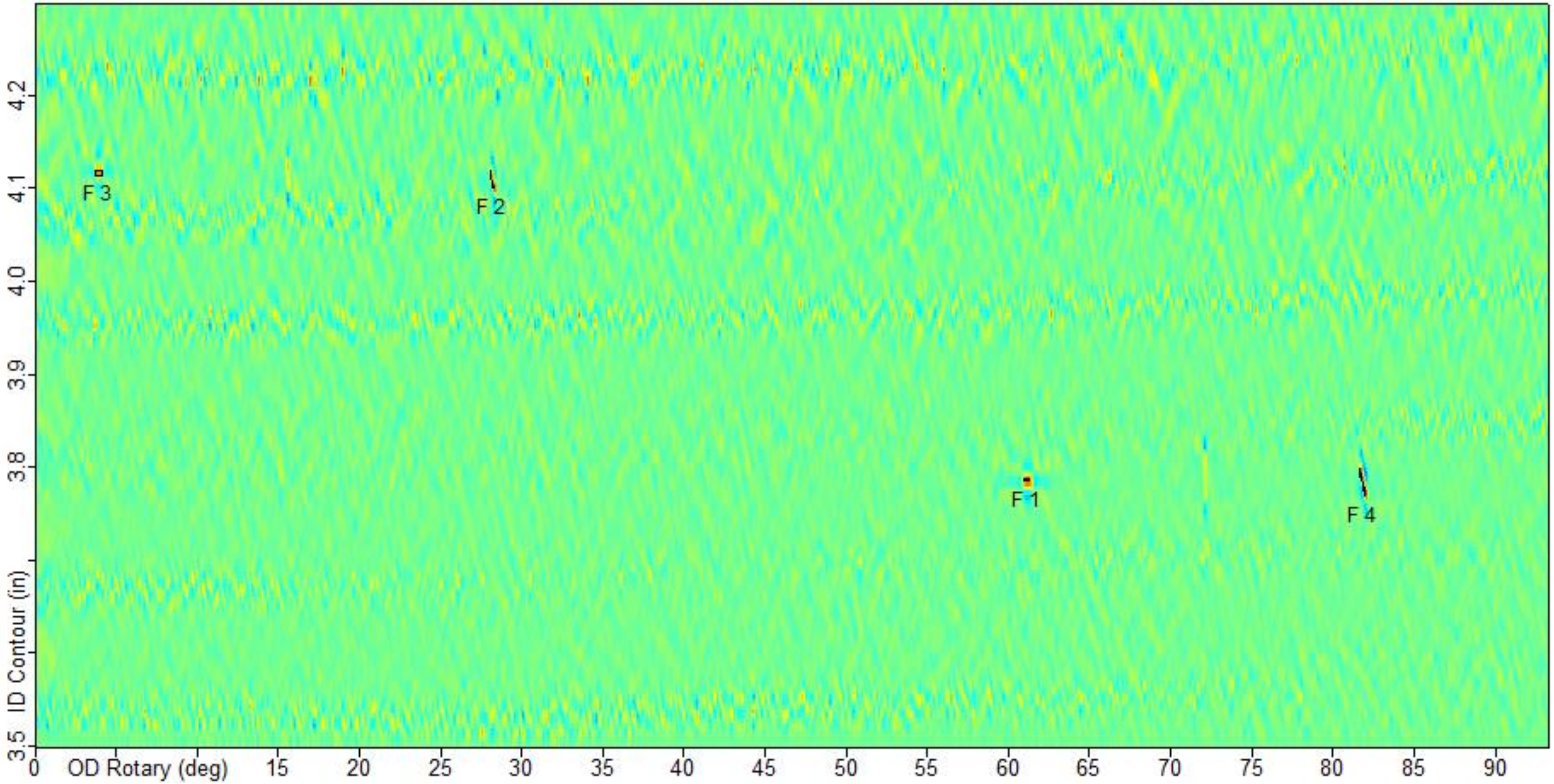
Rotary FIR filter applied - optimized for axial flaws

Flaw Detection – S/N 006 ID Dome Axial Coil - Pre-processing

Presenter
Regor Saulsberry
Date
June 25, 2015



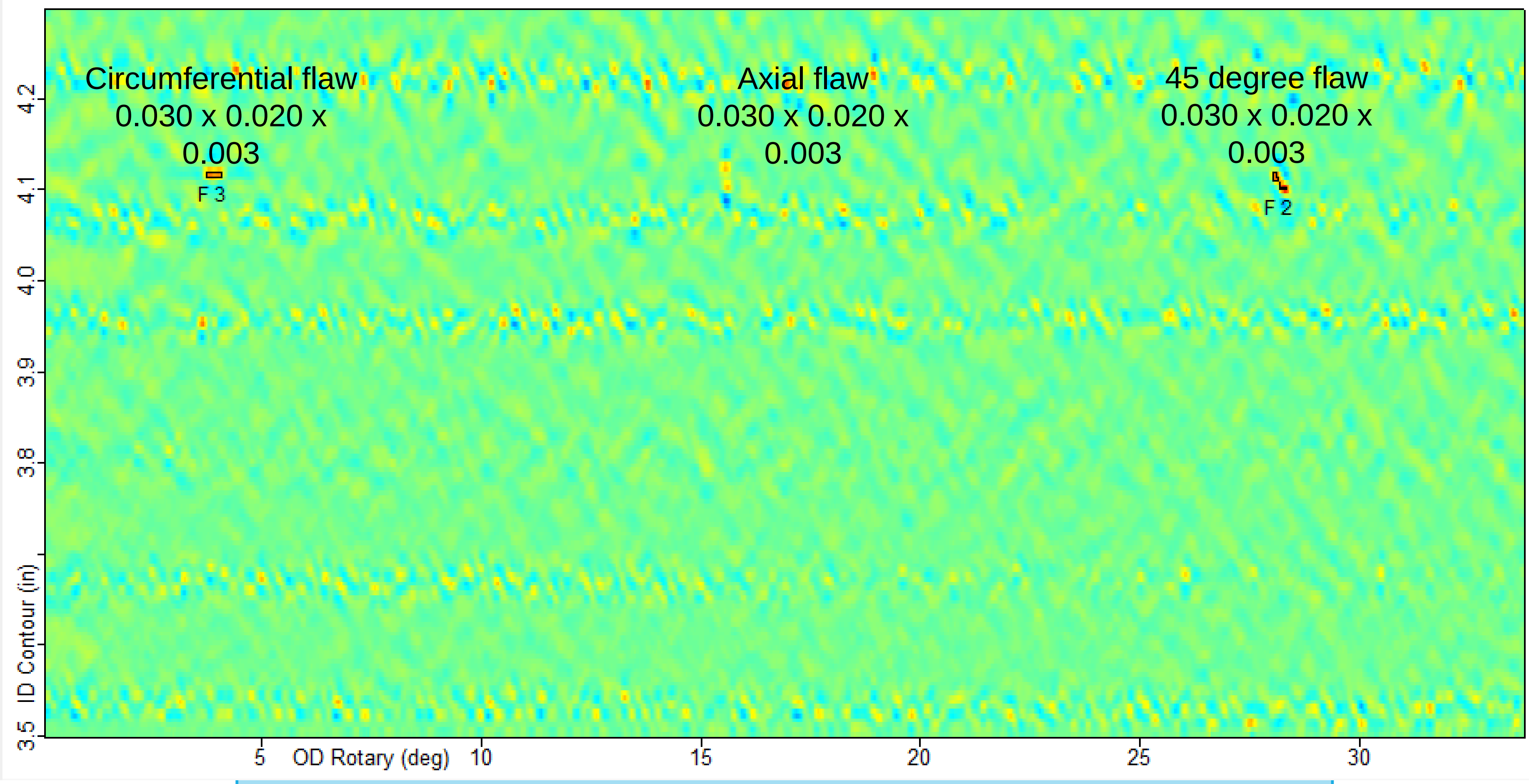
Flaw Detection – S/N 006 ID Dome Axial EC Coil - After Processing	Presenter Regor Saulsberry Date June 25, 2015



Linear FIR filter applied - optimized for Circumferential flaws

Flaw Detection – S/N 006 ID Dome 0.030 inch Long Flaws – Axial Coil

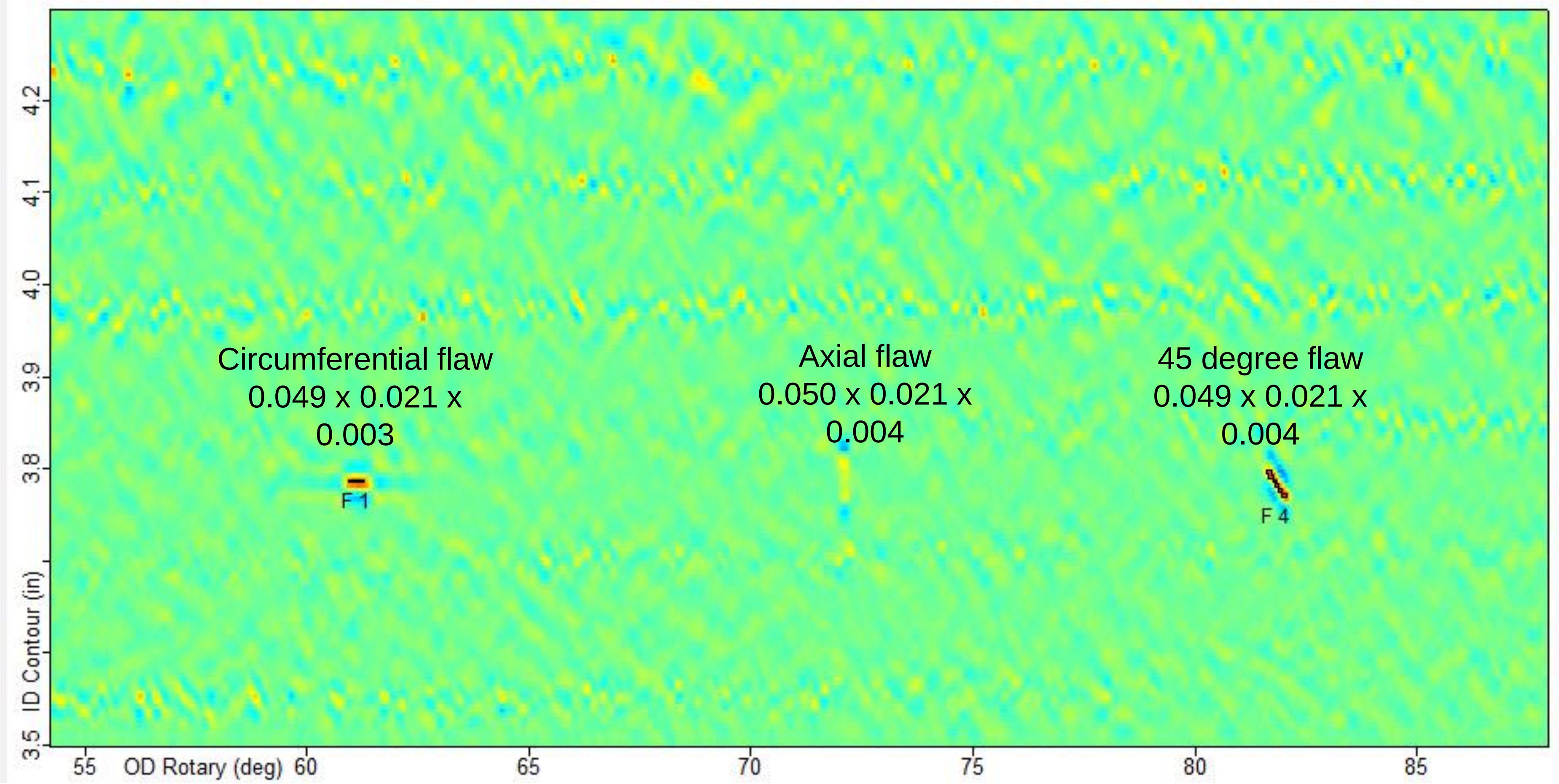
Presenter
Regor Saulsberry
Date
June 25, 2015



Linear FIR filter applied - optimized for Circumferential flaws

Flaw Detection – S/N 006 ID Dome 0.049 inch Long Flaws – Axial Coil

Presenter	Date
Regor Saulsberry	June 25, 2015



Linear FIR filter applied - optimized for Circumferential flaws

Automatic Flaw Detection Summary Liner S/N 006 ID

Presenter	Date
Regor Saulsberry	June 25, 2015

Circumferential EC Coil

Group	Flaw #	Flaw Length	Orientation	Flaw Strength	Noise Floor
A	1	0.030”	Circ.		
	2	0.030”	Axial	1.5 V	0.31 V
	3	0.030”	45°	2.0 V	0.31 V
B	4	0.049”	Circ.		
	5	0.049”	Axial	1.26 V	0.25 V
	6	0.049”	45°	1.50 V	0.25 V

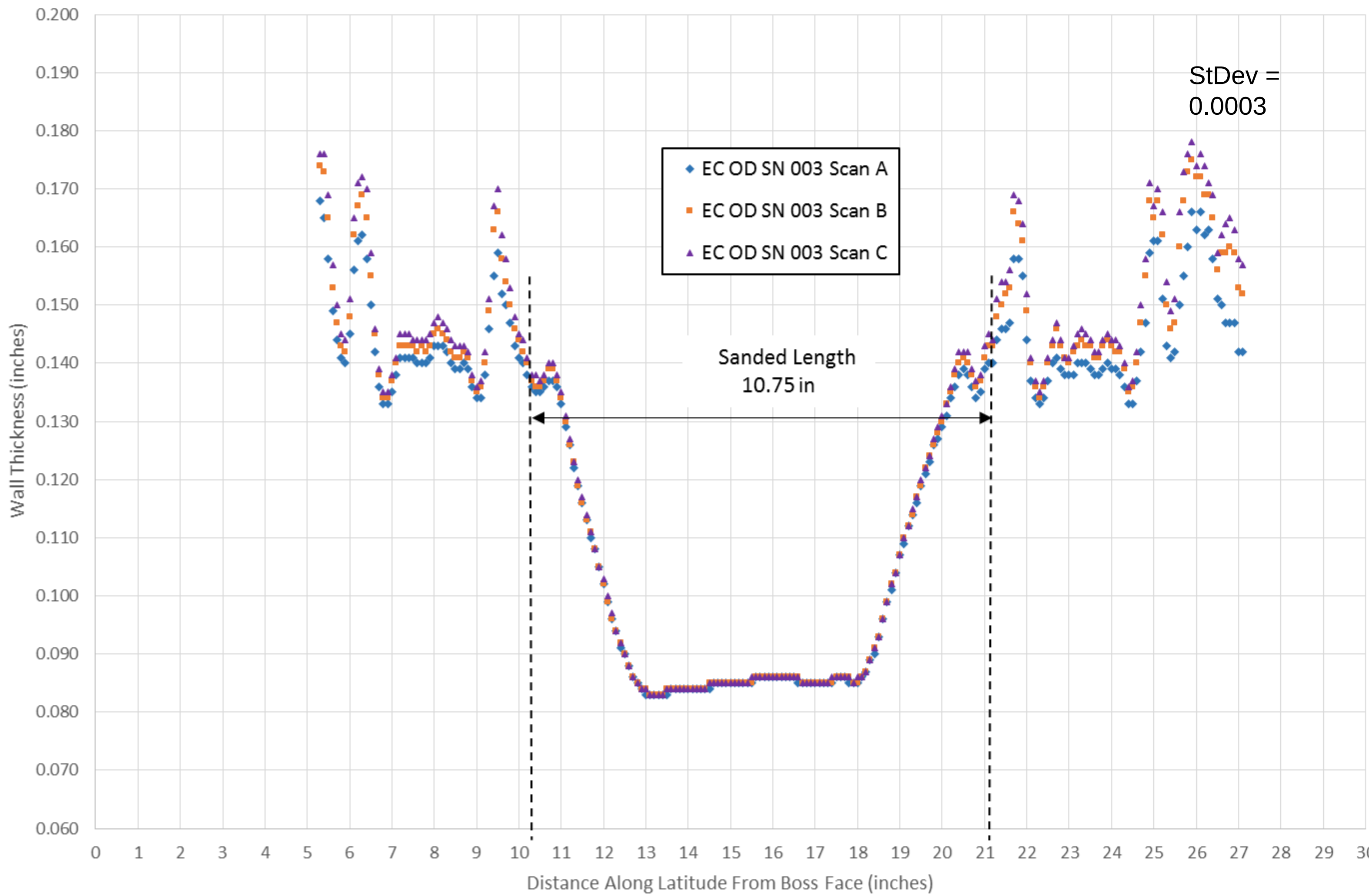
Axial EC Coil

Group	Flaw #	Flaw Length	Orientation	Flaw Strength	Noise Floor
A	1	0.030”	Circ.	2.1 V	0.41 V
	2	0.030”	Axial		0.41 V
	3	0.030”	45°	2.6 V	0.41 V
B	4	0.049”	Circ.	2.3 V	0.40 V
	5	0.049”	Axial		0.40 V
	6	0.049”	45°	2.8 V	0.40 V

Noise Floor $\equiv 3 \times \sigma$

15-in. Dia. Tank Thickness OD Repeatability- S/N 003

Presenter	Regor Saulsberry
Date	June 25, 2015



Specific Phase I Coupon Tests Goals

Presenter	Regor Saulsberry
Date	June 25, 2015

Create small fatigue cracks in flat 6061-T6 aluminum coupons

- Semi-circular cracks: depth = 0.007 inch, length = 0.014 inch
- Long-shallow cracks: depth = 0.007 inch, length = 0.041 inch

Evaluate the viability of using EDM notches to nucleate fatigue cracks

- Determine the number cycles required to nucleate fatigue cracks
  - Frequency possible for coupon tests: 10 Hz – 5 to 20 minutes to nucleate
  - Frequency possible for tank tests: 0.1 Hz – 10 to 30 hours to nucleate
- Validate the accuracy of EDM notch length and depth

Determine the viability of machining to remove notch without completely removing the fatigue crack

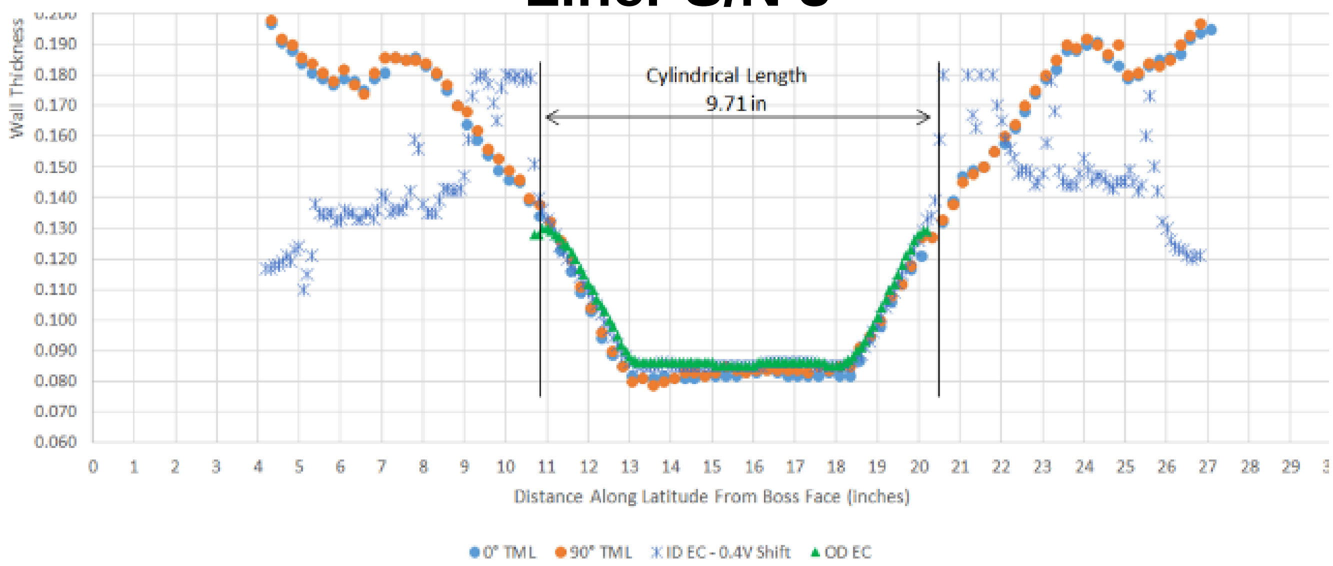
Perform EC inspections to characterize response

- Response of as received notches
- Response of notches with fatigue cracks
- Response after fatigue cracks have been removed

EC Thickness Mapping Acceptance Testing

Presenter Regor Saulsberry
Date June 25, 2015

Calibrated Liner Scan – ID/OD Comparison, 15-in Dia. Liner S/N 3



- The data acquisition and processing was significantly improved in the 3 weeks since this testing, with data now tracking actual thickness out to 0.5" of the dome region where the thickness increases to nearly 0.15 in.
- Will be revisited in later slides from repeatability testing.
  - Can now go out to 10.75 in. and have better