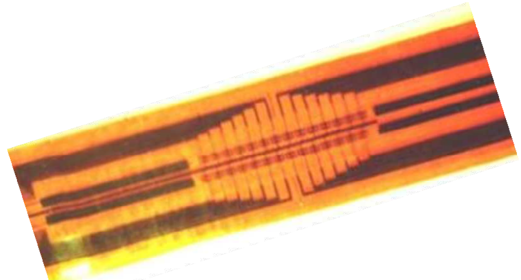
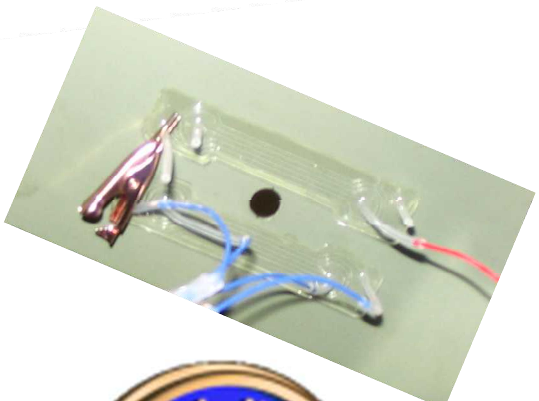
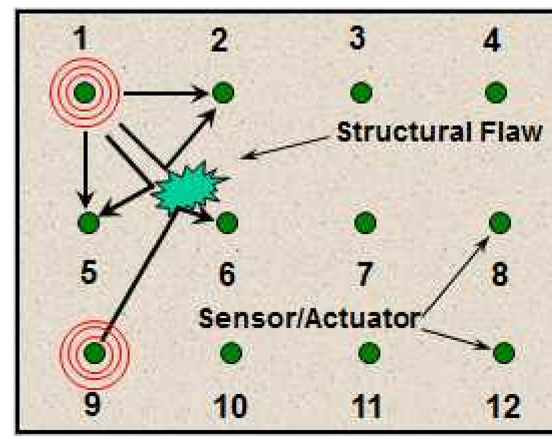
Calculating Probability of Detection for SHM Systems Using One-Sided Tolerance Intervals – Applications & Limitations

SAND2015-3998PE







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Structural Health Monitoring – Integration into Routine Maintenance

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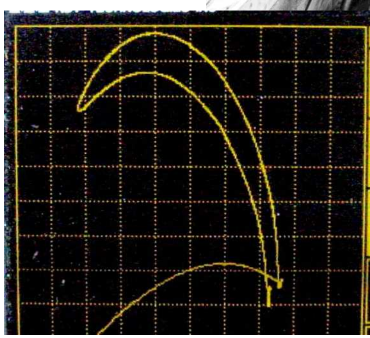
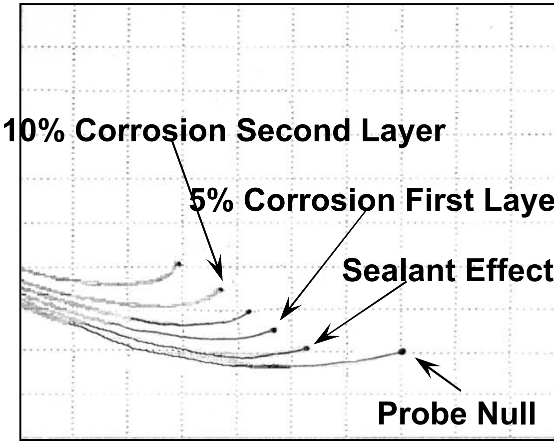
Typical A-Scan Signals Used for Flaw Detection with Hand-Held Devices

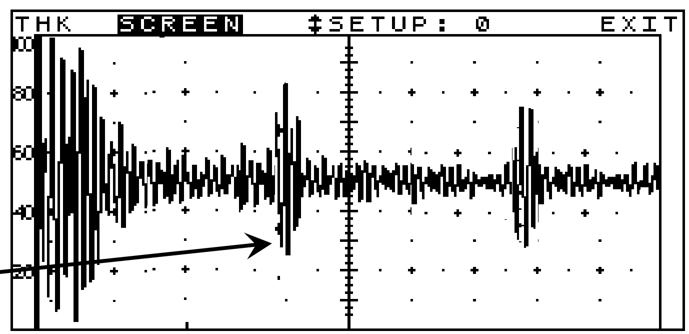


Eddy Current Signal at Crack Site



Corrosion Detection with Dual Frequency Eddy Current

Intermediate Echo Caused by Delamination

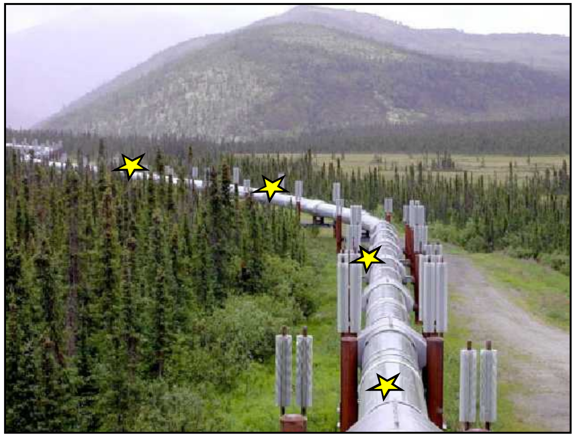


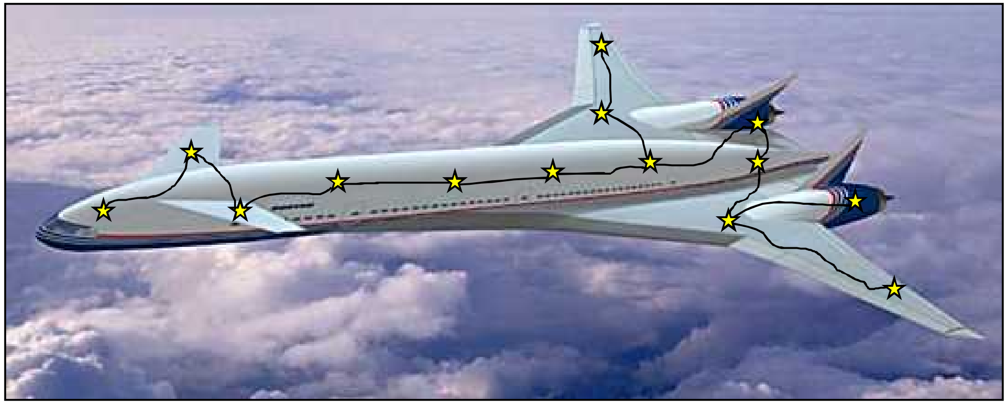
Ultrasonic Pitch-Catch UT Signals Comparing Flawed and Unflawed Signatures

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

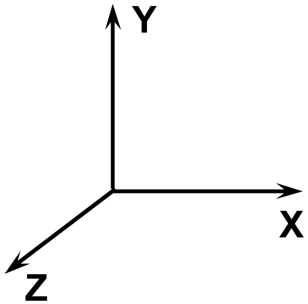
- Remotely monitored sensors allow for condition-based maintenance
- Automatically process data, assess structural condition, & signal need for maintenance actions
- SHM for:
  - Flaw detection
  - Flaw location
  - Flaw characterization
  - Condition Based Maintenance



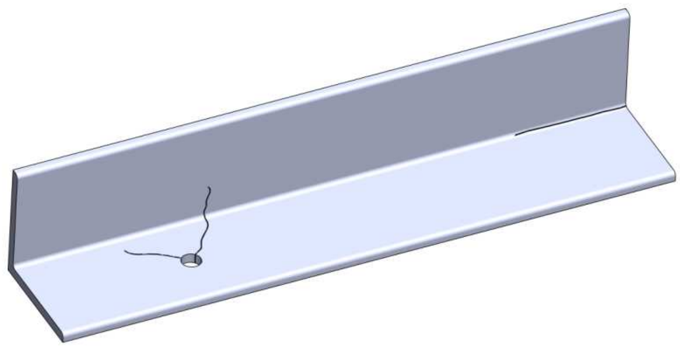


Reliability Assessment for Simple and Complex SHM Solutions

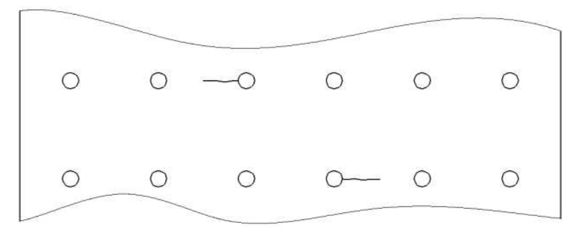
Complex Flaw Orientation



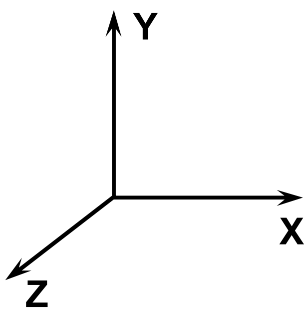
A. Crack with multiple growth paths in complex geometry

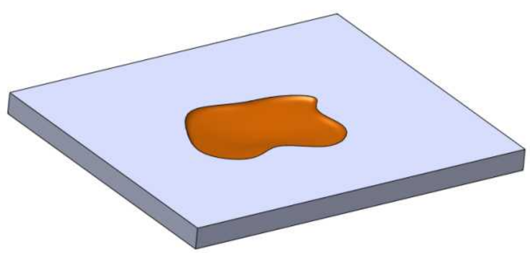


B. Crack with single, known crack direction in simple geometry



Complex Flaw Profile



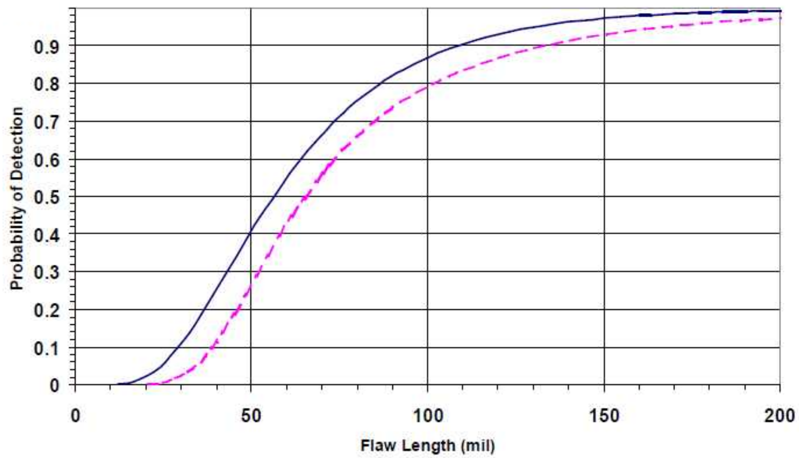


Example: corrosion size, shape and depth variations

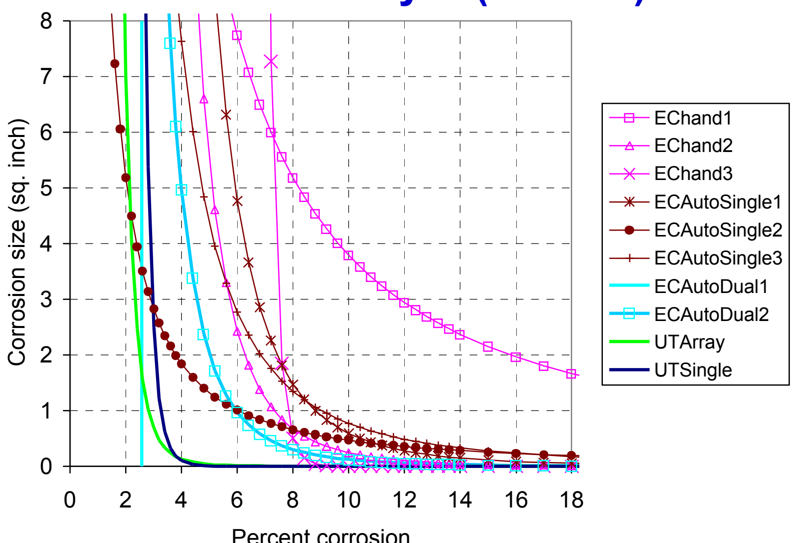
Analysis for one-dimensional entity simplifies significantly

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

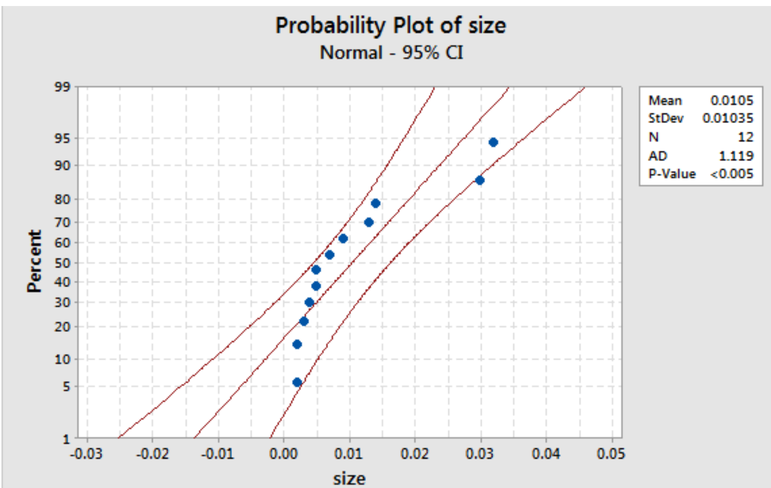
- Interval to cover a specified proportion of a population distributed with a given confidence – related to measures of process capability
- One-Sided Tolerance Interval – estimates the upper bound which should contain a certain percentage of all measurements in the population with specified confidence
- Since it is based on a sample of the entire population (n data points), confidence is less than 100%. Thus, it includes two proportions:
  - Degree of confidence (95%)
  - Percent coverage (90%)
- 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.

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

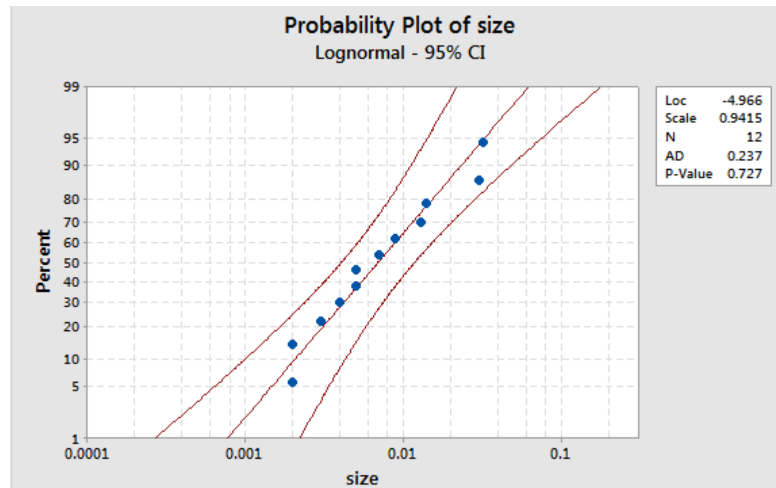
- Interested in a 1-tailed interval (utilize "+" in equation); upper limit of TI; Uncertainty in knowing the true mean and population variance requires that the estimate of the range of values encompassing a given percentage of the population must increase to compensate

POD Assessment Using One-Sided Tolerance Interval

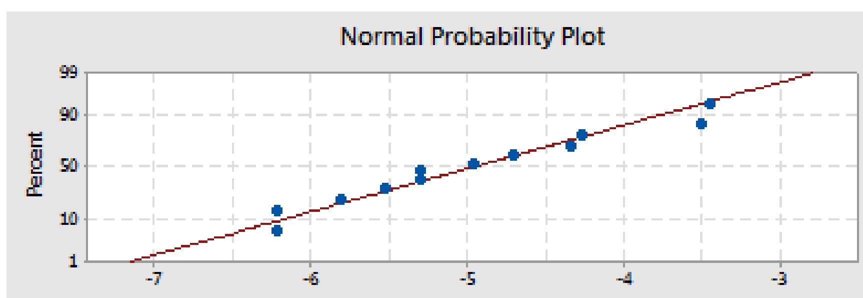
- Assume that the distribution of flaws is such that the logarithm of the lengths (strictly positive sizes) has a Gaussian distribution (log-normal distribution)
- Validity depends on distribution on the flaw lengths at which detection is first made – lognormal distribution plots on straight line with 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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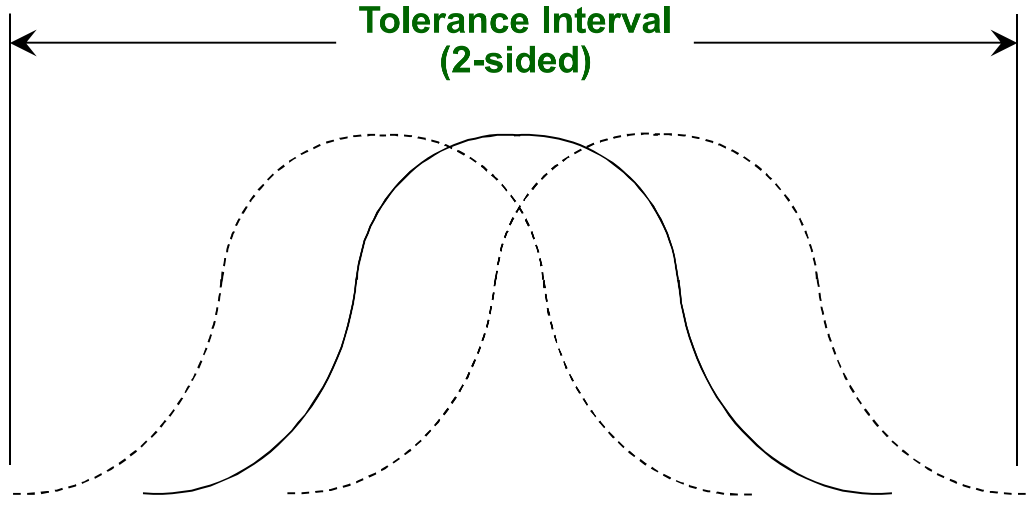
POD Assessment Using One-Sided Tolerance Interval

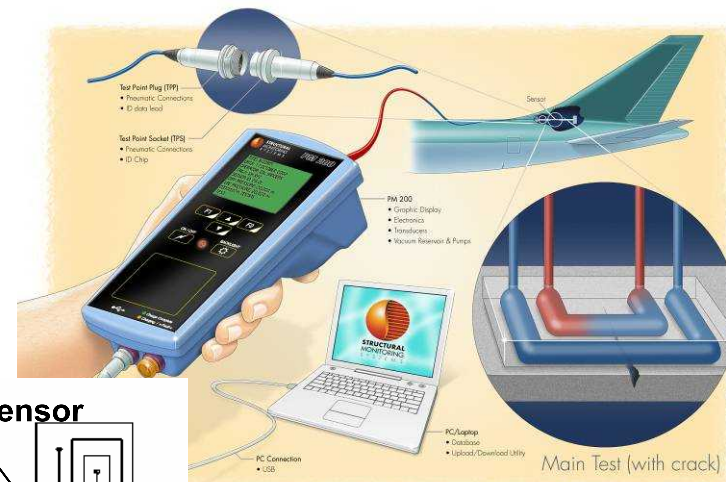
- Used to indicate values at which certain compliance is met
- Capability of the process is determined not only by the location of the sample mean but also by the tail areas of the distribution
- EPA recommends at least 8 points to calculate TI (vs. 51 flaws in a binary data POD) – gage entire population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



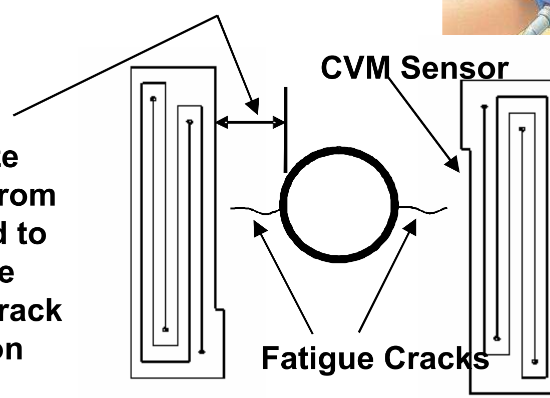
Solid Line = Population Distribution
Dotted Line = Uncertainty of Population Mean

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



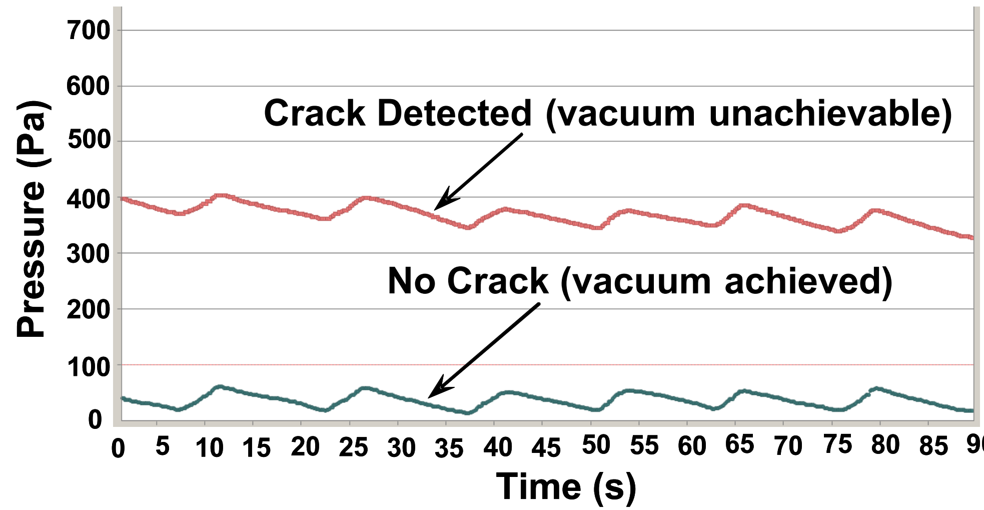
Minimize distance from rivet head to produce smallest crack detection

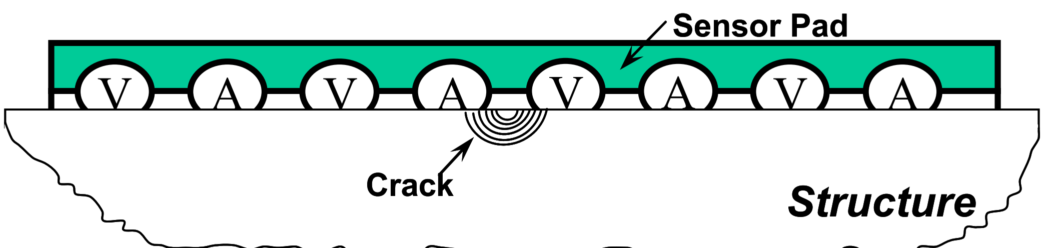


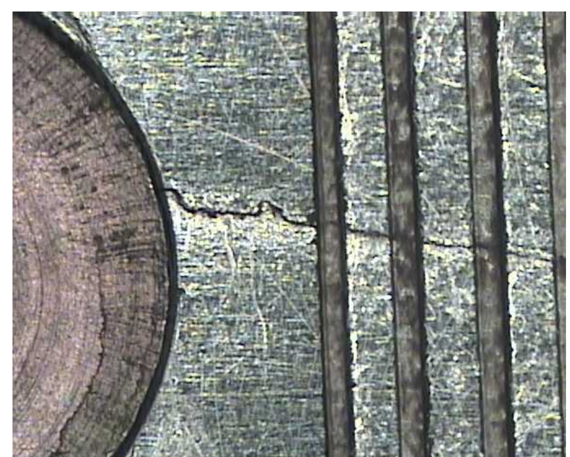
Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries (crack detection ~ 0.1” to 0.5” L for thick steel)
- 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







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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

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

ɣ = 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

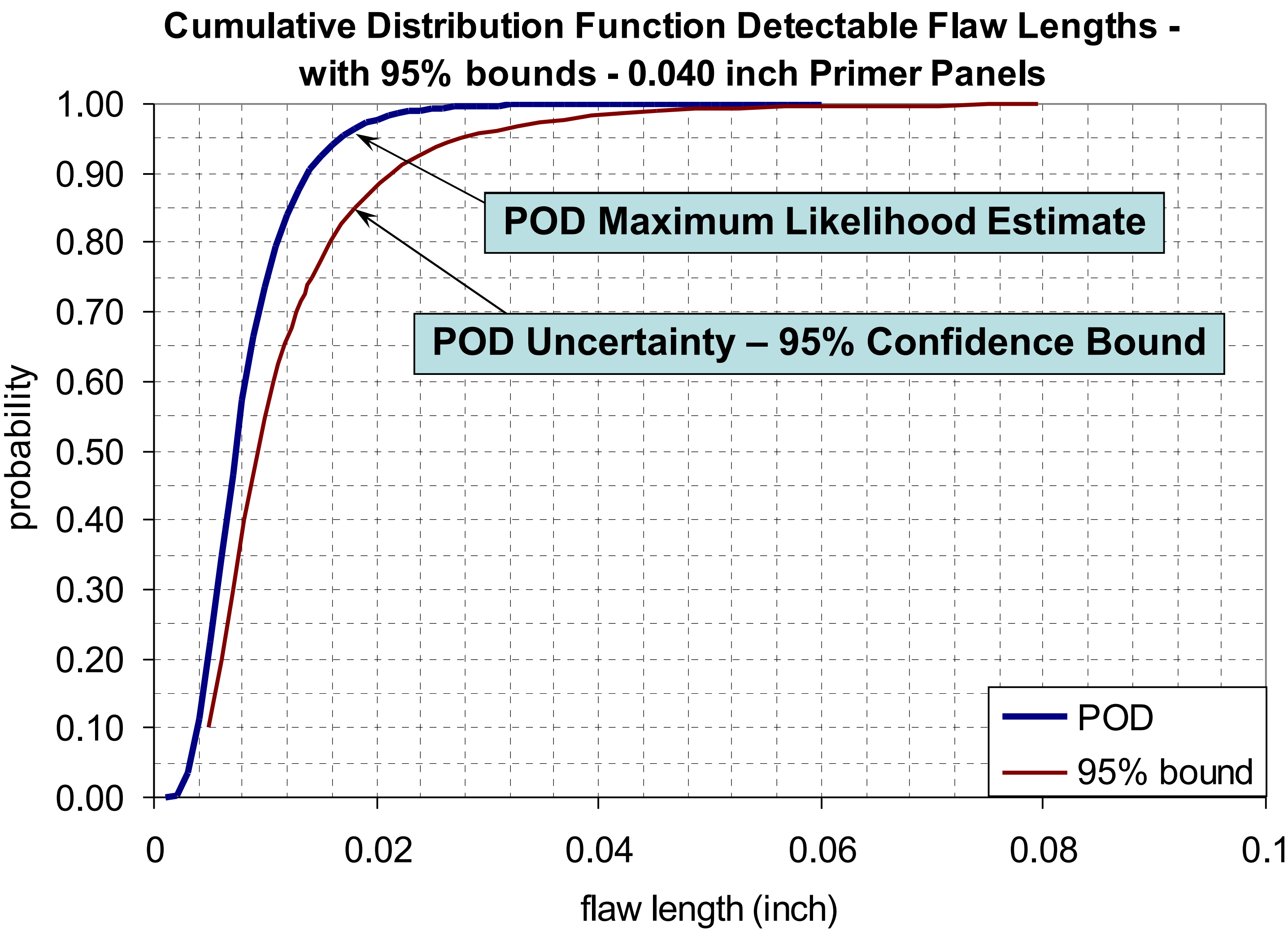
POD Detection Levels
(γ = 95%, n = 12 for bare, n=10 for primer)

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 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*

Sample Probability of Detection Curves for CVM



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]

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.

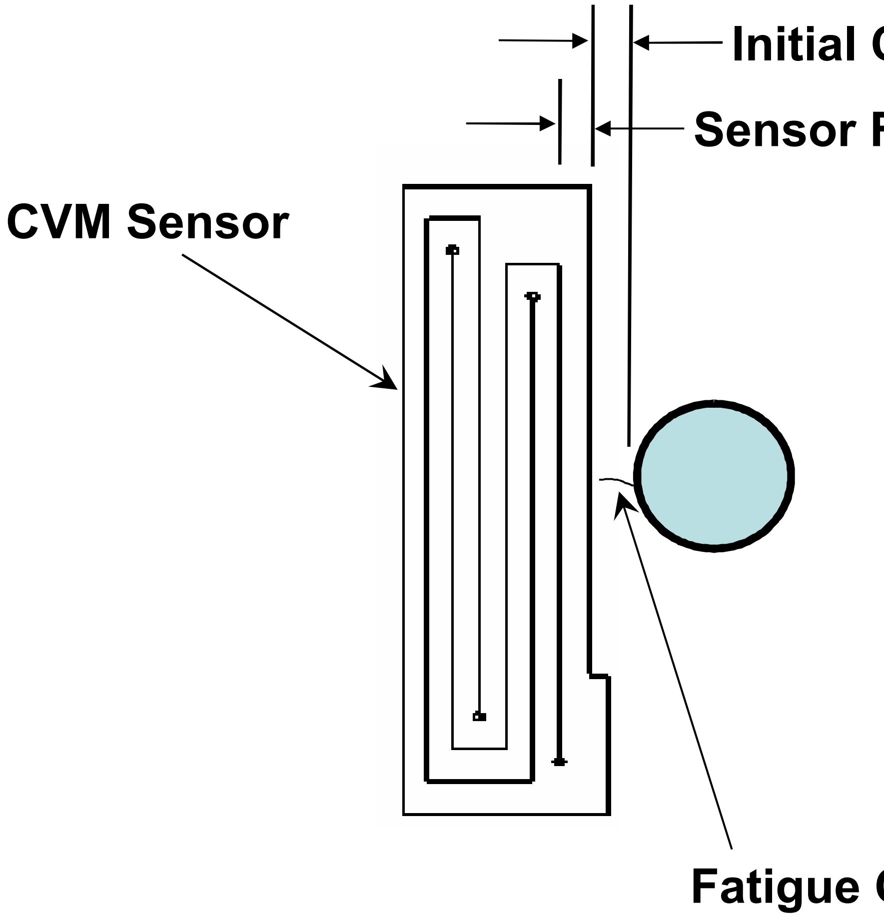
PHASE 2 TESTS

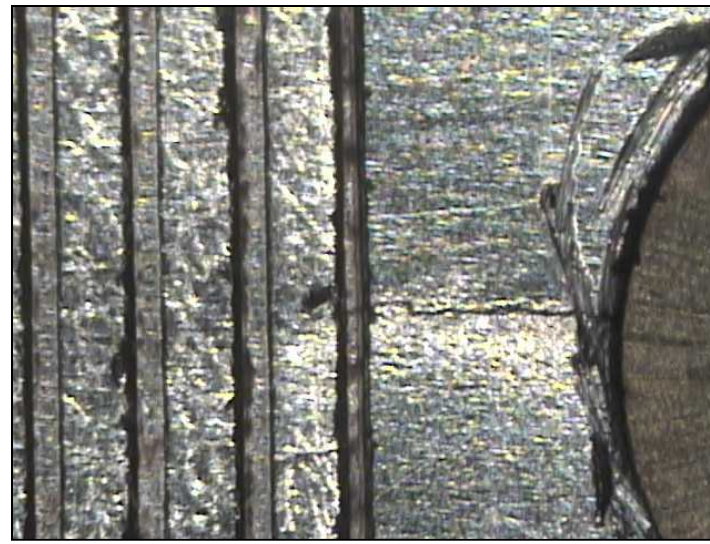
Panel	Fastener Crack Site	Distance from Fastener (inches)	Crack Length at CVM Detection (growth after install in inches)	SIM-8 Reading ΔPa (Pasm)	PM-4 Read-out	PM-4 Indicate Crack (Y or N)
1001	5L	0.350	0.065	773-825	1713	Y
1001	7R	0.206	0.054	697-722	1768	Y
1001	8R	0.115	0.060	560-600	1609	Y
1003	8L	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]

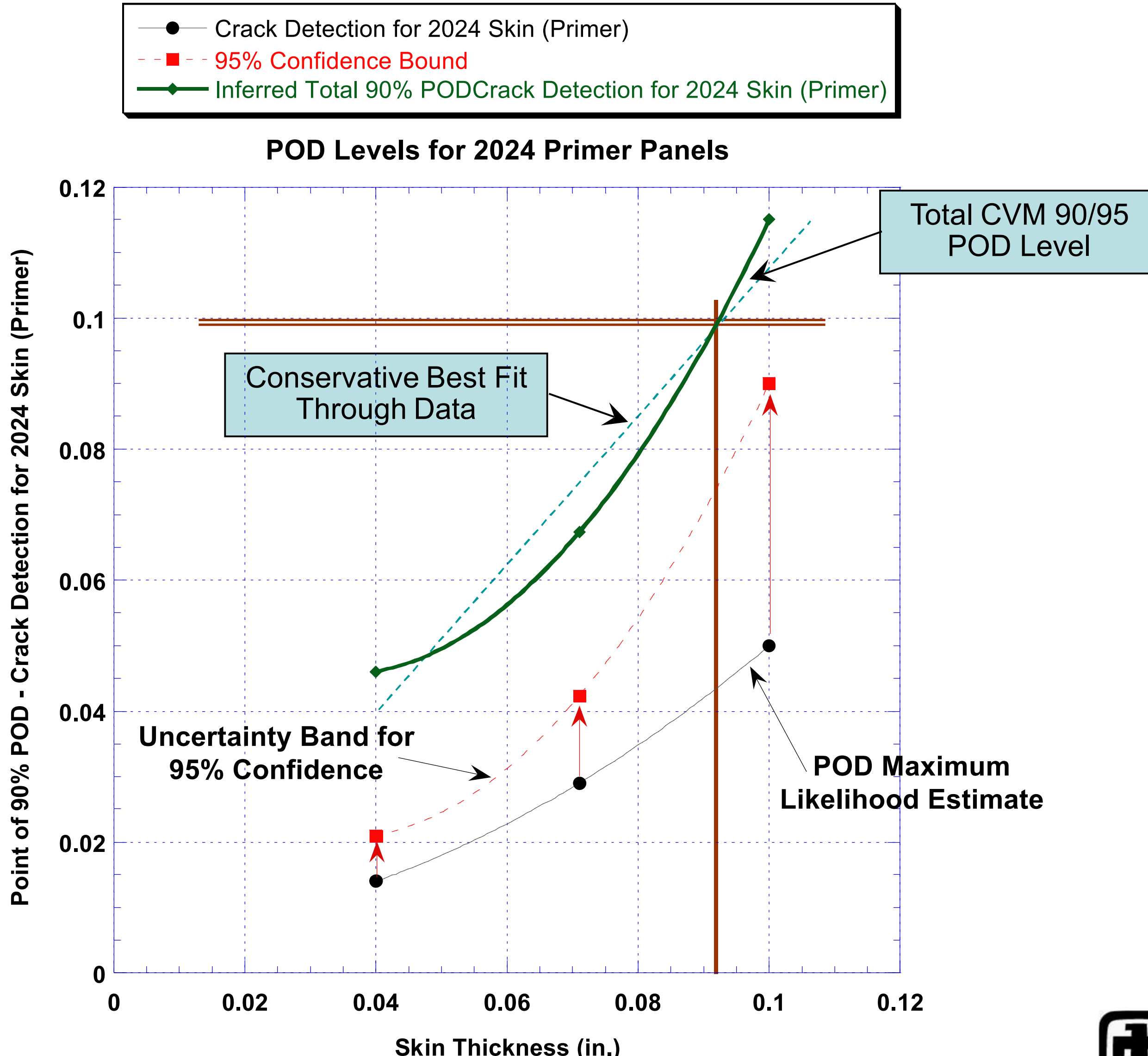
Determining Final CVM Crack Detection Level from Crack "Lag" Values





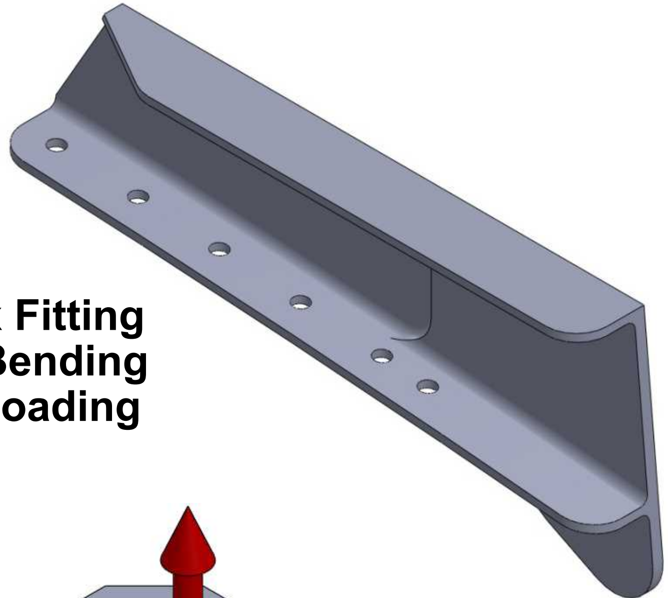
Total Crack Length at Detection = CVM Lag Detection + 0.014" + 0.010"

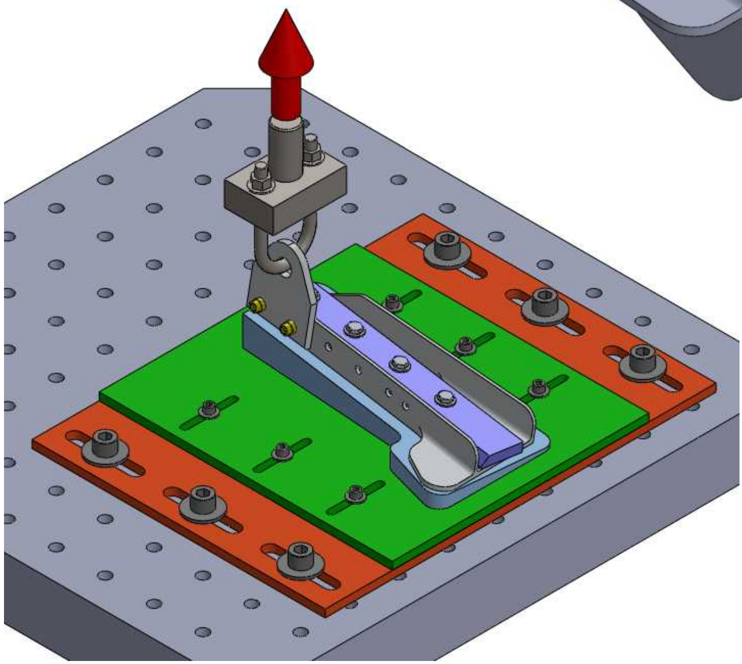
Overall Probability of Detection Values as a Function of Material Thickness

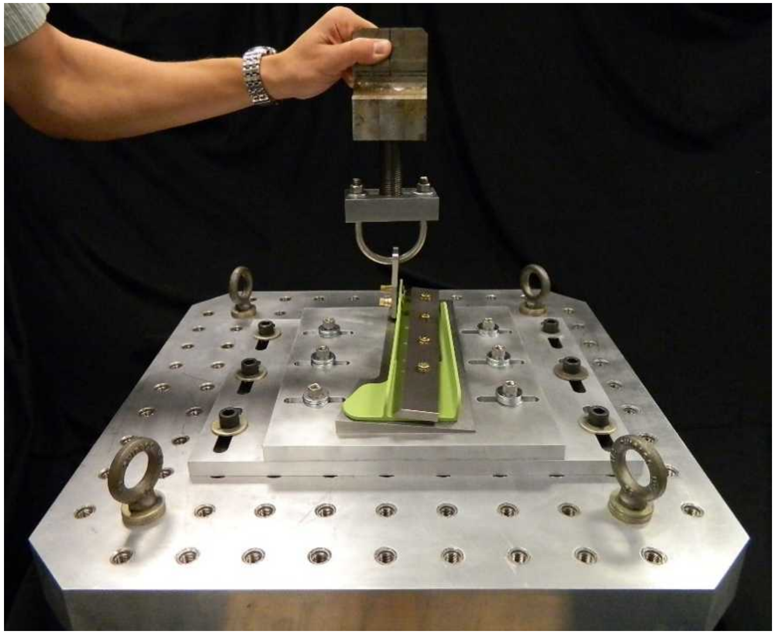


737NG Center Wing Box – CVM Performance Tests

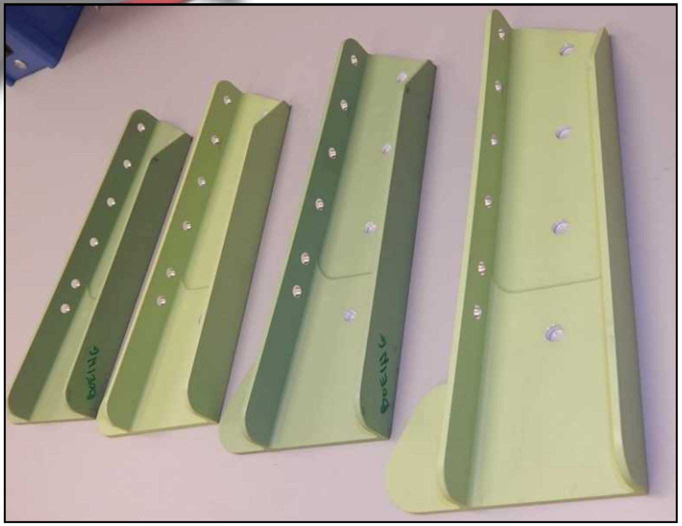
Wing Box Fitting Tension-Bending Fatigue Loading







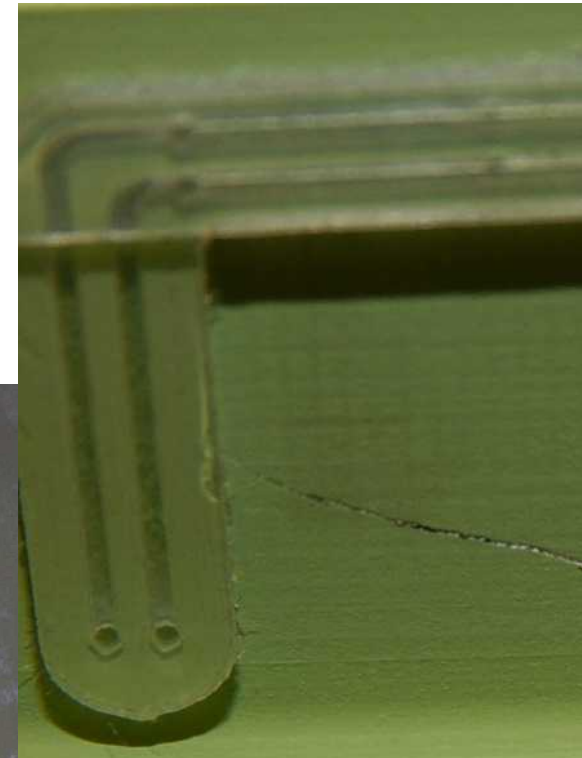
737NG Center Wing Box – CVM Performance Tests

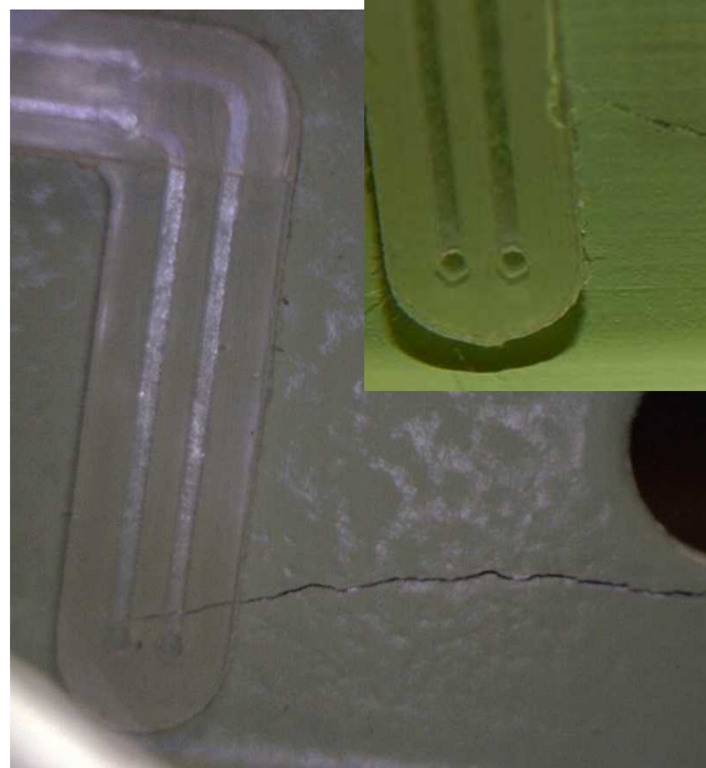


Sim-8 for real-time monitoring and PM-200 for final confirmation of CVM crack detection

737NG Center Wing Box – CVM Performance Tests

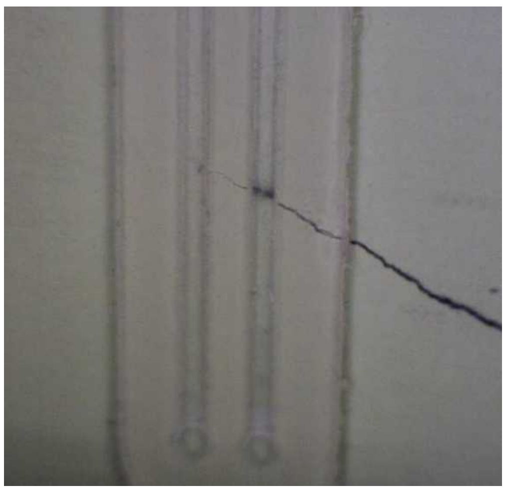
Fatigue crack intercepting dual gallery arrangement

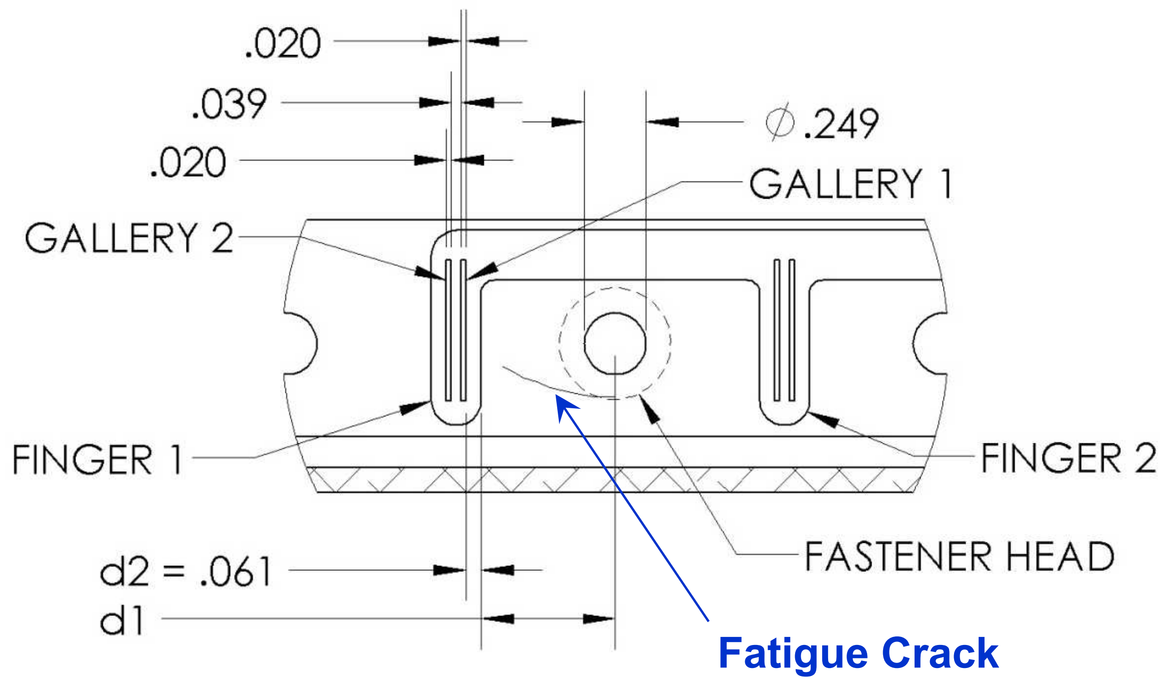




737NG Center Wing Box – CVM Performance Tests

- 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



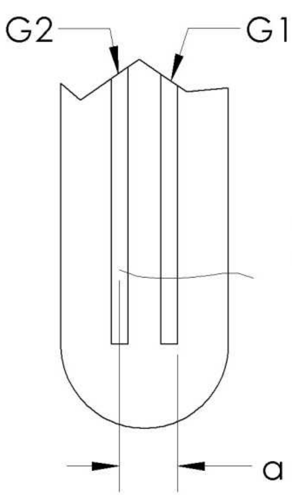


737NG Center Wing Box – CVM Performance Tests

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

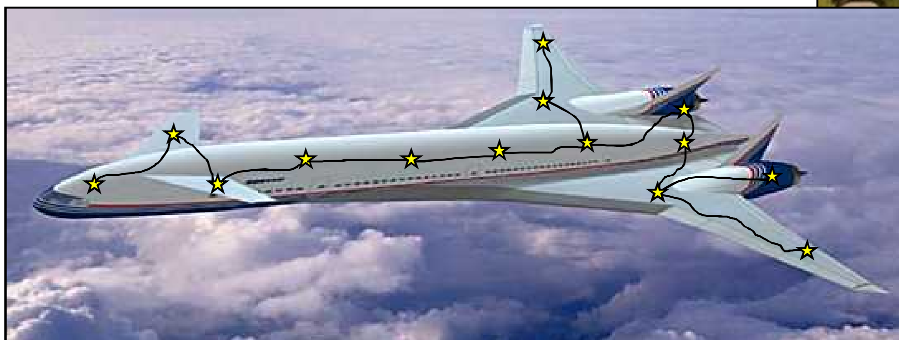
** Detection for unloaded state with sealed crack and sensor



Crack Length: a = excursion into CVM galleries

Field Evaluation of Sensor Networks for Structural Health Monitoring

Automatically assess structural condition, & signal need for maintenance actions



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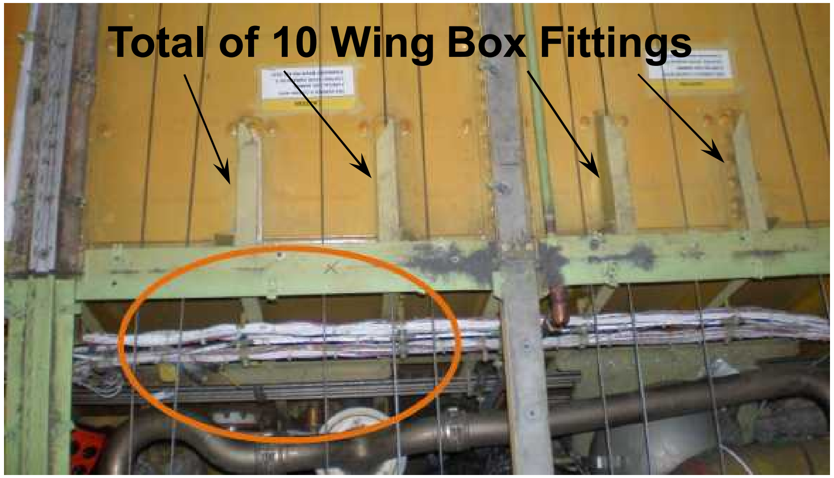
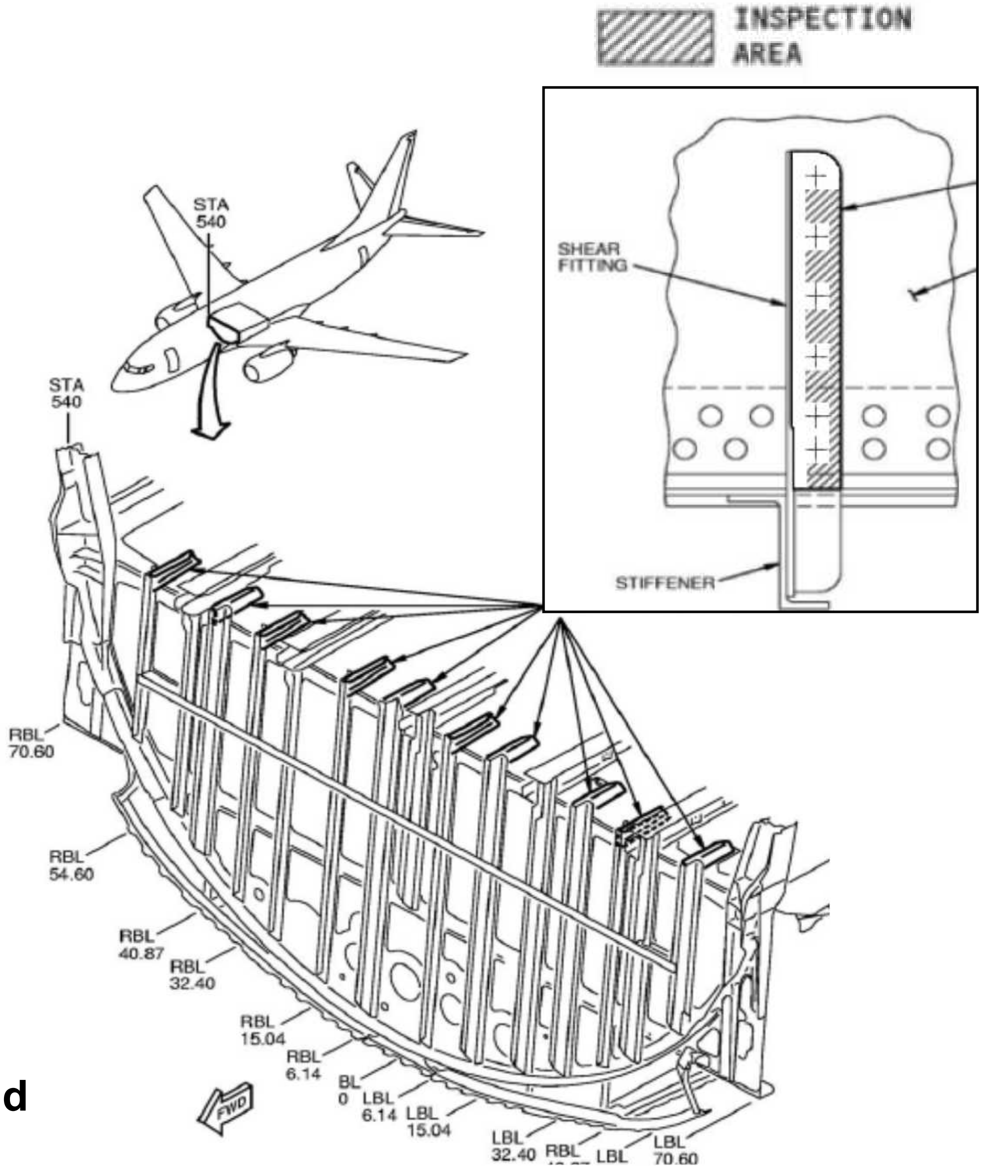
737NG Center Wing Box – CVM Flight Tests



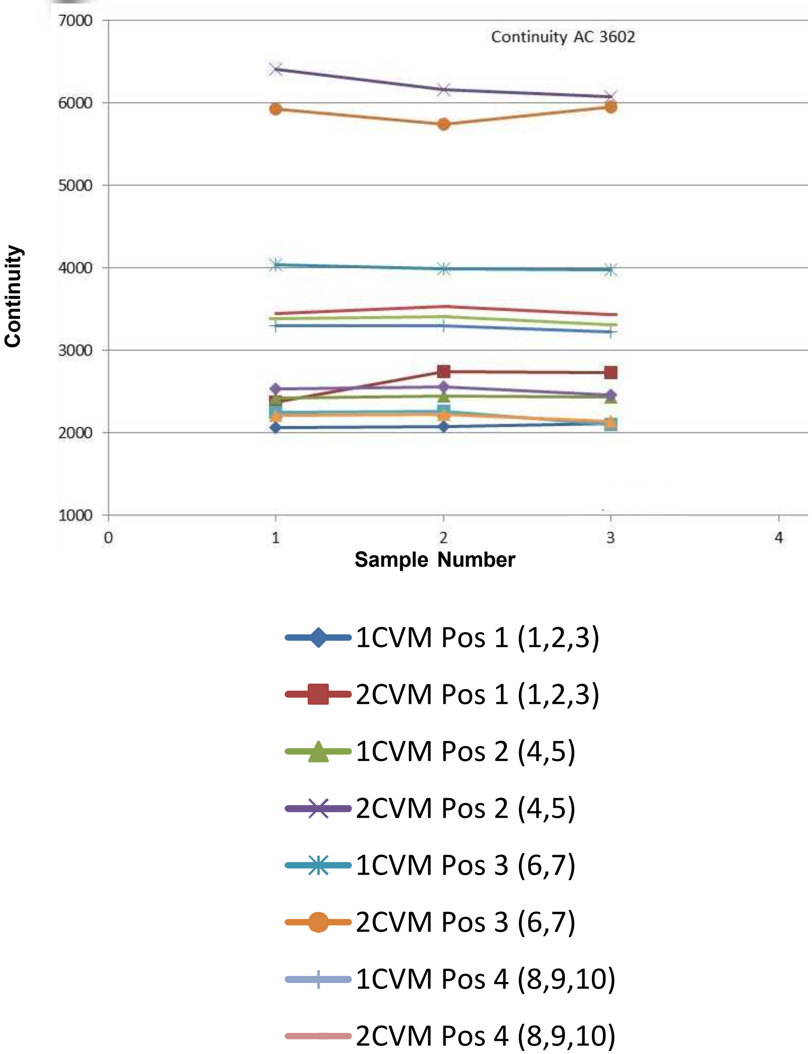
CVM Sensor on 737NG Wing Box Fitting and Top View of SLS Mount Location



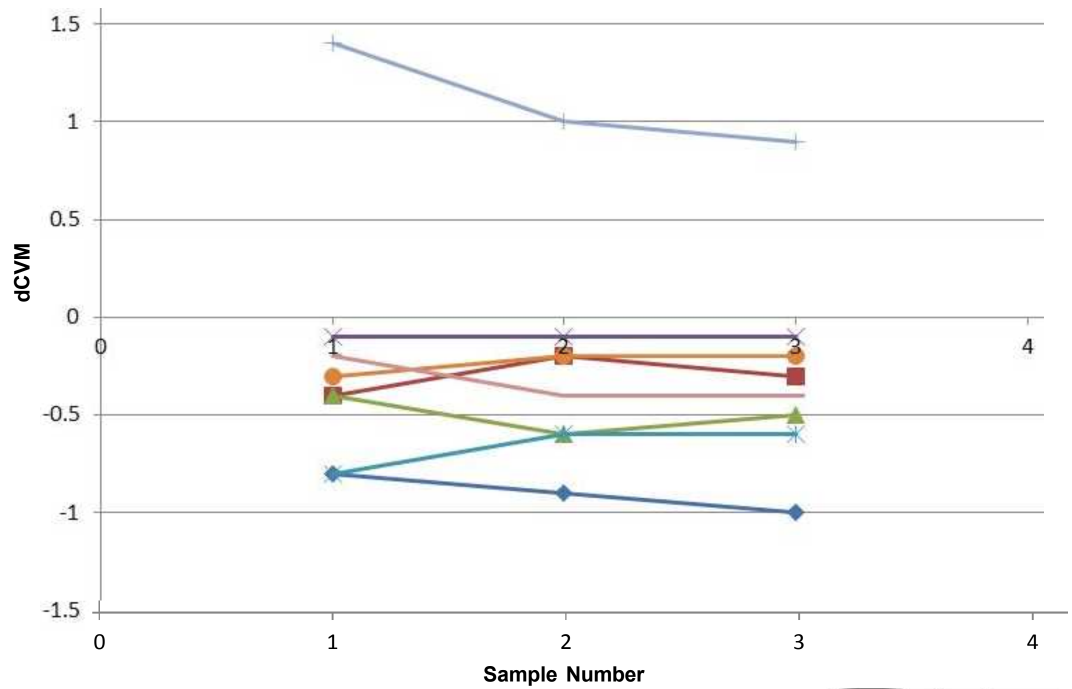
Sample CVM Flight Test Data

- **Fail-safe check – want continuity (flow) high**
- **Crack detection – dCVM (vacuum) low = no crack**
- **Conductivity Index = flow**

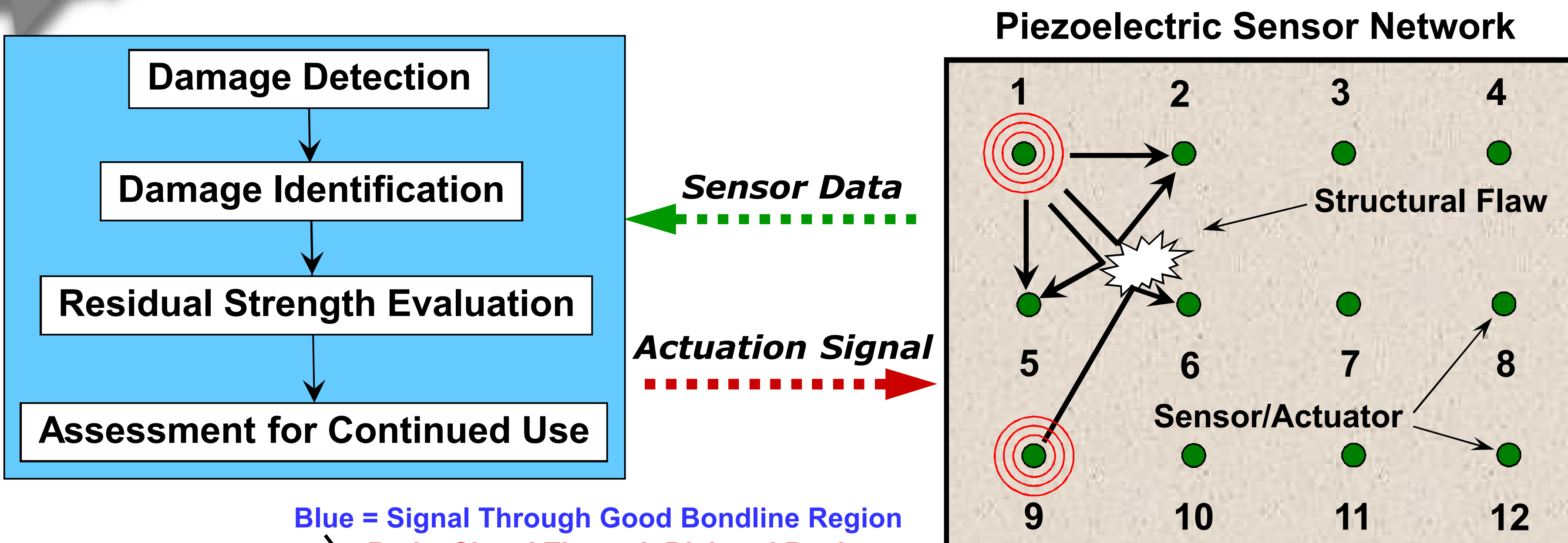
AC3602 Continuity Check

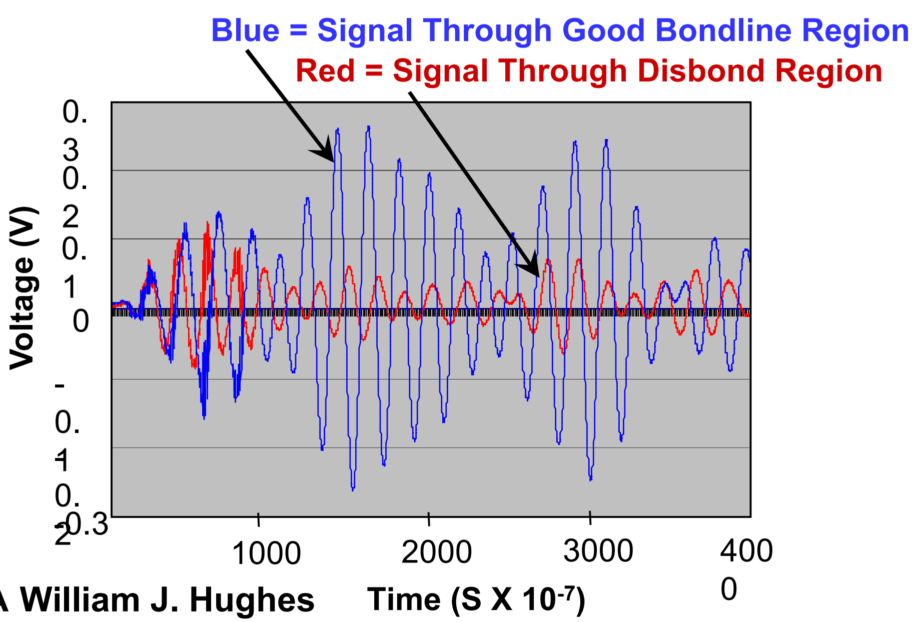


AC3602 CVM Readings

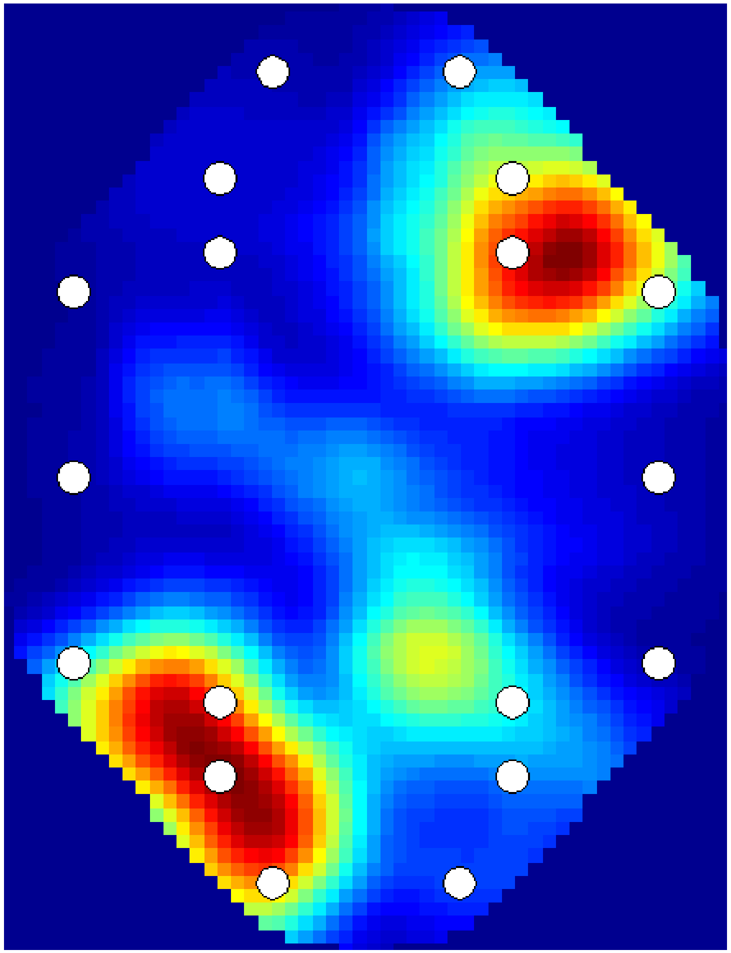


Global SHM - Disbond Detection & Growth Monitoring with Piezoelectric Sensors

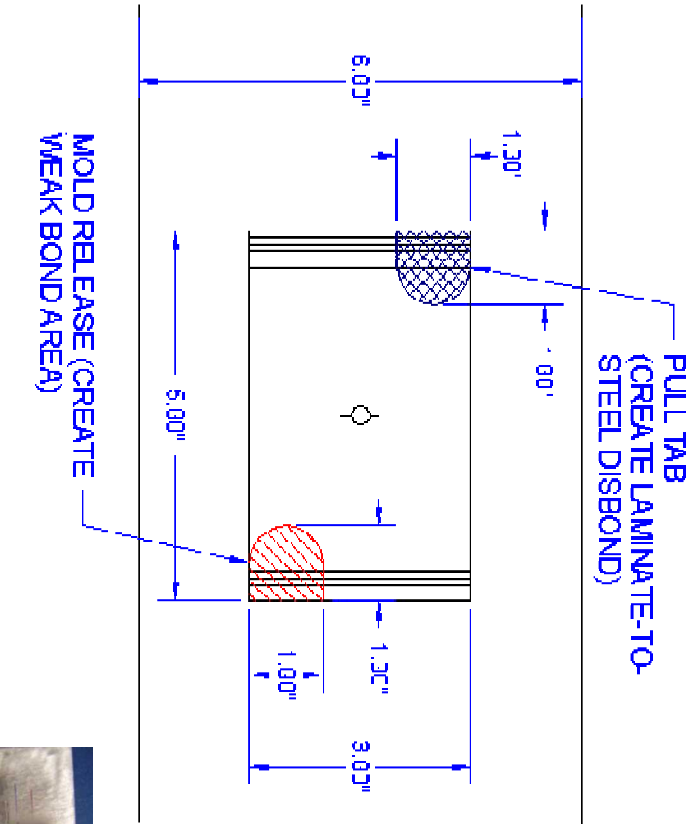


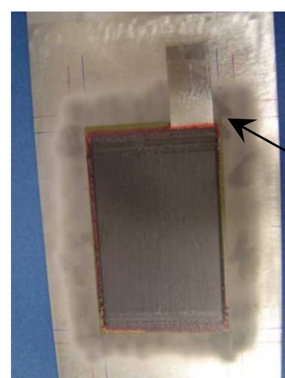


Disbond Detection & Growth Monitoring with Piezoelectric Sensors



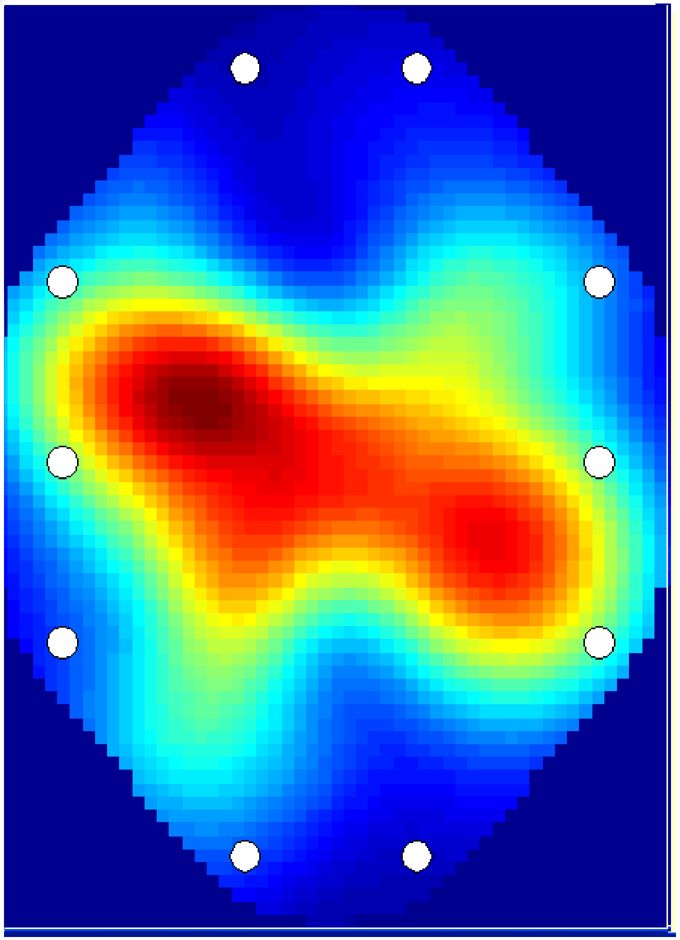
After mold release flaw growth
(50 KHz inspection)



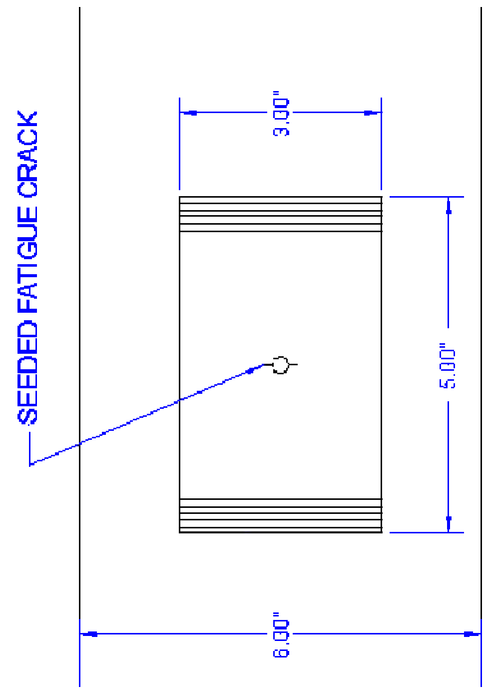


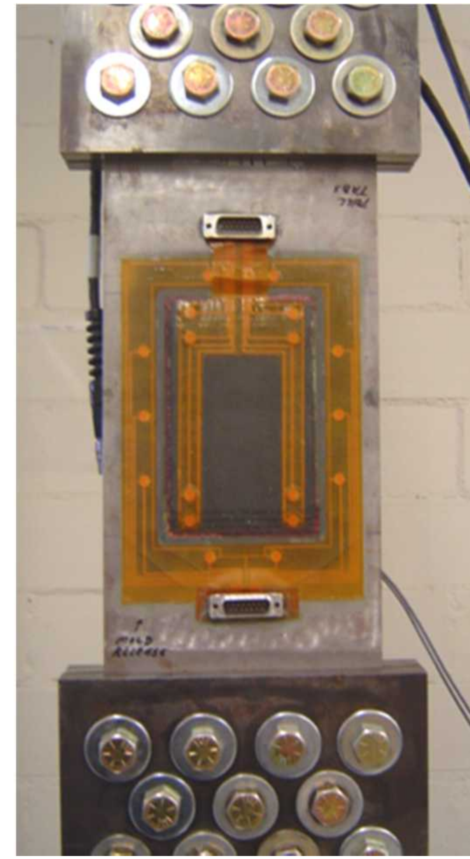
Pull tab flaw

Crack Detection & Growth Monitoring with Piezoelectric Sensors



87K Cycles





PZT crack length estimates within 5% of measured

Conclusions on Use of SHM Reliability

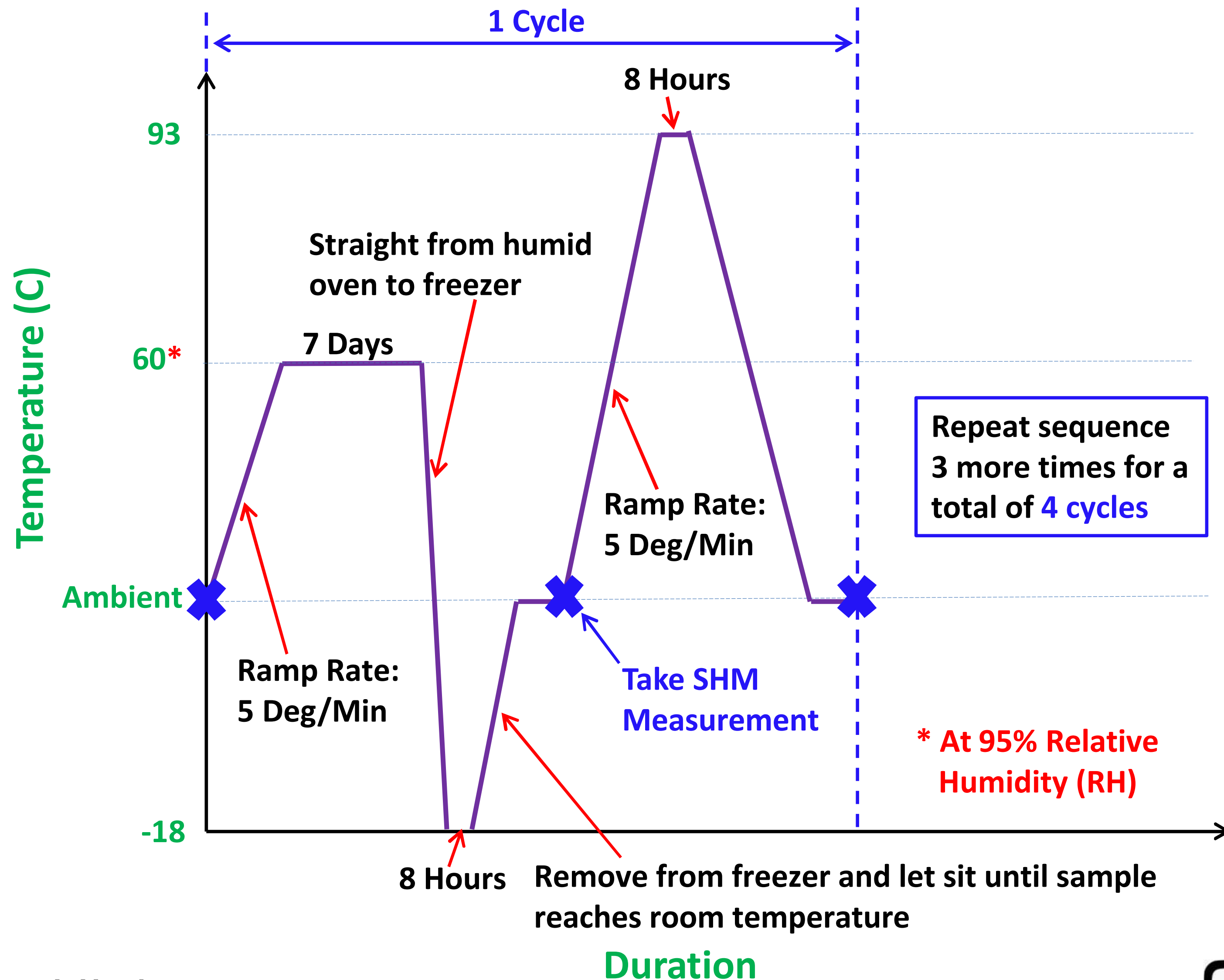
- Recent advances in health monitoring methods have produced viable systems for on-board aircraft inspections
- Sensors must be low-profile, easily mountable, durable, reliable & fail-safe
- Calibration for flaw identification (damage signatures) is key
- General lab performance (sensitivity/POD) & flight test data is needed
- Reliability/POD assessments will depend on sensor system, flaw type/orientation and application
- CVM sensor detects cracks in the component it is adhered to - inspection process and diagnosis is automated & remote
- One-sided tolerance interval can be used to calculate POD for certain circumstances (known flaw location and flaw direction)
- Can monitoring process & diagnosis be fully automated (green or red light)?
- Status –
  - Successful integration of SHM in NDT Standard Practices Manuals
  - AMOC for SBs and ADs or STCs – safety driven use is achieved in concert with OEMS & regulatory agencies; Certification & regulatory framework is being addressed (need for formal POD)

SHM Environmental Durability Performance Assessment

Environmental Durability Performance Assessment

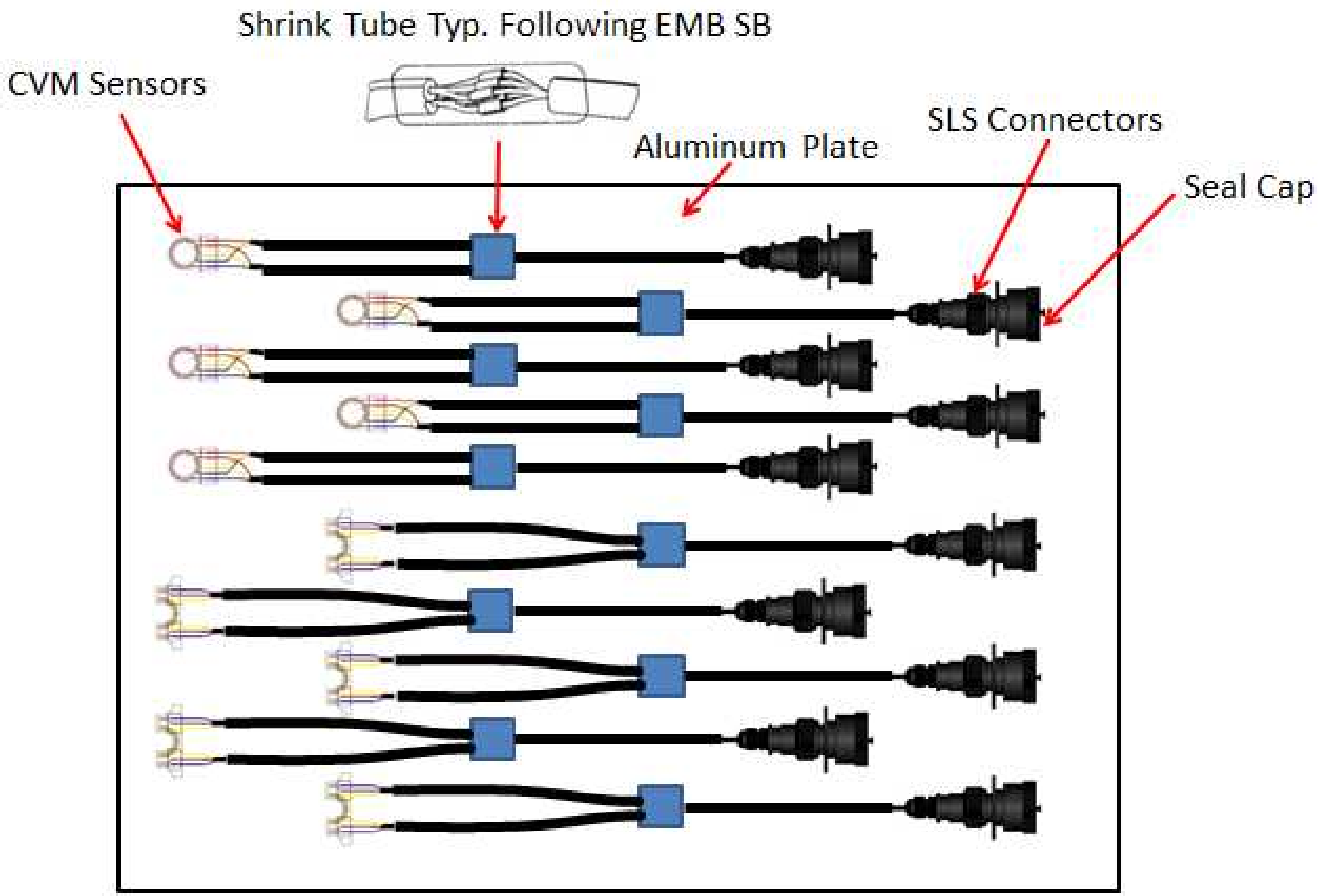
- Part of overall performance testing - meant to establish durability of sensor systems
- Utilize same approach as previous FAA certification effort with Boeing-Delta
- Sensor fail-safe feature is critical item – will be proven
- Environmental elements:
  - Hot-wet (55^{o}C and 95% +% RH)
  - Freeze (-18^{o}C)
  - Heat (93^{o}C)
  - 7 day cycle – repeated 4 times (28 days)
- Sensor function measurements will be acquired at each environment change
- Test specimens include all hardware that remains on the aircraft during operation

Environmental Exposure Tests for CVM and PZT Sensors



Environmental Test Configuration for CVM Sensors

CVM will be coated with Polysulfide sealant AMS 3281 (2007B002AM654SK, Manuf. PRC Desoto Int'l Inc.)



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:

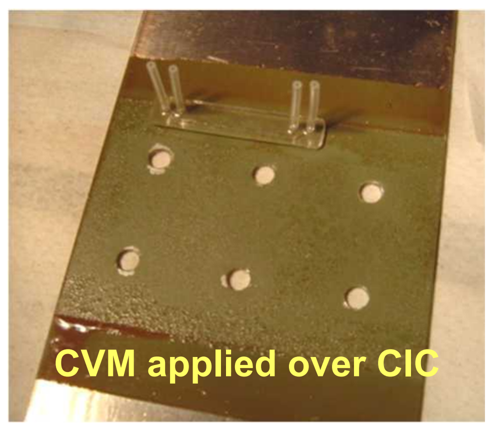
- BMS 3-35 which is Ardrox AV15 or Corban-35 (Zip Chem)
- BMS 3-23 which is LPS-3 or Ardrox AV-8 or Dinitrol

Crack Detection:

a_{90} = 0.011" w/o CIC

a_{90} = 0.013" w/ CIC

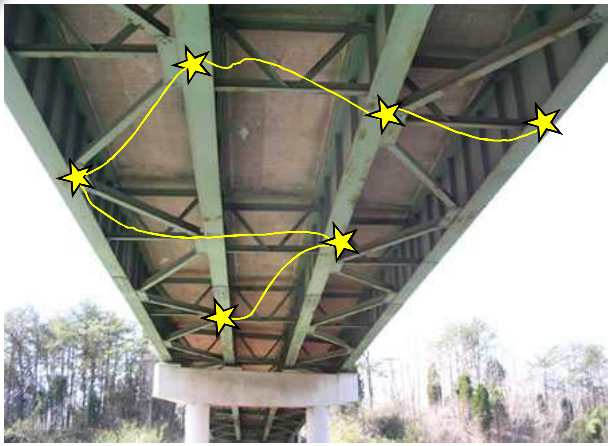
Multiple passes to produce flowing and accumulation of CIC

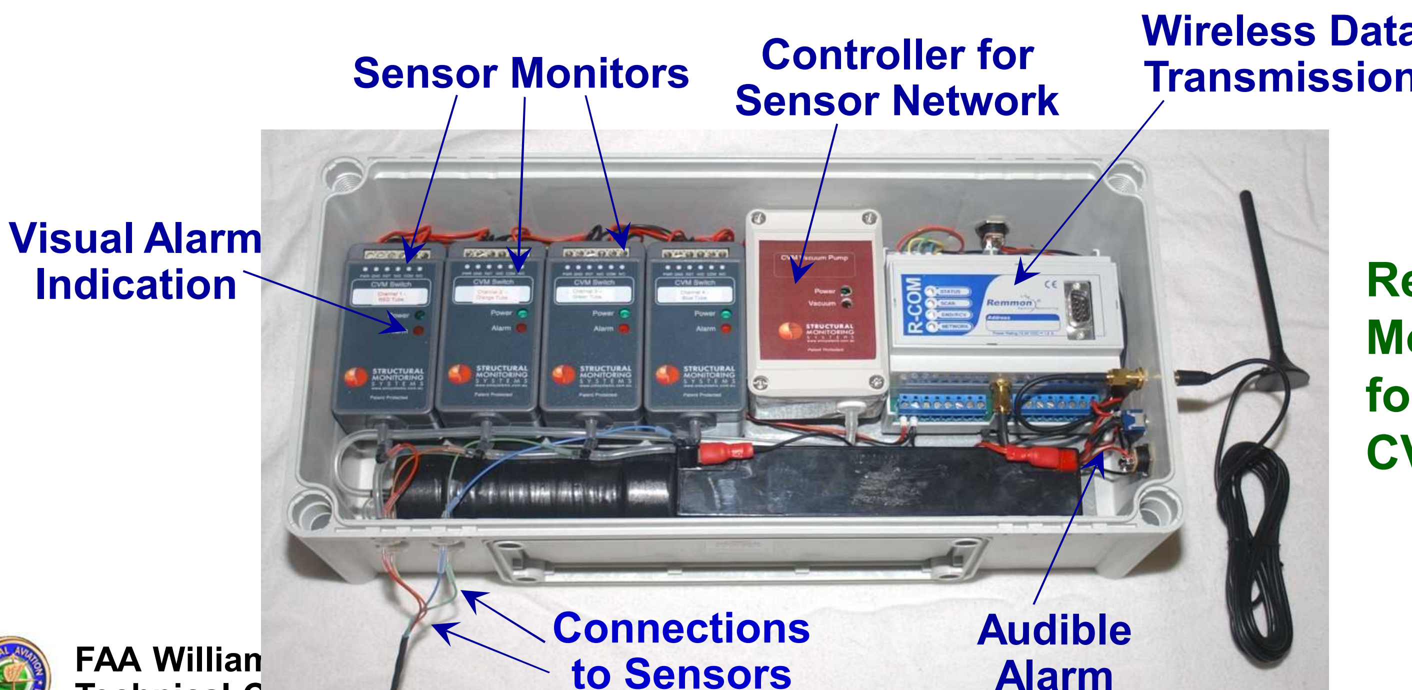


CVM applied over CIC

No CIC drawn into galleries

Real-Time Structural Health Monitoring of Bridges Using CVM Sensors





Real-Time, Remote Monitoring System for a Network of CVM Sensors