The Safety Course Design and Operations of Composite Overwrapped Pressure Vessels (COPV)

Regor Saulsberry
William Prosser
25-29 May, 2015
Presentation Overview

• 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

• 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.
<table>
<thead>
<tr>
<th>Last Name</th>
<th>First Name</th>
<th>Position/Team Affiliation</th>
<th>Center/Contractor</th>
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<tr>
<td>Prosser</td>
<td>William</td>
<td>Assessment Lead, NASA</td>
<td>LaRC</td>
<td>757-864-4960</td>
<td><a href="mailto:william.h.prosser@nasa.gov">william.h.prosser@nasa.gov</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Technical Fellow for NDE</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Saulsberry</td>
<td>Regor</td>
<td>Assessment Co-Lead</td>
<td>JSC/WSTF</td>
<td>575-635-7970</td>
<td><a href="mailto:regor.l.saulsberry@nasa.gov">regor.l.saulsberry@nasa.gov</a></td>
</tr>
<tr>
<td>Wincheski</td>
<td>Russell (Buzz)</td>
<td>Eddy Current Lead</td>
<td>LaRC</td>
<td>757-864-4798</td>
<td><a href="mailto:russell.a.wincheski@nasa.gov">russell.a.wincheski@nasa.gov</a></td>
</tr>
<tr>
<td>Lucero</td>
<td>Ralph</td>
<td>Integrated Testing</td>
<td>Jacobs/ WSTF</td>
<td>575-524-5345</td>
<td><a href="mailto:ralph.e.lucero@nasa.gov">ralph.e.lucero@nasa.gov</a></td>
</tr>
<tr>
<td>Nichols</td>
<td>Charles</td>
<td>Integration and Testing</td>
<td>JSC/WSTF</td>
<td>575-524-5389</td>
<td><a href="mailto:charles.nichols@nasa.gov">charles.nichols@nasa.gov</a></td>
</tr>
<tr>
<td>Moore</td>
<td>Linda</td>
<td>Program Analyst</td>
<td>LaRC</td>
<td>757-864-9293</td>
<td><a href="mailto:linda.j.moore@nasa.gov">linda.j.moore@nasa.gov</a></td>
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<tr>
<td>Dawicke</td>
<td>David</td>
<td>Flaw Characterization and Growth</td>
<td>LaRC/AMA</td>
<td>757-865-7093</td>
<td><a href="mailto:david.s.dawicke@nasa.gov">david.s.dawicke@nasa.gov</a></td>
</tr>
<tr>
<td>Grimes-Ledesma</td>
<td>Lorie</td>
<td>CPVWG Interface</td>
<td>JPL</td>
<td>818-393-3592</td>
<td><a href="mailto:lorie.r.grimes-ledesma@jpl.nasa.gov">lorie.r.grimes-ledesma@jpl.nasa.gov</a></td>
</tr>
<tr>
<td>Spencer</td>
<td>Paul</td>
<td>Eddy Current Expert</td>
<td>WSTF</td>
<td>575-524 5239</td>
<td><a href="mailto:paul.r.spencer@nasa.gov">paul.r.spencer@nasa.gov</a></td>
</tr>
<tr>
<td>Brinkman</td>
<td>Mike</td>
<td>Primary Systems Design and Integrator</td>
<td>Laser Techniques Company (LTC)</td>
<td>425-855-0607</td>
<td><a href="mailto:mikeb@laser-ndt.com">mikeb@laser-ndt.com</a></td>
</tr>
<tr>
<td>Waller</td>
<td>Jess</td>
<td>NDE Standards</td>
<td>Jacobs</td>
<td>575-524-5249</td>
<td><a href="mailto:jess.m.waller@nasa.gov">jess.m.waller@nasa.gov</a></td>
</tr>
<tr>
<td>Spencer</td>
<td>Floyd</td>
<td>Industry POD Expert</td>
<td>Sfhire/AMA</td>
<td>505-301-7540</td>
<td><a href="mailto:sfhire@comcast.net">sfhire@comcast.net</a></td>
</tr>
<tr>
<td>Administrative Support</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Derby</td>
<td>Terri</td>
<td>Project Coordinator</td>
<td>LaRC/AMA</td>
<td>757-864-9872</td>
<td><a href="mailto:t.b.derby@nasa.gov">t.b.derby@nasa.gov</a></td>
</tr>
<tr>
<td>Burgess</td>
<td>Linda</td>
<td>Planning and Control Analyst</td>
<td>LaRC/AMA</td>
<td>757-864.9139</td>
<td><a href="mailto:linda.i.burgess@nasa.gov">linda.i.burgess@nasa.gov</a></td>
</tr>
<tr>
<td>Moran</td>
<td>Erin</td>
<td>Technical Writer</td>
<td>LaRC/AMA</td>
<td>757-864-7513</td>
<td><a href="mailto:erin.moran-1@nasa.gov">erin.moran-1@nasa.gov</a></td>
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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
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.
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.
Double-joint mechanism enables single-scan for the full liner

0.65 Diameter shaft and sensor

Additional 90° elbow locks in place during scans

Outriggers pulled by cable provide stable rotation

Surface-riding mechanism & EC coil

10°  45°  90°  135°

170° Max for full scans full liner
Internal EC Sensor – liner Insertion

Inserting through port  Inside liner  90° elbow activated
No tools required for attachment

End Effector Lock Nut

Alignment Pin

12-pin Connectors

End Effector

Sensor
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

Scan direction
OD Thickness End Effector

Same end effector used for both thickness and flaw detection sensors
Calibration standards are NIST traceable
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

- End effector detaches below articulation mechanism
- Internal electrical connector in shaft
- Internal SID chip stores sensor type and liner geometry
- 22-inch EC flaw end effector
- 15-inch EC end effectors
- EC flaw
- EC thickness
Laser Profilometry (LP)

- 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

- Sensor
- Internal Stage
- External Stages
- Articulation Drive
- Rotary stage (Typically 30 rpm for larger vessels)
- Shaft sized to fit through port
- Laser end-effector

- liner
Laser Sensor in Shorty liner

Outriggers open, Lower dome scan
NIST Traceable LP Calibration Setup

22-inch laser End Effector for 300L liner

Measurement laser beam
Detection axes

Calibration blocks, set for 22-inch ID configuration
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
EC Thickness Mapping
Acceptance Testing

Calibration Tooling Measurements
OD EC Thickness Sensor - After Auto-cal

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EC Thickness Mapping
Acceptance Testing

Calibrated Liner Scan – OD EC
EC Flaw Detection
Acceptance Testing

- 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

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<th>Notch Orientation</th>
<th>Actual Notch Dimensions (Measured)</th>
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<tr>
<td>45deg</td>
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</table>

- All flaws clearly identified
  - Noise filtering and automated flaw detection
EC Flaw Detection
Acceptance Testing

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

Acceptance Testing

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

Coil A

Coil B
EC Flaw Detection Acceptance Testing

- 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

Group C

Group D
Laser Profilometry/Laser Video™
Acceptance Testing

OD Profile and Video Scans of “Shorty” Liner (ID Scans later)
OD Profile and Video Scans of 300 Liter Liner
# Repeatability Scan Testing

<table>
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<th>Task</th>
<th>Comments</th>
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<tr>
<td>Thickness Repeatability Shorty Liner SN005</td>
<td>Thickness completed with signal rotation and amplitude adjustments and 0.1 V offset applied</td>
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<tr>
<td>Thickness Repeatability Shorty Liner SN003</td>
<td>Thickness completed with signal rotation and amplitude adjustments and 0.1 V offset applied</td>
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<td>Flaw Repeatability Shorty Liner SN 005 (OD)</td>
<td>All flaws found reliably in automatic flaw detection SW</td>
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<tr>
<td>Flaw Repeatability Shorty Liner SN 006 (ID)</td>
<td>All 6 new flaws found by reporting software</td>
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</table>
Example
Shorty Tank Thickness ID Repeatability-SN 003

StDev = 0.0002

Sanded Length 10.75 in
Example
Shorty Tank Thickness OD Repeatability-SN 005

StDev = 0.0008
Shorty Tank Thickness ID Repeatability
Cross Section of SN 006 with Machined Grooves

Machined Grooves on OD

StDev = 0.0004

Sanded Length
10.75 in
Comparison of OD Thickness to UT
Shorty Liner SN 003

Sanded Length
10.75 in

0.1 V Offset applied to all EC data
Conclusions

• 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
1. Verify feasibility 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 feasibility of machining and polishing away starter notches and leaving cracks.
Flaw Growth Approach

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

Crack nucleation required ~ 3,500 cycles

Fatigue Crack

Estimate of New Surface Location After Machining

EDM Notch

25.4mm x50 SE 3/12/2015
Cracks from Semi-Circular Notches

Crack nucleation required ~ 14,000 cycles

Fatigue Crack

Estimate of New Surface Location After Machining

EDM Notch

0.002 inch

0.009 inch

0.012 inch

28.6mm x100 SE 3/12/2015
Long-Shallow Notch Post-Machining

Fatigue Crack

Coupon 0.080 A

0.076 inch

0.008 inch

Aspect Ratio a/c = 0.21

34.3mm x50 SE 3/13/2015
Semi-Circular Notch Post-Machining

Coupon 0.020 A

Aspect Ratio $a/c = 0.42$

Fatigue Crack

23.7mm x200 SE  3/13/2015
EC Response from 0.08” Starter Notch Sample
UniWest ETC-2446 Probe, 4MHz, Differential Filter

S#10 Notch Only

Sample A Crack Only

S#10 Notch + Crack
EC Response from 0.02” Starter Notch Sample
UniWest ETC-2446 Probe, 4MHz, Differential Filter

S#10 Notch Only

peak = 1.705, minimum=-0.867, Noise Floor = 0.262

Sample A Crack Only

peak = 0.354, minimum=-0.165, Noise Floor = 0.083

S#10 Notch + Crack

peak = 2.214, minimum=-1.047, Noise Floor = 0.341

Sample B Crack Only

peak = 0.385, minimum=-0.218, Noise Floor = 0.073
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
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

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

“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)

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<th>(a=0.007)</th>
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<td>2</td>
<td>2</td>
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**Notes:**

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

- 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
• 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

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

Shown with 15 inch ("Shorty") end effector

- Outriggers to hold adjustor cable
- End Effector Lock Nut
- End Effector
- EC Probe
- 90° Elbow
EC ID Sensor

Shown with 22-inch liner

1” Delivery shaft for stability

0.650” Max OD for ¾” port compatibility

EC Probe
Elbow Mechanism

Probe with 90° elbow for scanning

Spring to insure probe returns to vertical

Probe with straight elbow for insertion

Brace (activation cable on far side)
Videos of Laser Profilometry

Contour-following

Profilometry Scan
Flaw Summary – Liner S/N 006 ID

Uniwest EDM ID “Thumbnail” Flaws in Dome

<table>
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<th>Group</th>
<th>Flaw #</th>
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<th>Axial Position</th>
<th>Dimensions</th>
<th>Orientation</th>
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<td>3.6°</td>
<td>4.06”</td>
<td>0.030 x 0.015 x 0.003”</td>
<td>Circumferential</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>15.4°</td>
<td>4.06”</td>
<td>0.030 x 0.015 x 0.003”</td>
<td>Axial</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>28.0°</td>
<td>4.06”</td>
<td>0.030 x 0.015 x 0.003”</td>
<td>45°</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>60.9°</td>
<td>3.73”</td>
<td>0.049 x 0.021 x 0.003”</td>
<td>Circumferential</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>71.9°</td>
<td>3.73”</td>
<td>0.049 x 0.021 x 0.004”</td>
<td>Axial</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>81.7</td>
<td>3.73”</td>
<td>0.049 x 0.021 x 0.003”</td>
<td>45°</td>
</tr>
</tbody>
</table>

**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
May 25, 2015
Flaw Detection – S/N 006 ID Dome
Circumferential EC Coil - After Processing

Rotary FIR filter applied - optimized for axial flaws
Flaw Detection – S/N 006 ID Dome
0.030 inch Long Flaws – Circumferential Coil

Circumferential flaw
0.030 x 0.020 x 0.003

Axial flaw
0.030 x 0.020 x 0.003

45 degree flaw
0.030 x 0.020 x 0.003

Rotary FIR filter applied - optimized for axial flaws
Flaw Detection – S/N 006 ID Dome
0.049 inch Long Flaws – Circumferential Coil

Rotary FIR filter applied - optimized for axial flaws
Flaw Detection – S/N 006 ID Dome Axial Coil - Pre-processing
Flaw Detection – S/N 006 ID Dome Axial EC Coil - After Processing

Linear FIR filter applied - optimized for Circumferential flaws
Flaw Detection – S/N 006 ID Dome 
0.030 inch Long Flaws – Axial Coil

Circumferential flaw
0.030 x 0.020 x 0.003

Axial flaw
0.030 x 0.020 x 0.003

45 degree flaw
0.030 x 0.020 x 0.003

Linear FIR filter applied - optimized for Circumferential flaws
Flaw Detection – S/N 006 ID Dome
0.049 inch Long Flaws – Axial Coil

Circumferential flaw
0.049 x 0.021 x 0.003

Axial flaw
0.050 x 0.021 x 0.004

45 degree flaw
0.049 x 0.021 x 0.004

Linear FIR filter applied - optimized for Circumferential flaws
# Automatic Flaw Detection Summary
**Liner S/N 006 ID**

<table>
<thead>
<tr>
<th>Group</th>
<th>Flaw #</th>
<th>Flaw Length</th>
<th>Orientation</th>
<th>Flaw Strength</th>
<th>Noise Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circumferential EC Coil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>0.030”</td>
<td>Circ.</td>
<td>2.1 V</td>
<td>0.41 V</td>
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<tr>
<td></td>
<td>2</td>
<td>0.030”</td>
<td>Axial</td>
<td>2.6 V</td>
<td>0.41 V</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.030”</td>
<td>45°</td>
<td>2.6 V</td>
<td>0.41 V</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>0.049”</td>
<td>Circ.</td>
<td>2.3 V</td>
<td>0.40 V</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.049”</td>
<td>Axial</td>
<td>2.8 V</td>
<td>0.40 V</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.049”</td>
<td>45°</td>
<td>2.8 V</td>
<td>0.40 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group</th>
<th>Flaw #</th>
<th>Flaw Length</th>
<th>Orientation</th>
<th>Flaw Strength</th>
<th>Noise Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axial EC Coil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>0.030”</td>
<td>Circ.</td>
<td>1.5 V</td>
<td>0.31 V</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.030”</td>
<td>Axial</td>
<td>1.26 V</td>
<td>0.25 V</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.030”</td>
<td>45°</td>
<td>2.0 V</td>
<td>0.31 V</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>0.049”</td>
<td>Circ.</td>
<td>1.50 V</td>
<td>0.25 V</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.049”</td>
<td>Axial</td>
<td>1.26 V</td>
<td>0.25 V</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.049”</td>
<td>45°</td>
<td>1.50 V</td>
<td>0.25 V</td>
</tr>
</tbody>
</table>

Noise Floor $\equiv 3 \times \sigma$
15-in. Dia. Tank Thickness OD Repeatability-
S/N 003

StDev = 0.0003

Sanded Length 10.75 in
Specific Phase I Coupon Tests Goals

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
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