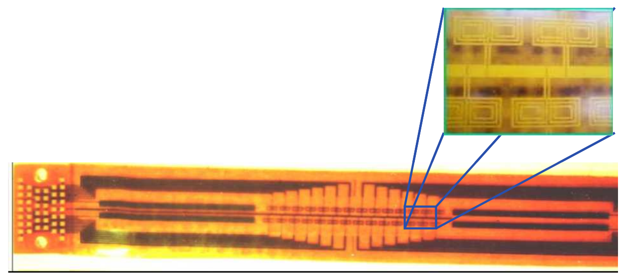
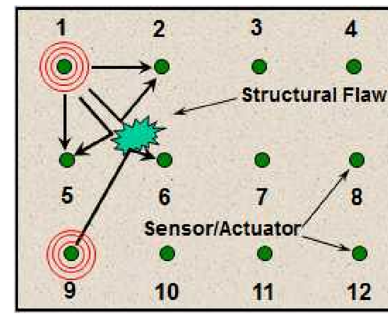
FAA Research Program Webinar Series on Structural Health Monitoring for Aircraft Maintenance

SAND2016-8002PE

MODULE 2: SHM Validation and Approval





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FAA Webinar Series on Structural Health Monitoring

Module 2 – SHM Validation and Approval for Routine Use

Part 1 – SHM System Requirements Drive Validation & Verification Tasks
Part 2 – SHM Performance Assessment
Part 3 – SHM Durability Assessment: Reliability & Environmental Effects
Part 4 – SHM Flight Testing: Durability & Integration into Maintenance Programs

FAA William J. Hughes
Technical Center

Sandia National Laboratories

FAA Research Program Webinar Series on Structural Health Monitoring for Aircraft Maintenance

MODULE 2: SHM Validation and Approval

Background: The FAA (William J Hughes Technical Center (WJHTC) has been conducting a research program on Structural Health Monitoring (SHM) for transport category aircraft to support the research needs of the Transport Aircraft Directorate (TAD). These programs have moved SHM solutions into the arena of routine maintenance activities with accompanying certification efforts and flight test programs with airlines and airline requests for SHM usage in their maintenance programs. The Webinars will be a brief introduction of that research and include the topics listed below.

Goal: To bring ACO and other FAA people up to speed on SHM and the prospects of needing to approve SHM for routine use. The webinars will expose attendees to SHM technology, what's out there & how mature, what is the present & expected near-future state of the technology, provide example SHM deployment via summaries of some of the SHM validation/utilization programs conducted to date, and present airline perspectives on SHM utilization.

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MODULE 2: SHM Validation and Approval

Target Audience: Members of the Aircraft Certification Offices (ACO) and TAD; particularly program managers and airframe specialists; engineers and managers. Members of PMI community that will oversee airline maintenance programs that include SHM deployment.

Webinar Topics:

1. Introduction to SHM – what it's about & why is it important to discuss; overview of what FAA folks should expect to see from an SHM applicant
2. FAA SHM Roadmap - status of SHM technologies (SHM survey, maturity & airline perspectives on use); issues to SHM implementation
3. SHM Performance Assessment – initial SHM program for general fuselage use (2005-2010 Boeing program)
4. SHM Certification/Approval for Use – validation; OEM approval, FAA approval (options); sample array of uses identified thus far
5. SHM Deployment – airline perspective (Delta)

Motivation for FAA SHM Program

- Ad-hoc efforts to introduce SHM into routine aircraft maintenance practices are valuable. However, there is a significant need for an overarching plan that will guide activities to uniformly and comprehensively support the evolution and adoption of SHM practices.
- Need input from OEMs, regulators, operators, and research organizations so that the full range of issues is appropriately considered → roadmap document
- Need guidelines for sensor and SHM system designers
- Need guidelines, or agreed-upon procedures, for assessing the performance of SHM systems or certifying them for use on aircraft
- Must identify SHM research needed to fill in critical information gaps
- FAA SHM Program supports the safe adoption of SHM practices and allow OEMs, regulators, and carriers to make informed decisions about the proper utilization of SHM.

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

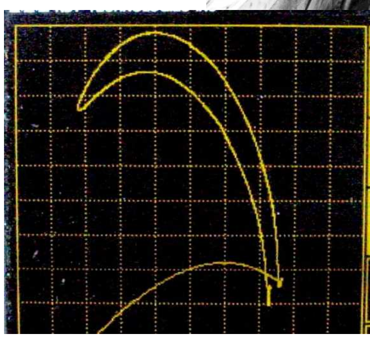
- High degree of human interaction
- Local, focused inspections
- Requires access to area of interest (applied at select intervals)

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 & mechanisms

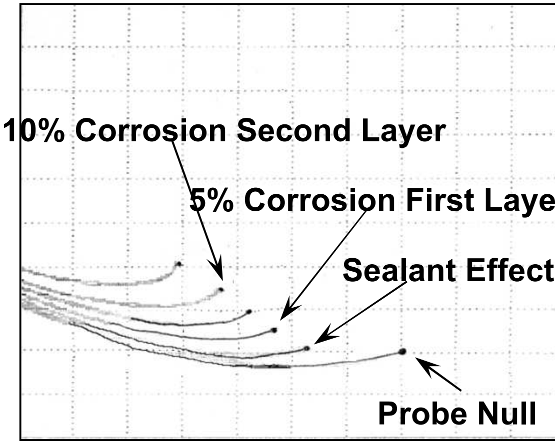
- Greater vigilance in key areas – address DTA needs
- Overcome accessibility limitations, complex geometries, depth of hidden damage
- Eliminate costly & potentially damaging disassembly
- Minimize human factors with automated data analysis

The use of in-situ mounted sensors and analysis to assess structural or mechanical condition.

Typical A-Scan Signals Used for Flaw Detection with Hand-Held Devices

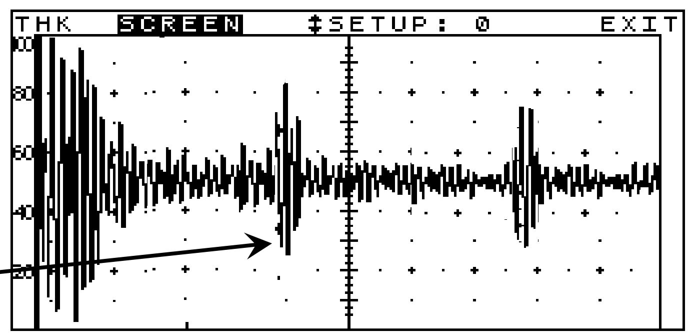


Eddy Current Signal at Crack Site



Corrosion Detection with Dual Frequency Eddy Current

Intermediate Echo Caused by Delamination

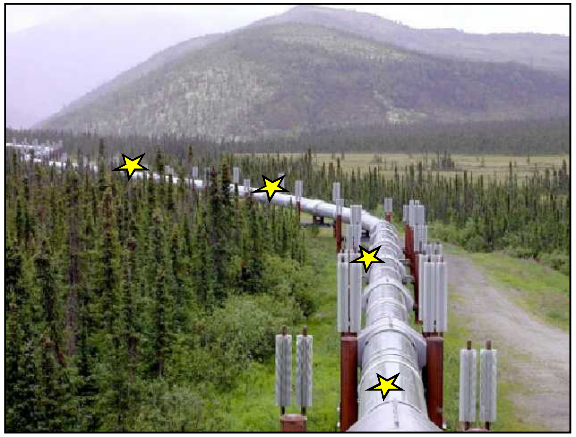


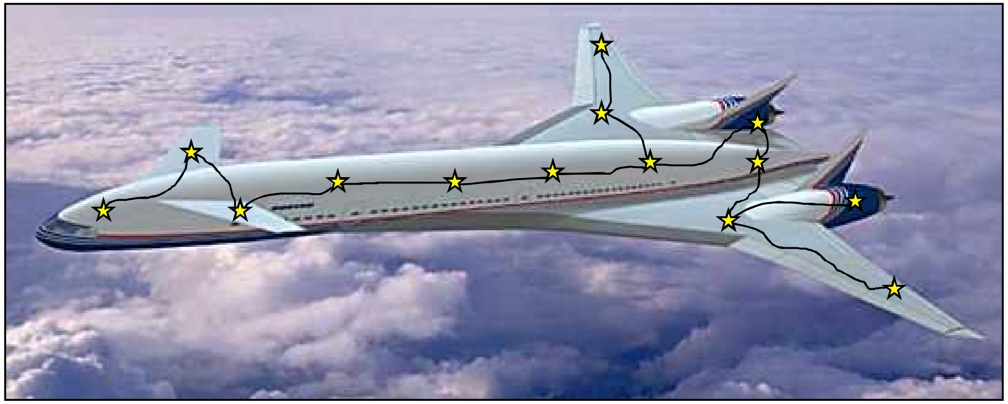
Ultrasonic Pitch-Catch UT Signals Comparing Flawed and Unflawed Signatures

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
- SHM for:
  - Flaw detection
  - Flaw location
  - Flaw characterization
  - Condition Based Maintenance





Part 1 – SHM System Requirements Drive Validation & Verification Tasks

SHM Requirements

Requirements capture would follow the establishment of intended functions (Ref ARP6461):

- **Safety and Reliability requirements**
- **Functional requirements**
- **Operational requirements**
- **Performance requirements**
- **Physical requirements**
- **Environmental requirements**
- **Structural requirements**
- **Installation requirements**
- **Maintainability requirements**
- **Interface requirements**

The approach was to offer general requirements only to highlight where SHM imposes some special considerations (e.g. flaw detection capability) beyond current on-board equipment and relevant standards, practices and guidelines.

The airborne equipment fulfils at least the functions of interrogating the structure and transmitting the information to equipment, whether airborne or ground-based

Deployment of Health Monitoring Sensor Networks

Various levels of autonomous health monitoring are possible:

1. **In-Situ Sensors Only – separate power, signal conditioning, and data acquisition which are transported to site via inspector**

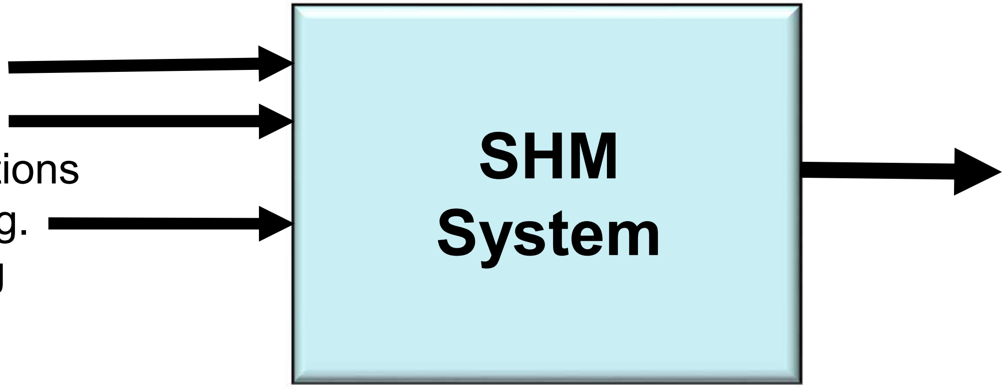
2. **Sensor Network with In-Situ Data Acquisition – miniature electronics package is mounted to structure with data logging capability; periodic data download at the site**

3. **Sensor Network with Data Transmission to Remote Site – same as item #2 with addition of telemetry system for continuous, wireless transmission to a web site; thresholds and other intelligence can be included in web site to automatically signal the need for repairs or other maintenance.**

Determine SHM System Goals

Maintenance Credit - The SHM system should detect presence of damage and operate with a specified probability of detection and confidence level for a for a predetermined set of operating conditions

- Damage State
- System Config
  - Repairs, Modifications
- Environmental Config.
  - Structural Loading
  - Temperature
  - Moisture
  - Electromagnetic

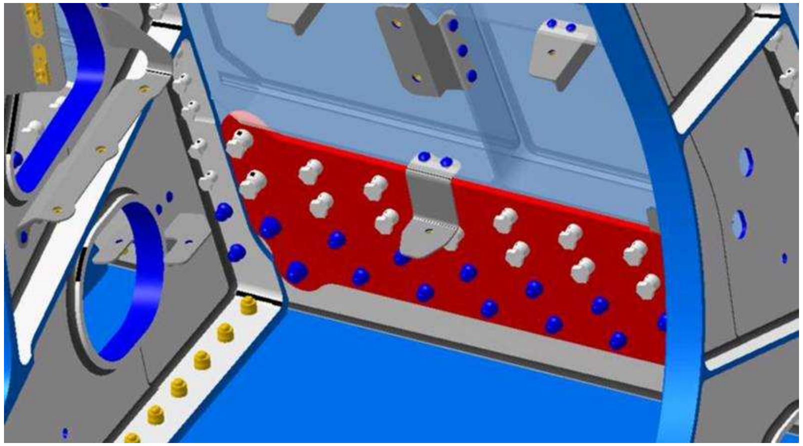


Detected Damage State [X% confidence Y% probability of detection]

SHM Validation Process Must Account for All Factors That Can Affect Performance

- **SHM Method - SHM solution, device, sensor spacing, data acquisition process, data analysis method, data interpretation (thresholds, S/N), use of baselines**
- **Structural Configuration – geometry, material type, number of layers, fastener types and spacing, hole geometry, assembly specifics (fit/gaps), surface condition, coating changes**
- **Flaw/Damage Condition – type, X-Y location, depth, orientation, dimensions, morphology, presence of by-products**
- **Environmental Conditions – load scenario to generate damage, impact, environment to generate damage & establish durability**

Complex Structure Requires Detailed SHM Validation



SHM Validation Considerations

- **Declared Intent** - application is for credit (replaces task or leads to changes in the requirements for a task); criticality describes the severity of the result of an SHM application failure or malfunction

- **Usage Mode for SHM System**
  - "Hot spot" or local monitoring (S-SHM)
  - Prognostic and condition-based health monitoring (P-SHM and C-SHM) - shift to predictive and continuous monitoring will require extensive validation and successful in-service experience so that regulatory agencies and operators can acquire confidence in these SHM approaches

- **Aircraft Maintenance Practices** – change in programs; how to adopt

- **Deployment** – operational performance & repeatability

- **Regulatory Actions and Industry Acceptance** – depends on certification process (AMOC, NDT SPM, SB/AD, STC)

SHM Validation Considerations (cont.)

- Key element in an SHM system is a calibration of sensor responses so that damage signatures can be clearly delineated from sensor data produced by undamaged structures
- Commercial implementation of SHM needs to be proven through statistically-viable lab performance data and successful field operation data
- Data requirements need to be established for determining the applicability of SHM (boundaries) and to address certification requirements
- Educational initiatives with key players – understanding of SHM, its usage and its limitations

SHM Validation and Verification

The ARP 6461 guidebook offers generalized, stepwise tasks through a V&V process:

Development Phase	Evaluation Activities
1. Conceptual	• Identify: 1. interrogated component and material type 2. flaw types and inspection requirements 3. inspector requirements 4. critical elements • Verify in laboratory • Assess inherent capabilities (theoretical) • Estimate (order of magnitude) capital equipment costs and material and power needs for routine operation.
2. Preliminary design	• Test in laboratory on specified test samples • Identify and enumerate preliminary: 1. SHM equipment procedures 2. Inspector requirements 3. Facility requirements
3. Final design	• Experiment to assess factors affecting reliability • Demonstrate feasibility through "blind" procedures • Gather inspection time data • Update procedures and inspector requirements • Early field trials
4. Field implementation	• Prepare (or specify) evaluation assemblies • Finalize procedures and inspection requirements • Conduct controlled trials using independent inspectors • Conduct field trials with potential users • Assess training (and retraining) needs for inspectors • Industry -site testing

Technology ready

Application ready

SHM Validation Process Tasks

- **Validation Process** should:
  1) provide a vehicle in which skills, instrument deployment & human error can be evaluated in an objective and quantitative manner
  2) provide an independent comparison between SHM solutions and alternate maintenance and monitoring methodologies
  3) optimize SHM utilization methodologies through a systematic evaluation of results obtained in laboratory and field test beds
  4) produce the necessary teaming between the airlines, aircraft manufacturers, regulators, and related SHM development and research agencies to ensure that all airworthiness concerns have been properly addressed
- **Validation Assemblies** – Assess technology and process; deployed under conditions identical to those of the day-to-day maintenance environment; use airline maintenance personnel who will perform the monitoring tasks using normal working practices and under normal working conditions
- **Comprehensive Evaluation** - Assess performance, training and integration into maintenance program (technical and admin)

SHM Validation and Verification

The validation efforts must ensure that the SHM system can adequately and reliably perform its the functions (meets requirements). The validation and verification efforts should consider the following steps:

- Identify SHM intended functions
- Identify physical items (and their functions) required to deliver intended function.
- Safety assessment: understand failure conditions and consequences, classify severity.
- Ensure requirements are complete
- Ensure that the Design Assurance Levels consistent with the severity of failure.
- Ensure that sufficient measurement characteristics are specified to achieve the intended function.
- Apply validation and verification methods determined from the DAL assignments.

Validation encompasses the efforts required to ensure that the allocated requirements are sufficiently correct and complete.

Verification encompasses the efforts required to check the correct implementation of the system requirements.

Summary of Potential SHM Evaluation Criteria

- **Accuracy** – POD and false calls
- **Sensitivity** – resolution, ID flaw type & severity
- **Analysis Capability** – presentation of data, clarity, remove subjectivity
- **Human Factors** – ease of use, compatibility with maintenance program
- **Versatility** – range of equipment use, depth of penetration, (re)calibration
- **Coverage and Scan Rate** – portability, set-up, area/second
- **Availability & Support** – history & stability of supplier
- **Cost** – cost-benefit analysis, multiple SHM applications needed
  - Sensor durability & failure rate
  - Data retention & link to baseline – time & coordination
  - SHM system sustainment
  - ROI time frame & global adoption of SHM

Approval for SHM Use – Sample Regulatory Process

Sample structure of validation process for regulatory approval (SB and AMOC) where OEM is the driver:

- **Part I: Validation & Verification**
  - **OEM certification of data quality via DER/AR**
  - **Regulator issues Acceptance Letter for data**
  - **Regulatory agency kept informed and may participate**
  - **Test plan – specimen conformity & test witness**
- **Part II: Formal Interface with Regulatory Agency**
  - **Application to regulatory agency for SHM approval via a Design Change Application - certification plan addressing compliance with pertinent regulations (e.g. ACs); drawings; SBs; manual modifications**
  - **Submission of Document Package**
  - **Regulatory agency prepares Statement of Compliance – design change meets design limitations & continued airworthiness requirements**
- **Approval Letter Received from Regulatory Agency**

Possible Forms of FAA Guidance on SHM

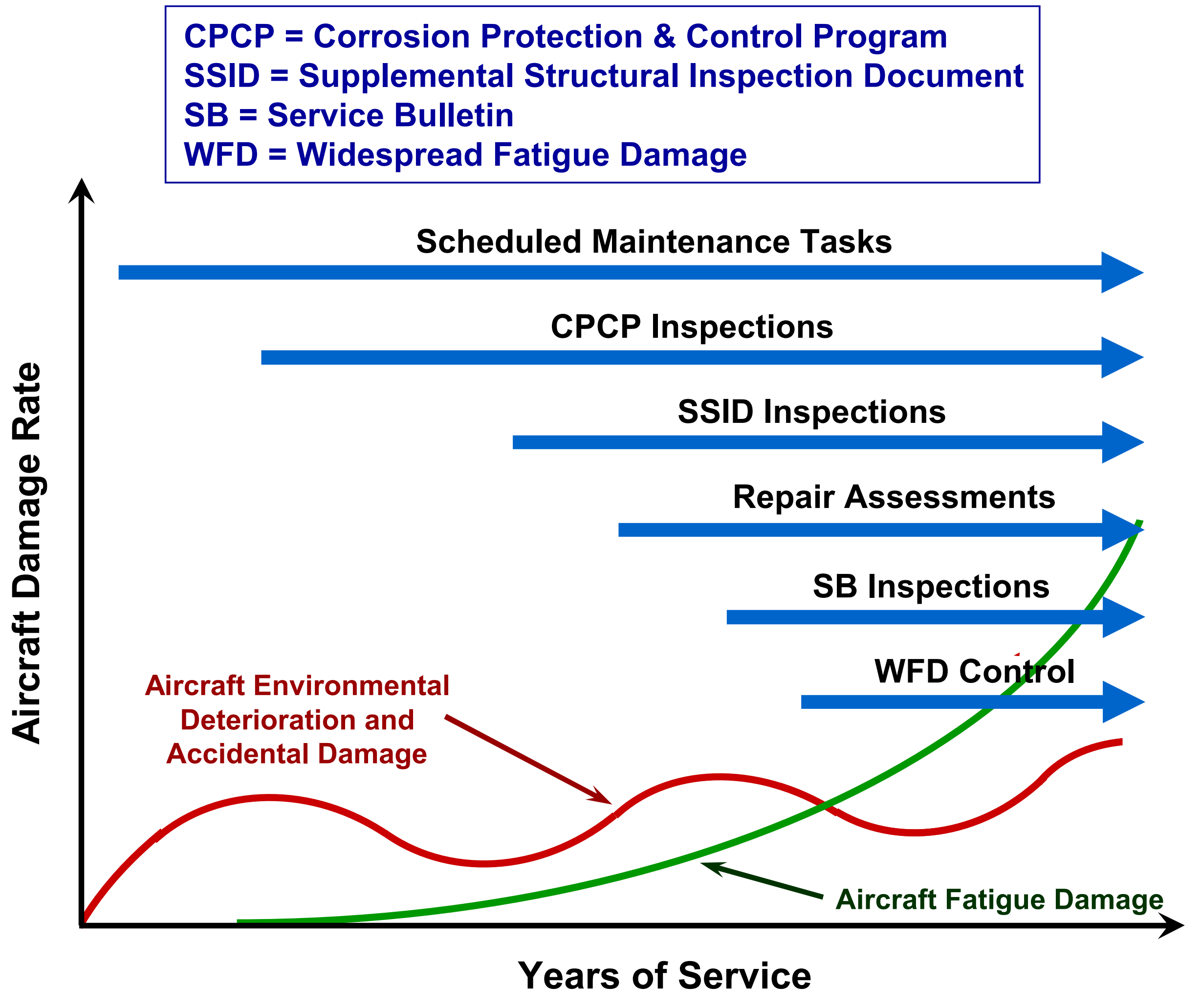
- In order to support the utilization of SHM solutions, the FAA is introducing SHM concepts into its various documents (e.g. MSG-3 document) - provide detailed information on the SHM validation, qualification, certification and utilization.

- SHM systems must demonstrate satisfactory performance (equivalent safety, reliability, flight operation), the ability to meet FAA validation requirements

- FAA regulations & guidance to ensure the safety of commercial aircraft operations: Federal Aviation Regulations (FARs), Advisory Circulars (ACs), Airworthiness Directives (ADs), Continued Operational Safety (COS) documents, Special Airworthiness Information Bulletins (SAIB), FAA Policy Memo, (SSID) (e.g. FAR Part 21 which addresses certification procedures for components, Part 25 which addresses airworthiness standards for aircraft)

  - ADs require recurring maintenance tasks, such as repeat inspections
  - ACs aid aircraft maintenance processes
  - Policy Memos give guidance or provide acceptable practices on how to show compliance with a specific regulation
  - Technical Standard Order establishes the performance requirements for materials, parts & systems on commercial aircraft
  - <u>Alternate Means of Compliance</u> - propose a safe alternative technology; FAA ACOs will have responsibility for AMOC approvals

Introduction of Maintenance Activities During an Airplane's Service Life

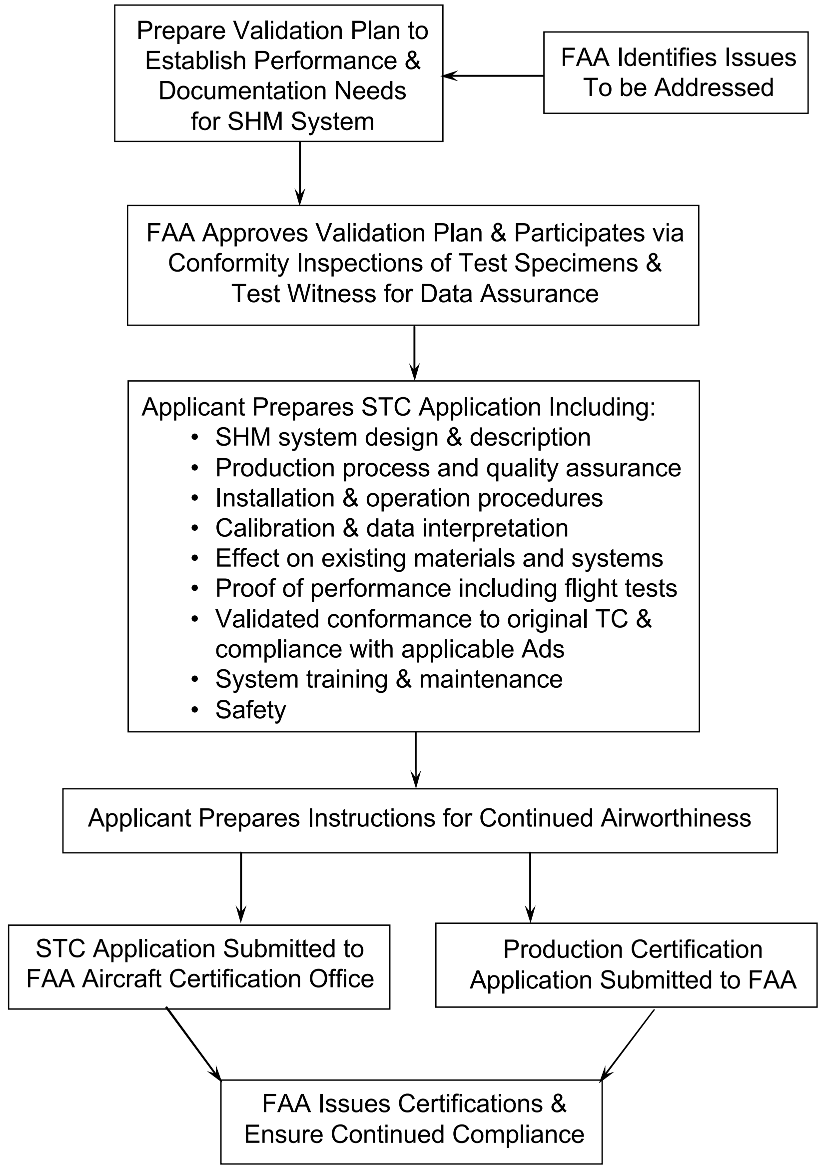


Possible Forms of FAA Guidance on SHM – OEM Interface

- **OEM Supplemental Structural Inspection Documents** – new inspections believed necessary to maintain structural integrity of their aircraft (in past 20 years, Boeing has introduced over 400 inspections through the SSIDs program & over 1,500 additional inspections through Service Bulletins)

- **FAA Designated Airworthiness Representatives (DARs) & FAA Designated Engineering Representatives (DERs)**
  - Personnel who play a role in testing, review, approval and implementation of SHM systems
  - Perform certain certification functions on behalf of the FAA.
  - FAA uses DARs and DERs to address matters related to the examination, testing, and inspection of aircraft parts for the purpose of issuing airworthiness approvals.

Sample Flow of an SHM System Through the Supplemental Type Certificate Process



FAA Guidance on SHM Certification

"*The FAA and Industry Guide to Product Certification*" (Prepared by AIA, GAMA and FAA Aircraft Certification Service, September 2004)

- Maintains the proper working relationship between the FAA and the applicant via Project Specific Certification Plan (PSCP)

- The Guide lists the five phases of certification and their primary deliverables as:
  - *Conceptual Design Phase* – determine certification basis and begin formulating PSCP.
  - *Requirements Definition* – determine critical requirements and means of compliance; establish FAA and applicant team; submit application via FAA Form 8110-12.
  - *Compliance Planning* – conformities, environmental and flight tests.
  - *Implementation* – compete test witnessing and compliance documentation
  - *Post Certification* – determine Airworthiness Limitations and Maintenance and Operations requirements; produce Instructions for Continued Airworthiness.

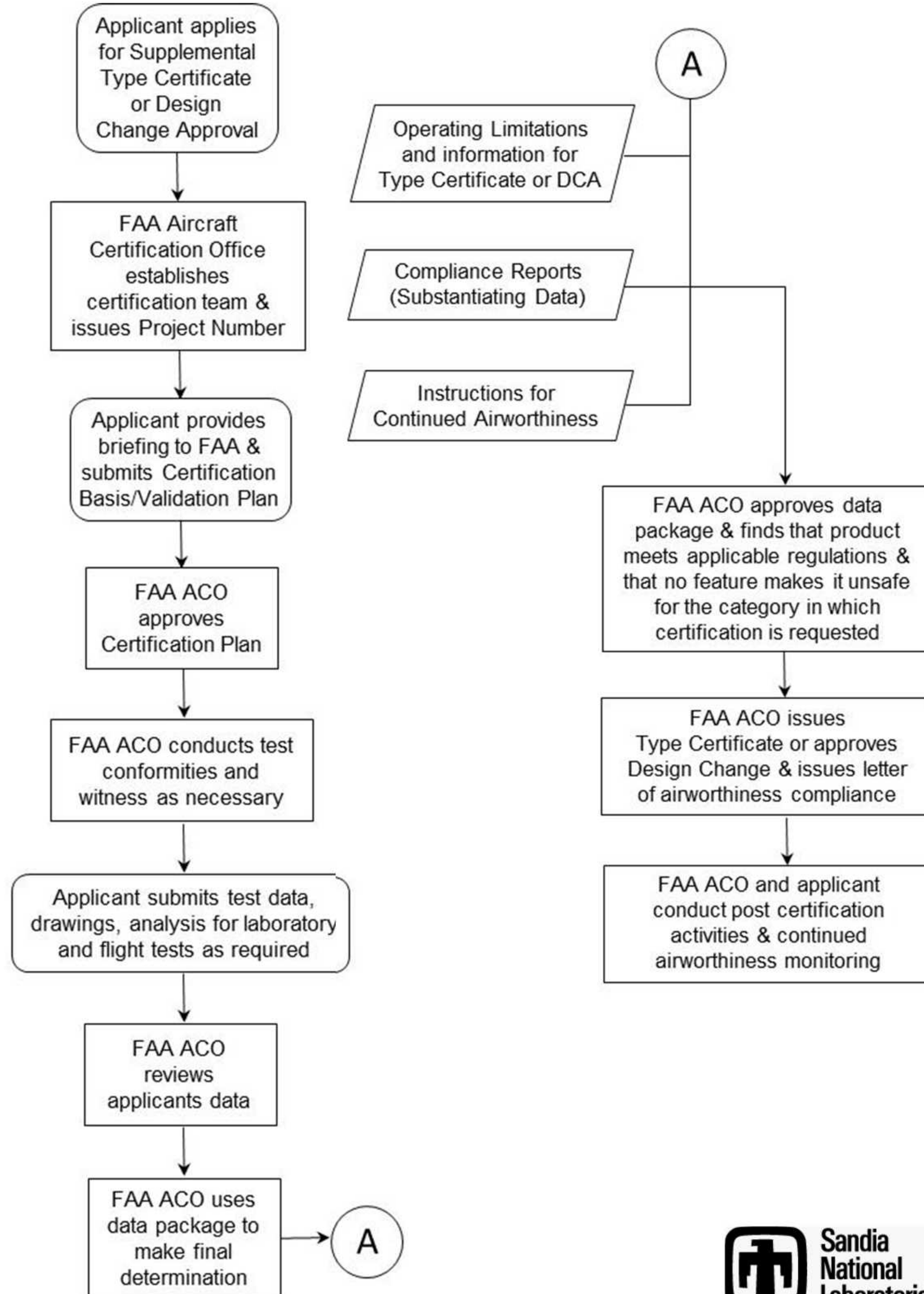
- Key players: applicant, FAA Aircraft Certification Office (ACO) staff, FAA engineers and designees (e.g. TAD), FAA inspectors and designees, FAA Aircraft Evaluation Group (AEG), OEM engineers, and operator staff

- Produce the Certification Document Package to formalize the SHM certification process (e.g. PSCP, ICA, OEM manuals, AMOC, Airworthiness Limitations, STC).

Example of Activities Associated with Movement of New Technology or Design Changes Through the FAA Review and Certification Process

- **Validation requirements are normally established through joint agreements between the FAA and the applicant (OEM input may be solicited)**

- **STC accompanied by Instructions for Continued Airworthiness**



Validation to Approve SHM Usage

- Strong interest in SHM – multitude of applications
- Industry's main concern with implementing SHM on aircraft is achieving a positive cost-benefit & time to obtain approval for SHM usage
- SHM should run in parallel with current NDI inspections for a period of time
- SHM performance – lab & multi-year flight test programs are needed
- SHM training and education - workshops
- AMOC & new SBs– safety driven use is achieved in concert with OEMS & regulatory agencies
- Approval through regulatory framework is the final formality to be addressed - standardization and guidelines have been initiated for certification and field validation

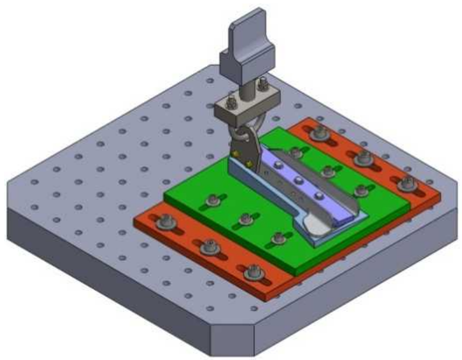
Validation of SHM Capability – Certification for Use

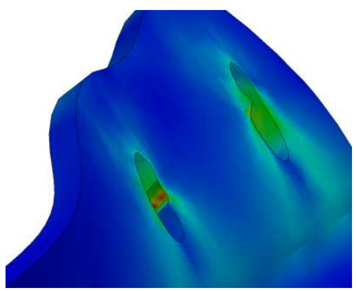
Laboratory Tests

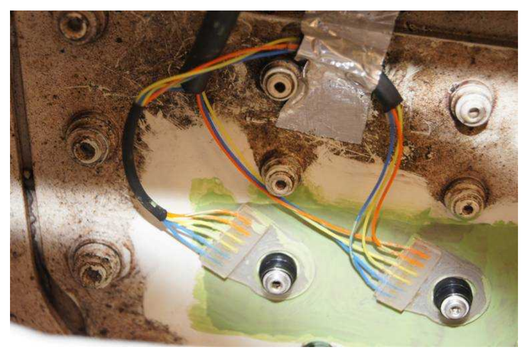
- Quantify performance
- Environmental/durability
- POD – statistically relevant evaluation
- Reliability/repeatability

Flight Tests

- Incomplete response statistics – lack of damage
- Deployed with airlines
- Need suite of monitoring data points (how many?, access to aircraft)
- Establish ability of current tech base to properly deploy SHM
- Establish ability of maintenance program to adopt SHM – admin obstacles

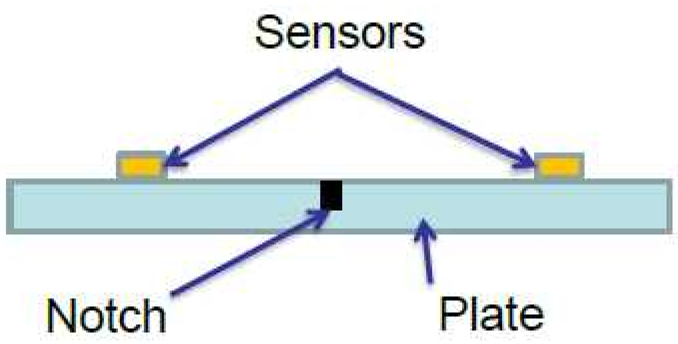






Validation with Representative Complexity

Required to translate laboratory success (performance assessment) to operational environment



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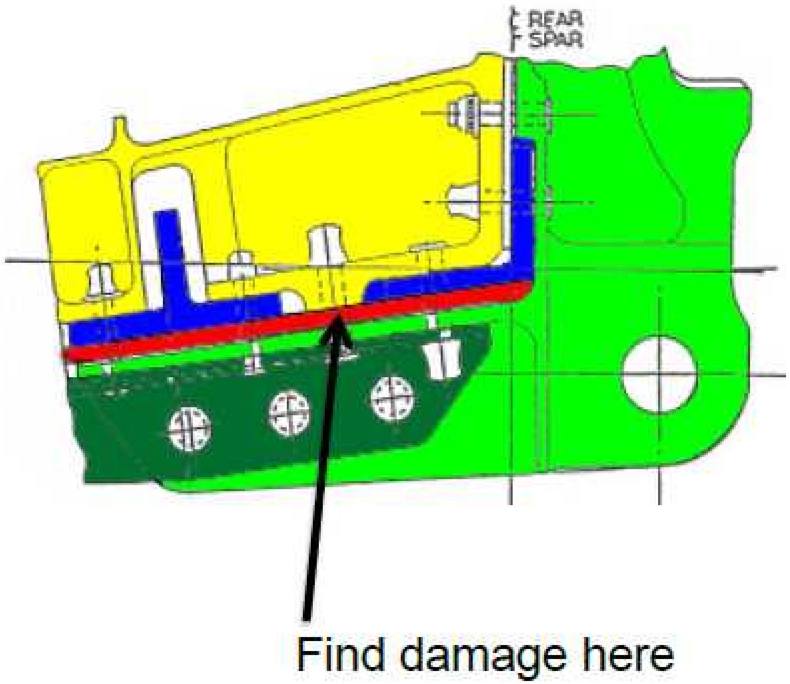
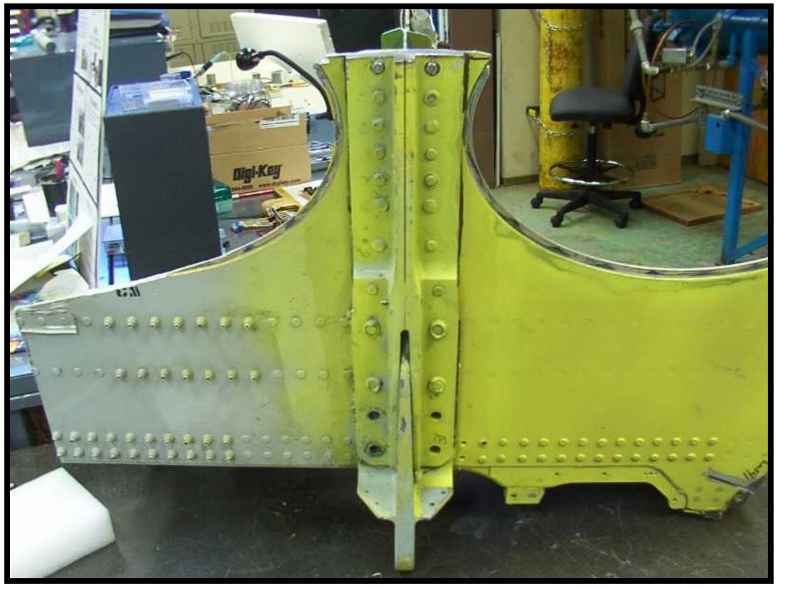


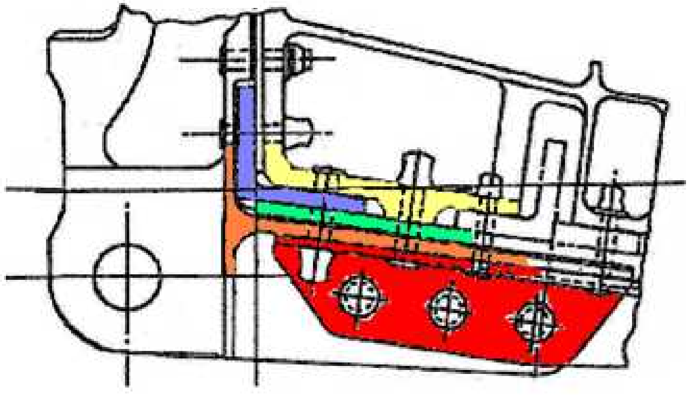
- Courtesy of Eric Lindgren, AFRL

Use of Validation Assemblies

- Degree of complexity in performance testing depends upon part configuration, load type(s), etc. associated with introduction of damage to be detected
- Environmental effects
- Normal and abnormal load considerations (e.g. impact damage)



Aft-left wing attachment fitting



Joint cross-section with various layers (aluminum and steel) highlighted

Part 2 – SHM Performance Assessment

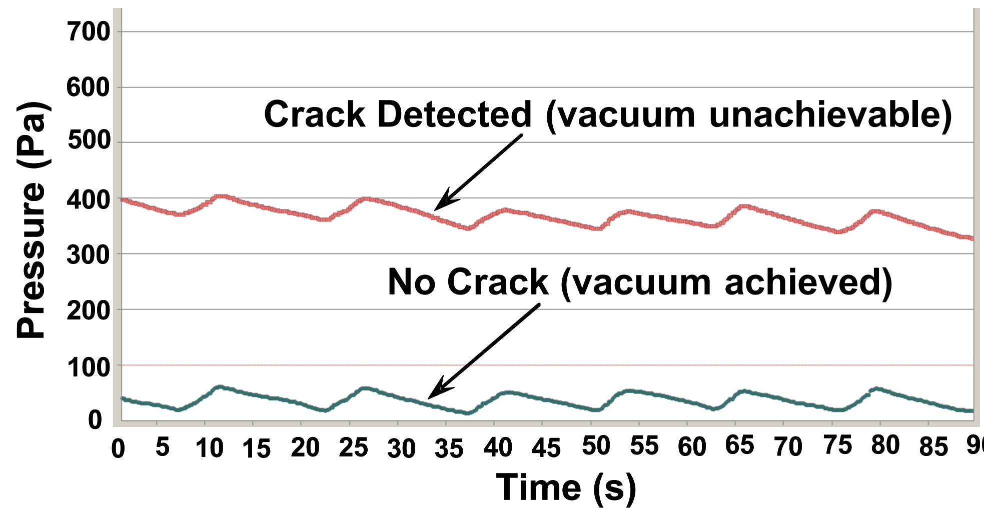
A.) Performance Assessment Methodology (POD) – Reliability & Sensitivity

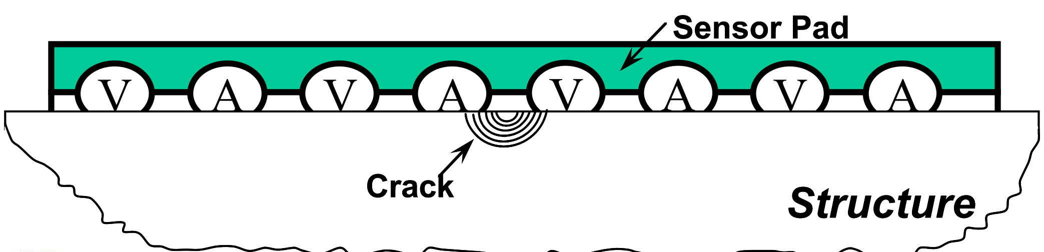
B.) SHM Performance Testing – General Fuselage Skin Crack Detection (CVM) for Modification to NDI Standard Practices Manual

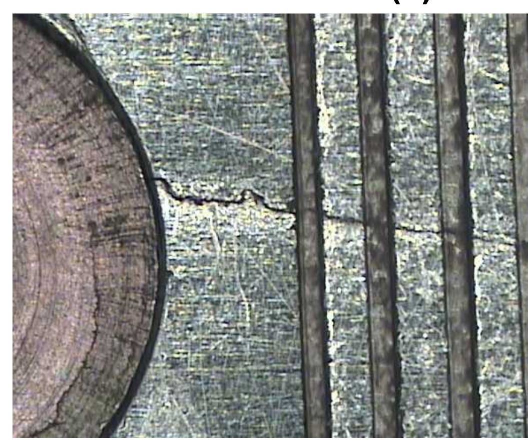
C.) SHM Performance Testing – Specific 737 Wing Box Fitting Application (CVM) for AMOC to Service Bulletin

Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries
- Leakage path produced by a growing crack produces a measurable change in the vacuum level
- Doesn't require electrical excitation or couplant/contact

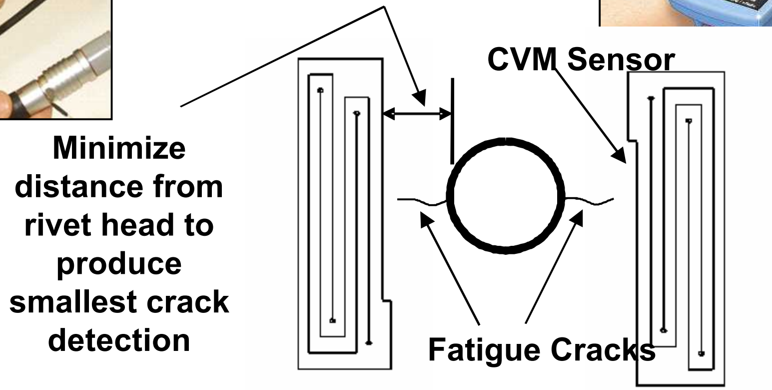


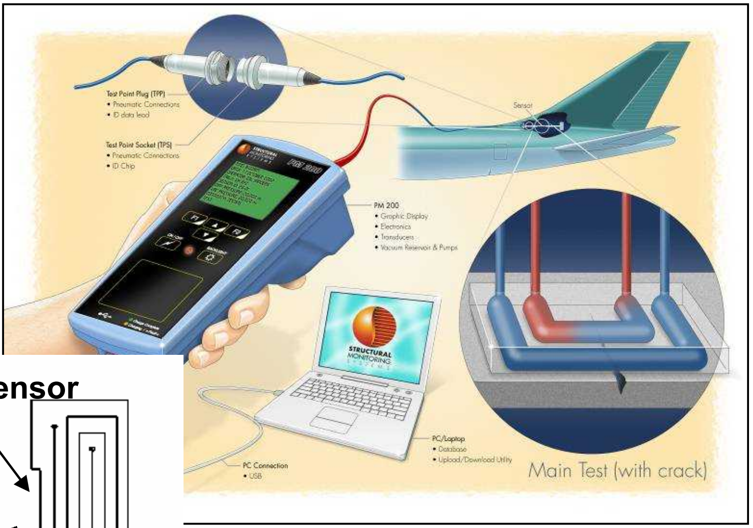




Drivers for Application of CVM Technology

- Overcome accessibility problems; sensors ducted to convenient access point
- Improve crack detection (easier & more often)
- Real-time information or more frequent, remote interrogation
- Initial focus – monitor known fatigue prone areas
- Long term possibilities – distributed systems; remotely monitored sensors allow for condition-based maintenance





Validation of Comparative Vacuum Monitoring for On-Aircraft (In-Situ) Damage Detection

- FAA's Airworthiness Assurance NDI Validation Center (AANC) at Sandia Labs, in conjunction with Boeing, Structural Monitoring Systems, and multiple, interested airlines has conducted a long-term research program to develop and validate Comparative Vacuum Monitoring (CVM) Sensors for crack detection.

- AANC's validation approach is designed to address the equipment, the inspection task, the resolution required, the inspection procedures, the conditions under which the inspection will occur

- Some of the methodology to quantify NDI performance can be adapted to the validation of SHM systems.

- Initial goal - to provide Boeing Commercial Aircraft with sufficient data to place CVM sensor technology into the Nondestructive Testing Standard Practices Manual.

Validation of Comparative Vacuum Monitoring for On-Aircraft (In-Situ) Damage Detection

- Multi-year field tests were also conducted to study the deployment and long-term operation of CVM sensors on aircraft.
- Follow-on effort looked at the application of SHM solutions to a particular aircraft application - detect cracks in the wing box fitting of a Boeing 737 aircraft.
- Validation process: 1) produced a quantitative performance assessment of the SHM system and, 2) teaming between the airlines, aircraft manufacturers, regulators, and related SHM development and research agencies to ensure that all airworthiness concerns have been properly addressed.

Types of Utilization Considered for CVM on Regional Jets

1 - Maintenance Planning

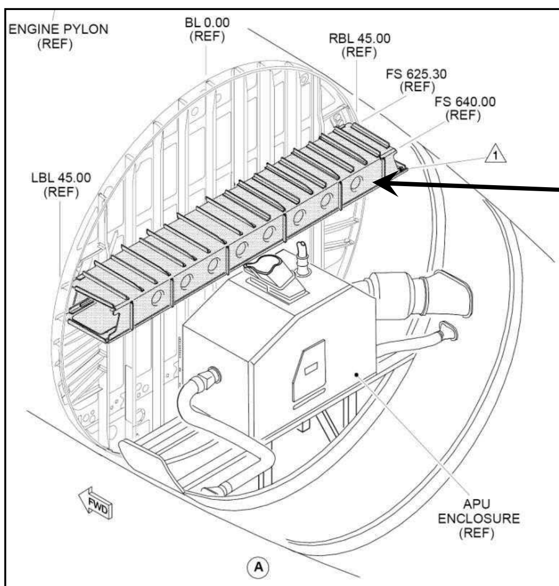
- Objective
  - Provide an early indication of a flaw to schedule a repair instead of only an inspection
- Benefit
  - Reduce the rate of aircraft grounded after an inspection by scheduling repairs in advance
- Process
  - Maintain all current processes to meet applicable maintenance requirements
  - Perform a CVM measurement at a reasonable time prior the scheduled inspection task
- Airworthiness Impact
  - No airworthiness claim for the method required
  - Approval required for process proposed

2 - Maintenance Credit

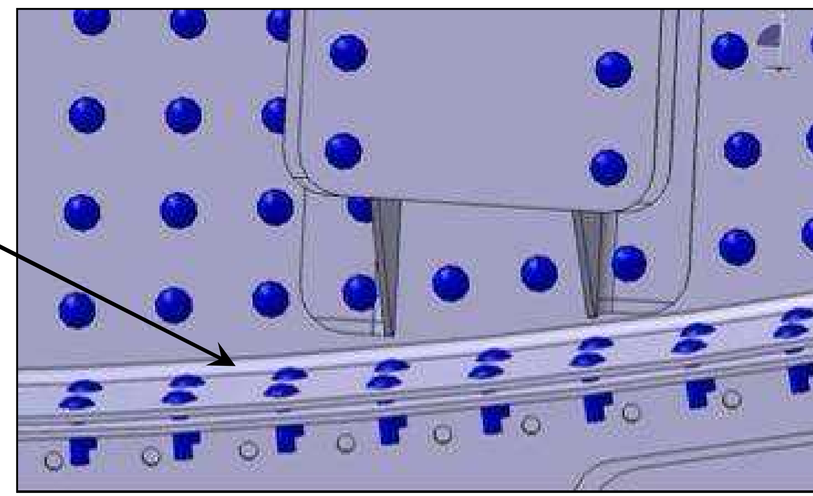
- Objective
  - Meet the inspection requirements of a Principal Structural Element (PSE) with CVM
- Benefit
  - Reduce maintenance costs associated with the inspection tasks
  - Increase threshold and repeat intervals for Fatigue Driven PSEs.
- Process
  - Perform CVM measurements as an alternate method of inspection
- Airworthiness Impact
  - Certification of the method required

SHM Selection Process/Criteria

- **All NDI tasks were reviewed (more than 100)**
- **Criteria**
  - Required Detectable Crack Size
  - Area to Inspect
  - Cracking Scenarios
  - Inspection Interval
  - Operational Benefit
  - Baseline Cost (Access, Preparation, Inspection, Close-Out)
  - Type of Structure (Material, Geometry)
  - Capability to Maintain Current Applicable Tasks

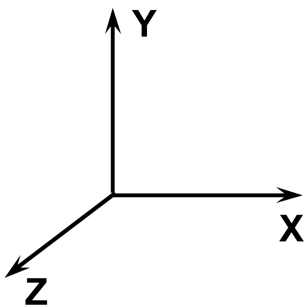


Inspect in the radius

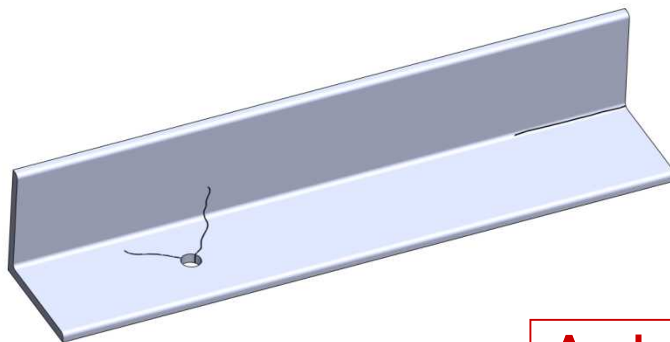


Reliability Assessment for Simple and Complex SHM Solutions

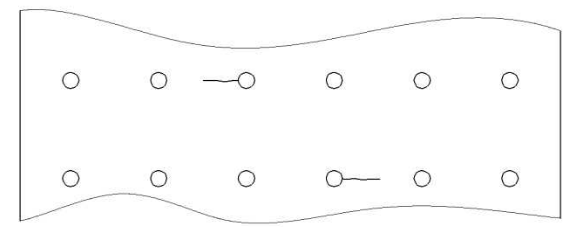
Complex Flaw Orientation



A. Crack with multiple growth paths in complex geometry

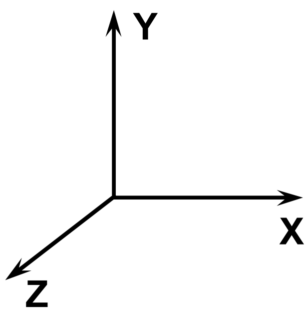


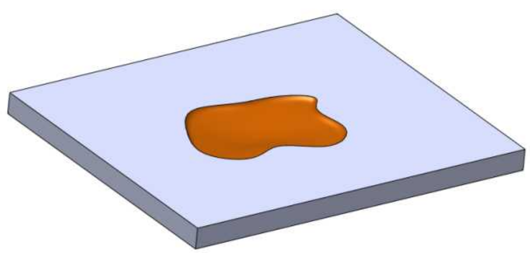
B. Crack with single, known crack direction in simple geometry



Analysis for one-dimensional entity simplifies significantly

Complex Flaw Profile

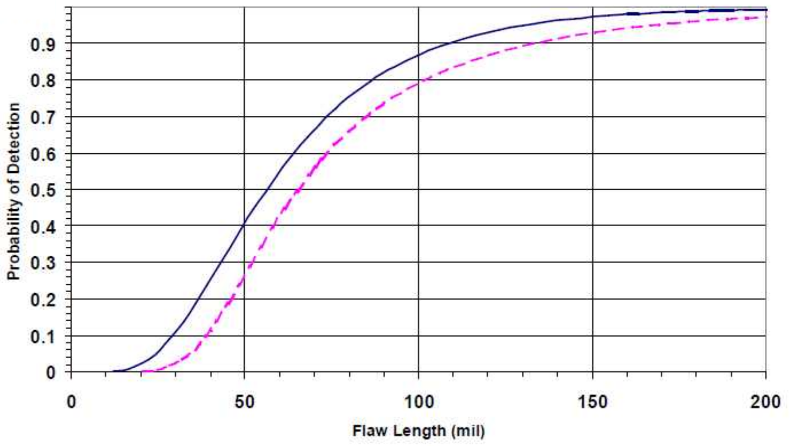




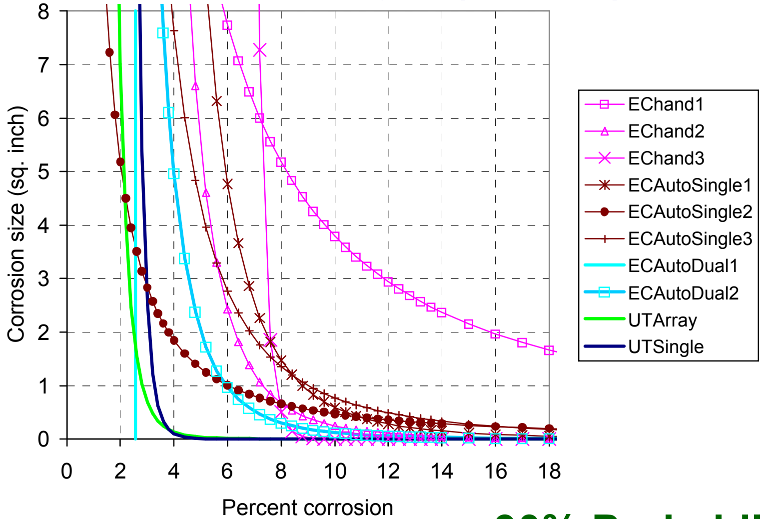
Example: corrosion size, shape and depth variations

Presenting NDI POD Values for Different Flaw Geometries

Lap Splice Fatigue Cracks



Interlayer (Hidden) Corrosion



90% Probability of Flaw Detection Contours

POD Assessment Using One-Sided Tolerance Interval

- SHM reliability calculations will depend greatly on the complexity of the structure and geometry of the flaw profile
  - corrosion damage has a widely-varying flaw shape, both in the surface dimensions and in the changing depth
  - fatigue crack that grows in a known propagation path such that the damage scenario can be described in a single parameter: crack length

- For cracks, the one-dimensional entity allows for a direct calculation using the One-Sided Tolerance Interval (OSTI) approach.

- The OSTI estimates the upper bound which should contain a certain percentage of all measurements in the population with a specified confidence.

- Because of physical, time or cost constraints, it is often impractical to inspect an entire population - a small sample of the total population is tested and the data is used to gauge how well the entire population conforms to specifications.

- The data captured is that of the flaw length at the time for which the SHM system provided sustainable detection.

POD Assessment Using One-Sided Tolerance Interval

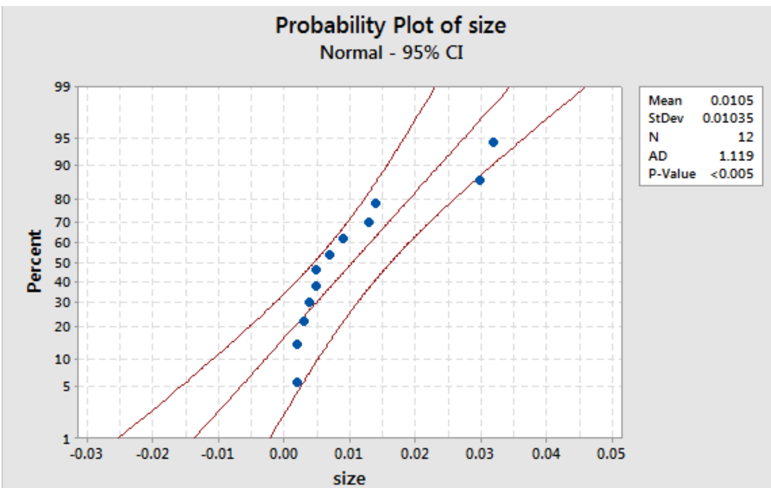
- **Interval to cover a specified proportion of a population distributed with a given confidence – related to measures of process capability**
- **One-sided Tolerance Interval – estimates the upper bound which should contain a certain percentage of all measurements in the population with a specified confidence**
- **Since it is based on a sample of the entire population (n data points), confidence is less than 100%. Thus, it includes two proportions:**
  - **Percent coverage (90%)**
  - **Degree of confidence (95%)**
- **The reliability analysis becomes one of characterizing the distribution of flaw lengths and the cumulative distribution function is analogous to a Probability of Detection (POD) curve:**

$$TI = X \pm (K_{n,\gamma,\alpha})(S) \qquad \text{[log scale calculation]}$$

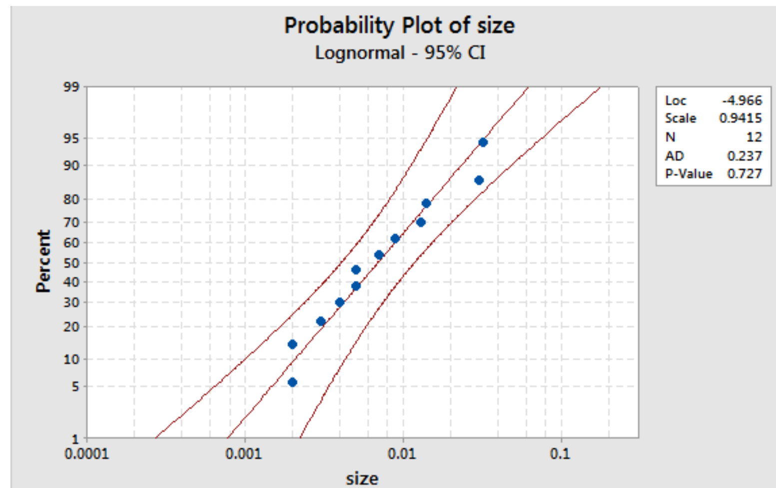
- **Interested in a 1-tailed interval (utilize "+" in equation); upper limit of TI. Uncertainty in knowing the true mean and population variance requires that the estimate of the range of values encompassing a given percentage of the population must increase to compensate.**

POD Assessment Using One-Sided Tolerance Interval

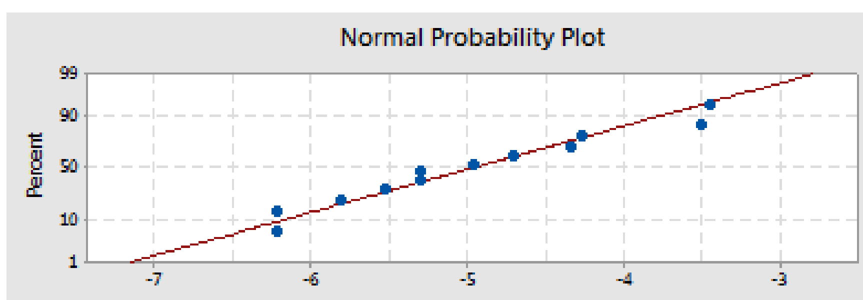
- Assume that the distribution of flaws is such that the logarithm of the lengths (strictly positive sizes) has a Gaussian distribution (log-normal distribution)
- Validity depends on distribution on the flaw lengths at which detection is first made – lognormal distribution plots on straight line with data clustered near 50th percentile
- Anderson-Darling test requires P-value > 0.05



Normal Distribution



Lognormal Distribution



Normal plot of log values of data

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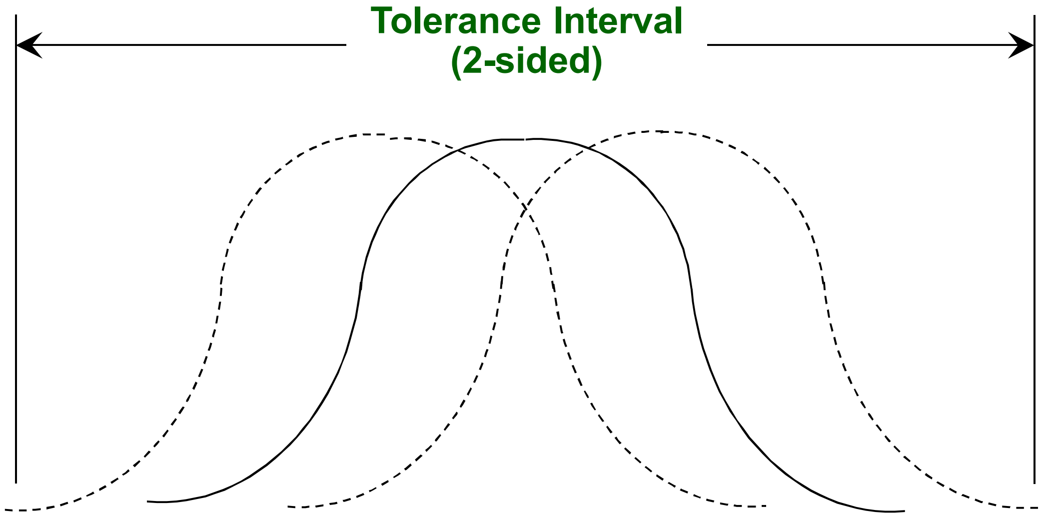
POD Assessment Using One-Sided Tolerance Interval

- Used to indicate values at which certain compliance is met
- Capability of the process is determined not only by the location of the sample mean but also by the tail areas of the distribution
- EPA recommends at least 8 points to calculate TI (vs. 51 flaws in a binary data POD) – gage entire population from a small sampling



Solid Line = Population Distribution
Dotted Line = Uncertainty of Population Mean

$\overline{X}$

CVM Validation – Data Analysis Using One-Sided Tolerance Intervals

- Crack detection based on PM-200 “Green Light” – “Red Light” results
- Data captured is the crack length at the time when CVM provided permanent (unloaded) detection
- Reliability analysis – cumulative distribution function provides maximum likelihood estimation (POD)
- One-sided tolerance bound for various flaw sizes:

$$POD_{95\%\ Confidence} = \overline{X} + (K_{n,\ 0.95,\ \alpha})\ (S)$$

X = Mean of detection lengths

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

S = Standard deviation of detection lengths

n = Sample size

α = Detection level

γ = Confidence level

POD Calculations - One-Sided Tolerance Interval

POD Determined from CVM Response Data

CVM Crack Detection Data (0.040” th)

Bare Metal		Over Primer	
Flaw size (inch)	Log (flaw size)	Flaw size (inch)	Log (flaw size)
0.003	-2.52	0.002	-2.70
0.007	-2.15	0.007	-2.15
0.002	-2.70	0.010	-2.00
0.030	-1.52	0.009	-2.05
0.009	-2.05	0.004	-2.40
0.005	-2.30	0.006	-2.22
0.004	-2.40	0.010	-2.00
0.002	-2.70	0.009	-2.05
0.014	-1.85	0.011	-1.96
0.005	-2.30	0.007	-2.15
0.013	-1.89		
0.032	-1.49		

Statistic Estimates on Log Scale

Statistic	Over Bare metal	Over Primer
Mean	-2.1566	-2.1679
Stnd deviation	0.40889	0.22809

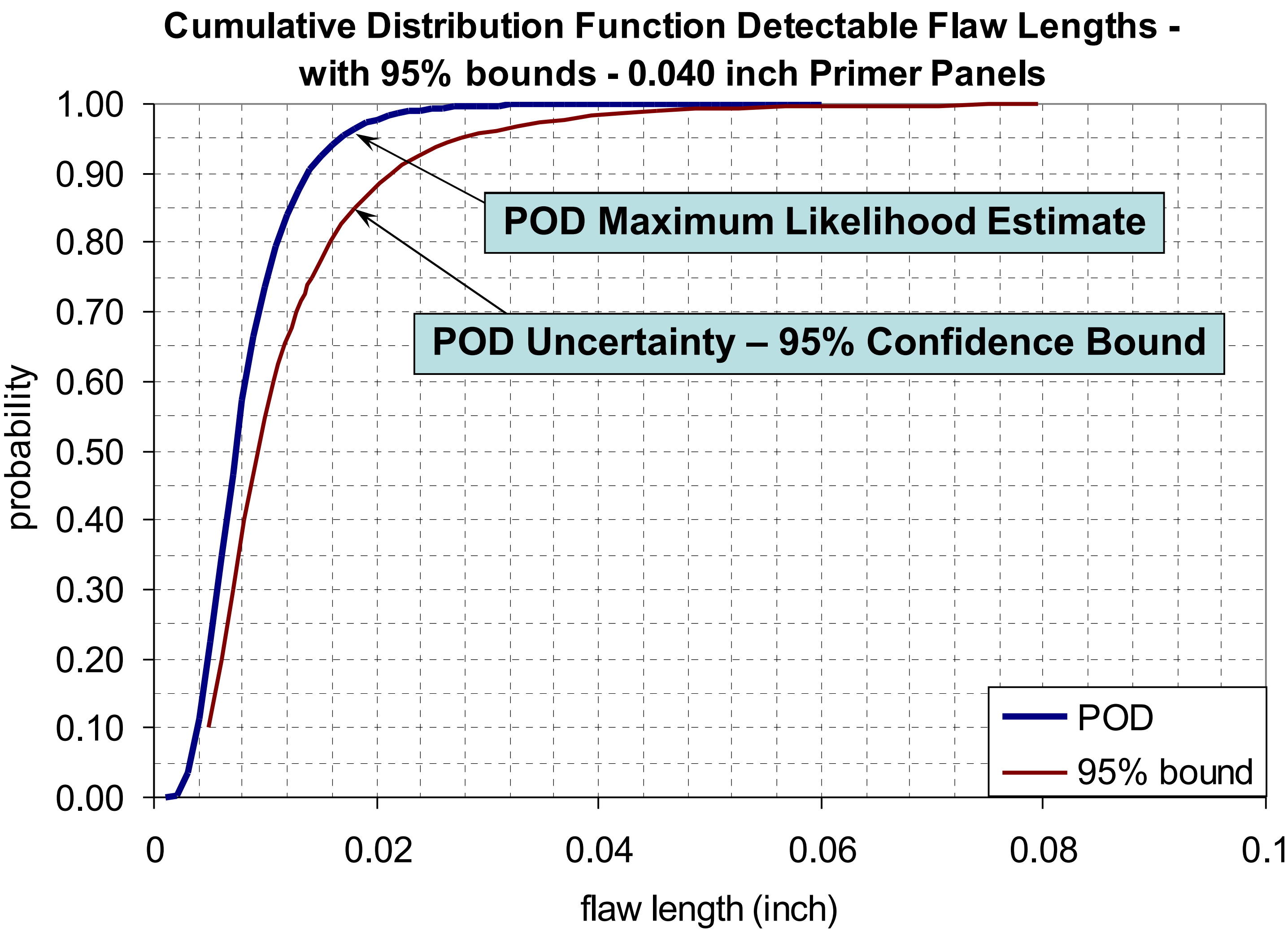
POD Detection Levels
(ɣ = 95%, n = 12 for bare, n=10 for primer)

Detection level $(1-\alpha)$	$K_{n,0.95,\alpha}$		$\bar{X} + K_{n,0.95,\alpha} \cdot S$ (log scale)		Flaw size in inches	
	bare	primer	bare	primer	bare	primer
0.75	1.366	1.465	-1.598	-1.834	0.025	0.015
0.90	2.210	2.355	-1.253	-1.631	0.056	0.023
0.95	2.736	2.911	-1.038	-1.504	0.092	0.031
0.99	3.747	3.981	-0.624	-1.260	0.237	0.055
0.999	4.900	5.203	-0.153	-0.981	0.703	0.104

$$\text{POD}_{\text{(Max Likelihood Est)}} = \frac{1}{xS\sqrt{2\pi}} \, EXP\left(\frac{-(ln(x)-\bar{X})^2}{2S^2}\right)$$

It is possible to calculate a one sided tolerance bound for various percentile flaw sizes - find factors $K_{n,\gamma,\alpha}$ to determine the confidence ɣ such that at least a proportion (α) of the distribution will be less than *X* + ($K_{n,\gamma,\alpha}$)S where *X* and *S* are estimators of the mean and the standard deviation computed from a random sample of size *n*

Sample Probability of Detection Curves for CVM



Part 2 – SHM Performance Assessment

A.) Performance Assessment Methodology (POD) – Reliability & Sensitivity

B.) SHM Performance Testing – General Fuselage Skin Crack Detection (CVM) for Modification to NDI Standard Practices Manual

C.) SHM Performance Testing – Specific 737 Wing Box Fitting Application (CVM) for AMOC to Service Bulletin

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

Laboratory and Field Evaluation Program for the Purposes of Including Usage of CVM as an Option in the Boeing NDT Standard Practices Manual

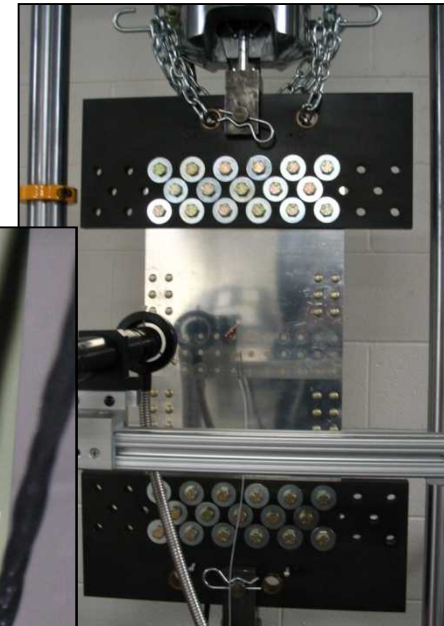
This was the first CVM Validation Program (Phase 1) and was intended to establish the overall capability of CVM sensors such that CVM technology could be included in Boeing's NDT "tool box" (NDT Standard Practices Manual). The testing was designed to establish the ability of CVM sensors to detect cracks in fuselage skin structure and to determine the limits on skin thickness applications so that a crack of 0.10" length could be reliably detected. The end result of the laboratory and flight testing was that Boeing's NDT Standard Practices Manual was revised to include CVM sensors as a possible structural monitoring option.

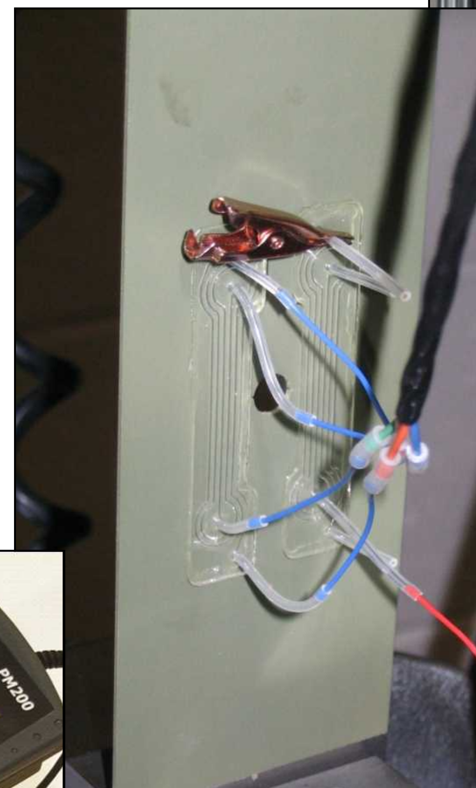
Team: Jeff Kollgaard, John Linn – Boeing, Seattle; Masood Zaidi – Boeing, Long Beach; Dennis Roach, Floyd Spencer – Sandia Labs FAA AANC; John Bohler, Dave Piotrowski, Alex Melton – Delta Air Lines; Dave Galella – FAA; Kyle Colavito, Erdrogan Madenci – Univ. of Arizona

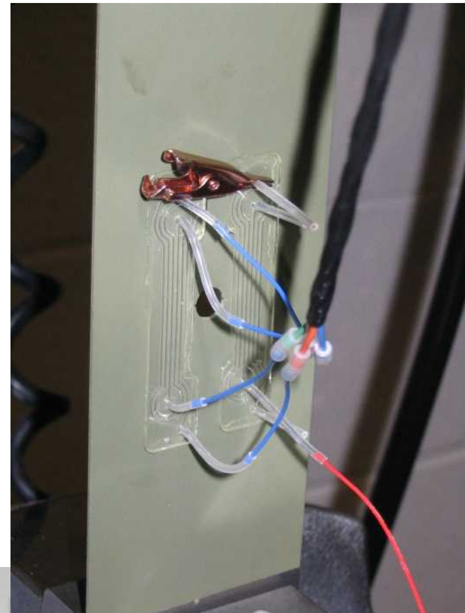
Test Matrix to Quantify Probability of Crack Detection

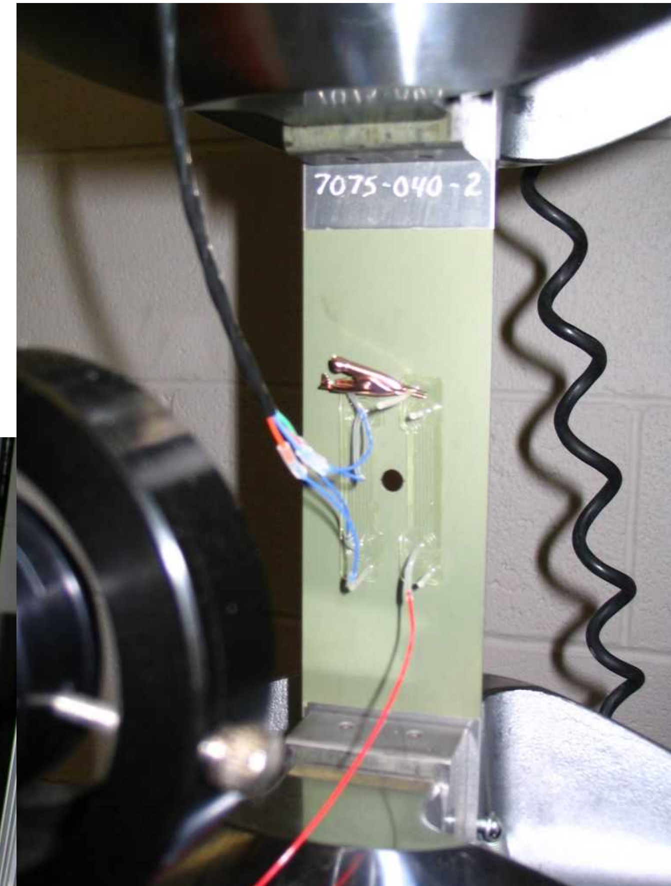
Test Scenarios:

Material	Thickness	Coating
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





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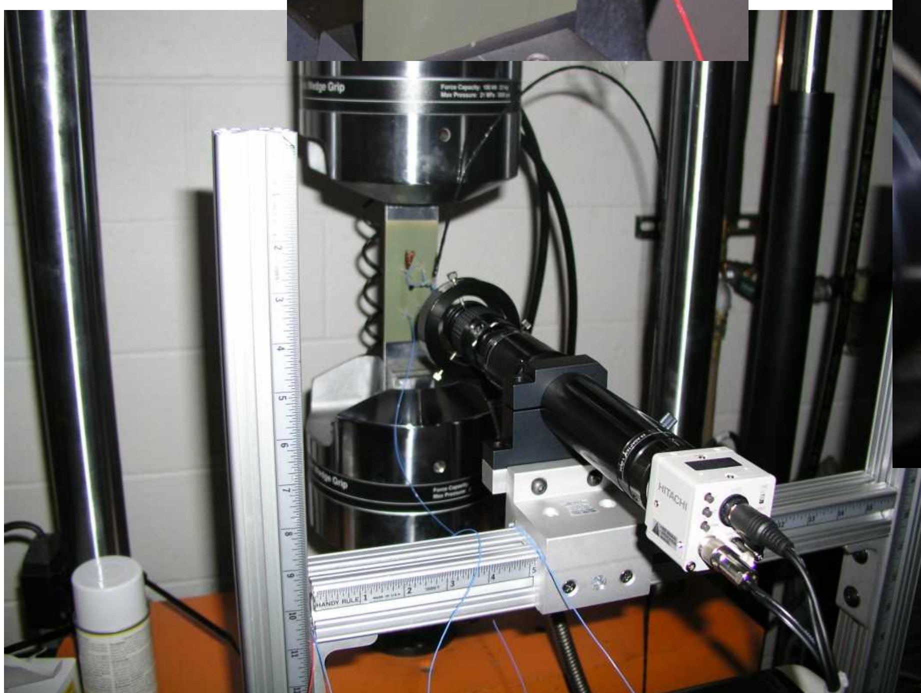

HITACHI

CVM Validation - Crack Detection Results

All POD levels listed are for 95% confidence

2024-T3 Alum.

Description: 0.040 inch thick panel (primer surface)

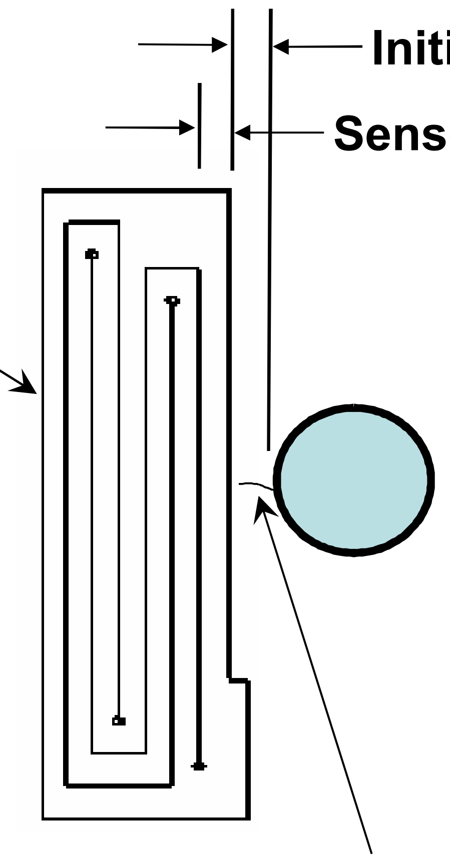
PHASE 2 TESTS						
Panel	**Fastener Crack Site**	**Distance from Fastener (inches)**	**Crack Length at CVM Detection (growth after install in inches)**	**SIM-8 Reading ∆Pa (Pasm)**	**PM-4 Read-out**	**PM-4 Indicate Crack (Y or N)**
4018	5R	0.040	0.002	400-500	1607	Y
4018	6R	0.014	0.007	1700-1800	2847	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

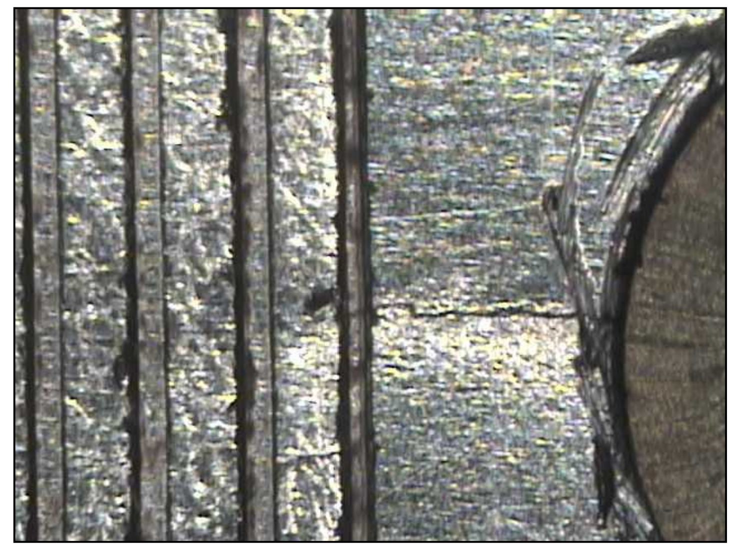
90% POD Level	False Calls
0.021"	0

No false calls experienced in over 150 fatigue crack detection tests

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

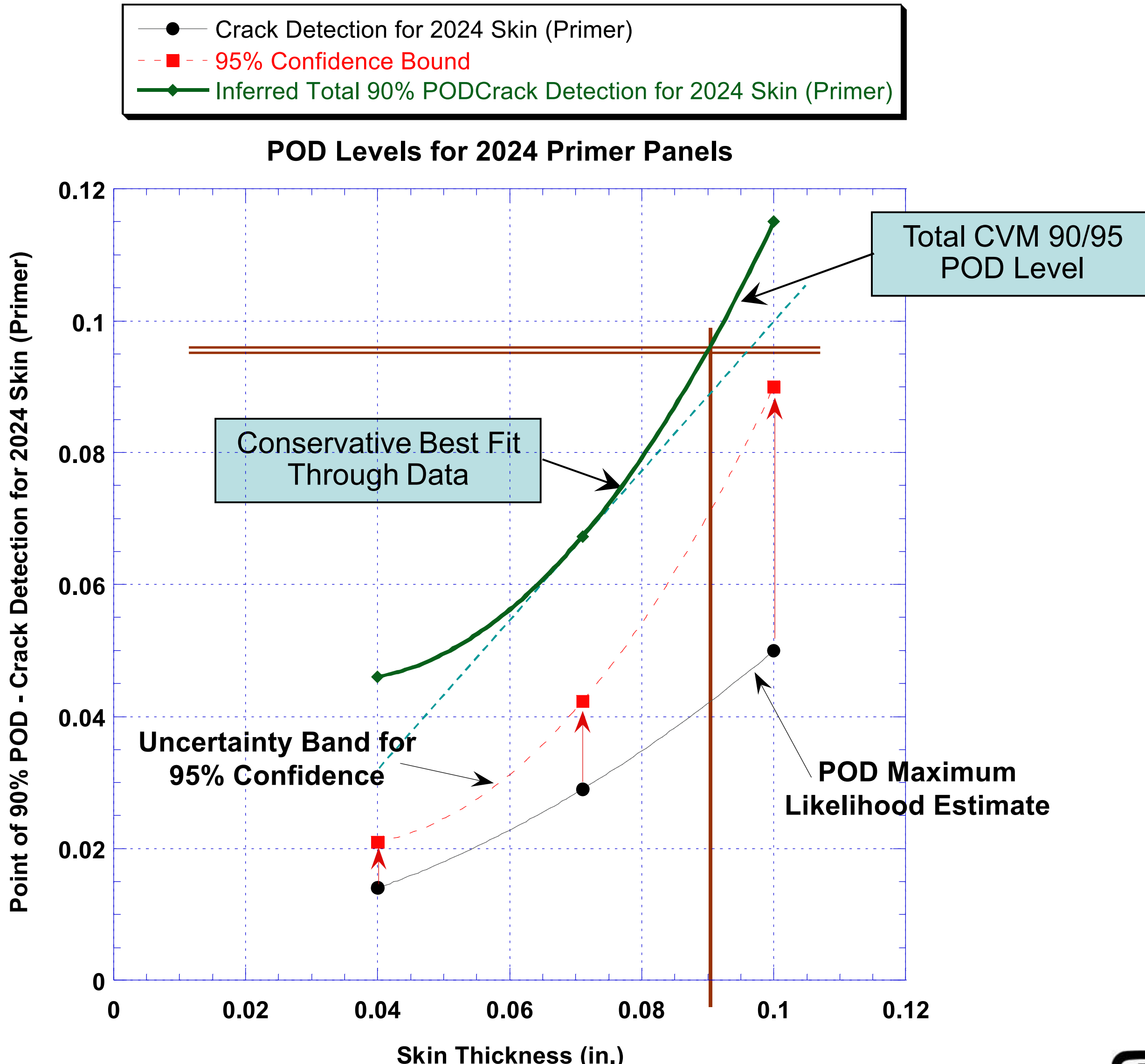
Determining Final CVM Crack Detection Level from Crack "Lag" Values





Total Crack Length at Detection = CVM Lag Detection + 0.014" + 0.010"

Overall Probability of Detection Values as a Function of Material Thickness



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CVM Validation - Crack Detection Results (cont.)

All POD levels listed are for 95% confidence

Description: 0.071 inch thick panel (primer surface)

PHASE 3 TESTS					
Panel	**Fastener Crack Site**	**Number of Fatigue Cycles**	**Crack Length at CVM Detection (growth after install in inches)**	**PM-4 Read-out (Pasm)**	**PM-4 Indicate Crack (Y or N)**
1	1-L	2600	0.008	1439	Y
1	1-R	2500	0.007	1341	Y
1	2-L	4100	0.014	1411	Y
1	2-R	3900	0.011	1484	Y
2	1-L	3800	0.012	1825	Y
2	1-R	3500	0.017	2056	Y
2	2-L	4800	0.003	2618	Y
2	2-R	5000	0.005	2634	Y
2	3-L	5900	0.007	4142	Y
2	3-R	6100	0.003	6012	Y
4	1-L	3500	0.004	1589	Y
4	1-R	3400	0.013	1706	Y
4	2-L	5600	0.007	3035	Y
4	2-R	5600	0.027	2734	Y
4	3-L	6400	0.003	2778	Y
4	3-R	6400	0.020	11380	Y

90% POD Level	False Calls
0.033"	0

7075-T6 Alum.

[all panels are 7075-T6 alum.]

Overall Probability of Detection Values for General CVM Validation – Fuselage Skin Structure

Material	Plate Thickness (mm)	Coating	90% POD for Crack Detection (mm)
2024-T3	1.02	Bare	1.24
2024-T3	1.02	Primer	0.53
2024-T3	1.80	Primer	1.07
2024-T3	2.54	Bare	6.91
2024-T3	2.54	Primer	2.29
7075-T6	1.02	Primer	0.66
7075-T6	1.8	Primer	0.84
7075-T6	2.54	Primer	0.58

Summary of Crack POD Levels for CVM Deployed on Different Materials, Surface Coatings, and Plate Thicknesses

Part 2 – SHM Performance Assessment

A.) Performance Assessment Methodology (POD) – Reliability & Sensitivity

B.) SHM Performance Testing – General Fuselage Skin Crack Detection (CVM) for Modification to NDI Standard Practices Manual

C.) SHM Performance Testing – Specific 737 Wing Box Fitting Application (CVM) for AMOC to Service Bulletin

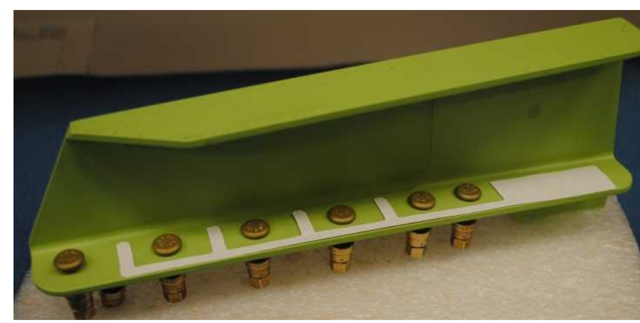
SHM Certification & Integration Activity

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

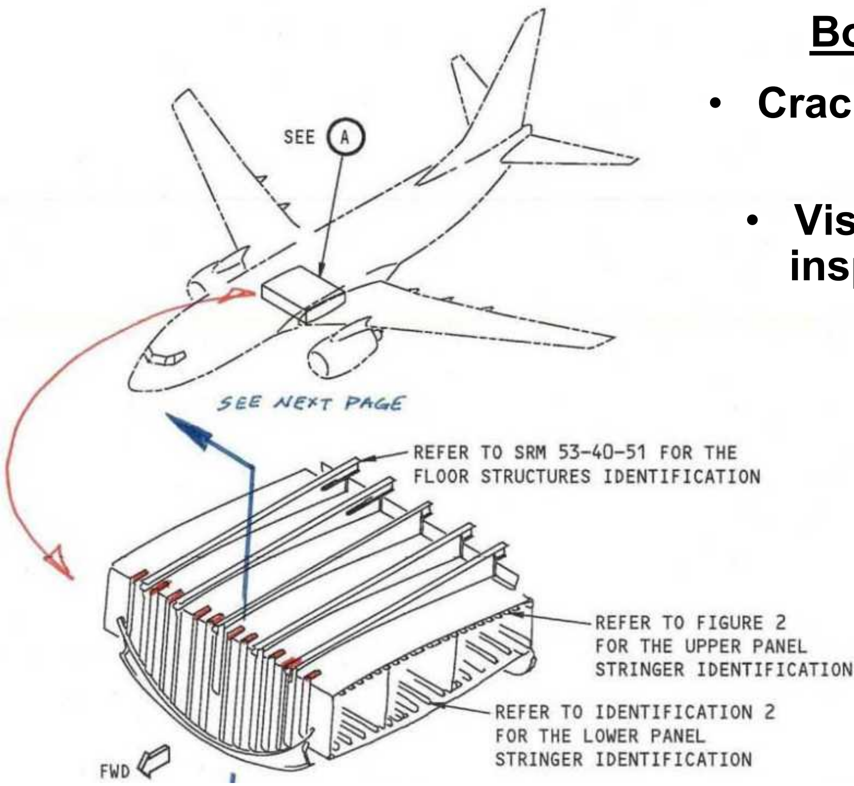
- Certification/usage effort intended to exercise and evolve the SHM certification path – address all "cradle-to-grave" issues
- Identify SHM applications – assess positive cost-benefit analysis
- Customize SHM system to the selected application(s)
- Develop validation/certification plan – serve as the 'blueprint' for the industry to follow (OEMs, airlines, MROs, regulatory agencies, vendors and academia)
- 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

CVM Sensor Network Applied to 737 Wing Box Fittings

Alternate Means of Compliance with Current Visual Inspection Practice

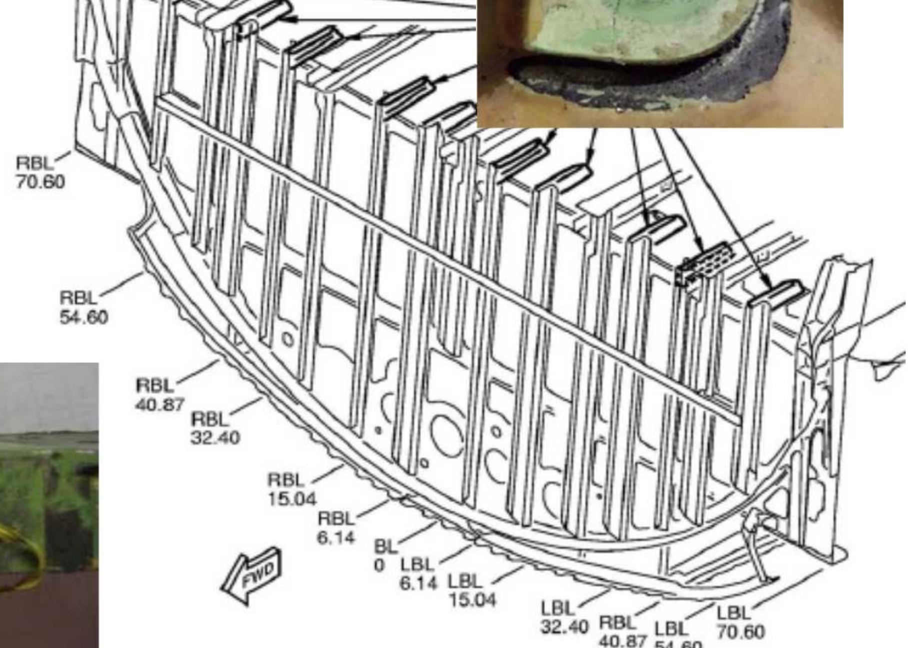


737NG Center Wing Box, Front Spar Shear Fitting



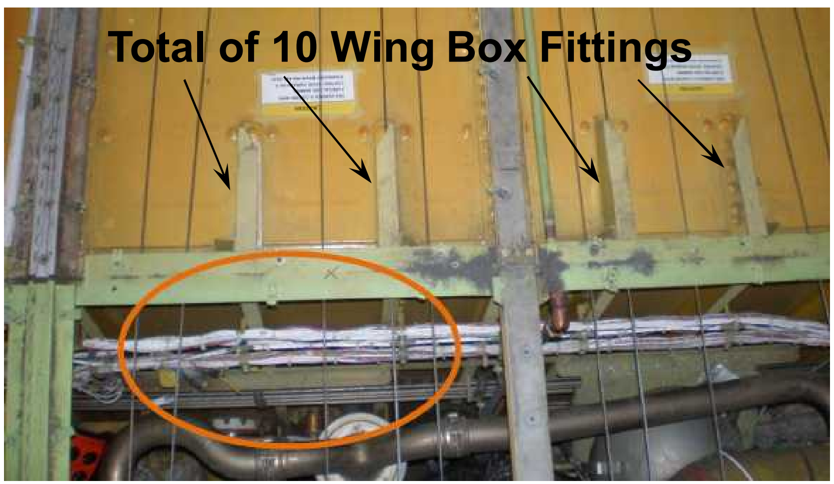
Boeing 737 SB:

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

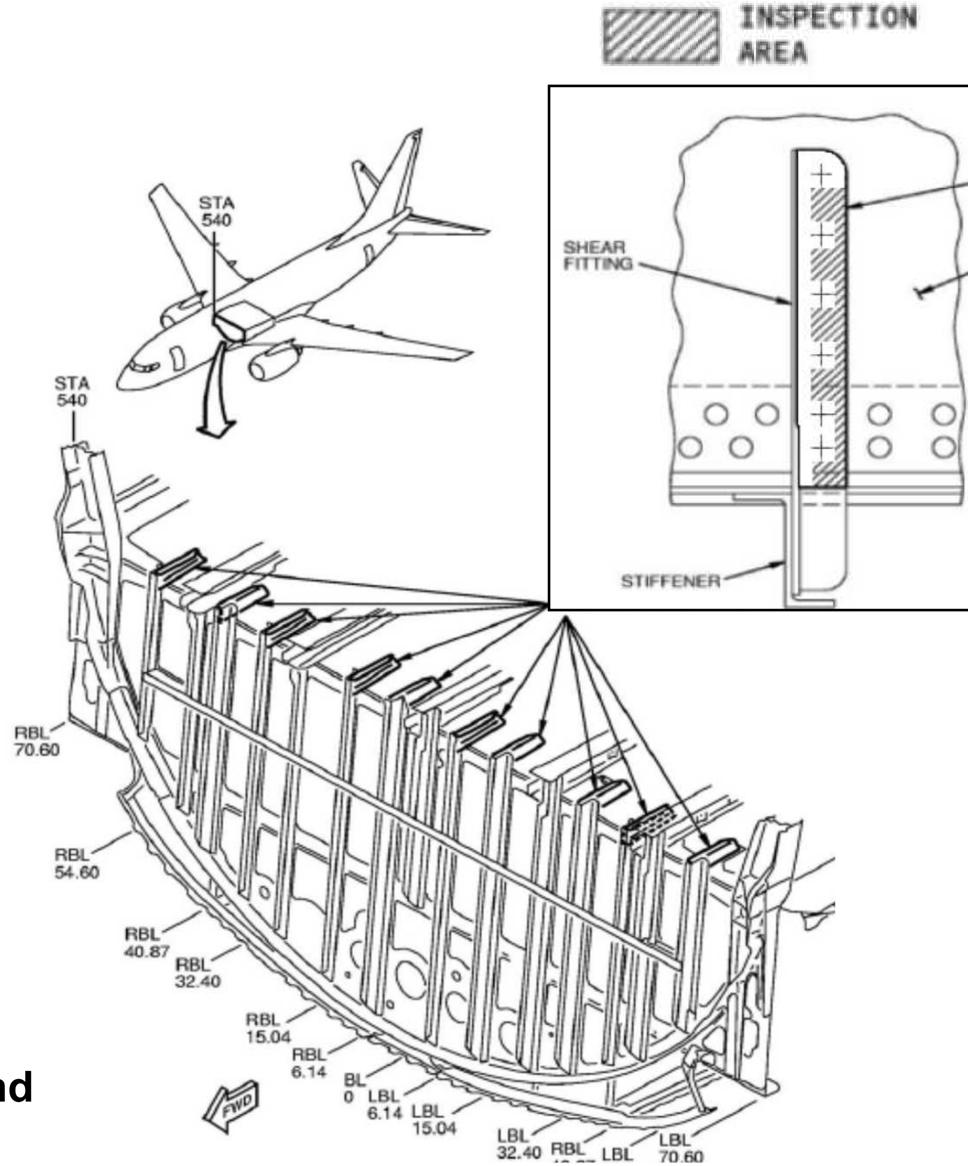


FRONT SPAR AND WING CENTER SECTION

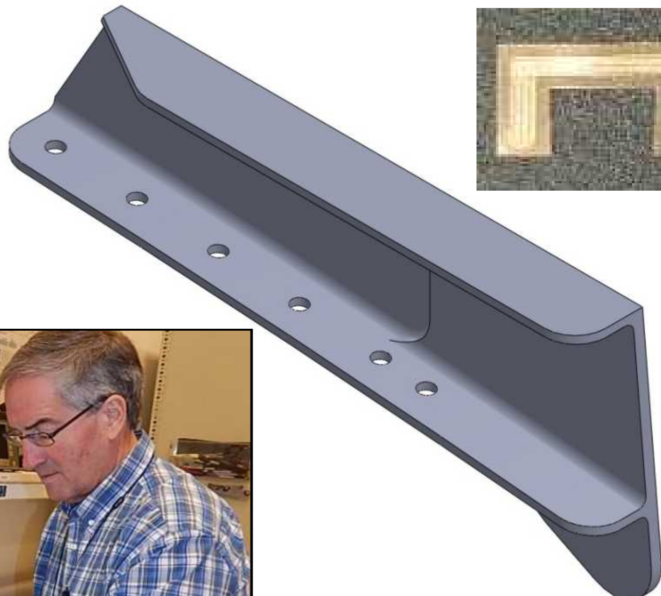
737NG Center Wing Box – CVM Flight Tests

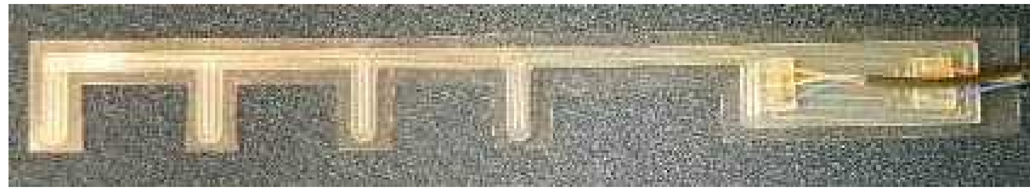


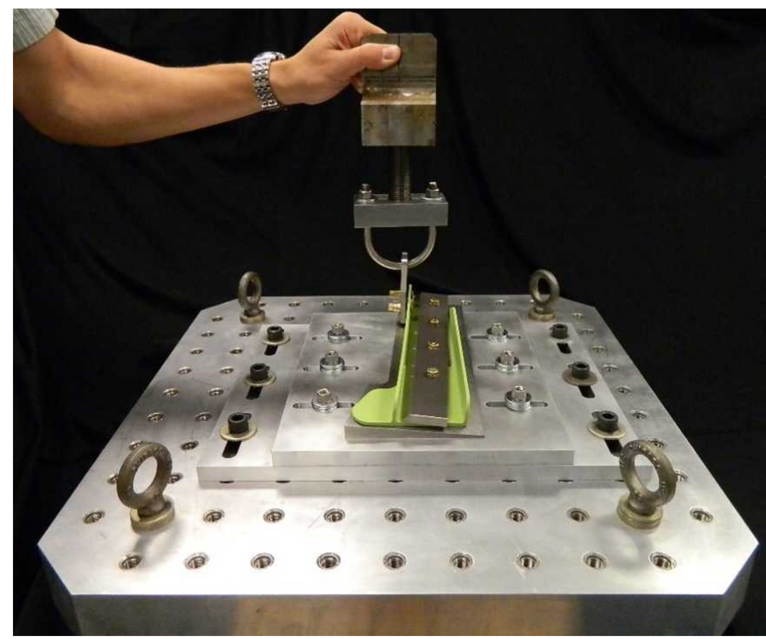
CVM Sensor on 737NG Wing Box Fitting and Top View of SLS Mount Location



CVM Performance Tests - Specific 737NG Center Wing Box Application



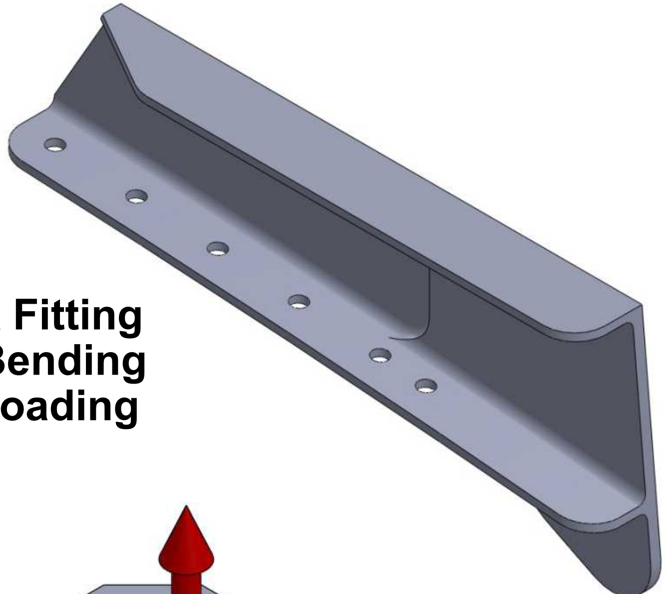




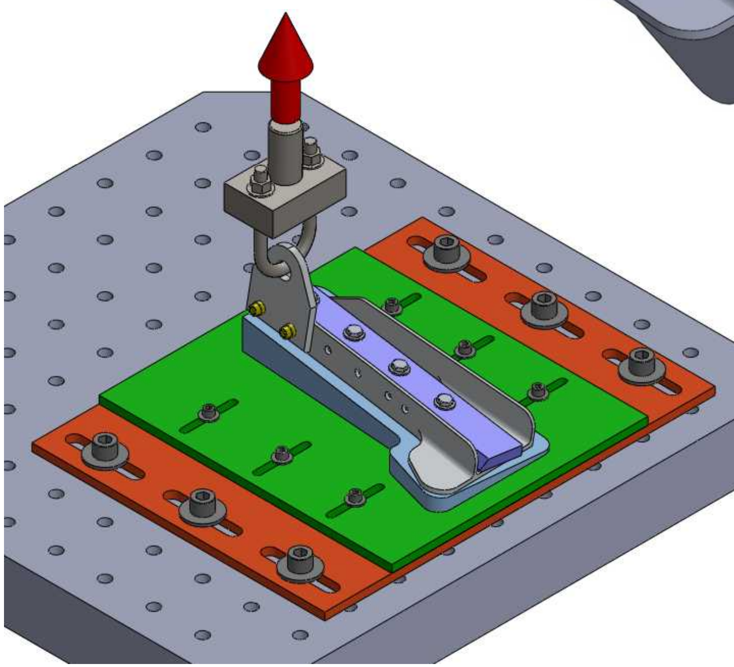
Boeing Review of CVM Validation – Performance Testing

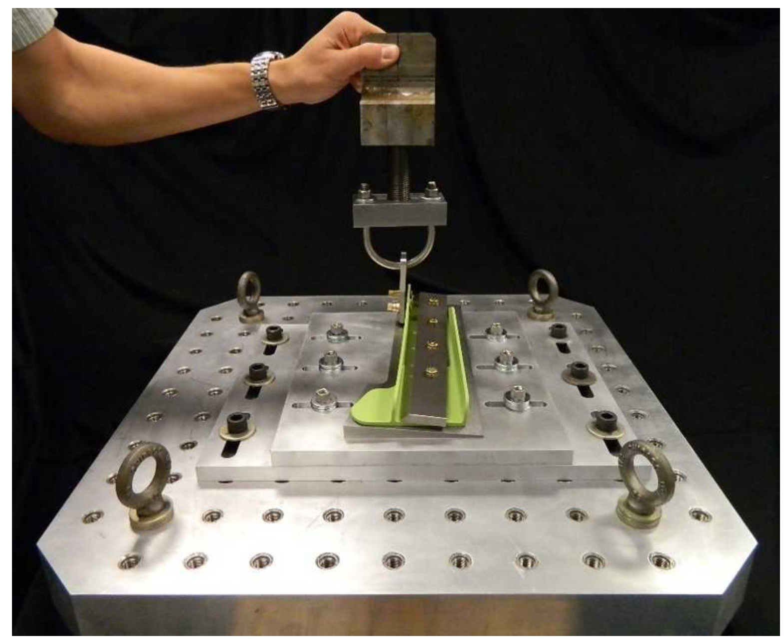
- Review of all CVM Validation Test Plans
- Review of fatigue test set-up, loading, equipment and calibration
- Review of data acquisition for CVM crack detection via SIM-8 and PM-200 devices
- Review of crack measurement for POD assessment
- Participation in fatigue testing on one specimen until permanent crack detection by CVM is achieved – crack growth through Gallery 1 and Gallery 2
- Review of environmental testing procedures, equipment and calibration
- Trail run of environmental chamber to demonstrate feedback & control of temperature and humidity
- Review and observation of application of fuel vapor barrier to wing box fitting such that CVM and backside of fitting are coated with FVB

737NG Center Wing Box – CVM Performance Tests



**Wing Box Fitting
Tension-Bending
Fatigue Loading**

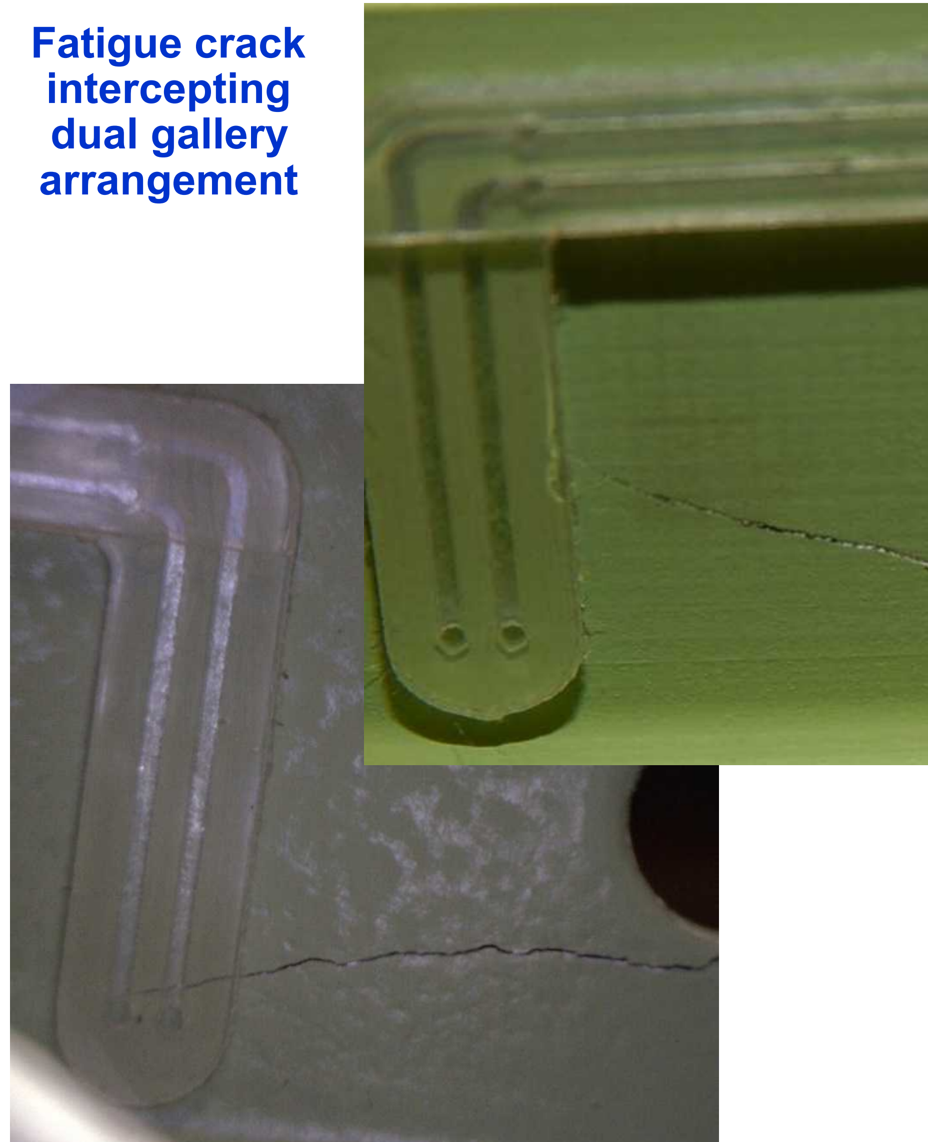




737NG Center Wing Box – CVM Performance Tests

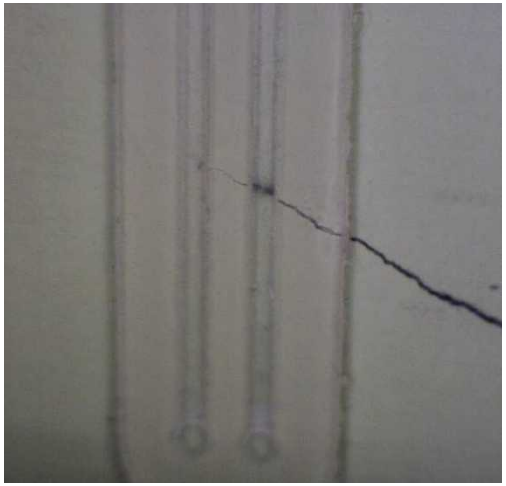
737NG Center Wing Box – CVM Performance Tests

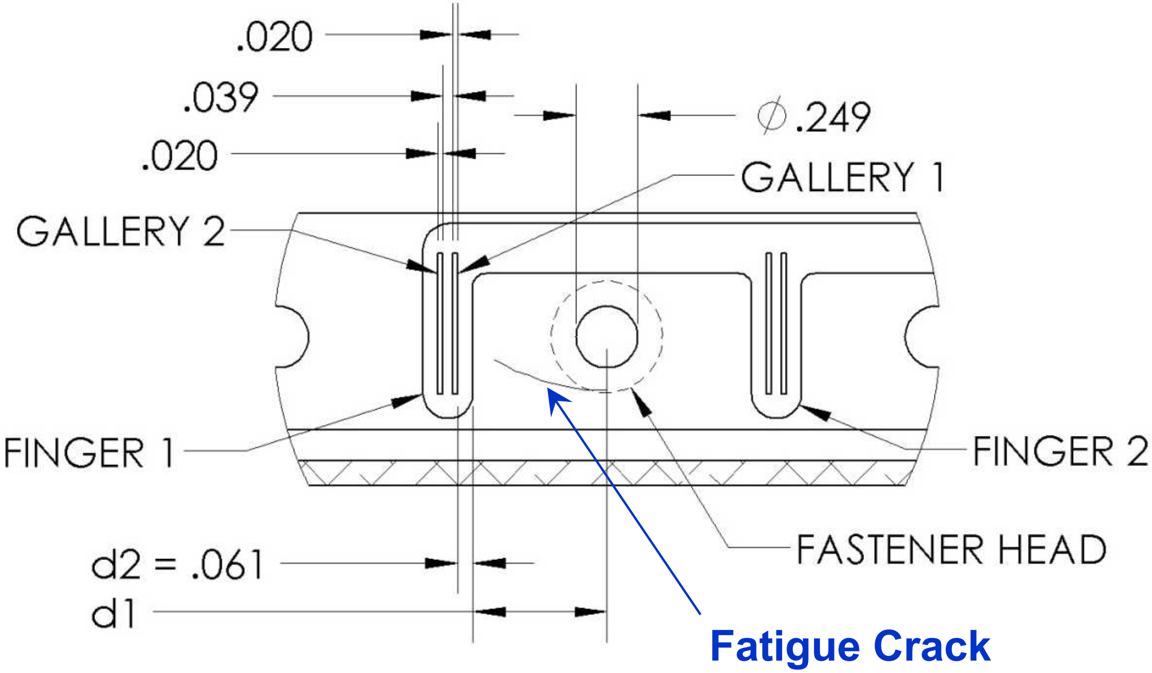
Fatigue crack intercepting dual gallery arrangement



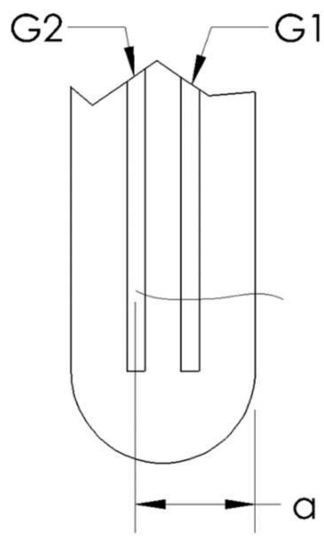
737NG Center Wing Box – CVM Performance Tests

- Bending crack has increased closure loads
- Monitoring for permanent crack detection – unloaded, unfastened and multiple day lag in readings
- Sealant (FVB) applied to determine crack detection when entire surface is sealed
- POD $_{[90/95]}$ for 1st & 2nd gallery; $S/N > 10$





737NG Center Wing Box – CVM Performance Tests for Gal1 Detection



Crack Length:

a = excursion into CVM sensor

CVM Sensor Wing Box Fitting Performance Tests

Test No.	CVM Finger Location	Sensor Distance from Fastener d_1 (In)	Crack Length at CVM Detection a (In)	SIM-8 Reading (Pa)	PM200 Reading (dCVM)
T1	2	0.488	0.084	282	7.4
T2	1	0.524	0.109	496	35.5
T3	1	0.550	0.089	2017	157.5
T4	1	0.570	0.094	330	14.4
T5	1	0.574	0.084	285	8.9
T6	1	0.580	0.079	2901	264.8
T7	2	0.546	0.124	318	22.5

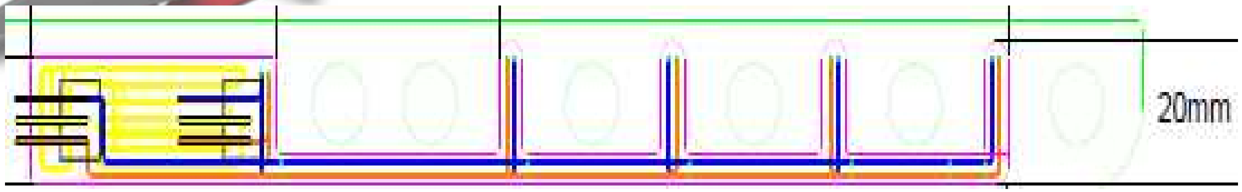
* Final values being confirmed

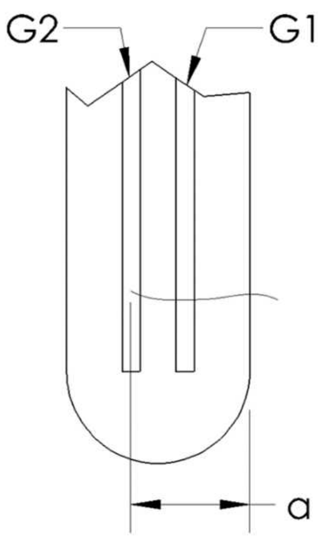
** Detection for unloaded state with sealed crack and sensor

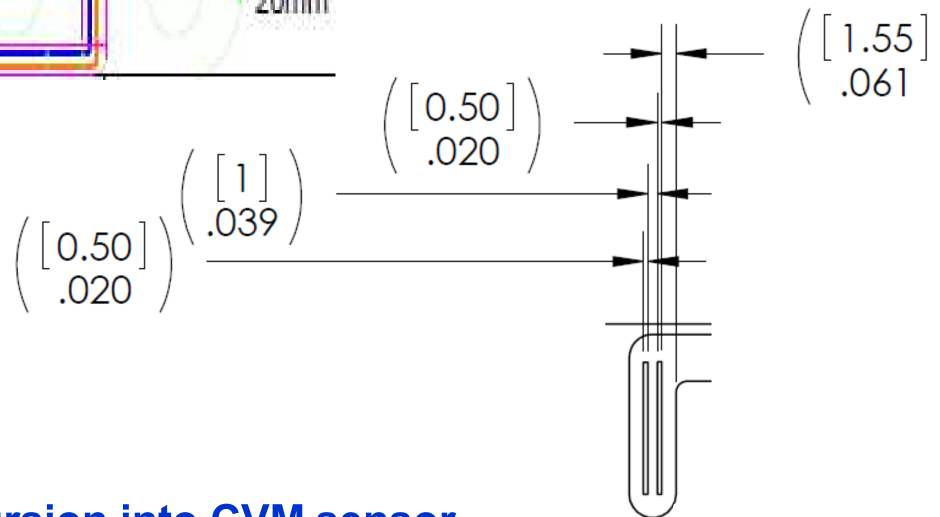
Results for Gallery 1 Permanent Detection (viable without complete FVB seal)

Avg CVM Gal 1 Detect Length = 0.095”
Distance from CVM Edge through Gal 1 = 0.081”

Measurement of CVM Crack Detection







Crack Length: a = excursion into CVM sensor

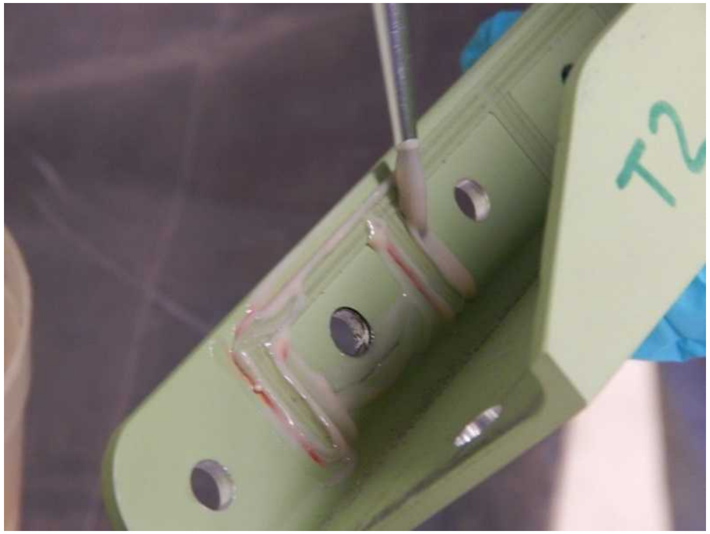
From Edge of Finger to Start of Second Gallery:
0.061 + 0.0197 + 0.0394 = 0.120 Inches

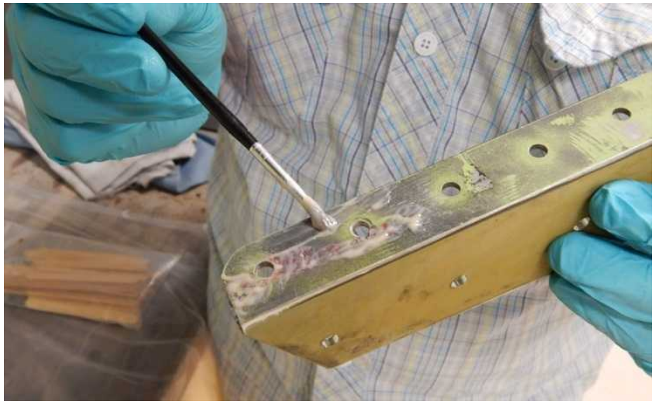
From Edge of Finger Through Second Gallery:
0.061 + 0.0197 + 0.0394 + 0.0197 = 0.140 Inches

Finger Width = 0.200 Inches

Application of Fuel Vapor Barrier

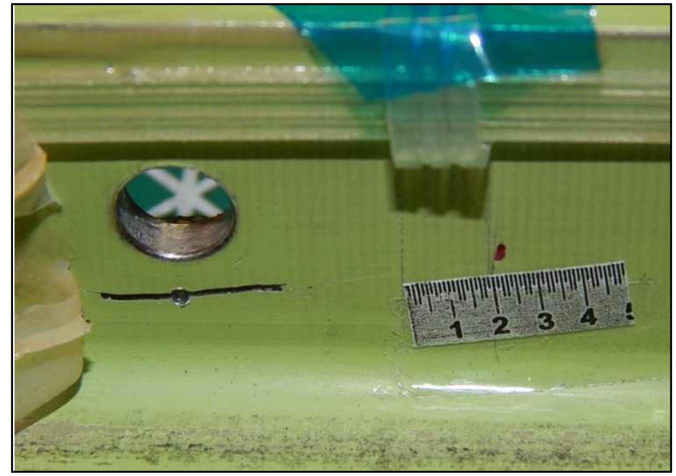
- Fuel vapor barrier seals sensor from atmosphere via crack path
- Initial Gallery 1 crack detection is not observed after FVB is applied
- Crack detection now requires connection between Gal1 and Gal2 which alternately act as vacuum and atmosphere galleries

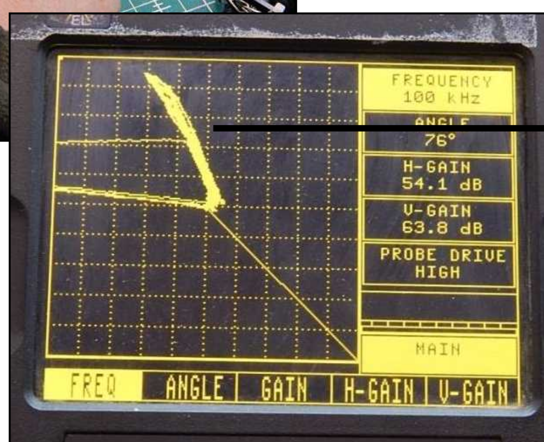


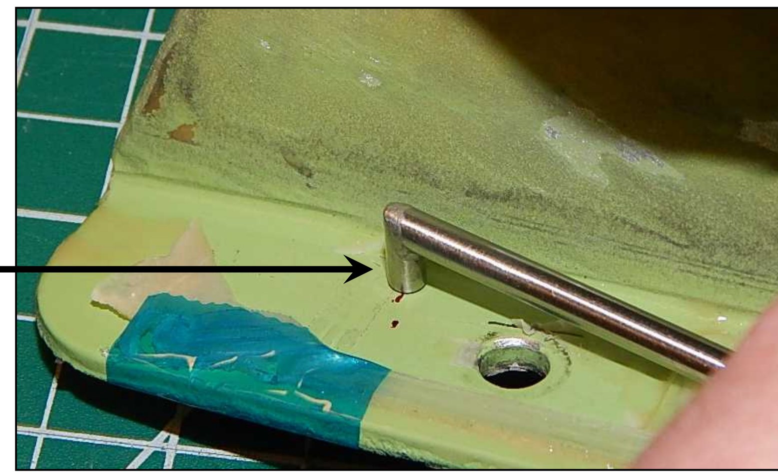


Determining Final Crack Length at CVM Detection

Eddy Current (EC) Measurement – scribe finger location & peel back CVM finger







CVM Crack Detection Performance with FVB (Gal1 to Gal2 Connect)

CVM Sensor Wing Box Fitting Performance Tests								
Test No.	Fatique Cycles at permanent CVM Crack Detection	Sensor Distance from Fastener d_1 (In)	Eddy Current Crack Length at CVM Detection a (In)	Total Crack Length (In)	SIM-8 Reading Gallery 1 (Pa)	SIM-8 Reading Gallery 2 (Pa)	PM200 Reading (1dCVM)	PM200 Reading (2dCVM)
T1	87,098	0.488	0.215	0.703	338	720	18.3	44.5
T3	58,528	0.550	0.193	0.743	1468	1456	130.7	129.3
T4	53,726	0.570	0.193	0.763	318	330	14.1	14.4
T5	91,273	0.574	0.205	0.779	232	228	12.9	13.6
T6	84,277	0.580	0.200	0.780	2602	2692	257	264.8
T7	69,459	0.546	0.243	0.789	271	310	12.4	15.7
T9	105,239	0.605	0.180	0.785	560	390	37.6	25.1
T10	59,392	0.570	0.205	0.775	271	277	17.4	18.3
T11	20,225	0.621	0.238	0.859	261	274	15.5	16.2
T12	21,229	0.569	0.240	0.809	2451	2491	253.6	258
T13	39,553	0.528	0.258	0.786	304	227	19	19.7
T14	79,508	0.588	0.218	0.806	N/A	N/A	10.4	10.3
T15	148,139	0.566	0.178	0.744	200	205	9.9	11.1
T16	131,596	0.481	0.175	0.656	332	309	20.2	19.4
T17	26,367	0.566	0.220	0.786	243	258	14.2	14.7
T19	300,292	0.584	0.198	0.782	1328	511	97	29.3
T20	79.413	0.572	0.208	0.780	278	270	15.7	16.6
T21	191,030	0.526	0.193	0.719	244	255	13.9	14.9
T22	192,987	0.432	0.235	0.667	252	234	13	10.8
T23	213,030	0.529	0.183	0.712	205	214	13.3	13.8

POD Calculations - One-Sided Tolerance Interval

POD Determined from CVM Response Data on Wing Box Fitting

CVM Crack Detection Data

Eddy Current Crack Length at CVM (In)	Log of Crack Length at CVM Detection a (In)
0.215	-0.66756154
0.193	-0.714442691
0.193	-0.714442691
0.205	-0.688246139
0.200	-0.698970004
0.243	-0.614393726
0.180	-0.744727495
0.205	-0.688246139
0.238	-0.623423043
0.240	-0.619788758
0.258	-0.588380294
0.218	-0.661543506
0.178	-0.749579998
0.175	-0.756961951
0.220	-0.657577319
0.198	-0.70333481
0.208	-0.681936665
0.193	-0.714442691
0.235	-0.628932138
0.183	-0.73754891

Statistic Estimates on Log Scale

Statistic	Value in Log Scale	Value in Linear Scale
Mean (X)	-0.682724025	0.209
Stnd Deviation (S)	0.049124663	0.023962471

POD Detection Levels
(γ = 95%, n = 20)

Flaw Size: POD = X + K(S)	0.258160667

$$\text{POD}_{\text{(Max Likelihood Est)}} = \frac{1}{xS\sqrt{2\pi}} EXP\left(\frac{-(ln(x)-\bar{X})^2}{2S^2}\right)$$

It is possible to calculate a one sided tolerance bound for various percentile flaw sizes - find factors $K_{n,\gamma,\alpha}$ to determine the confidence γ such that at least a proportion (α) of the distribution will be less than *X* + ($K_{n,\gamma,\alpha}$)S where *X* and *S* are estimators of the mean and the standard deviation computed from a random sample of size *n*

POD Calculations - One-Sided Tolerance Interval With Check on Robustness of Results

POD Determined from CVM Response Data on Wing Box Fitting Results with 10 Additional Detections at 10% Above Avg.

Statistic Estimates on Log Scale

Results with 10 Additional Detections at 10% Above Avg.		
Statistic	Value in Log Scale	Value in Linear Scale
Mean (X)	-0.667906738	0.216
Stnd Deviation (S)	0.045114619	0.02187572

Revised POD Detection Levels
(ɣ = 95%, n = 30)

Flaw Size: POD = X + K(S)	0.258381812

Actual POD Detection Levels
(ɣ = 95%, n = 20)

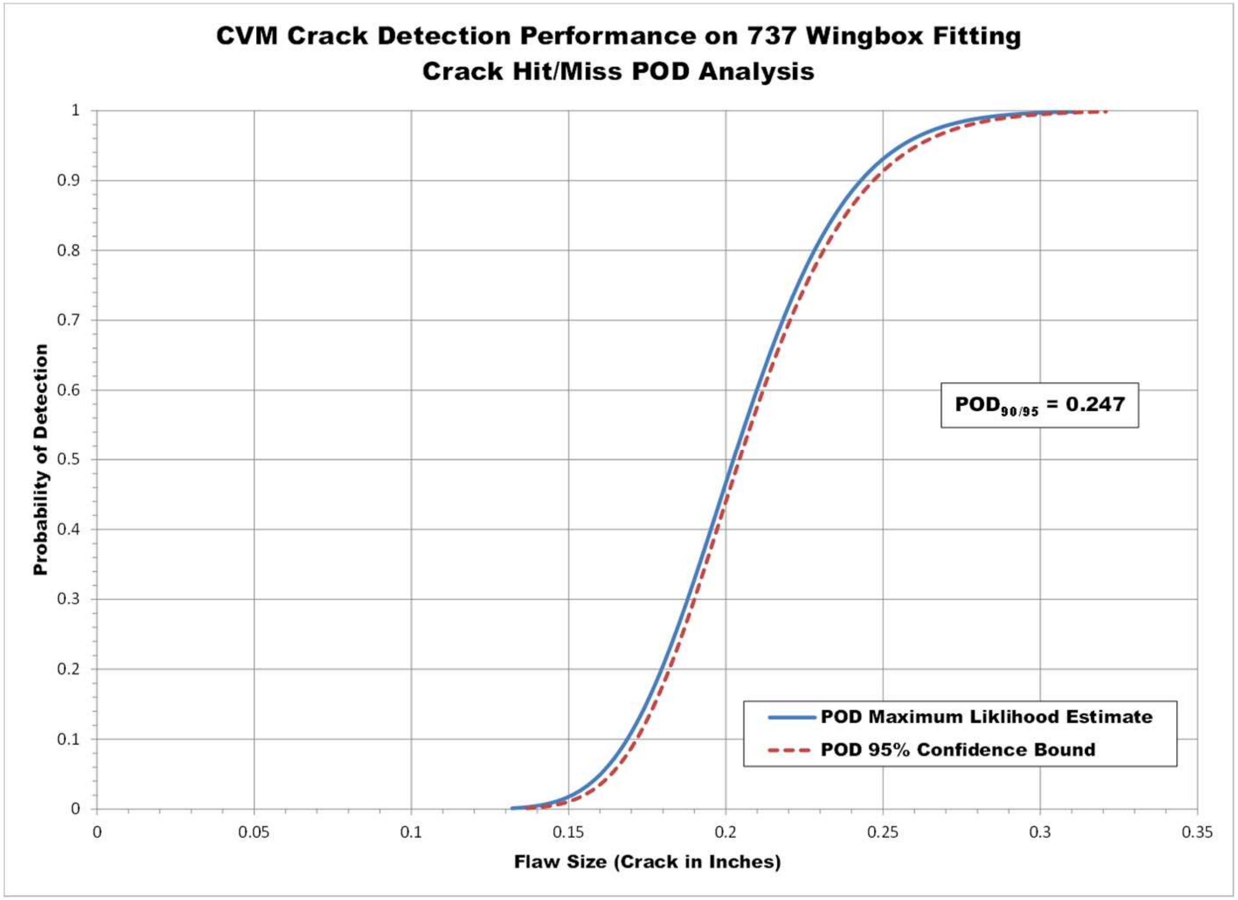
Flaw Size: POD = X + K(S)	0.258160667

Eddy Current Crack Length at CVM (In)	Log of Crack Length at CVM Detection a (In)
0.215	-0.66756154
0.193	-0.714442691
0.193	-0.714442691
0.205	-0.688246139
0.200	-0.698970004
0.243	-0.614393726
0.180	-0.744727495
0.205	-0.688246139
0.238	-0.623423043
0.240	-0.619788758
0.258	-0.588380294
0.218	-0.661543506
0.178	-0.749579998
0.175	-0.756961951
0.220	-0.657577319
0.198	-0.70333481
0.208	-0.681936665
0.193	-0.714442691
0.235	-0.628932138
0.183	-0.73754891
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164
0.230	-0.638272164

CVM Crack Detection Data

POD Analysis Using Standard Hit-Miss Methodology

Gaussian distribution of hit-miss data was compiled using crack CVM detection length from each test with assumed, missed crack detections below CVM detection level & assumed, hit crack detections above the CVM detection level.



CVM Sensor Wing Box Fitting Performance Tests Hit/Miss POD Values

Test No.	Eddy Current Crack Length at CVM (In)	$POD_{90/95}$
T1	0.215	0.252
T3	0.193	0.232
T4	0.193	0.232
T5	0.205	0.243
T6	0.200	0.224
T7	0.243	0.279
T9	0.180	0.220
T10	0.205	0.243
T11	0.238	0.274
T12	0.240	0.276
T13	0.258	0.293
T14	0.218	0.255
T15	0.178	0.228
T16	0.175	0.225
T17	0.220	0.257
T19	0.198	0.236
T20	0.208	0.246
T21	0.193	0.232
T22	0.235	0.271
T23	0.183	0.223
Cumulative		0.247

Part 3 – SHM Durability Assessment

A.) Extreme environment assessment

B.) Exposure to corrosion inhibiting compounds

Environmental Durability Performance Assessment

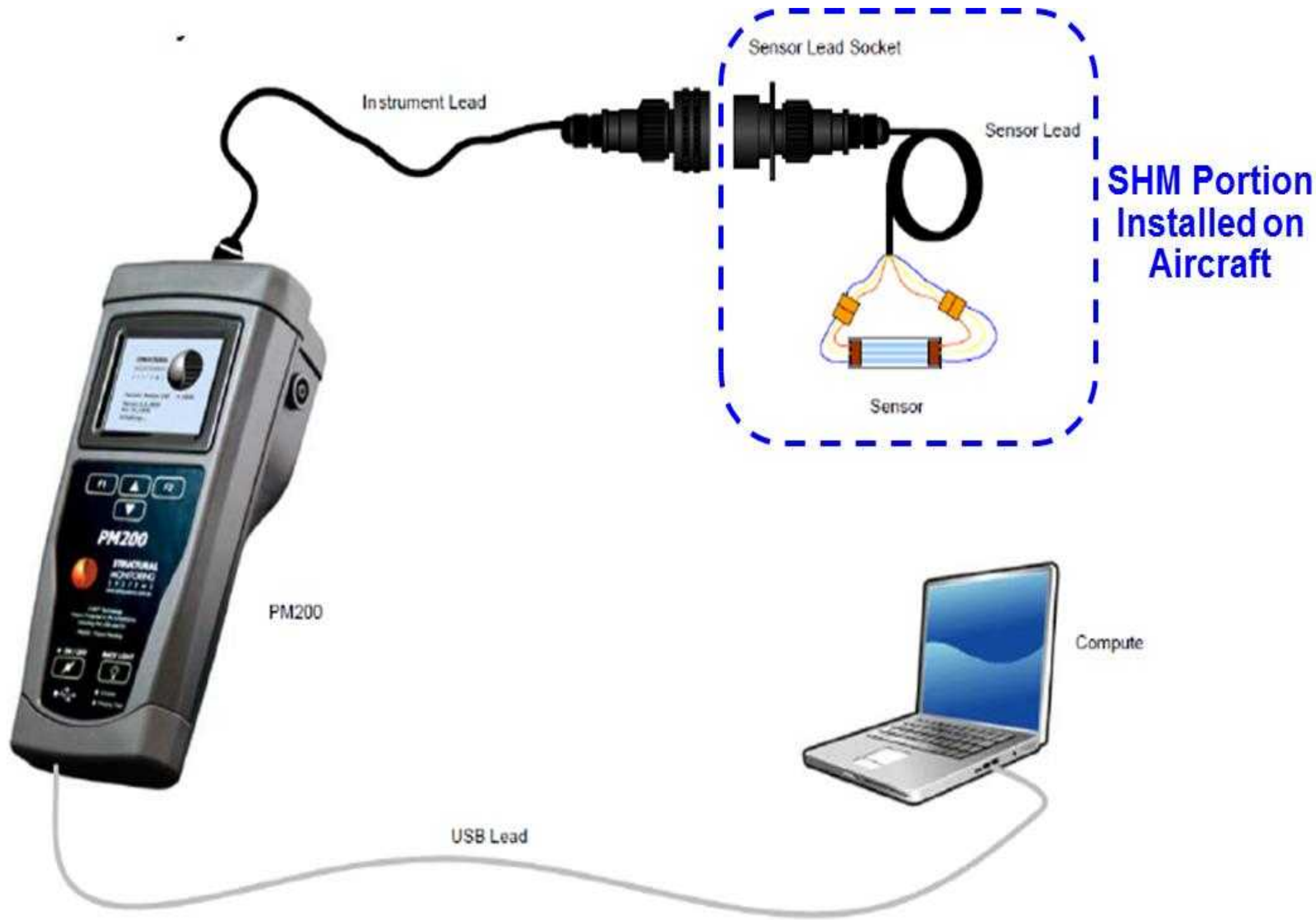
- Part of overall performance testing - meant to establish durability of sensor systems
- Sensor fail-safe feature is critical item – will be proven
- Temperature environment selected to match similar testing to certify metal primer
- Environmental elements:
  - Hot-Wet (7 days @ 60°C and 95% ±3% RH)
  - Freeze (8 hours @ -18°C)
  - Heat (8 hours @ 74°C)
  - Environmental elements repeated 4 times (total of 28 day hot-wet environment and 36 day minimum total ENV TEST)

Three components equal one total ENV cycle

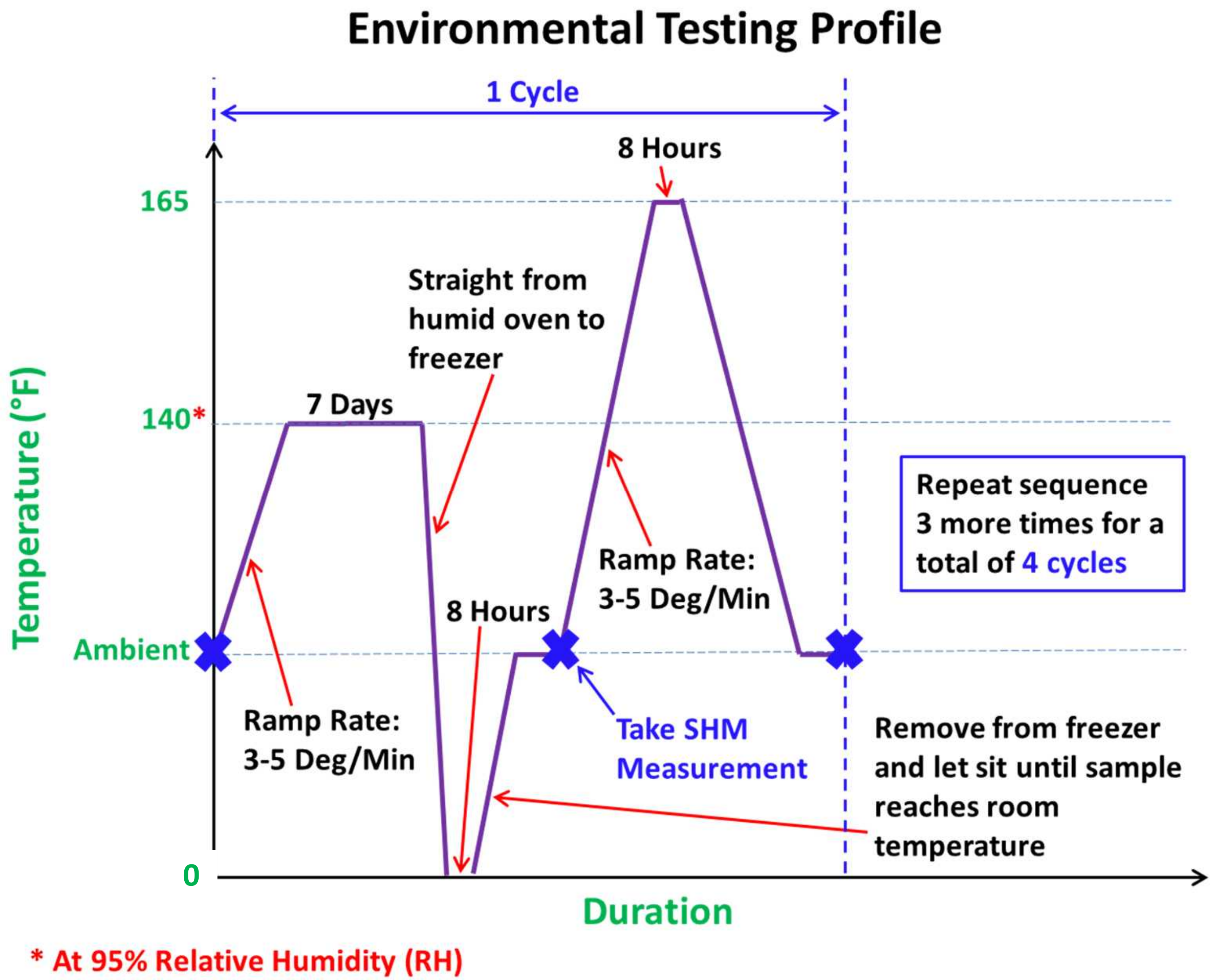
- CVM Sensor function measurements were acquired before each overall cycle, at the end of each cold exposure component and after total ENV test completion (total of 9 CVM monitoring events)
- Test specimens include all hardware that remains on the aircraft during flight operations

Environmental Test Configuration for CVM Sensors

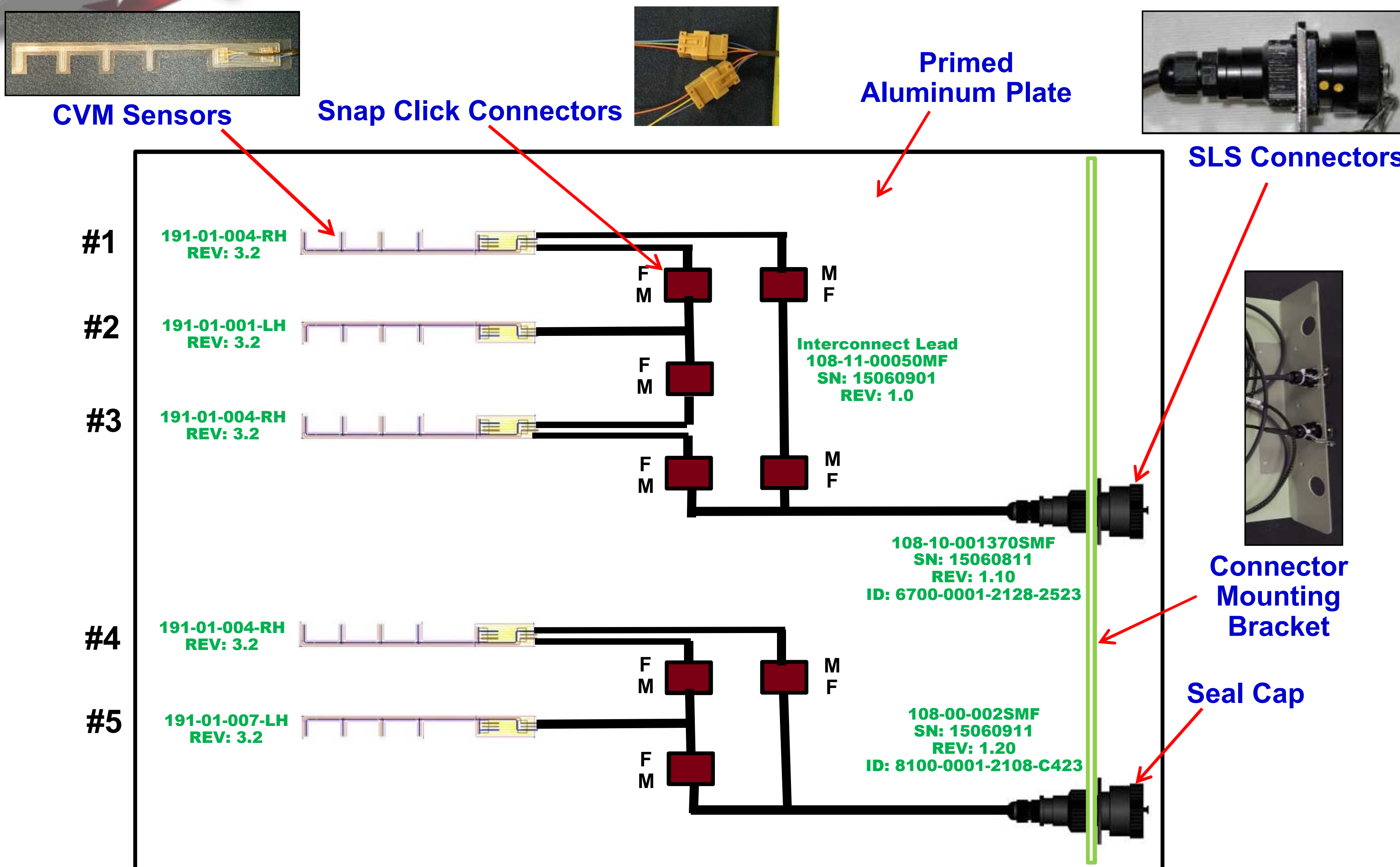
Environmental Testing - Complete connection routing showing CVM sensors, Sensor Lead, Instrument Lead and Snap-Click connectors to connect CVM sensors to data acquisition equipment, data analysis and logging



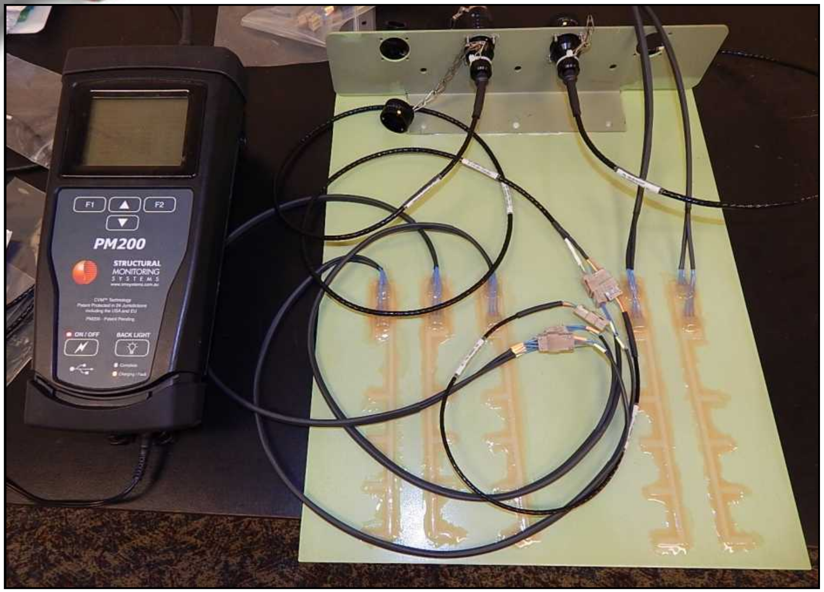
Environmental Exposure Tests for CVM Sensors



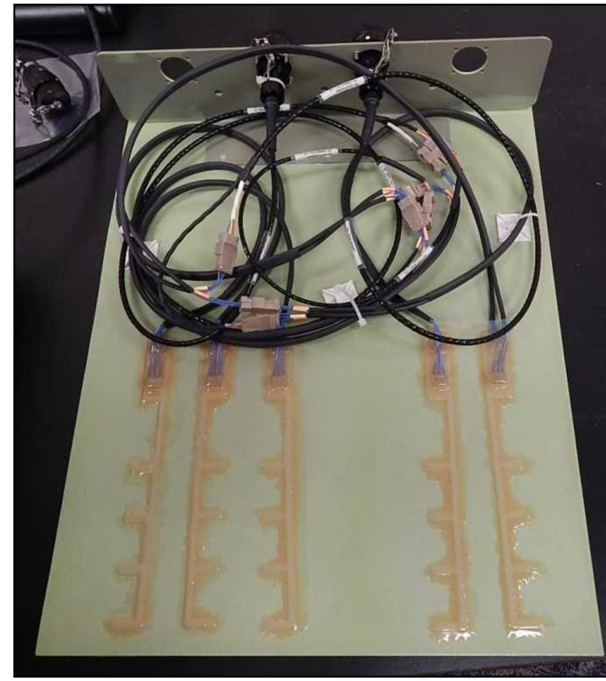
Environmental Durability Performance Assessment – Test Specimen Preparation

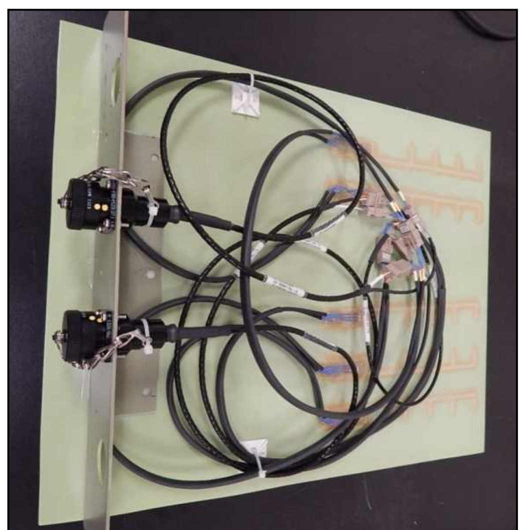


Environmental Durability Performance Assessment – Test Specimen Preparation



Connect CVM Sensors into Groupings as on the 737 Wing box Monitoring; Conduct PM200 Test on Sensor Sets After Final Installation





Environmental Durability Performance Assessment – Sensor Readings Prior to Beginning ENV Tests

Initial PM200 Tests on Individual Sensors and Grouping of Sensors as Per 737 Wing box Installation – Baseline Data Prior to Environmental Exposure

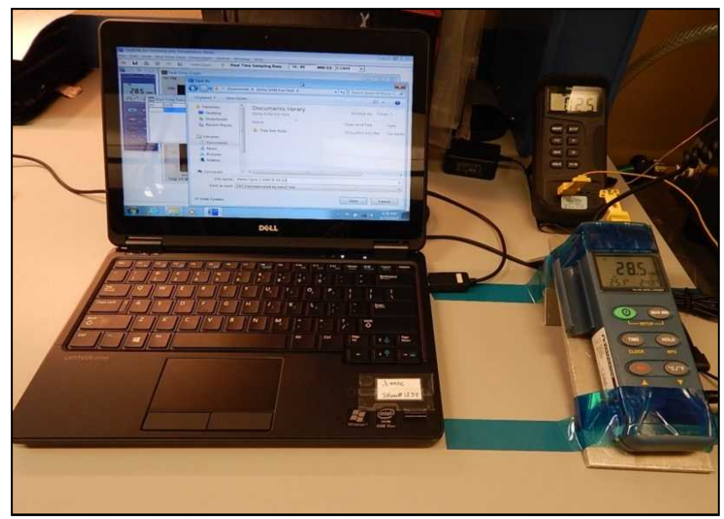
Environmental Tests - Delta Program

Sensor #	Ccont	1Cont	2Cont	dCVM1	dCVM2	CVM Screen Reading	Notes:
Individual CVM Sensor Readings on PM200 Device After Installation							
1	Max CI	Max CI	16939.0	-0.6	0.7	Pass	Cable ID: AB00-0001-2133-D323
2	16737.0	Max CI	15966.0	-0.7	0.0	Pass	Cable ID: AB00-0001-2133-D323
3	Max CI	17087.0	15190.0	-0.6	-0.1	Pass	Cable ID: AB00-0001-2133-D323
4	Max CI	13546.0	16740.0	-0.4	0.1	Pass	Cable ID: AB00-0001-2133-D323
5	Max CI	13521.0	Max CI	-0.8	-0.1	Pass	Cable ID: AB00-0001-2133-D323
3-2 Grouping of CVM Sensors - Readings on PM200 Device After FVB Coating							
1, 2, 3	6589.0	6010.0	6715.0	-1.0	1.9	Pass	Cable ID: 6700-0001-2128-2523
4, 5	10605.0	10927.0	10431.0	-0.8	-0.1	Pass	Cable ID: 8100-0001-2108-C423

All tests passed – high conductivity (flow rate) and low dCVM (vacuum level) on all sensor sets

Environmental Test Chamber

Loading Specimen in Temperature-Humidity Chamber



Logging Data to Ensure Proper Environment

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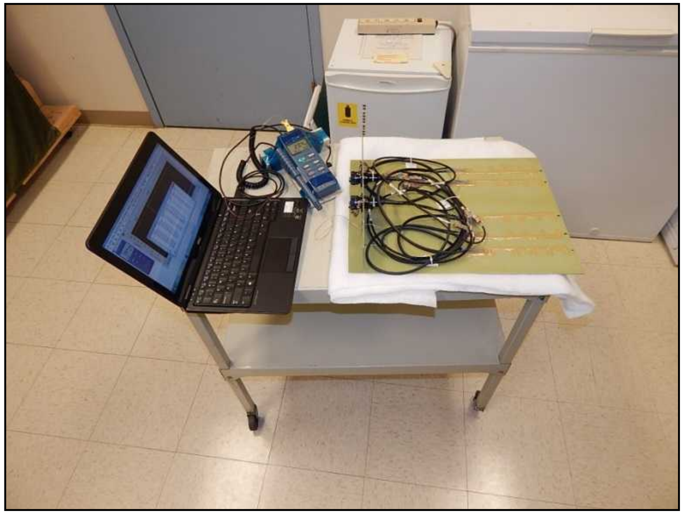
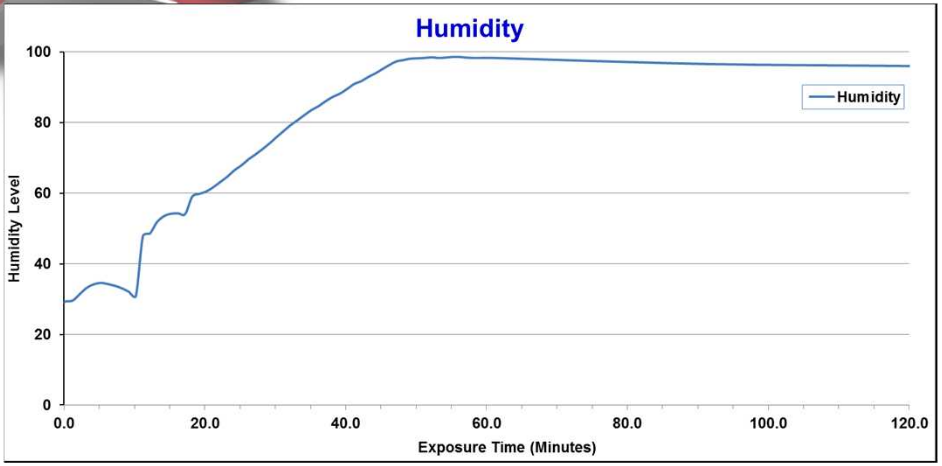
Freezer for Extreme Cold Environment


Loading Specimen into Freezer




Logging Data to Ensure Proper Environment

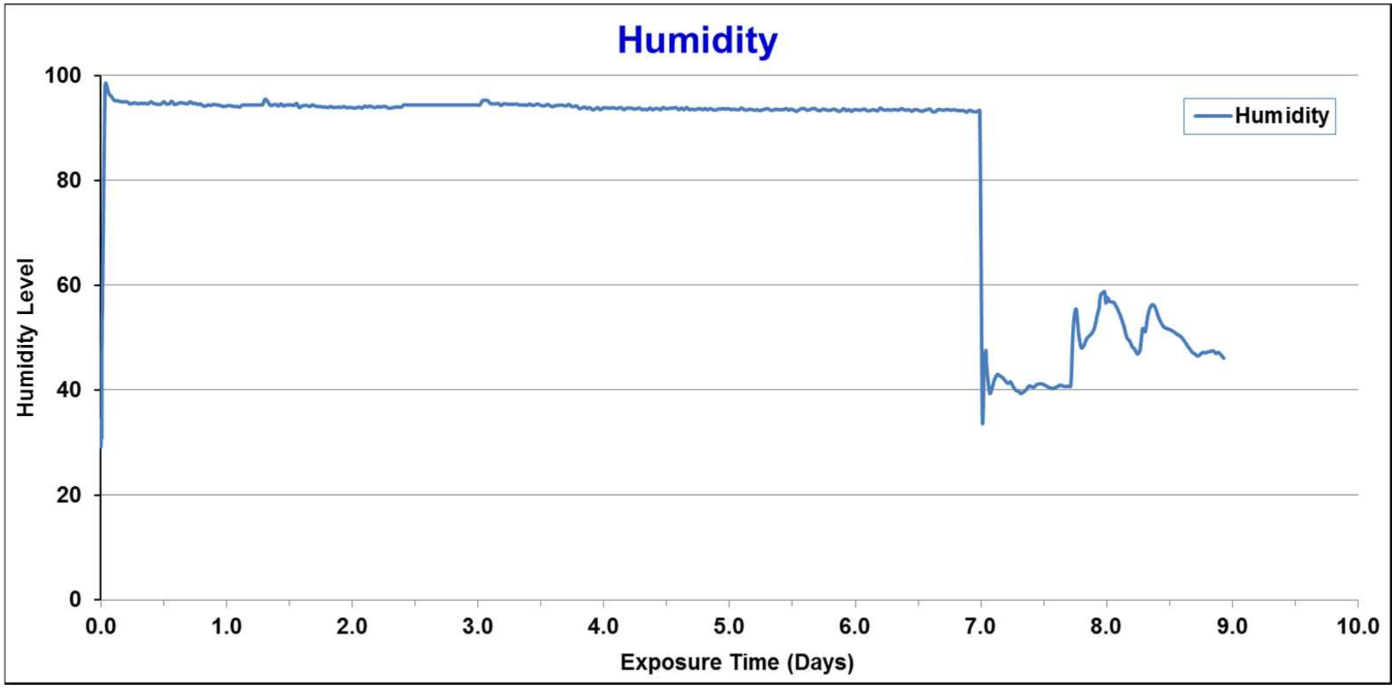
CVM Environmental Durability Test – Cycle 1 (Humidity)



Day 1-7: Hot-Wet (140 °F, 60 °C, 95% RH)
Day 8: Extreme Cold (0 °F, -18 °C) *
Day 9: Extreme Heat (165 °F, 74 °C) *

* = CVM check

Humidity Ramp-Up (Day 1)



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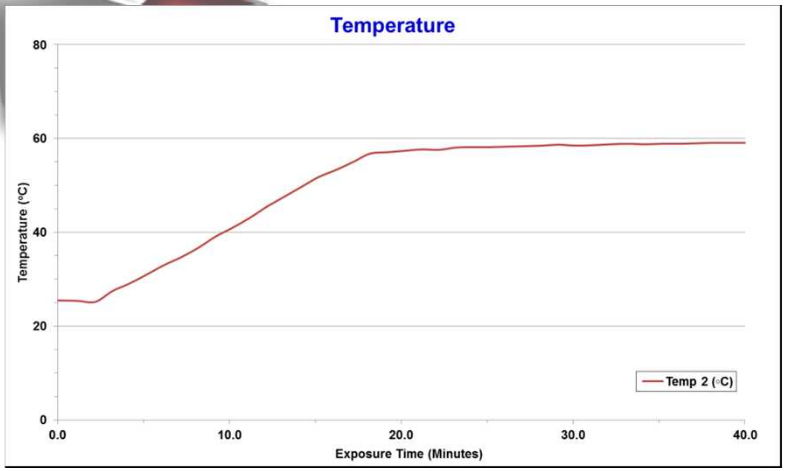
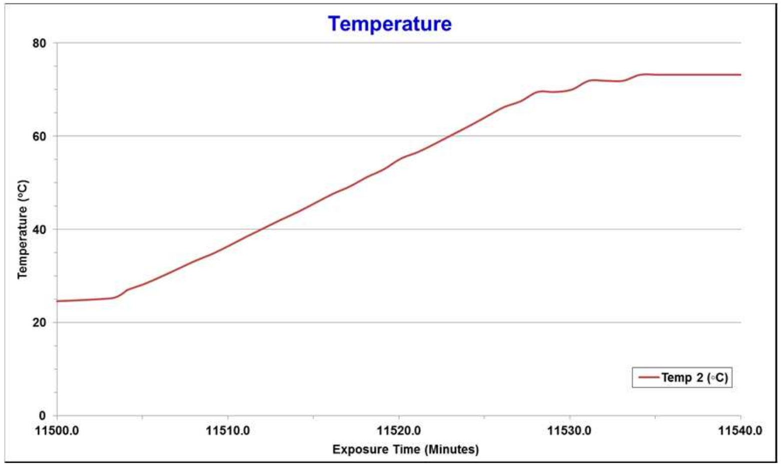
CVM Environmental Durability Test – Cycle 1 (Temperature)



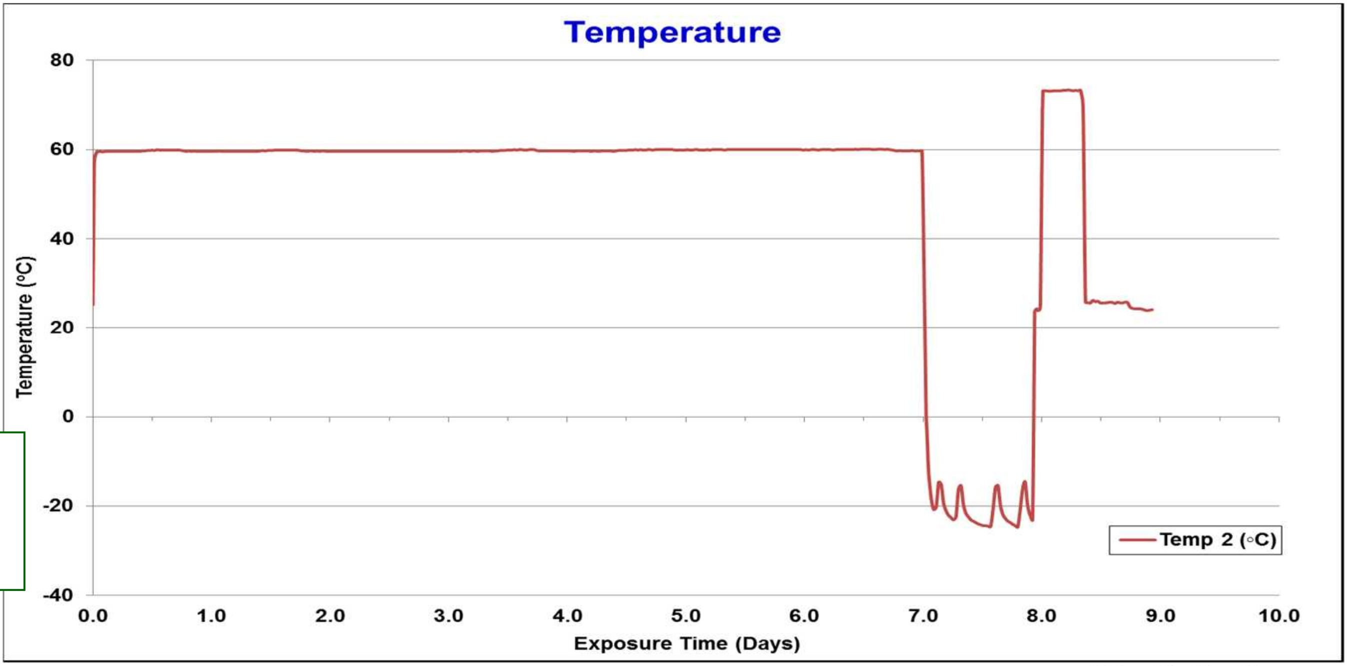
Temperature Ramp-Up to 140°F (Day 1)



Temperature Ramp-Up to 165°F (Day 9)

Day 1-7: Hot-Wet
(140°F, 60°C, 95% RH)
Day 8: Extreme Cold (0°F, -18°C) *
Day 9: Extreme Heat (165°F, 74°C) *

* = CVM check



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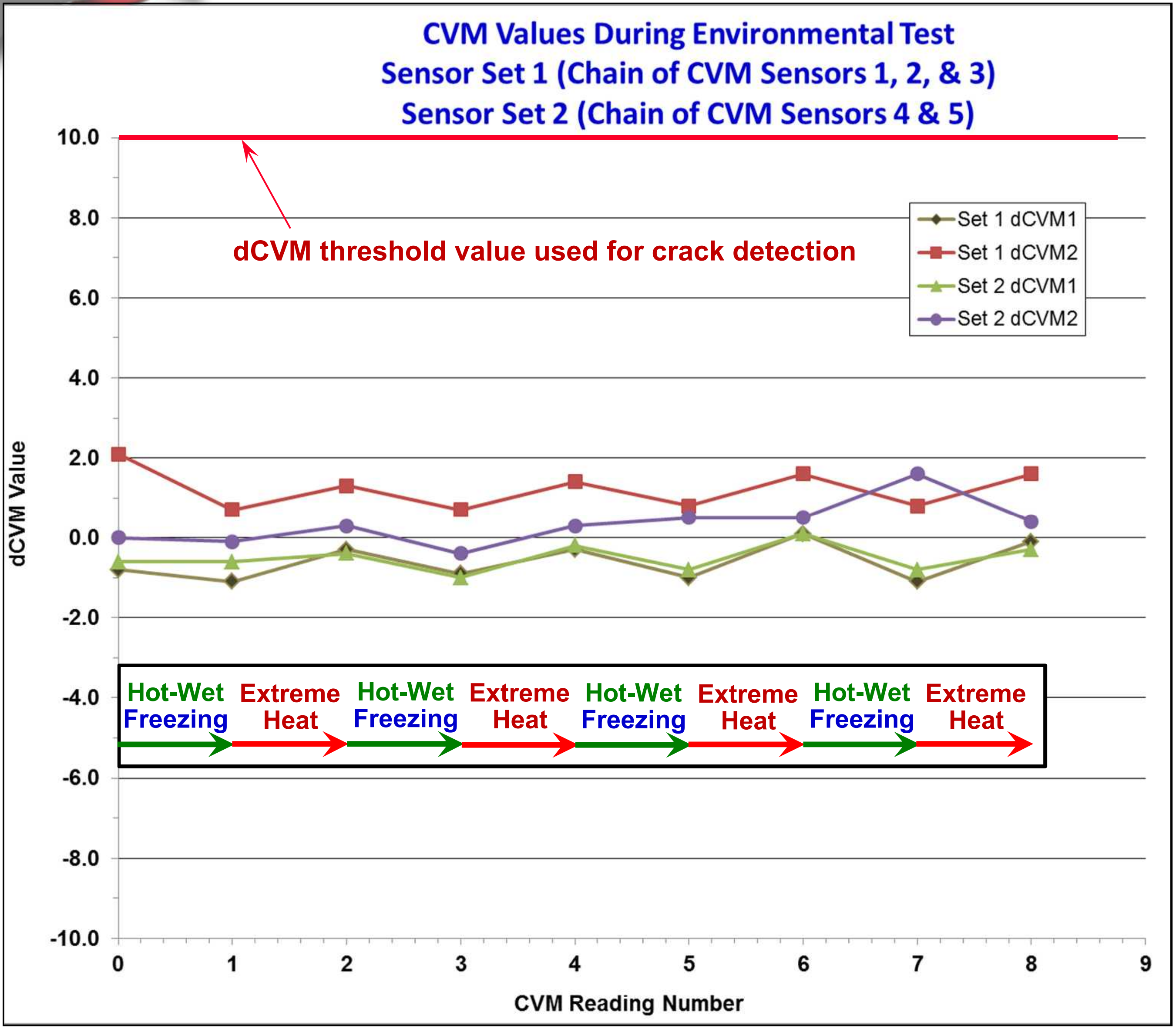
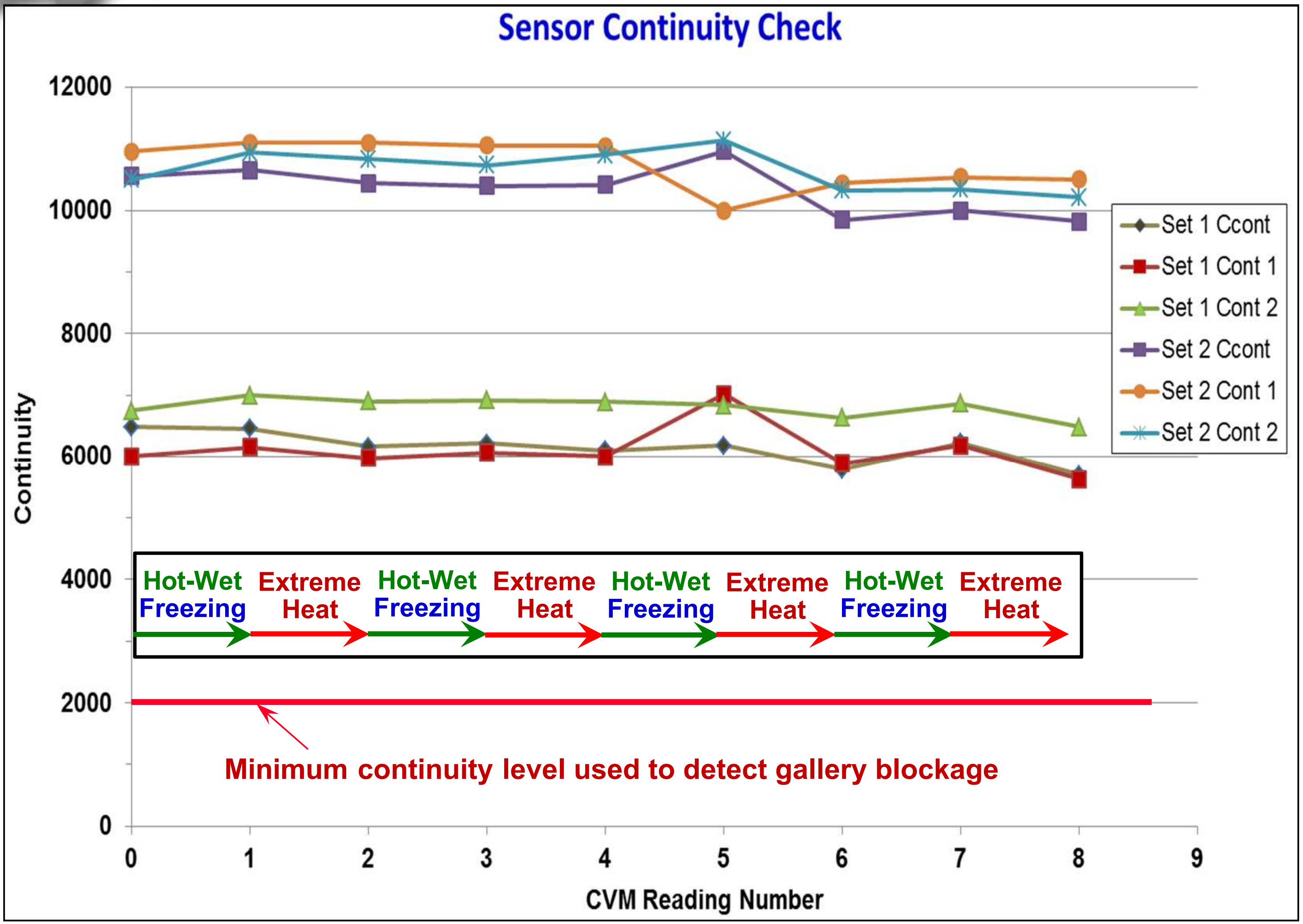
CVM Sensor Readings – Unchanged During Environmental Tests



Sensor readings during 40 day environmental tests remained small compared to threshold level required for crack detection:

- **dCVM values ranged +/- 2.0; crack detection set for dCVM = 10.0**
- **Good durability of SHM system; no degradation**
- **Signal-to-noise (S/N) for crack detection is a minimum of 5 (most exceeded 20 in fatigue tests)**
- **Desired S/N for normal NDI operations is a minimum of 3**

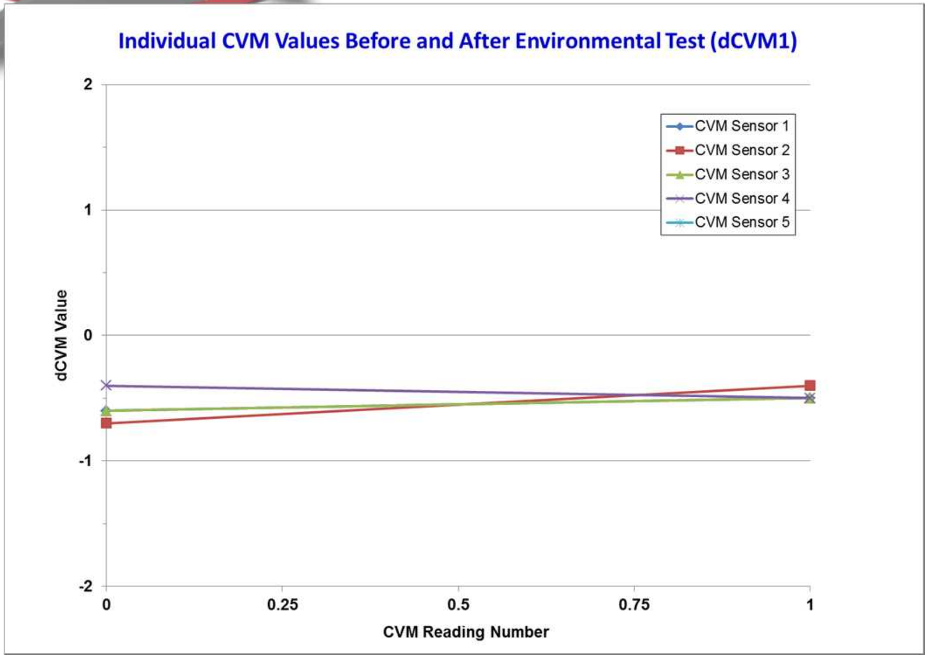
CVM Continuity – Unchanged During Environmental Tests



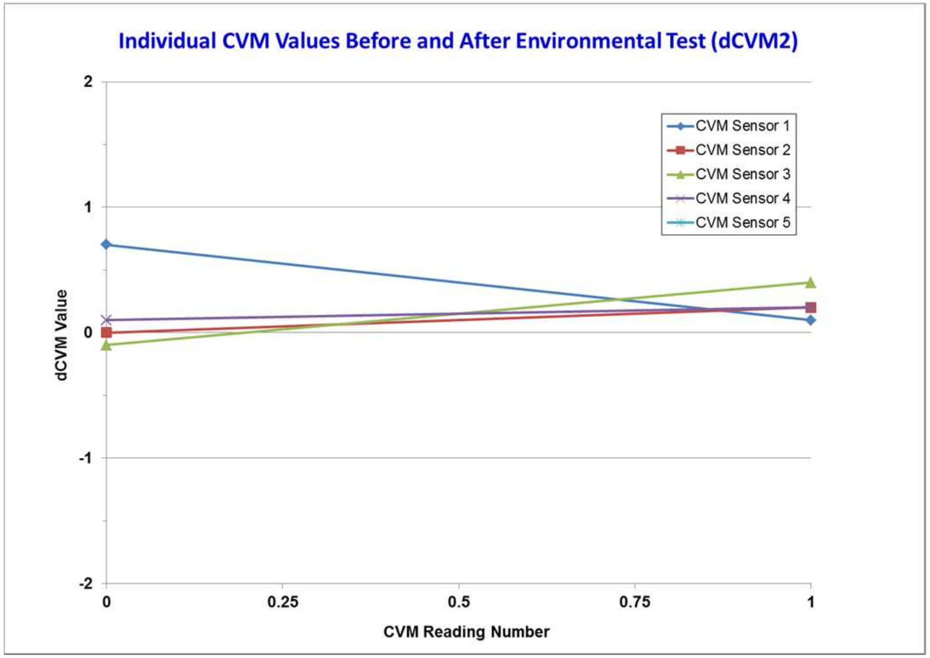
Sensor continuity measures for possible gallery blockage. During 40 day environmental tests, continuity remained large compared to lower threshold level that indicates blockage:

- **Continuity values ranged 6,000 to 12,000; minimum levels allowed Cont = 2,000**
- **Good durability of SHM system; no degradation**

Individual CVM Sensor Readings Remain Unchanged



dCVM readings before and after 40 day environmental test show no change in values; no affect of 4 cycles of extreme hot-wet-cold-heat environment on CVM performance



Part 3 – SHM Durability Assessment

A.) Extreme environment assessment

B.) Exposure to corrosion inhibiting compounds

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 (silicon CVM sensors)

CIC Selected:

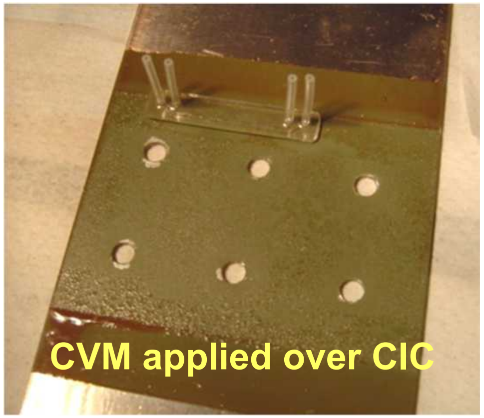
- BMS 3-35 which is Ardrox AV15 or Corban-35 (Zip Chem)
- BMS 3-23 which is LPS-3 or Ardrox AV-8 or Dinitrol

Crack Detection:

a_{90} = 0.011” w/o CIC

a_{90} = 0.013” w/ CIC

Multiple passes to produce flowing and accumulation of CIC



CVM applied over CIC

No CIC drawn into galleries

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

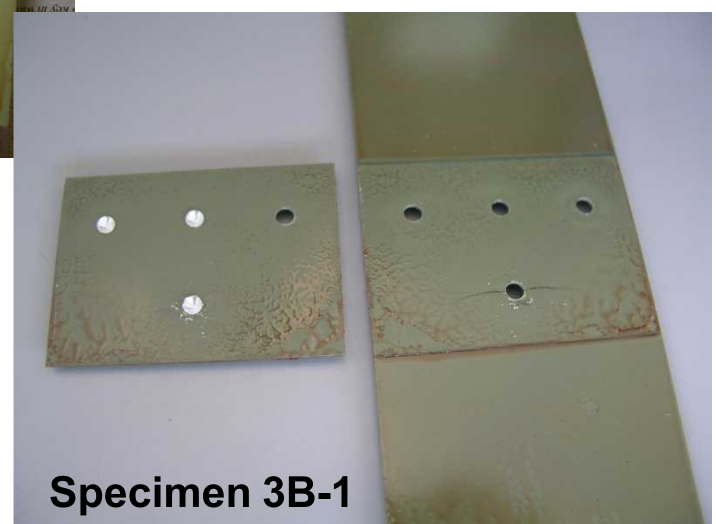
Assumptions on Worst Case Conditions:

- CIC has access to CVM via wicking into a joint and along a rivet shank
- Greatest opportunity for CIC wicking is in a joint where there is no sealant at all
- Some CICs remain liquid for extended periods thus providing the opportunity to wick into cracks that were not present when it was initially applied
- Assume a small crack exists in the structure such that it is currently not detectable by CVM but could possibly allow for CIC ingress; will CIC continue to wick into a growing crack and, if so, will it "fill" the crack to make it transparent to the CVM sensor? Tests were conducted to assess this.

Application of CIC to Initial Set of Specimens

No clamps used on single rivet row

Specimen 3B-2



Specimen 3B-1

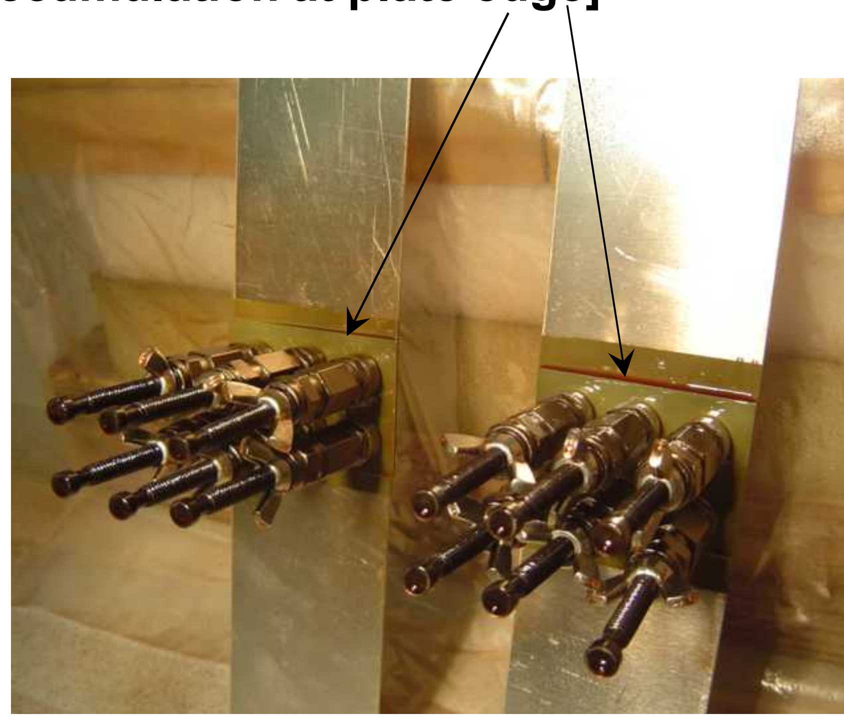
Trial 2 - CIC Cure (Corban-35)

CIC applied to extreme levels:

a) **Cor-35-Cure-1 thru Cor-35-Cure-3: Spray <u>inside</u> of faying surface directly and then assemble panel; [excessive accumulation/pooling on Cor-35-Cure-1 after 5 passes]**

b) **Cor-35-Cure-4 and Cor-35-Cure-5: Spray CIC to excess until it is flowing [10 passes with liquid accumulation at plate edge]**

(a)

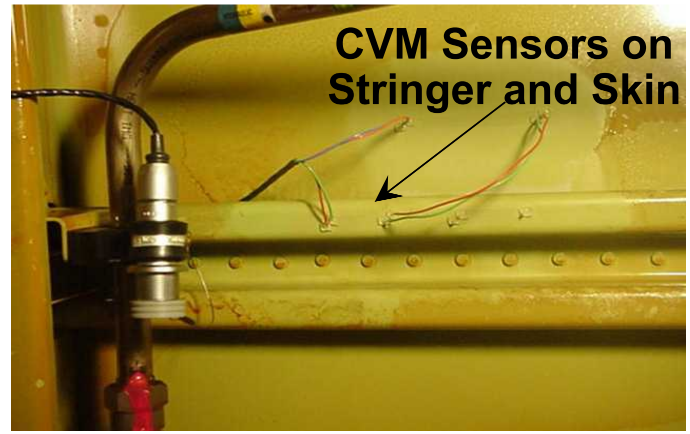


(b)

Part 4 – SHM Flight Testing: Durability & Integration into Maintenance Programs

Delta Air Lines Field Installations

Environmental Durability Testing - To assess the long-term viability of CVM sensors in an actual operating environment, 22 sensors were installed on DC-9, 757 & 767 aircraft for functional evaluation:



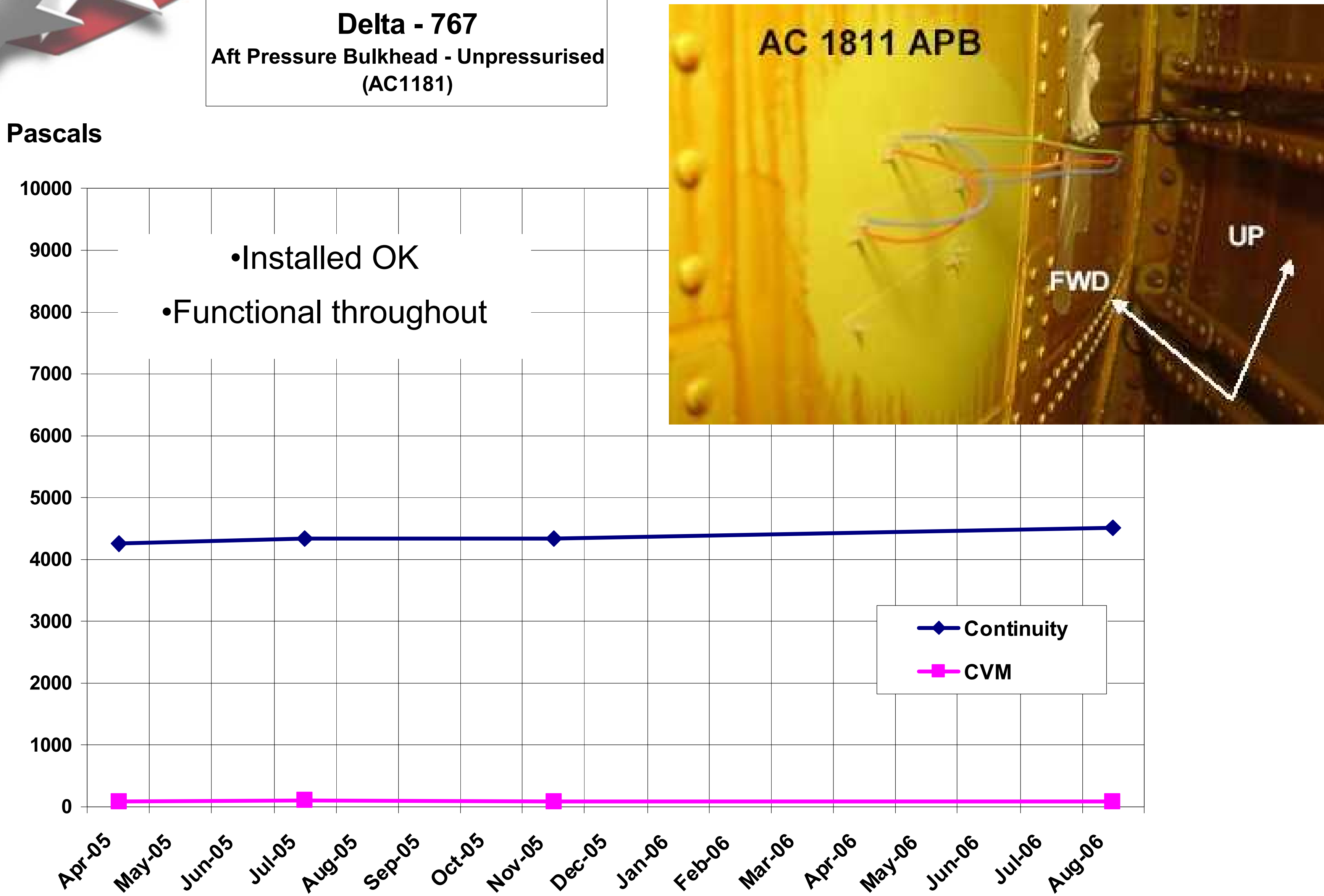
SLS connector routed to access panel

Monitoring CVM

Delta - 767

Aft Pressure Bulkhead - Unpressurised (AC1181)

- Installed OK
- Functional throughout



737NG Center Wing Box – CVM Flight Tests

- **Goal: accumulate successful flight history**
- **CVM sensors installed on 7 aircraft (68 sensors in 7 weeks)**
- **Step through formal process of integrating SHM into airline maintenance program (e.g. management education/approvals, Job Cards, training)**
- **Develop guidelines for safely adopting SHM solutions**

In addition to the lab-based certification tests, a set of 68 sensors were mounted on wing box fittings in seven different B-737 aircraft in the Delta Air Lines fleet. The sensors have been monitored every 90 days for the past 18 months, producing 385 sensor response data points. These flight tests demonstrated the successful, long-term operation of the CVM sensors in actual operating environments. This environmental durability study compliments the laboratory flaw detection testing described below as part of an overall CVM certification effort.

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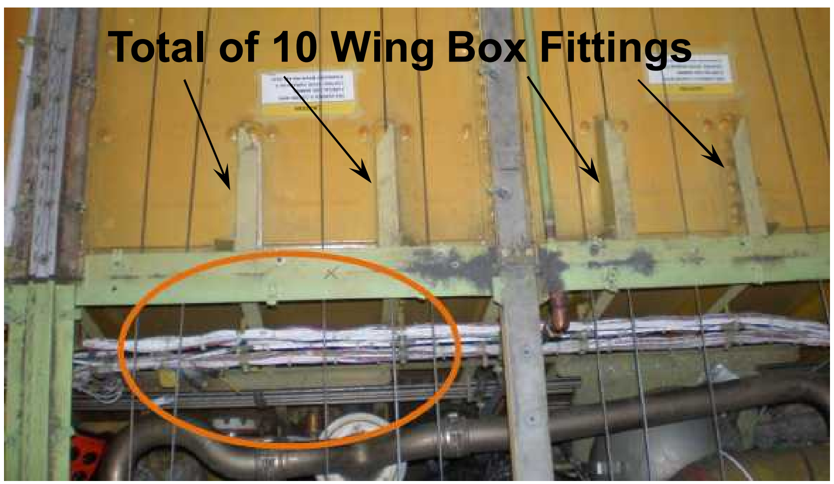
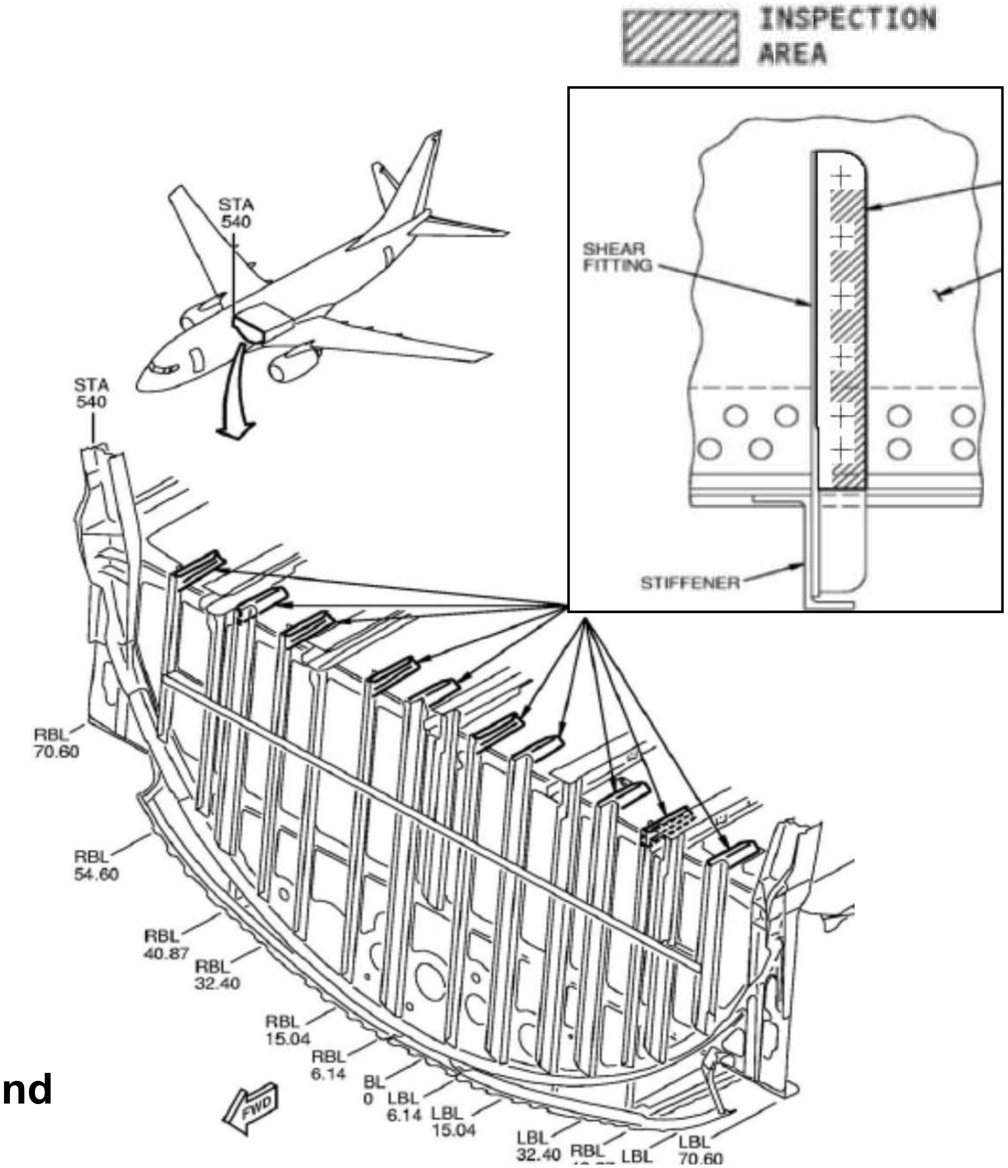
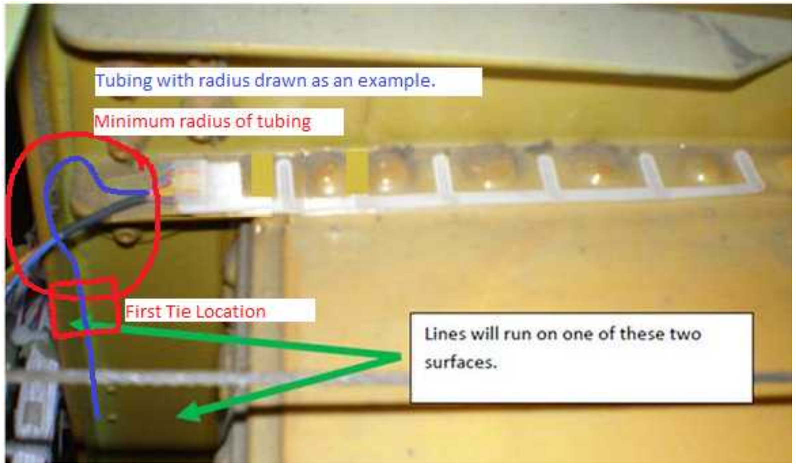
737NG Center Wing Box – CVM Flight Tests



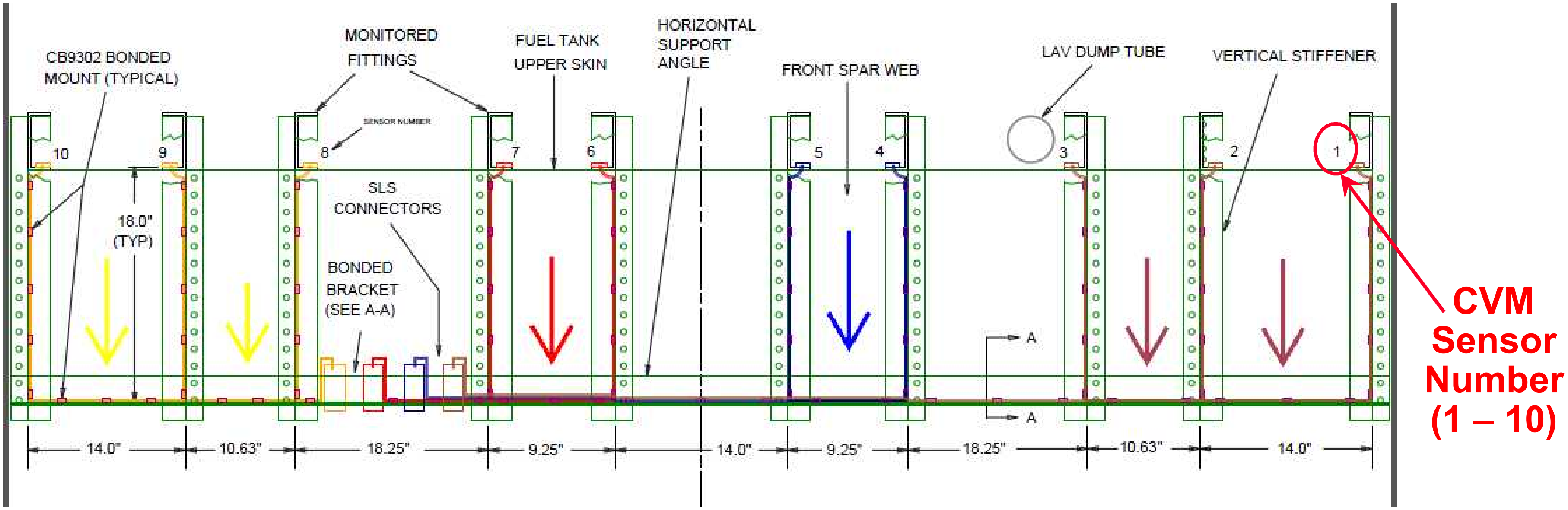
CVM Sensor on 737NG Wing Box Fitting and Top View of SLS Mount Location



737NG Center Wing Box – CVM Installation Layout



Wing Box Fittings with CVM Sensor and Top View of SLS Mount Location



Sensor Layout & Routing Plan to the 4 SLS Connectors

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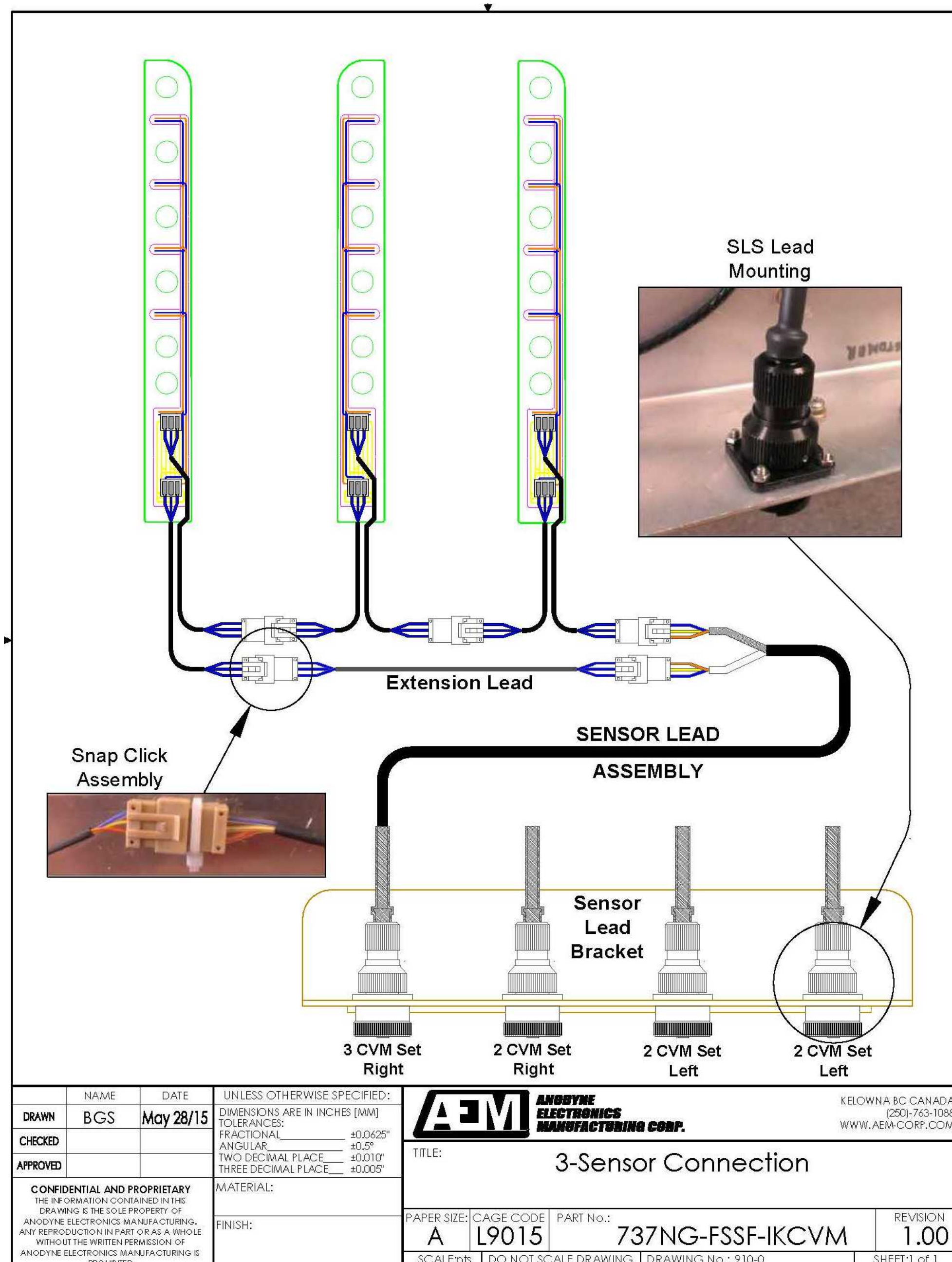
737NG Center Wing Box – Sensor Connection into Groups

CVM Sensors Daisy-Chained into Groups of 3 and Groups of 2 Sensors on Each of the Left and Right Wing Sides = 10 CVM Sensors in Total with 4 SLS Connectors



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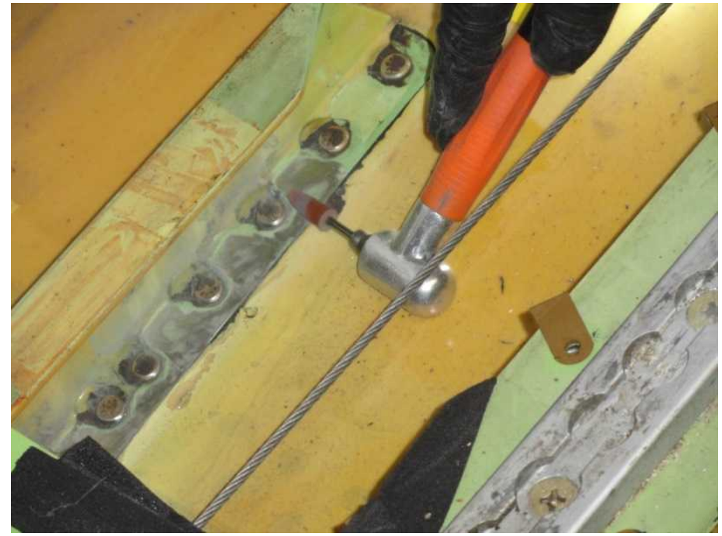
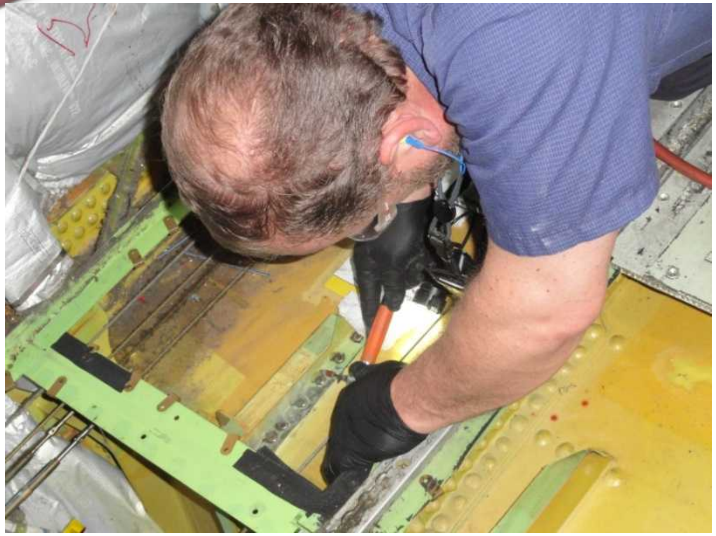
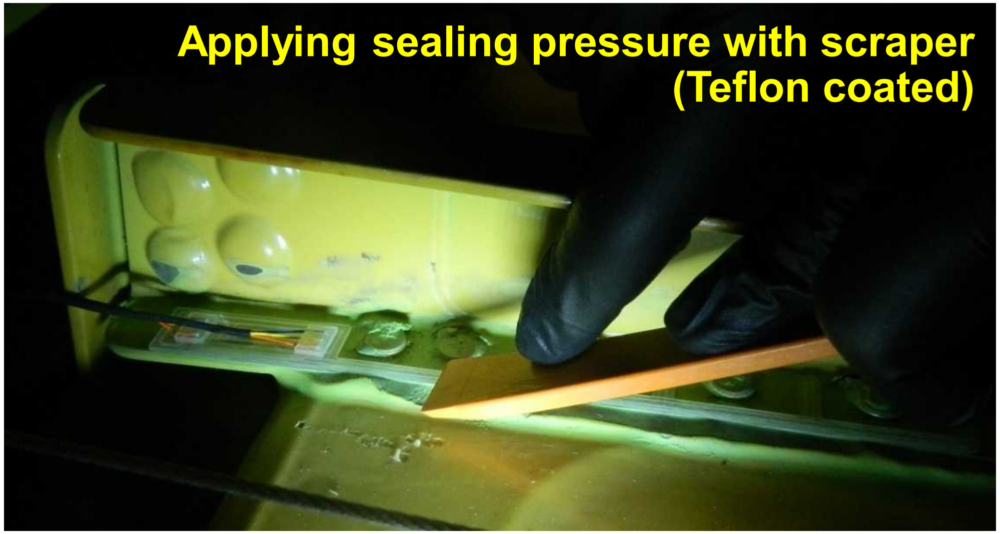
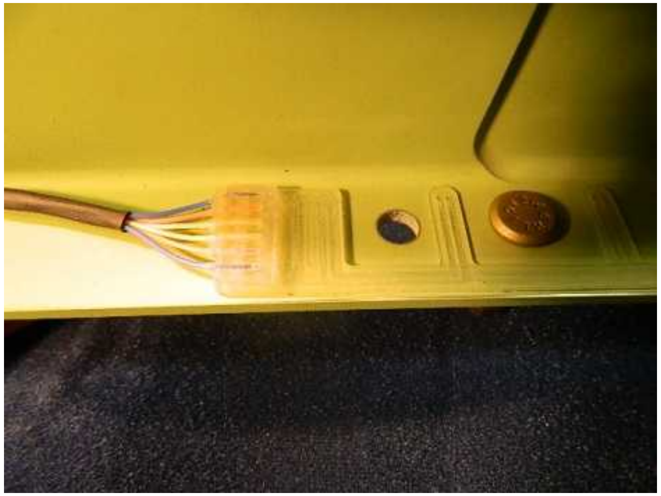
1) Remove rivet head sealant , fuel vapor barrier and primer 2) Inspect for cracks with HFEC, 3) Re-prime surface



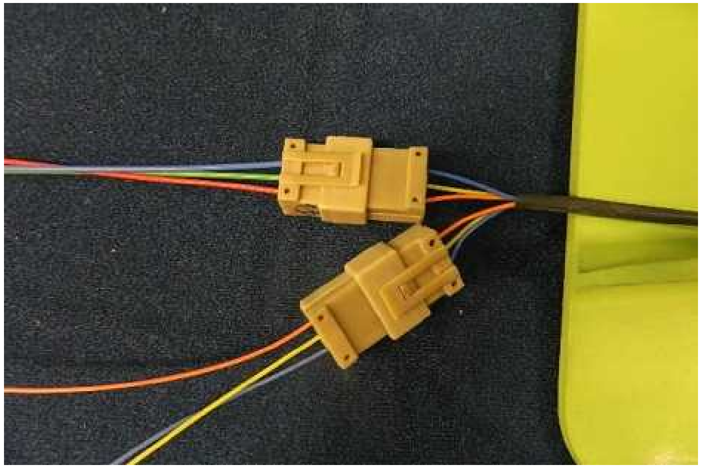
4) CVM surface prep (sandpaper, acetone & deionized water), 5) CVM sensor placement on wing box fittings

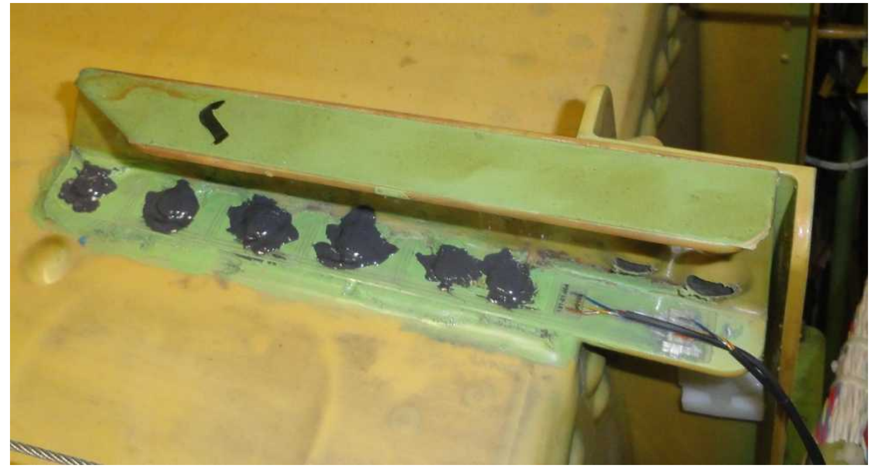


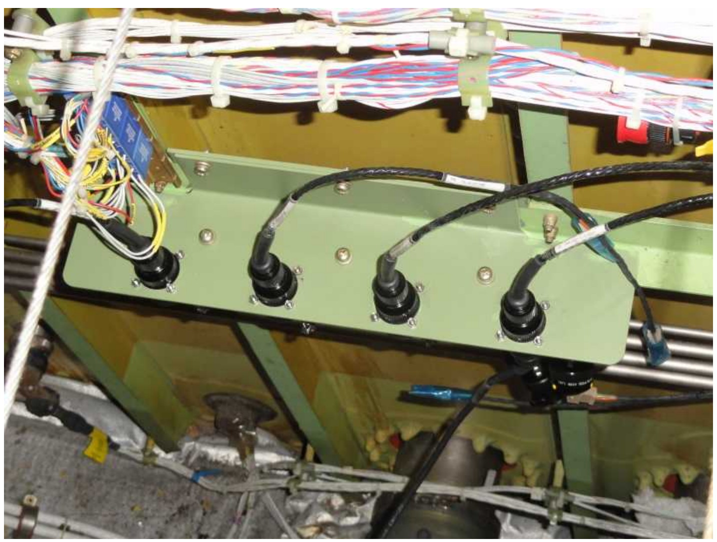




6) Seal CVM to surface & daisy-chain with Snap-Clicks, 7) Reapplication of rivet head sealant and fuel vapor barrier, 8) Installation of SLS connector set







9) Connection of multiple CVM sensors to individual SLS connectors and 10) Monitoring CVM with PM-200 device

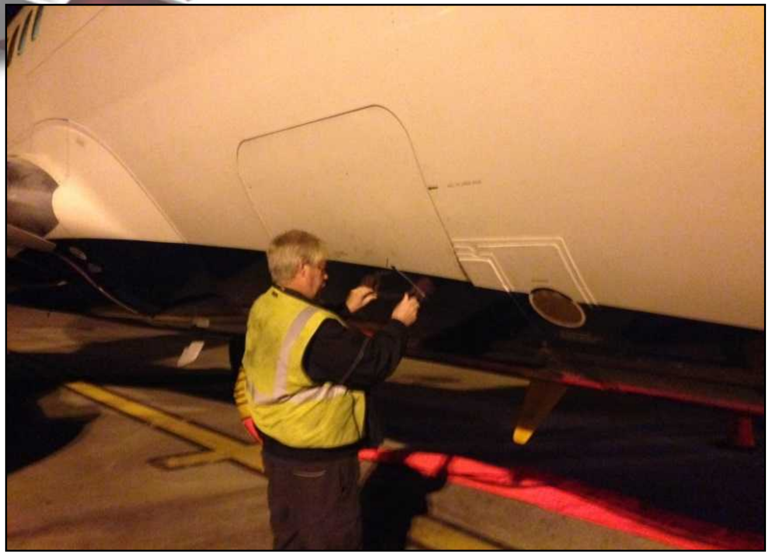
737NG Center Wing Box – CVM Sensor Monitoring

Rapid sensor interrogation with minimum access time allowed many inspections to be completed at the airport gate during overnight parking

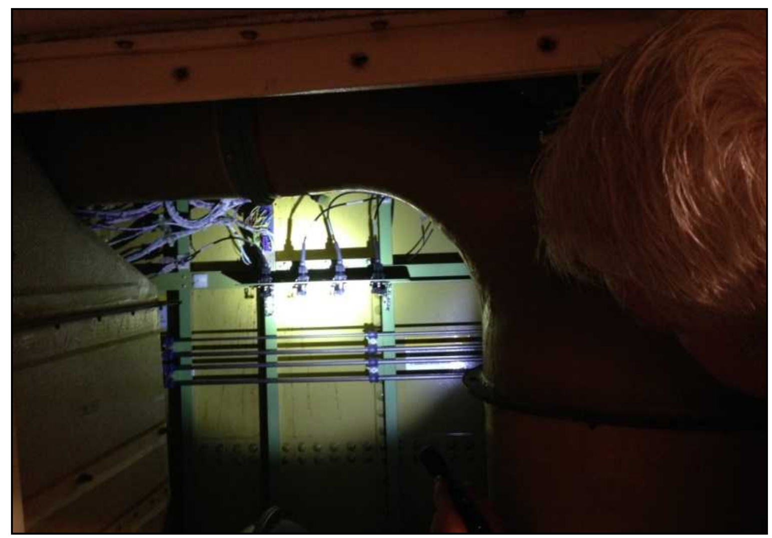
Aircraft Parked at Gate After Final Flight of the Day

Equipment Prep at Delta Depot – Calibration of PM-200

737NG Center Wing Box – CVM Sensor Monitoring

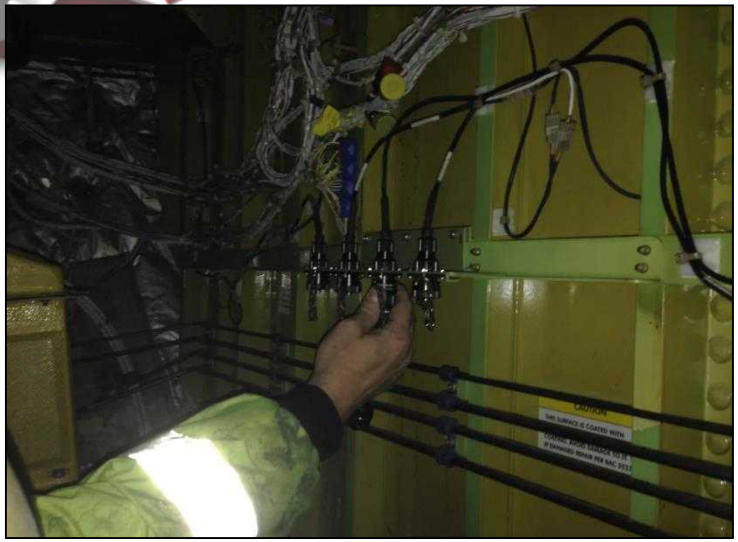


Access to SLS Connectors Through Forward Baggage Compartment

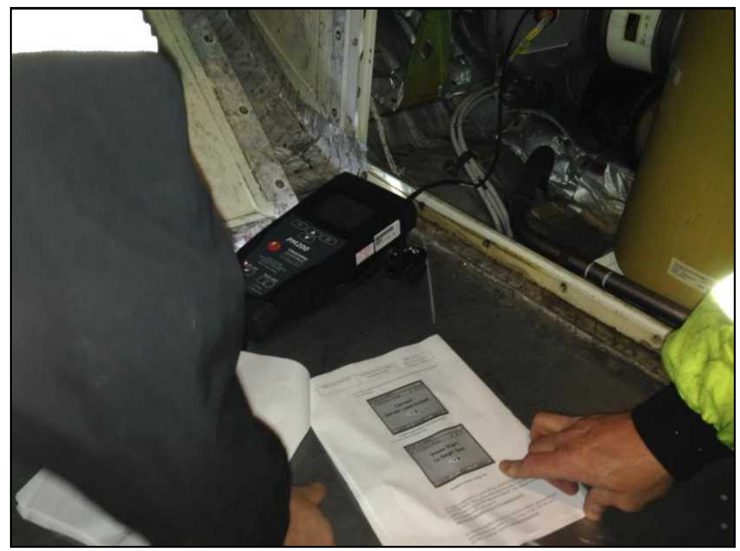


Removal of Baggage Liner to Access 4 SLS Connectors Mounted to Bulkhead

737NG Center Wing Box – CVM Sensor Monitoring



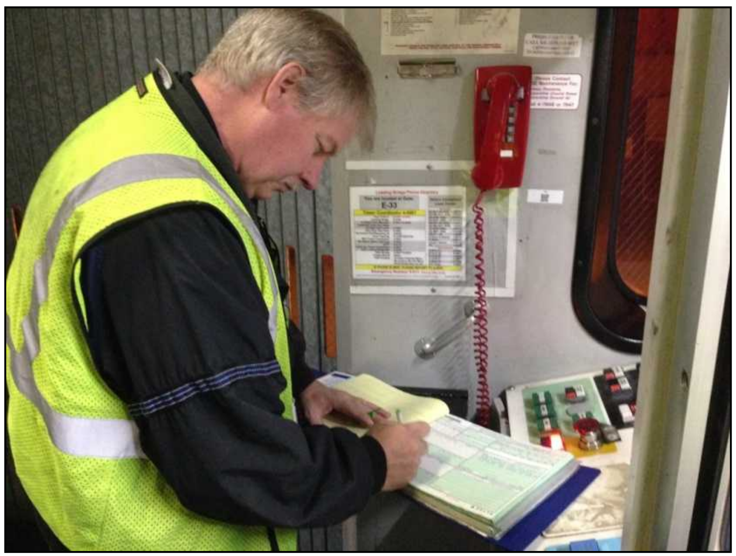
Connecting SLS Leads from PM-200 to On-Board SLS Connectors



Running PM-200 Monitoring Device to Measure dCVM Levels of Each Sensor Group

737NG Center Wing Box – CVM Sensor Monitoring

Reinstallation of Forward Baggage Liner and Close-Up of Compartment



Logging Inspection Completion at Aircraft Gate

737NG Center Wing Box – CVM Flight Test Data

- Sensors installed on 7 aircraft in Delta fleet (A/C #3601 to #3607)
- Repetitive inspections conducted every 90 days
- Goal - produce a data package with 1 to 1.5 years of monitoring (5-7 readings after installation).
  - Flight test CVM data (desired data is 5 checks for a total of 70 sensors X 5 checks = 350 data points)
  - Combine flight test data with lab performance data
- Review by Boeing ARs and presented to the FAA for approval
  - Current requirement is a visual inspection (assume DVI = 2” long crack)
    - Sensor fingers placed between fasteners ~ 0.5” crack detection

** Note: Any CVM sensor failure is a Fail-Safe Failure (false call) which will induce a site visit for eddy current inspection for confirmation.

737NG Center Wing Box – CVM Flight Test Data

- **Fail-safe check – want continuity (flow) high = no gallery blockage**
- **Crack detection: if dCVM (vacuum) is low = no crack**

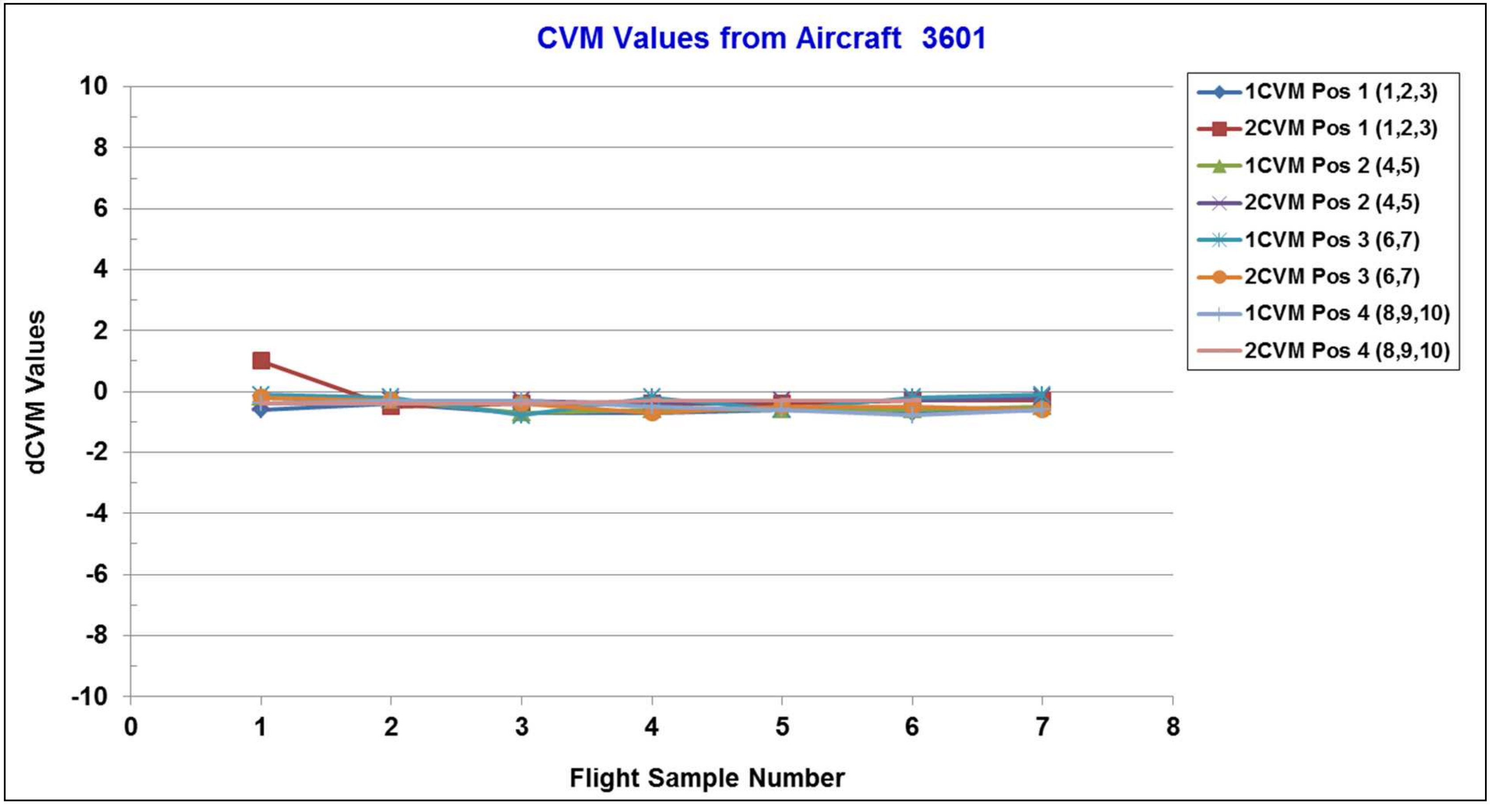
Summary of Data Acquired During Delta Air Lines Flight Test Program

Aircraft	CVM Readings (Number of Monitors)	Number of Sensors at Beginning	Number of Sensors at End	Number of Data Points	Date Range for Flight Operation	Duration of Monitoring	Notes
3601	7	10	9	65	2/14 to 6/15	15 months	Sensor failed at 2nd check (6 months)
3602	6	9	9	54	2/14 to 4/15	14 months	No time to replace faulty CVM installation (9 sensors)
3603	5	10	10	50	3/14 to 5/15	14 months	All sensors functioned throughout
3604	5	10	9	46	3/14 to 3/15	12 months	Sensor failed at first check - faulty CVM installation
3605	6	9	9	54	3/14 to 8/15	17 months	No time to replace faulty CVM installation (9 sensors)
3606	6	10	9	56	3/14 to 5/15	14 months	Sensor failed at 2nd check (6 months)
3607	6	10	10	60	4/14 to 10/15	18 months	All sensors functioned throughout

- **Aircraft were available for 1 ½ to 2 days during a 7 day check for sensor installation**
- **Two instances where faulty sensor installations occurred with no remaining time to remove and install new sensor – sensors were removed from data acquisition plan; all others were monitored**
- **Post-installation failures occurred on 3 aircraft (1 sensor each)**
- **Failure rate (excluding initial faulty installations) = 4.4% (65 out of 68 sensors functioning)**
- **Failure rate = 3% (if A/C 3604 sensor, believed to also be faulty install, is removed)**
- **Total data points acquired = 385 (out of a possible 398) = 96.7% data success rate**

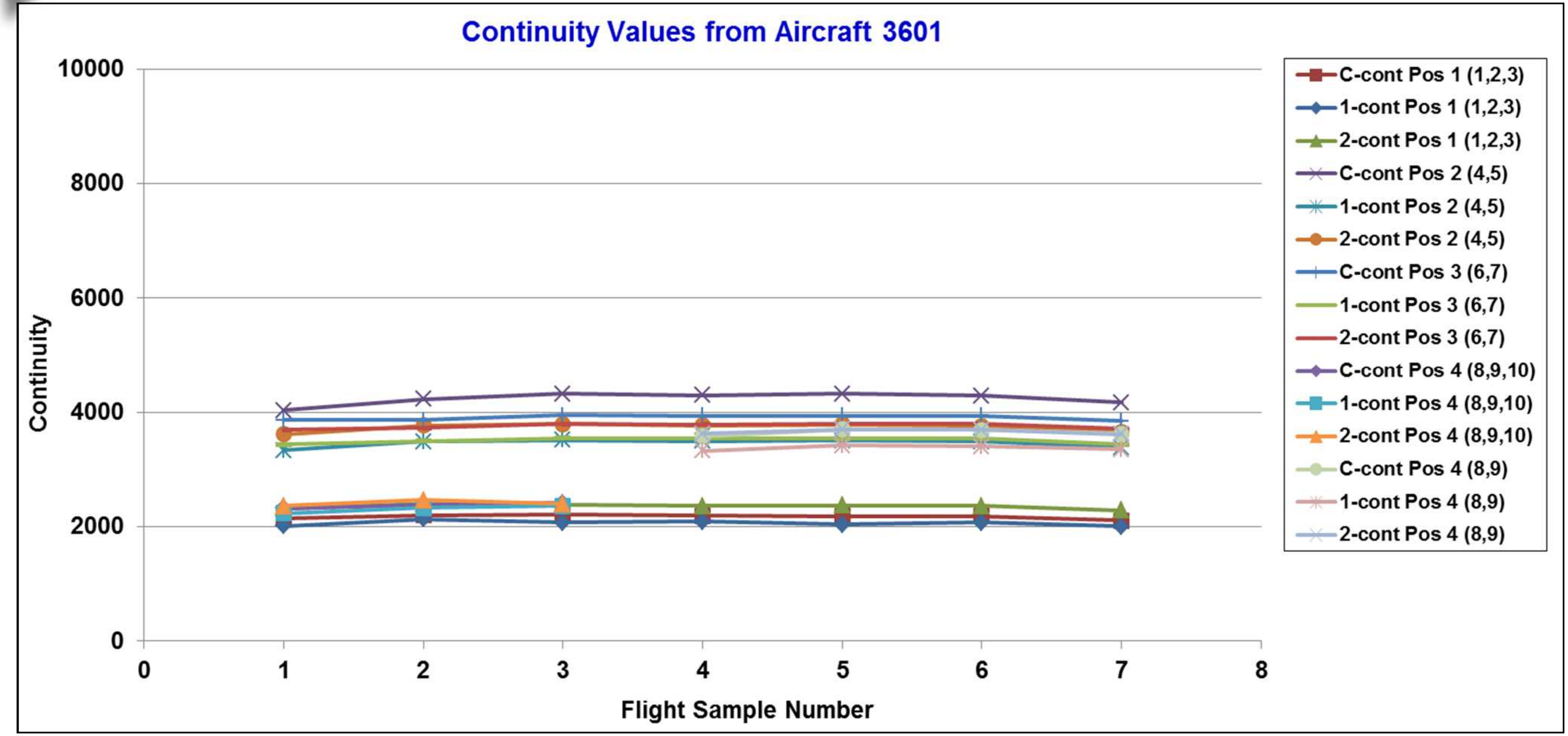
- **CVM failures are believed to be attributable to the difficult installation coupled with challenging surface prep (due to existing coatings) and access time constraints**
- **Spray-on primer was substituted for the paint-on primer which left an uneven surface for sealing CVMs**

CVM Flight Test Data – A/C 3601



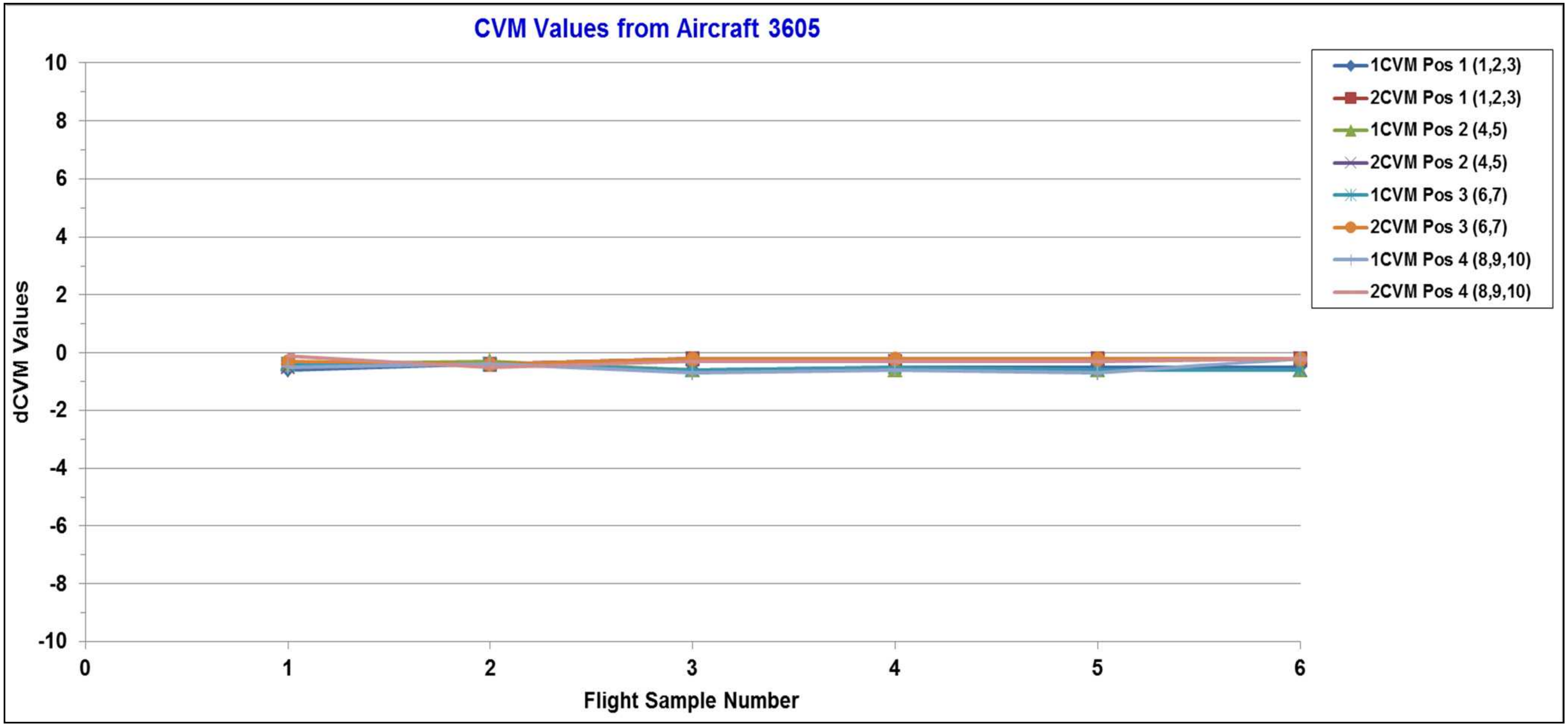
AC3601 Sensor CVM Readings

CVM Flight Test Data – A/C 3601



AC3601 Sensor Continuity Check

CVM Flight Test Data – A/C 3605



AC3605 Sensor CVM Readings

737 NDT Manual - New SHM Chapter Published (Nov 2015)

Building Block to Approval for Routine Use of SHM

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- FRONT MATTER
- PART 01 - GENERAL
- PART 02 - X-RAY
- PART 04 - ULTRASONIC
- PART 05 - COMPARATIVE VACUUM MONITORING
- PART 06 - EDDY CURRENT
- PART 09 - THERMOGRAPHY
- PART 10 - VISUAL/OPTICAL

Changed to

PART 05 – STRUCTURAL HEALTH MONITORING

737 NDT Manual – CVM Procedure Added

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NON-DESTRUCTIVE TEST MANUAL

PART 5 - COMPARATIVE VACUUM MONITORING

WING CENTER SECTION - SHEAR FITTINGS AT THE FRONT SPAR

1. Purpose
   - A. Use this comparative vacuum monitoring (CVM) procedure to help find cracks in the 111A2401-1 and -2 shear fittings at the front spar of the wing center section. See Figure 1 for the inspection areas.
   - B. This procedure can find cracks that are 0.75 inch (19.1 mm) long or longer.
   - C. The shear fittings are 7050-T7451 aluminum alloy.
   - D. Service Bulletin Reference:
     - (1) 737-57-1309
2. Equipment
   - A. General
     - (1) Comparative vacuum monitoring (CVM) is a structural health monitoring (SHM) system. The CVM system measures the different pressures between sensor galleries that have a vacuum or are at atmospheric pressure to find cracks in parts. See Figure 2 for some examples of CVM equipment.
     - (2) Use the equipment specified in this inspection procedure to do this procedure.
   - B. Instrument
     - (1) PM200; Structural Monitoring Systems (SMS)
   - C. Functional Test Socket
     - (1) PM200-9 or SP1131; Structural Monitoring Systems (SMS)
   - D. Comparative Vacuum Monitoring kit
     - (1) 737NG-FSSF-1KCVM CVM Installation Kit; Structural Monitoring Systems (SMS)
   - E. Software
     - (1) PM200 Management Software version 0.0.3276 or newer
   - F. Special Tools
     - (1) Consumables kit. See set up file: Part 5, 57-10-01 List of Necessary Materials
3. Prepare for the Inspection
   - A. See Set Up File Part 5, 57-10-01, for the List of Necessary Materials.
   - B. See Set Up Files Part 5, 57-10-01, CVM installation instructions for the instructions that follow:
     - (1) Prepare the surface of the 111A2401-1 and -2 shear fittings for inspection.
     - (2) Install the CVM sensors onto the shear fittings.
     - (3) Install the CVM leads.
     - (4) Install four sensor lead sockets (SLS) on the (SLS) bracket.
4. Instrument Calibration and Functional Test

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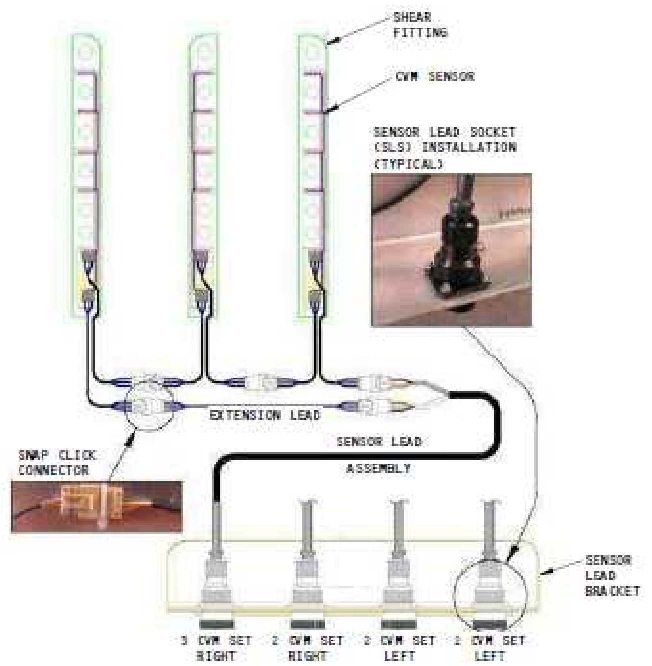
NON-DESTRUCTIVE TEST MANUAL



737 NDT Manual – CVM Installation Instructions Added (Jan 2016)

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PART 05 - COMPARATIVE VACUUM MONITORING

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- [x] PART 05, FRONT MATTER
- [x] SECTION 57-10, MAIN FRAME

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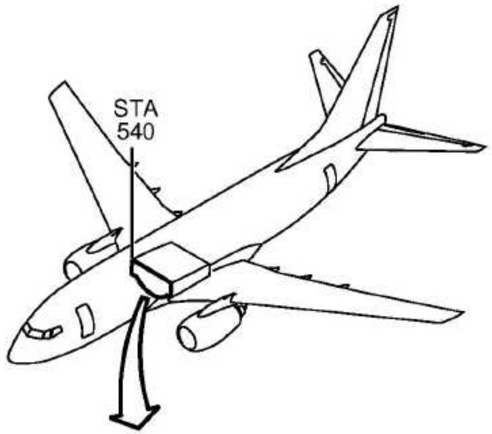
Release 20. (Build 30) (boldwp2)

Installation Instructions

Boeing Service Bulletin – Modification to Allow for Routine Use of SHM Solution (June 2016)



DO A DETAILED INSPECTION OR COMPARATIVE VACUUM MONITORING (CVM) 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.

AT EACH SHEAR FITTING, IF NO CRACKING IS FOUND IT IS OPTIONAL TO ACCOMPLISH THE PREVENTIVE MODIFICATION BY REPLACING THE SHEAR FITTINGS.

BOEING SERVICE BULLETIN 737-57-1309

BOEING Commercial Airplanes

737
Service Bulletin

Number: **737-57-1309**
Original Issue: January 28, 2011
Revision 1: June 27, 2016
ATA System: 5714

Revision Transmittal Sheet

SUBJECT: WINGS - Center Wing Box - Front Spar Shear Fitting - Inspection, Repair and Preventive Modification

This revision includes all pages of the service bulletin.

COMPLIANCE INFORMATION RELATED TO THIS REVISION

Effects of this Revision on airplanes on which Original Issue was previously done:

None.

REASON FOR REVISION

This revision is sent to add a Comparative Vacuum Monitoring (CVM) inspection as an alternative inspection method for the front spar shear fitting. In addition, illustrations in figures are changed to show correct views, footnotes are added in fastener tables for clarification and footnotes in figures are changed to clarify sealing instructions.

Validation of CVM Sensors for SHM Crack Detection

- Recent advances in health monitoring methods have produced viable systems for on-board aircraft inspections
- Early detection = less costly repairs
- Sensors must be low-profile, easily mountable, durable, reliable & fail-safe
- Calibration for flaw identification (damage signatures) is key
- Reliability/POD assessments depends on sensor system, flaw type/orientation and application
- One-sided tolerance interval can be used to calculate POD for certain circumstances (known flaw location and flaw direction)
- Monitoring process & diagnosis is fully automated (green or red light)
- Approval and Certification –
  - ➢ Successful integration of SHM into OEM manuals
  - ➢ AMOC for SBs and ADs or STCs – safety driven use is achieved in concert with OEMS & regulatory agencies
  - ➢ Forms of certification & regulatory framework have been established

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
- Actual application on commuter (CRJ) aircraft successful
- CVM system is fail-safe (inert sensors produce an alarm)
- CVM sensors - lab performance assessment (sensitivity/POD and durability) & multi-year flight test program have been completed
- Integration of CVM tool in NDT Standard Practices Manuals completed
- Addition of SHM Chapter in Boeing NDT Manual with CVM use as first entry
- Modification of Boeing Service Bulletin to allow for first routine use of SHM on commercial aircraft
- Ease of monitoring sensor network - structural health assessments can occur more often, allowing operators to be even more vigilant with respect to flaw onset (less invasive repairs)
- Evolution of an SHM certification process, including the development of regulatory guidelines and advisory materials for the implementation of SHM systems.

OVERVIEW

FAA Webinar Series on Structural Health Monitoring

Module 3 – Integration of SHM into Airline Maintenance Programs

Part 1 – SHM Adoption: Motivation for Airlines
Part 2 – SHM Implementation at Airlines: Maintenance Program Logistics
Part 3 – SHM Equipment: Quality Assurance and Calibration
Part 4 – SHM Adoption by Airlines: Considerations and Lessons Learned
Part 5 – Future Prospects for SHM at Airlines

Delta Air Lines - Operator Perspective

- **Vision for SHM usage at Delta**
  - — Initially: alternate inspections of difficult to access areas.
    - Inconvenient MTC visits.
    - Hotspot monitoring – AMOCs.
  - — Medium term:
    - Early warning of issues.
  - — Future: Condition Based MTC & Crack Monitoring.
    - 'Smart Signal' for engines.
    - OEM Support.

- **Two main hurdles to implementation.**
  - — Business Cases (payback).
  - — Lack of regulatory guidance, education.
- **Solution: FAA program with Delta for SHM implementation.**
  - — Delta & Sandia Labs will write the experience-based guidance for SHM certification.
- **G-11 SHM => ARP 6461**

SHM is the next level of NDT = it's coming soon

Validation of a Structural Health Monitoring (SHM) System and Integration Into an Airline Maintenance Program