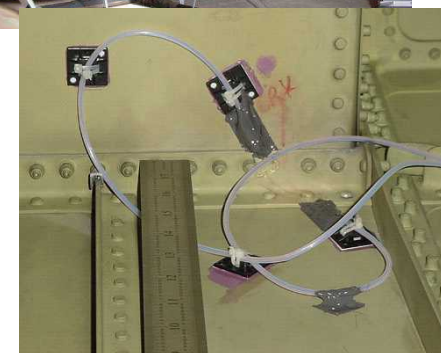
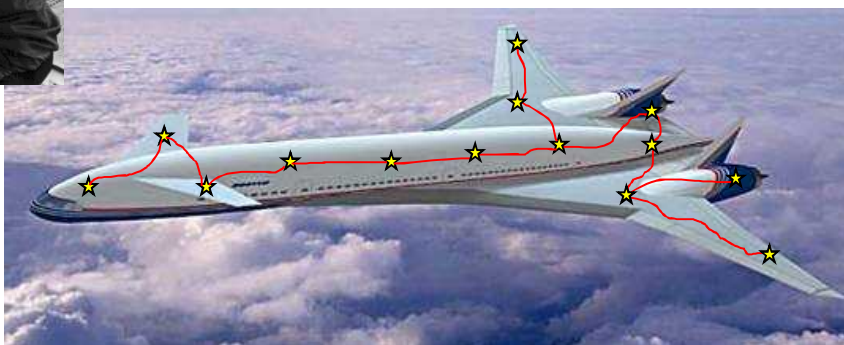
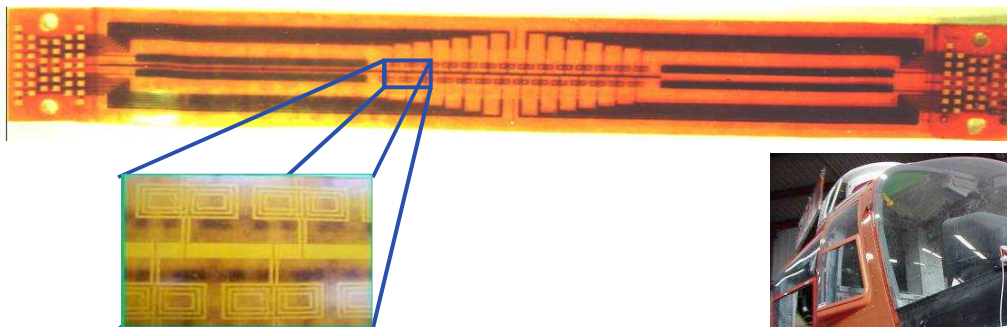


Paving the Path: Structural Health Monitoring Certification Program

SAND2013-7870C



Dennis Roach
Tom Rice
Sandia National Labs
FAA Airworthiness Assurance Center

David Piotrowski
John Bohler
Alex Melton
Delta TechOps

John Linn
Boeing
Paul Swindell
FAA



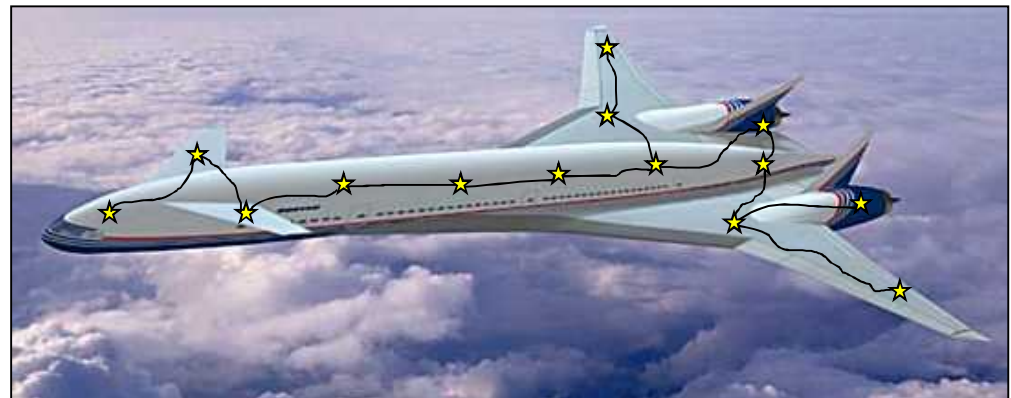
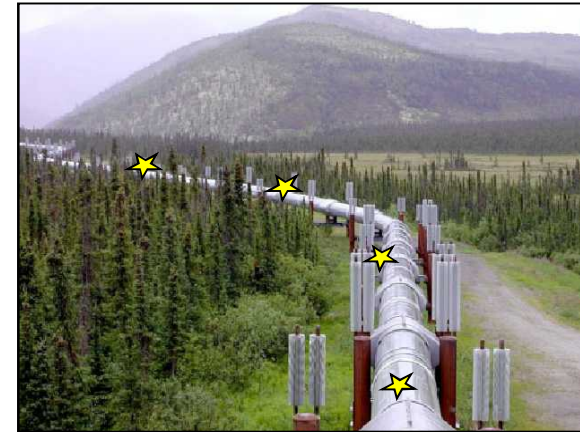
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



Distributed Sensor Networks for Structural Health Monitoring

Smart Structures: include in-situ distributed sensors for real-time health monitoring; ensure integrity with minimal need for human intervention

- Remotely monitored sensors allow for condition-based maintenance
- Automatically process data, assess structural condition, & signal need for maintenance actions



NDI vs. SHM – Definition

Nondestructive Inspection (NDI) – examination of a material to determine geometry, damage, or composition by using technology that does not affect its future usefulness

- High degree of human interaction
- Local, focused inspections
- Requires access to area of interest (applied at select intervals)

Structural Health Monitoring (SHM) – “Smart Structures;” use of NDI principles coupled with in-situ sensing to allow for rapid, remote, and real-time condition assessments (flaw detection); goal is to reduce operational costs and increase lifetime of structures

- Greater vigilance in key areas – address DTA needs
- Overcome accessibility limitations, complex geometries, depth of hidden damage
- Eliminate costly & potentially damaging disassembly
- Minimize human factors with automated data analysis
- Reduce maintenance costs
- Early flaw detection = enhanced safety & less costly repairs
- Condition-based maintenance practices



Structural Health Monitoring

Structural
Damage Sensing
(in-situ NDI)

Structural Models
and
Analyses

Loads
and
Environmental
Monitoring

Reasoner

Structural Health

Prognostic Health Management

SHM for:

- **Flaw detection**
- **Flaw location**
- **Flaw characterization**
- **Condition Based Maintenance**





In-Situ Health Monitoring for Aircraft Using Comparative Vacuum Monitoring Sensors

Laboratory and Field Evaluation Program for Modification of Boeing NDT Standard Practices Manuals

Drivers for Application of CVM Technology

- Overcome accessibility problems; sealed parts
- Improve crack detection
- Real-time information or more frequent, remote interrogation
- Initial focus – identified problem areas (hot spot monitoring)
- Long term possibilities – distributed systems; remotely monitored sensors allow for condition-based maintenance

Team: Jeff Kollgaard, John Linn – Boeing, Seattle; Masood Zaidi – Boeing, Long Beach; Dennis Roach, Floyd Spencer – Sandia Labs FAA AANC; John Bohler, Dave Piotrowski – Delta Air Lines; Alex Melton – Northwest Airlines; Dave Galella – FAA; Kyle Colavito, Erdrogan Madenci – Univ. of Arizona

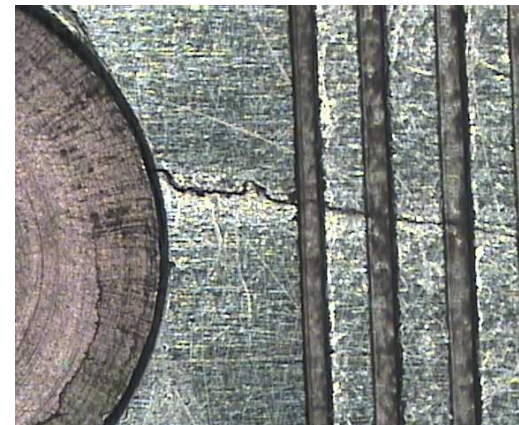
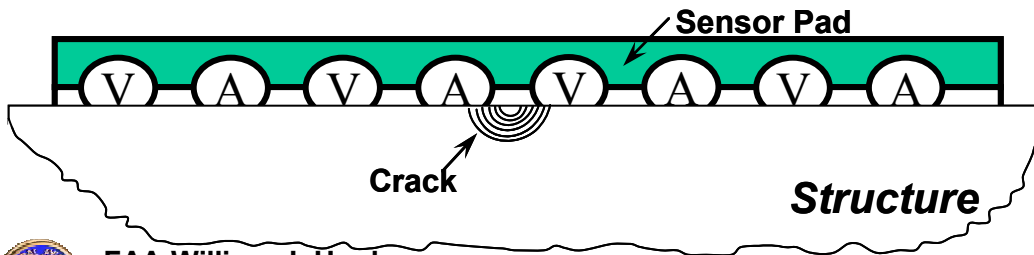
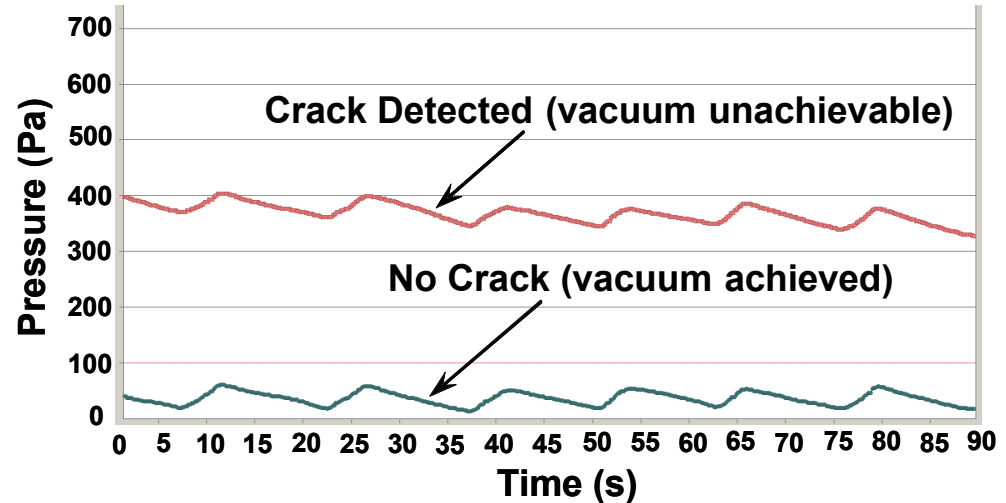


Comparative Vacuum Monitoring System

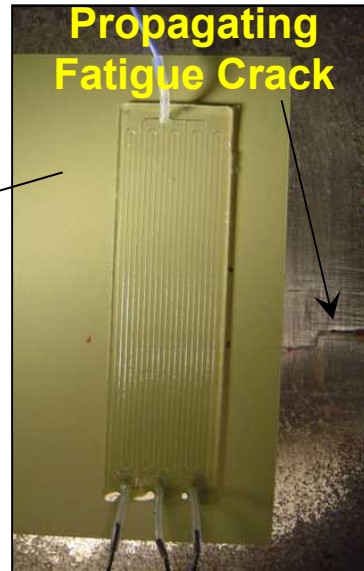
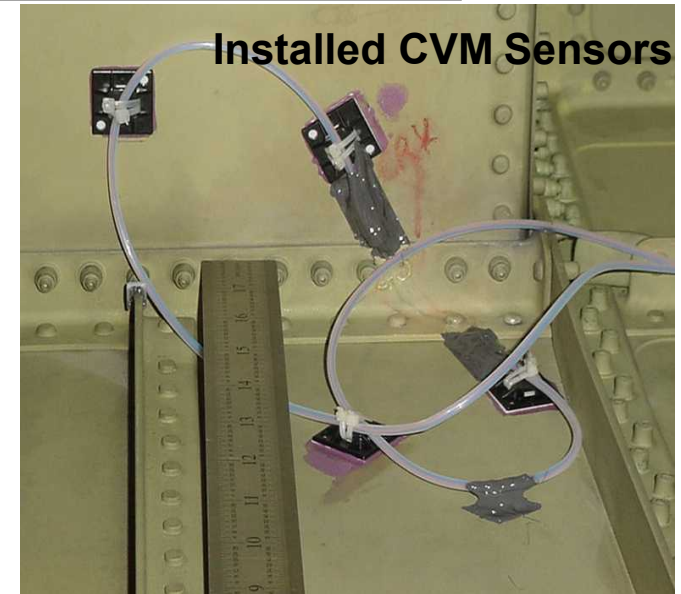
- Sensors contain fine channels - vacuum is applied to embedded galleries (**crack detection < 0.1" for alum. < 0.1" th.**)
- Leakage path produces a measurable change in the vacuum level
- Doesn't require electrical excitation or couplant/contact



CVM Sensor Adjacent to Crack Initiation Site



Crack Detection Via CVM System and Test Installation of Sensors



CVM Sensor Installation & Crack Growth Monitoring

For 0.040" th. Skins

90% POD Level	False Calls
0.021"	0



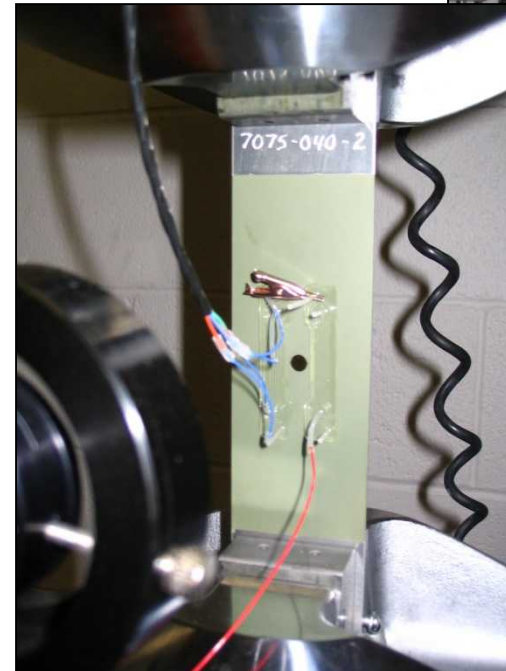
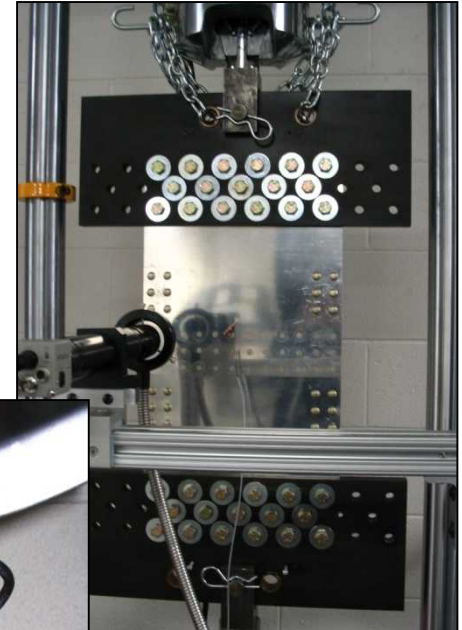
FAA William J. Hughes
Technical Center



Test Matrix to Quantify Probability of Crack Detection

Test Scenarios:

<u>Material</u>	<u>Thickness</u>	<u>Coating</u>
2024-T3	0.040"	bare
2024-T3	0.040"	primer
2024-T3	0.071"	primer
2024-T3	0.100"	bare
2024-T3	0.100"	primer
7075-T6	0.040"	primer
7075-T6	0.071"	primer
7075-T6	0.100"	primer



CVM Validation – Data Analysis Using One-Sided Tolerance Intervals

- Data captured is crack length at CVM detection
- Reliability analysis – cumulative distribution function provides maximum likelihood estimation (POD)
- One-sided tolerance bound for various flaw sizes:

$$\text{POD}_{95\% \text{ Confidence}} = \bar{X} + (K_{n, 0.95, \alpha}) (S)$$

X = Mean of detection lengths

K = Probability factor (~ sample size, confidence level)

S = Std. deviation of detection lengths

n = Sample size

1- α = Detection level



CVM Validation - Crack Detection Results

All POD levels listed are for 95% confidence

Description: 0.040 inch thick panel (primer surface)

2024-T3 Alum.

PHASE 2 TESTS						
Panel	Fastener Crack Site	Distance from Fastener (inches)	Crack Length at CVM Detection (growth after install in inches)	SIM-8 Reading ΔPa (Pasm)	PM-4 Read-out	PM-4 Indicate Crack (Y or N)
4018	5R	0.040	0.002	400-500	1607	Y
4018	6R	0.014	0.007	1700-1800	2847	Y
4018	7R	0.040	0.010	400-500	1704	Y
4018	5R(2)	0.050	0.009	1700-1800	2768	Y
4018	6L	0.052	0.004	1000-1100	2161	Y
407	7L	0.118	0.006	3758-3786	4790	Y
407	5L	0.125	0.010	654-695	1769	Y
407	7R	0.147	0.009	345-375	1426	Y
407	5R	0.139	0.011	374-409	1391	Y
4018	6L	0.194	0.007	530-560	1628	Y
4018	5L	0.253	0.006	380-430	1553	Y
4018	8R	0.262	0.011	320-360	1452	Y
407	6R	0.189	0.012	450-510	1661	Y

90% POD Level	False Calls
0.021"	0

[all panels are 2024-T3 alum. (AMS-4040, 41, QQ-A-250/5) with 0.0005" th. clad]



CVM Validation - Crack Detection Results (cont.)

All POD levels listed are for 95% confidence

Description: 0.100 inch thick panel (primer surface)

2024-T3 Alum.

PHASE 2 TESTS						
Panel	Fastener Crack Site	Distance from Fastener (inches)	Crack Length at CVM Detection (growth after install in inches)	SIM-8 Reading ΔPa (Pasm)	PM-4 Read-out	PM-4 Indicate Crack (Y or N)
1001	5L	0.350	0.065	773-825	1713	Y
1001	7R	0.206	0.054	697-722	1768	Y
1001	8R	0.115	0.060	560-600	1609	Y
1003	8L	0.044	0.068	297-320	1410	Y
1003	7L	0.086	0.058	342-386	1411	Y
1003	8L	0.187	0.069	~1800	3391	Y
1003	6L	0.061	0.065	476-500	1846	Y
1003	6L	0.131	0.076	800-946	2117	Y
1003	8R	0.160	0.045	380-420	1508	Y

90% POD Level	False Calls
0.090"	0

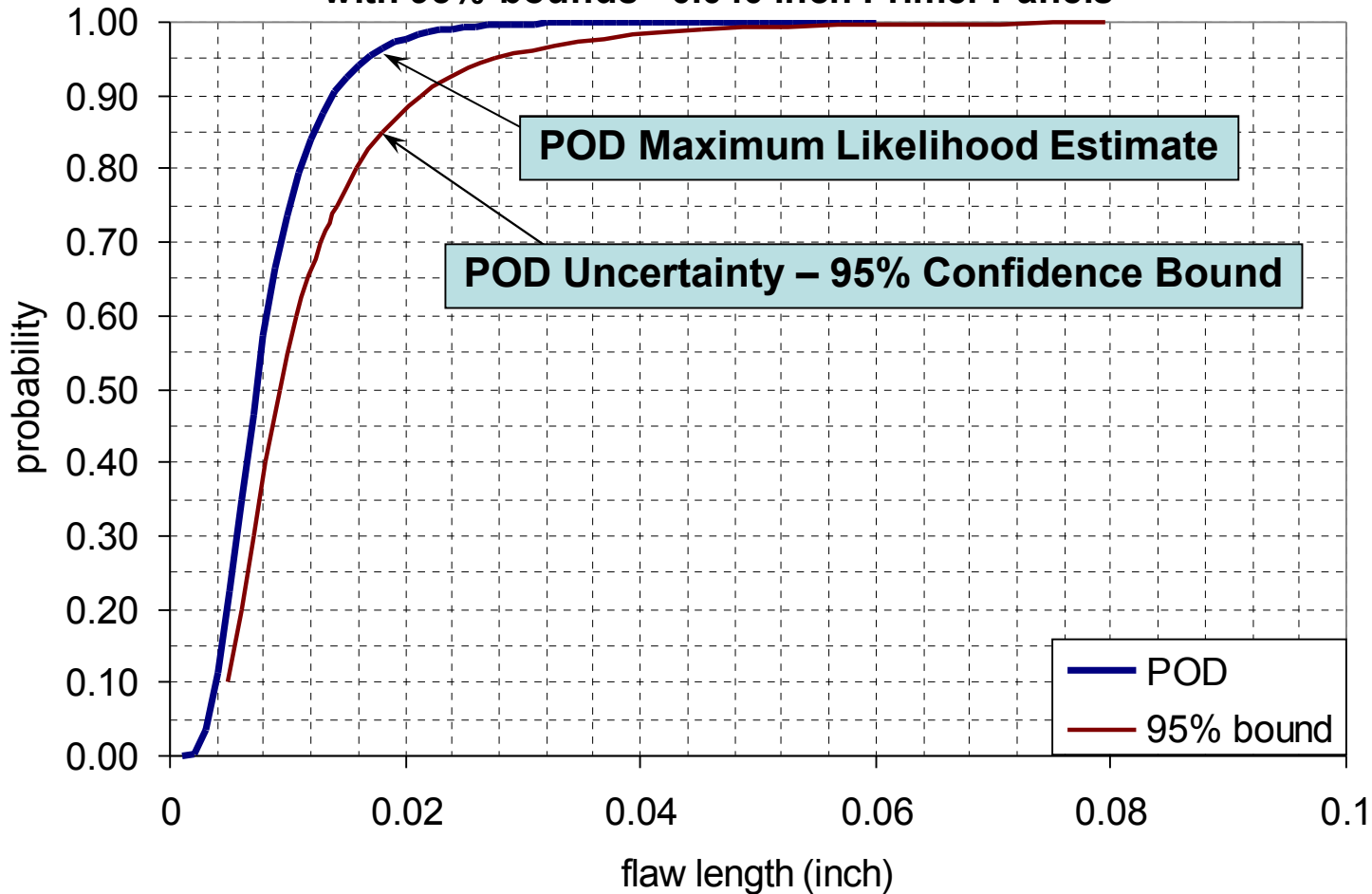
[all panels are 2024-T3 alum. (AMS-4040, 41, QQ-A-250/5) with 0.0005" th. clad]



Sample Probability of Detection Curves for CVM

2024-T3 Alum.

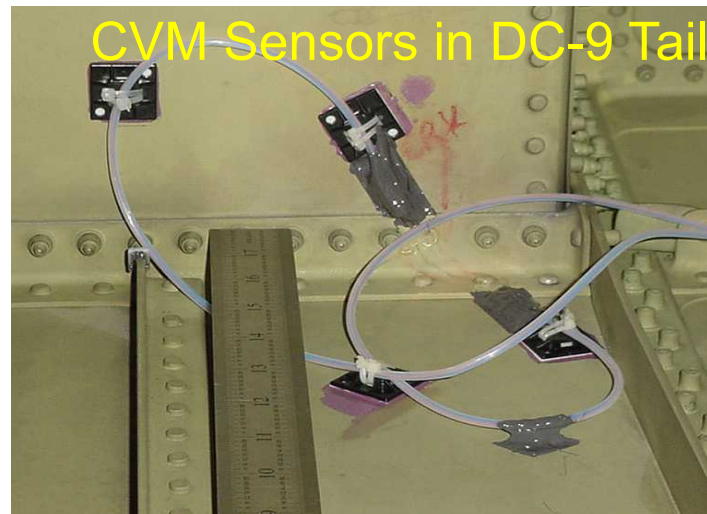
Cumulative Distribution Function Detectable Flaw Lengths -
with 95% bounds - 0.040 inch Primer Panels



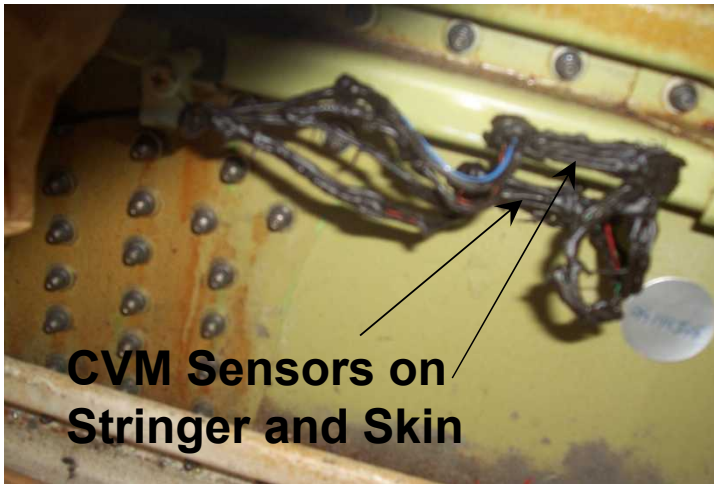
Field Evaluation of Sensor Applications

Environmental Durability Testing - To assess the long-term viability of CVM sensors in an actual operating environment, 22 sensors were installed on the following civil aircraft for functional evaluation:

Aircraft	Tail	Operator	Date	# Sensors	Status
DC-9	9961	NWA	Feb 04	6 (4 remaining)	2 sensors removed by NWA
DC-9	9968	NWA	Apr 05	6	3 sites
B757	669	Delta	Apr 05	8	4 sites in empennage on stringers, frames & near APB
B767	1811	Delta	Apr 05	6 (4 connected)	3 sites in empennage



CVM Durability - NWA Aft Baggage Compartment Sensor (A/C 9968)



CVM Sensors on Stringer and Skin



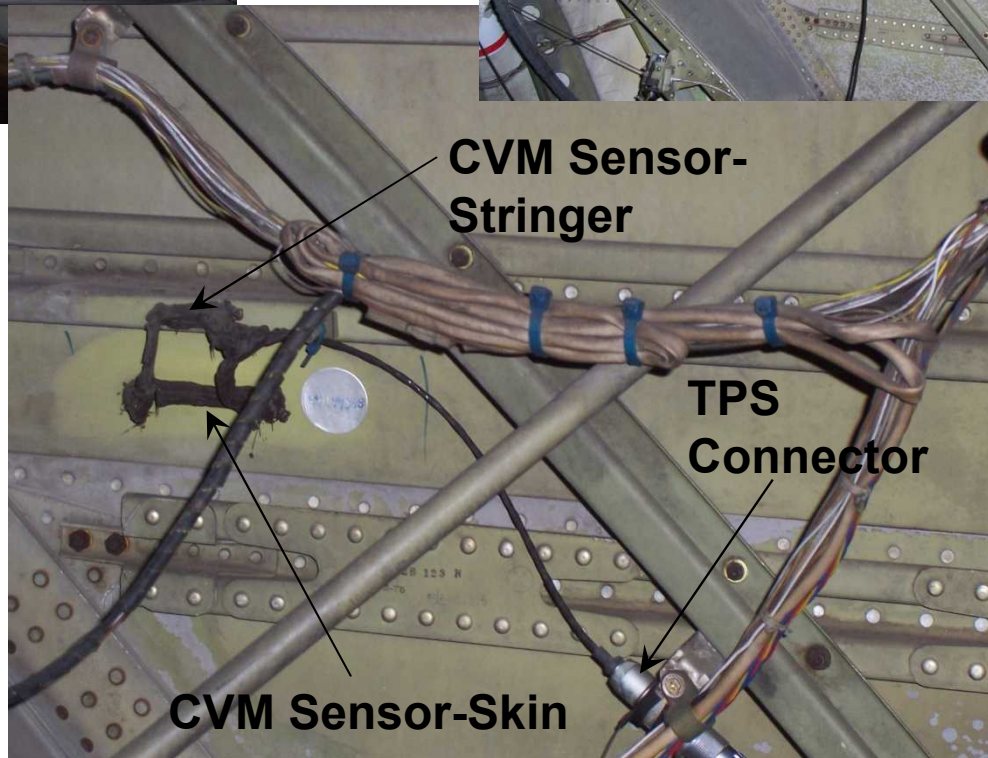
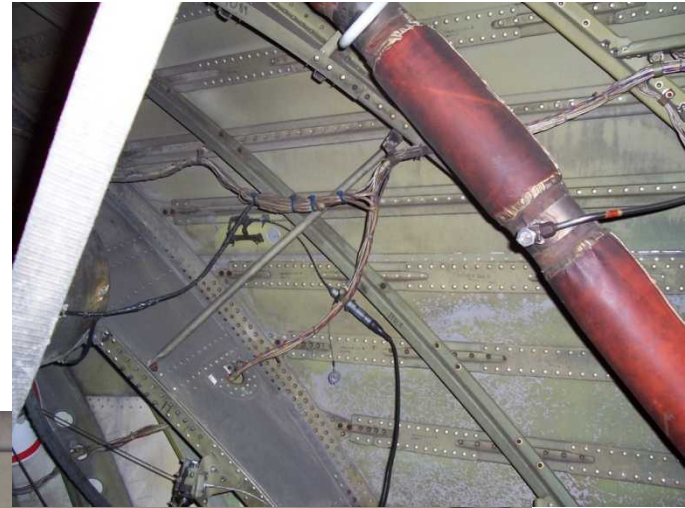
TPS connector routed to access panel



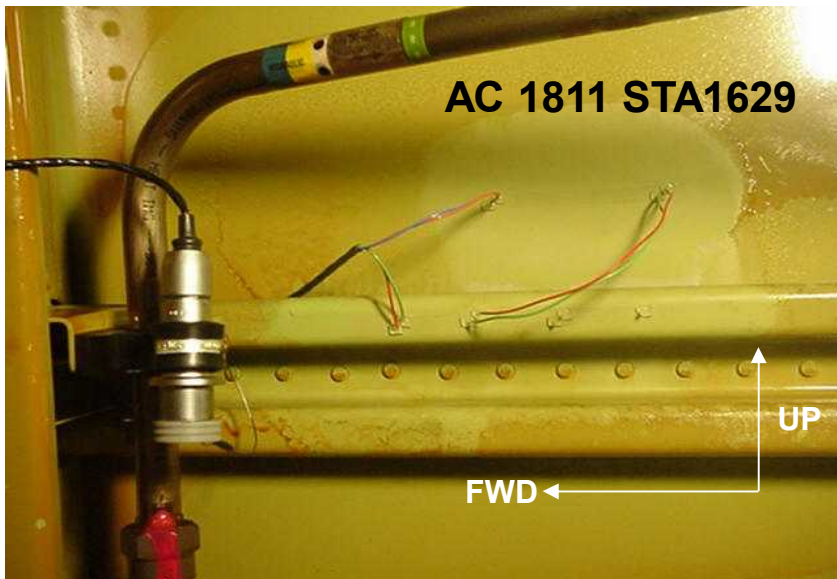
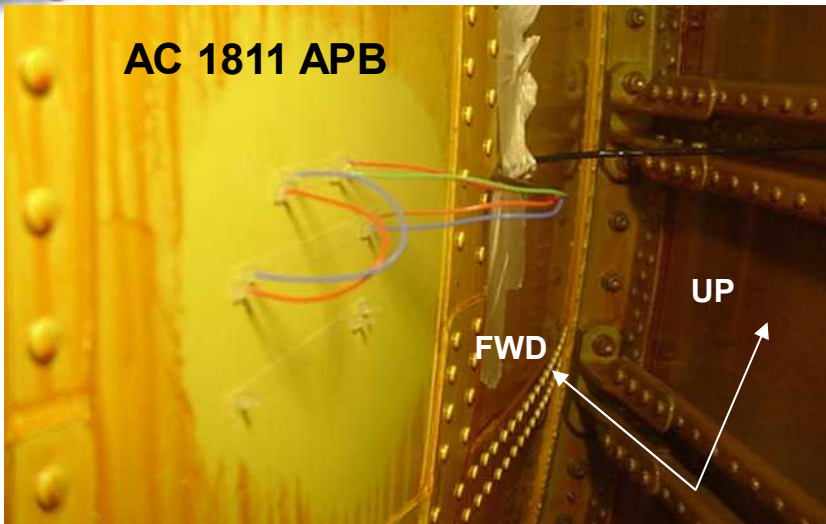
Monitoring CVM with PM-4 device



NWA Empennage Sensor (A/C 9968)

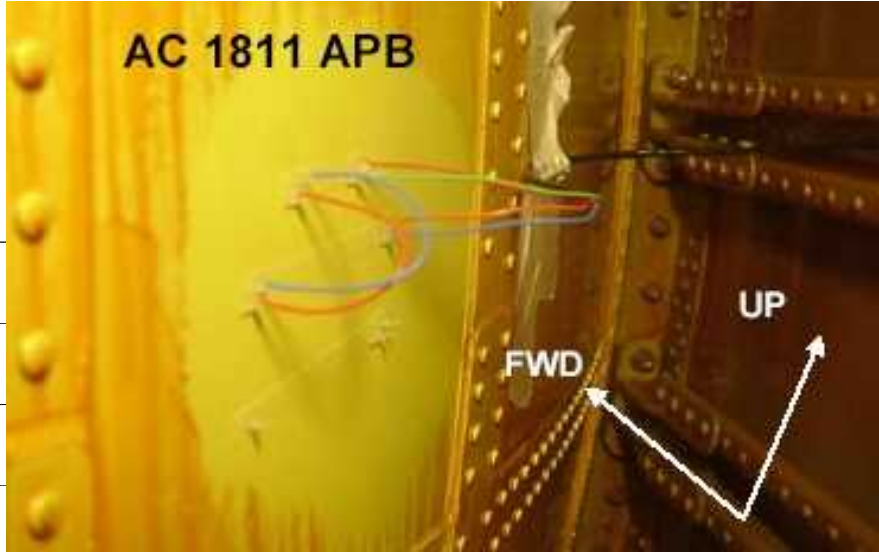


Delta Air Lines Field Installations

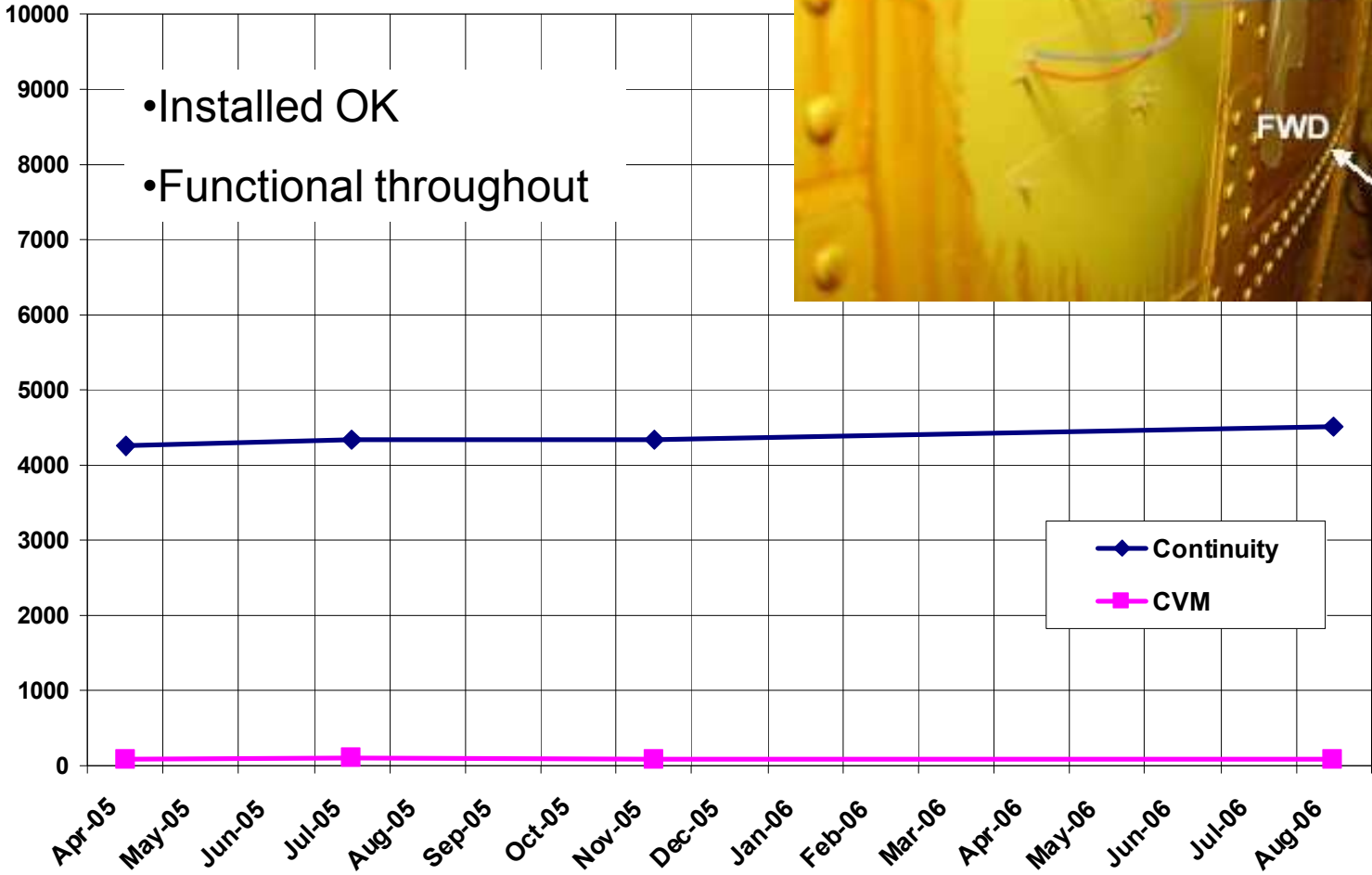




Delta - 767
Aft Pressure Bulkhead - Unpressurised
(AC1181)



Pascals

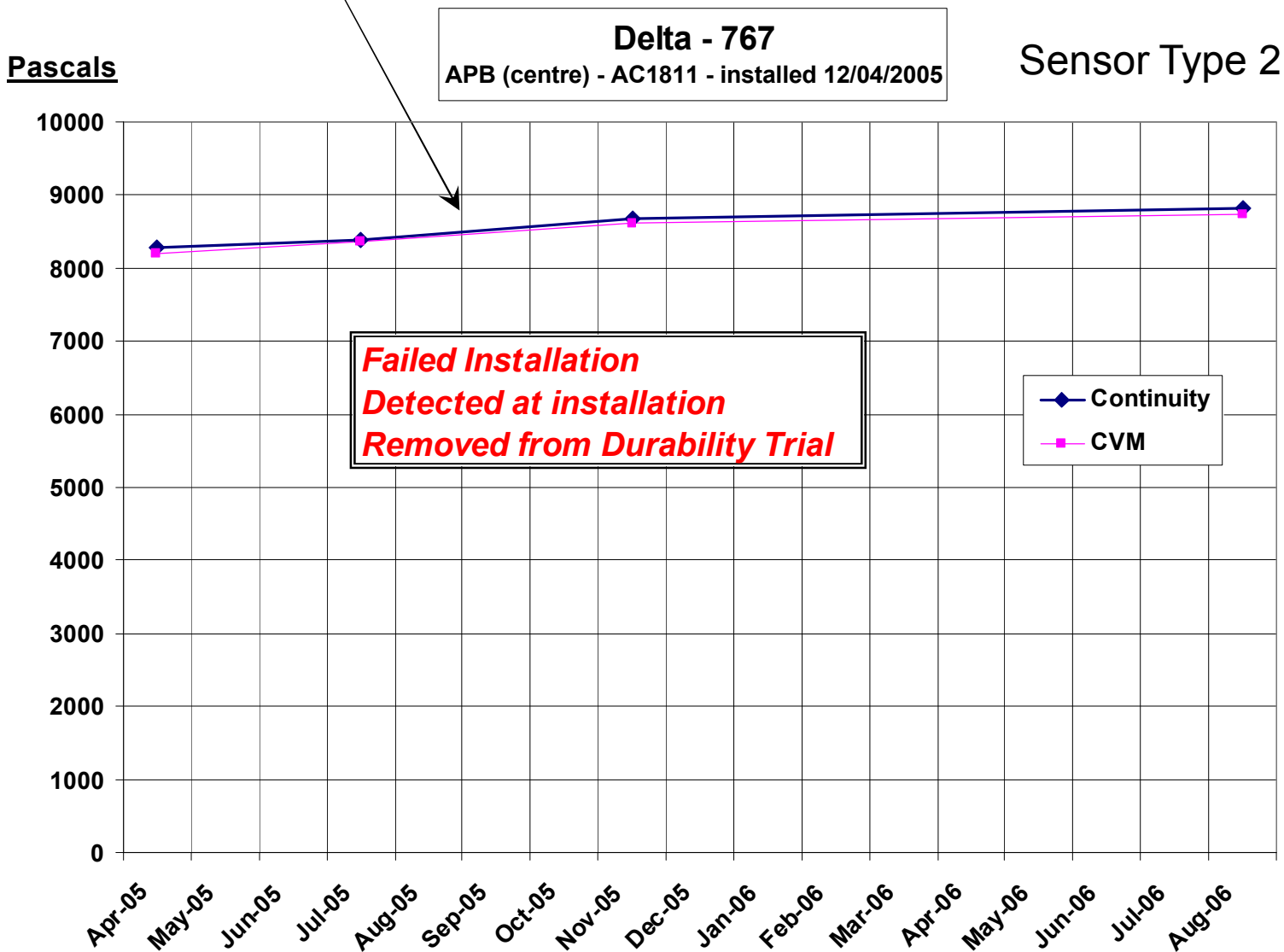


- Installed OK
- Functional throughout

◆ Continuity
■ CVM



Fail-Safe Feature – poor installation (cannot pull vacuum) is detectable prior to use for monitoring and sensor can be replaced (i.e. will not produce false or missed calls); this sensor was left in place and monitored but would be replaced in a real application



Study to Assess the Effects of Corrosion Inhibiting Compounds on the Performance of CVM

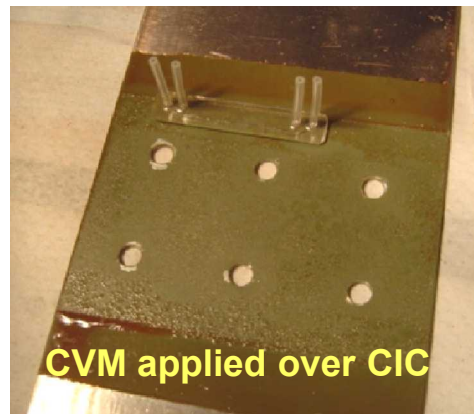
Objective: Provide confidence in the performance of CVM in the presence of CICs during crack growth

CIC Selected:

- BMS 3-35 which is Ardrox AV15 or Corban-35 (Zip Chem)
- BMS 3-23 which is LPS-3 or Ardrox AV-8 or Dinitrol



Multiple passes to produce flowing and accumulation of CIC



CVM applied over CIC

Crack Detection:

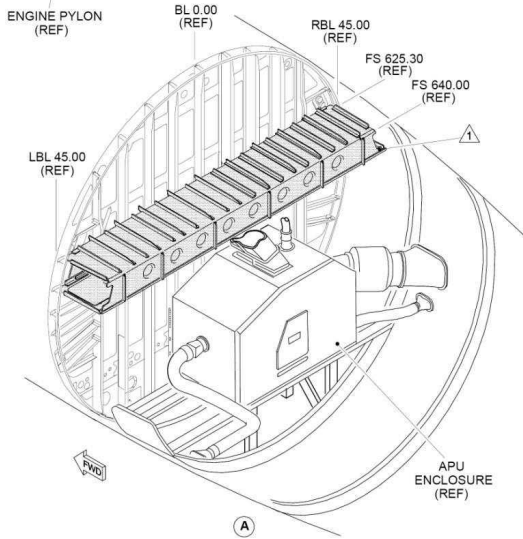
$a_{90} = 0.011''$ w/o CIC

$a_{90} = 0.013''$ w/ CIC

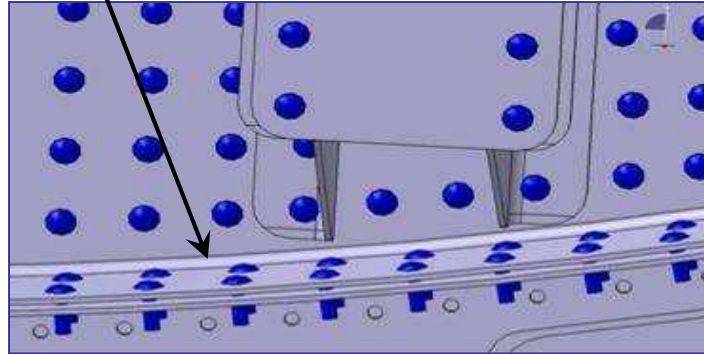
No CIC drawn into galleries

CVM Success on CRJ Aircraft

Pilot program with Bombardier and Air Canada

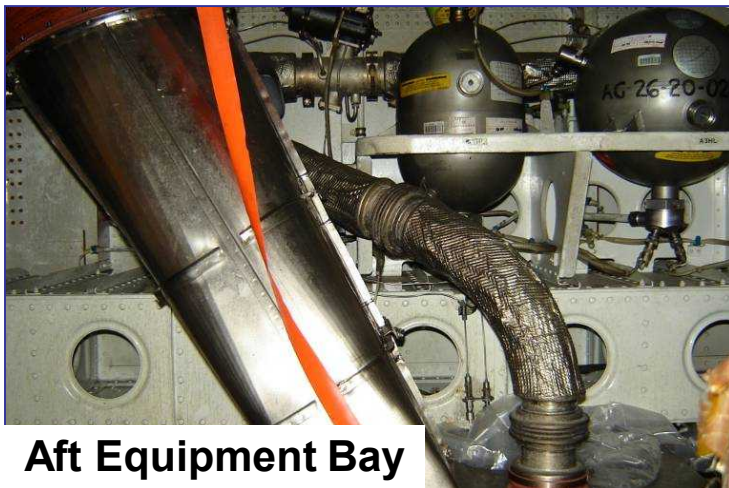


Inspect in the radius



Sensor Issues:

- Design
- Surface preparation
- Access
- Connection
- Quality control



Aft Equipment Bay





Validation of CVM Sensors for SHM Crack Detection

- **CVM sensor detects cracks in the component it is adhered to**
- **Inspection process and diagnosis is fully automated – remote**
- **Early detection = less costly repairs**
- **CVM system is fail-safe (inert sensors produce an alarm)**
- **Lab performance & multi-year flight test program completed**
- **Integration of CVM in NDT Standard Practices Manuals**
- **Actual application on commuter (CRJ) aircraft successful; additional applications being pursued**
- **AMOC for SBs and ADs – safety driven use is achieved in concert with OEMS & regulatory agencies**
- **Certification & regulatory framework needs to be addressed**



SHM Certification & Integration Activity

Delta-OEM-FAA-AANC joint effort to leverage airline activities

- **Certification/usage effort intended to investigate, exercise and evolve the SHM certification path – address all “cradle-to-grave” issues for airlines, OEMs, and regulators**
- **Identify SHM applications with positive cost-benefit analysis**
- **Customize SHM system to the selected application(s)**
- **Develop validation/certification plan – utilize precedents from existing sensors**
- **Complete SHM indoctrination and training for Delta personnel (engineering, maintenance, NDI) and FAA as needed**
- **Hardware specifications, installation procedures, operation processes, continued airworthiness instructions**
- **Complete modifications to Delta maintenance program as a result of SHM use**
- **Assess aircraft maintenance depots’ ability to adopt SHM and the FAA support needed to ensure airworthiness**

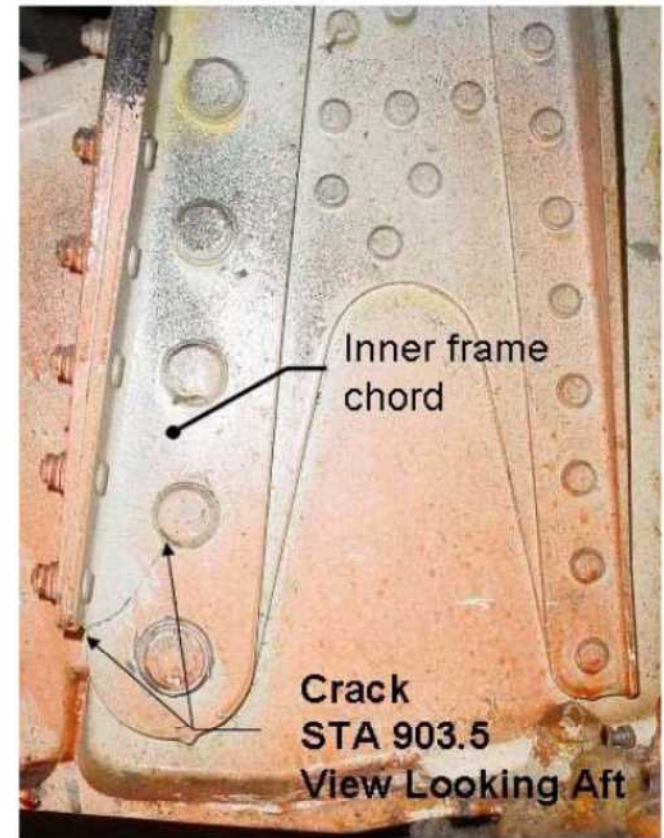


SHM Certification & Integration Activity

Delta-OEM-FAA-AANC joint effort to leverage airline activities

Some Potential SHM Applications:

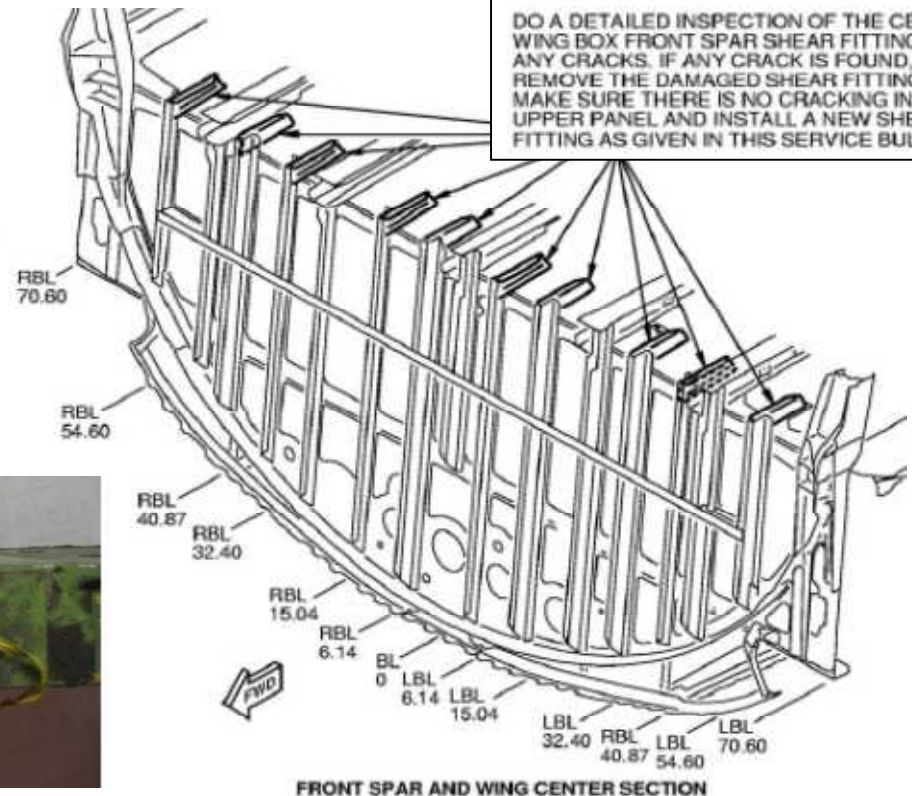
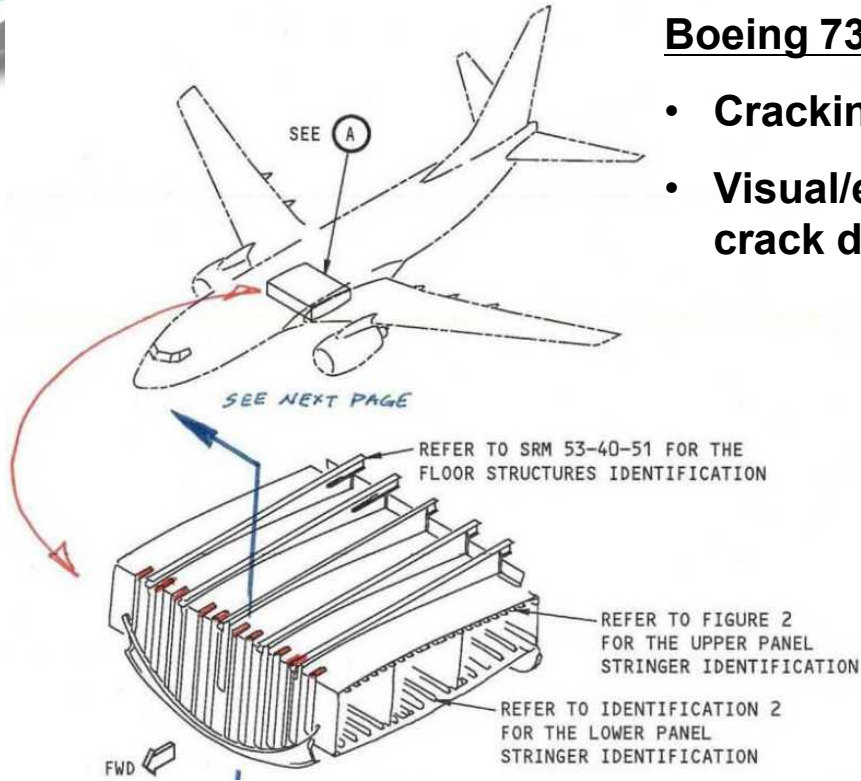
- 737 aft pressure bulkhead
- 737 center wing box spar fitting
- 747 fuselage
- DC-9 aft pressure bulkhead
- MD-88 and DC-9 substructure
- MD-88 belly skin
- MD-88 and 90 Stringer Cracking
- 767 frames
- MD-88 and MD-90 vertical & horizontal stabilizers



737NG Center Wing Box, Front Spar Shear Fitting

Boeing 737 SB:

- Cracking between 21K-36K cycles
- Visual/eddy current inspection for crack detection



DO A DETAILED INSPECTION OF THE CENTER WING BOX FRONT SPAR SHEAR FITTINGS FOR ANY CRACKS. IF ANY CRACK IS FOUND, REMOVE THE DAMAGED SHEAR FITTING. MAKE SURE THERE IS NO CRACKING IN THE UPPER PANEL AND INSTALL A NEW SHEAR FITTING AS GIVEN IN THIS SERVICE BULLETIN.

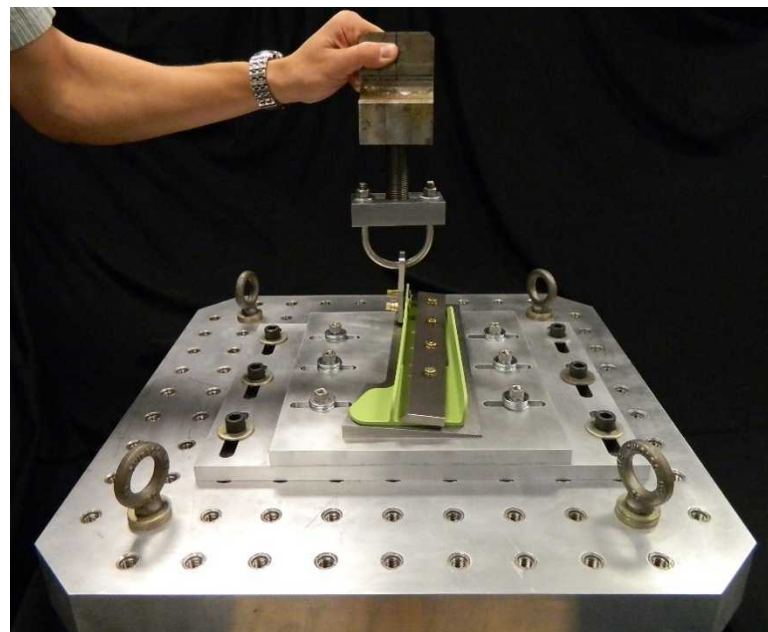
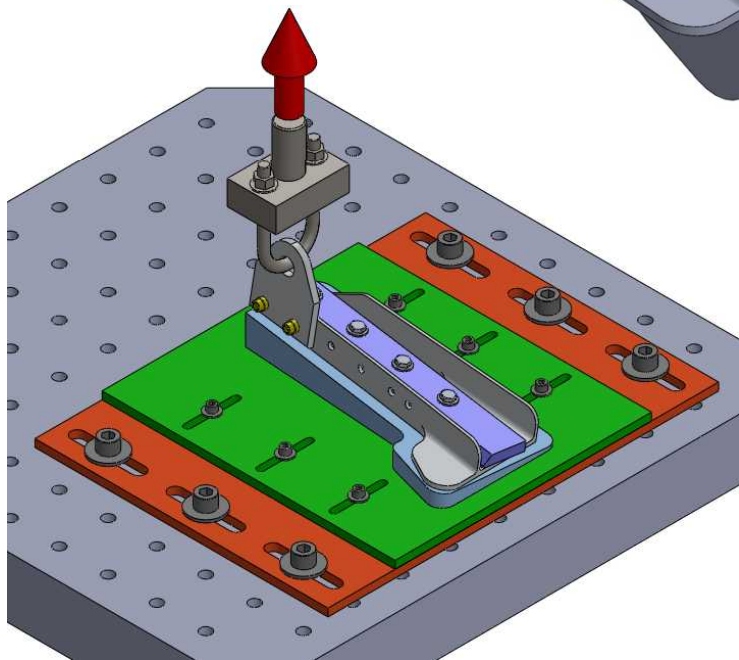


FRONT SPAR AND WING CENTER SECTION



737NG Center Wing Box – SHM Validation Testing

Wing Box Fitting
Tension-Bending
Fatigue Loading



737NG Center Wing Box – CVM Installation & Operation Workshop

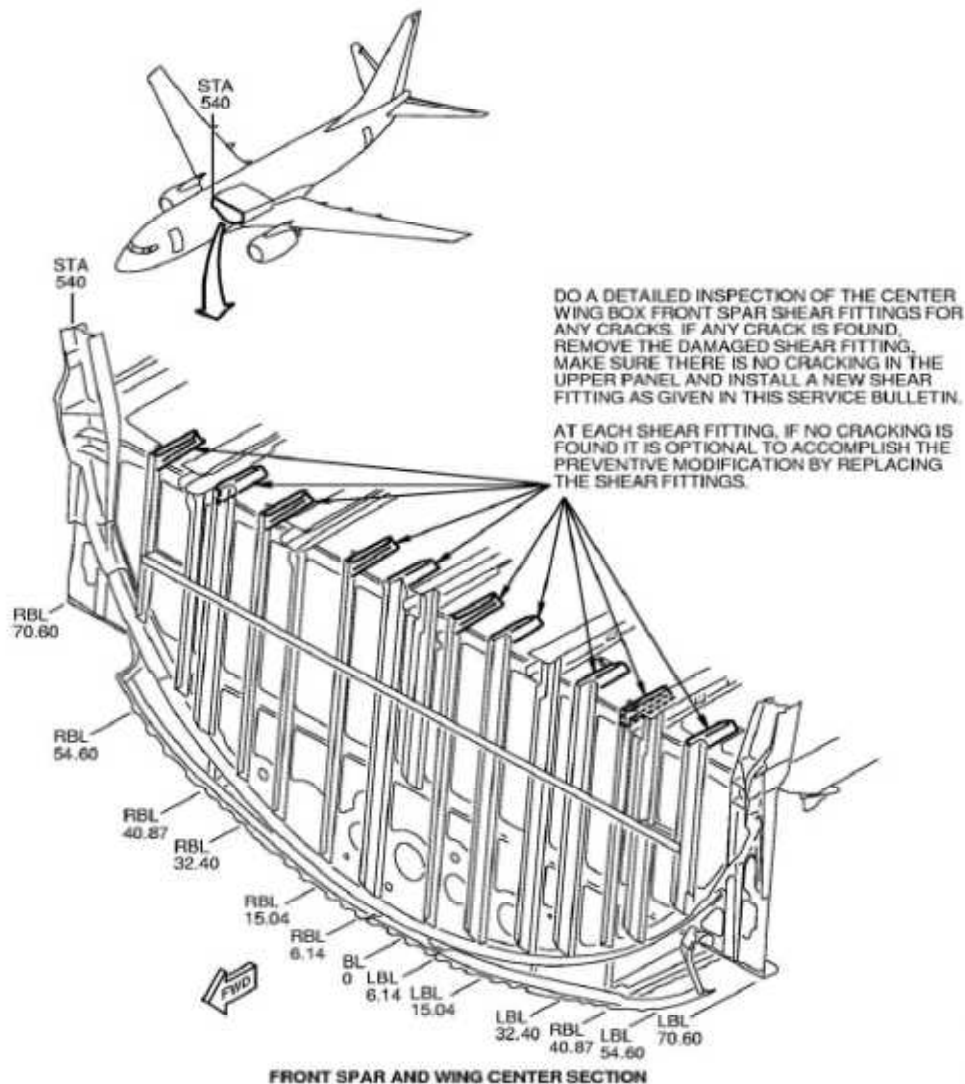
- Workshop conducted in November 2012 in anticipation of on-aircraft flight test program
- Attendees included: Boeing, Delta Air Lines, AAR MRO, SMS, AEM, Sandia Labs
- Details on sensor placement, sensor lead routing, tie-downs and logistics (e.g. kits) were determined
- Facilitate Action Authorization (generation of job/task cards) & Delta incorporation of CVM installation and operation documents into maintenance program



737NG Center Wing Box – CVM Flight Tests



CVM Sensor on 737NG Wing Box Fitting and Top View of SLS Mount Location





Paving the Path: Structural Health Monitoring Certification Program

Dennis Roach

Tom Rice

FAA Airworthiness Assurance Center
Sandia National Laboratories

David Piotrowski

John Bohler

Alex Melton

Delta TechOps

Abstract

Structural Health Monitoring (SHM) is the next adaptation of inspection technology. The FAA has funded sensor development programs over the years, laying the foundation for sensitivity, durability, and repeatability issues. Several OEMs have embraced SHM with some even incorporating it into their NDT Manuals. However, SHM still remains stagnant about actual implementation and usage. This presentation will provide the background for what has been accomplished already, issues plaguing the industry and preventing adoption, and finally, provides a path forward to full adoption and usage.

