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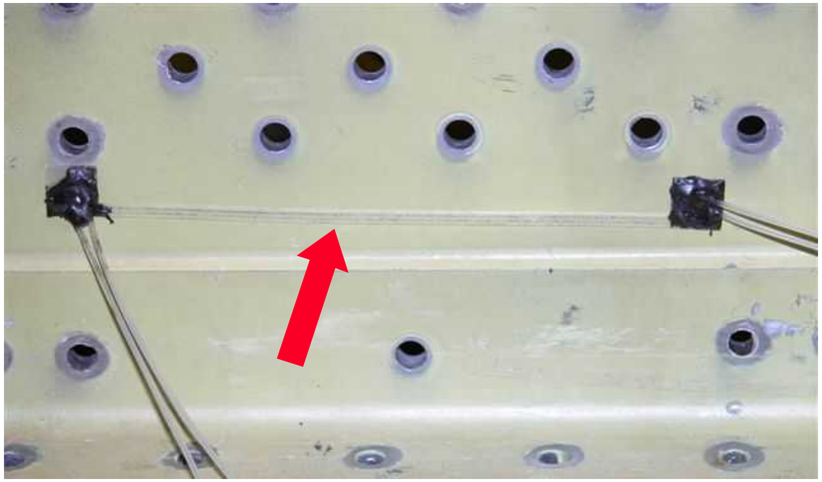
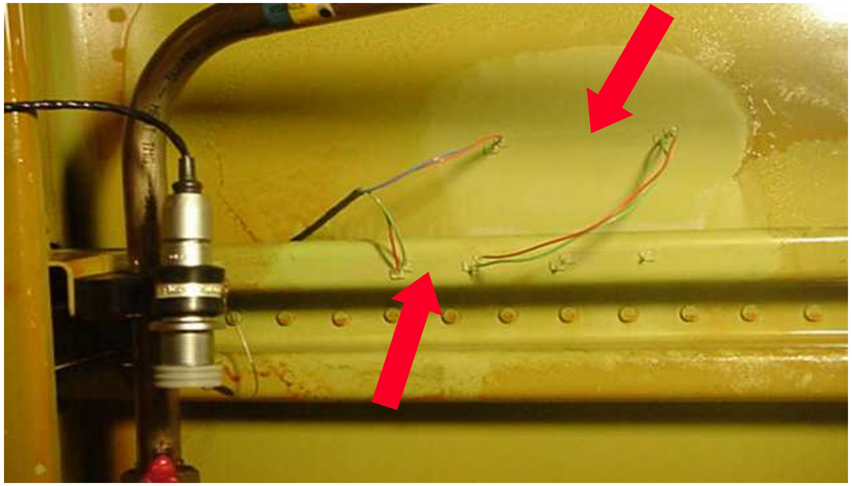
SAND2008-1789P

Data Package Supporting Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection





CVM Validation Activities Conducted in Concert with Boeing

FAA Hughes Technical Center

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

Results from Laboratory and Field Evaluation Program for Modification of NDT Common Practices and Standard Practices Manuals and AMOC Applications

Drivers for Application of CVM Technology

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

Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection

TEAM MEMBERS

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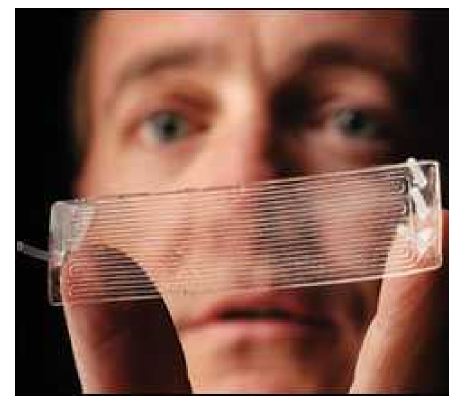
Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection

Part 1: Introduction to Sensor System and Operation

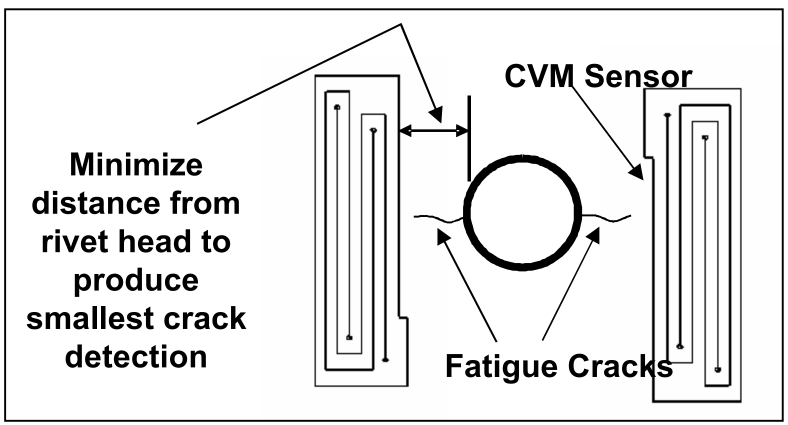
Drivers for Application of CVM Technology

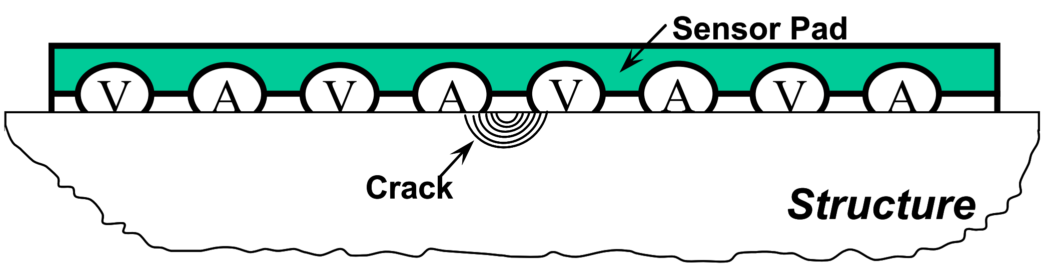
- Overcome accessibility problems; sensors ducted to convenient access point
- Improve crack detection (easier & more often)
- Real-time information or more frequent, remote interrogation
- Initial focus – monitor known fatigue prone areas
- Long term possibilities – distributed systems; remotely monitored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

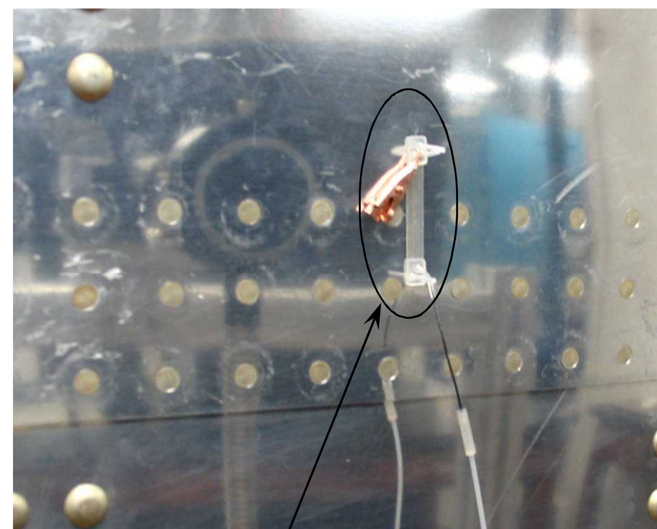


Comparative Vacuum Monitoring System

- Sensors with fine channels on the adhesive face - applies a vacuum to a thin film sensor with embedded galleries open to the surface
- Leakage path between the atmospheric and vacuum galleries producing a measurable change in the vacuum level
- Doesn't require electrical excitation or couplant/contact







CVM Sensor Adjacent to Crack Initiation Site

Step 1: Continuity test

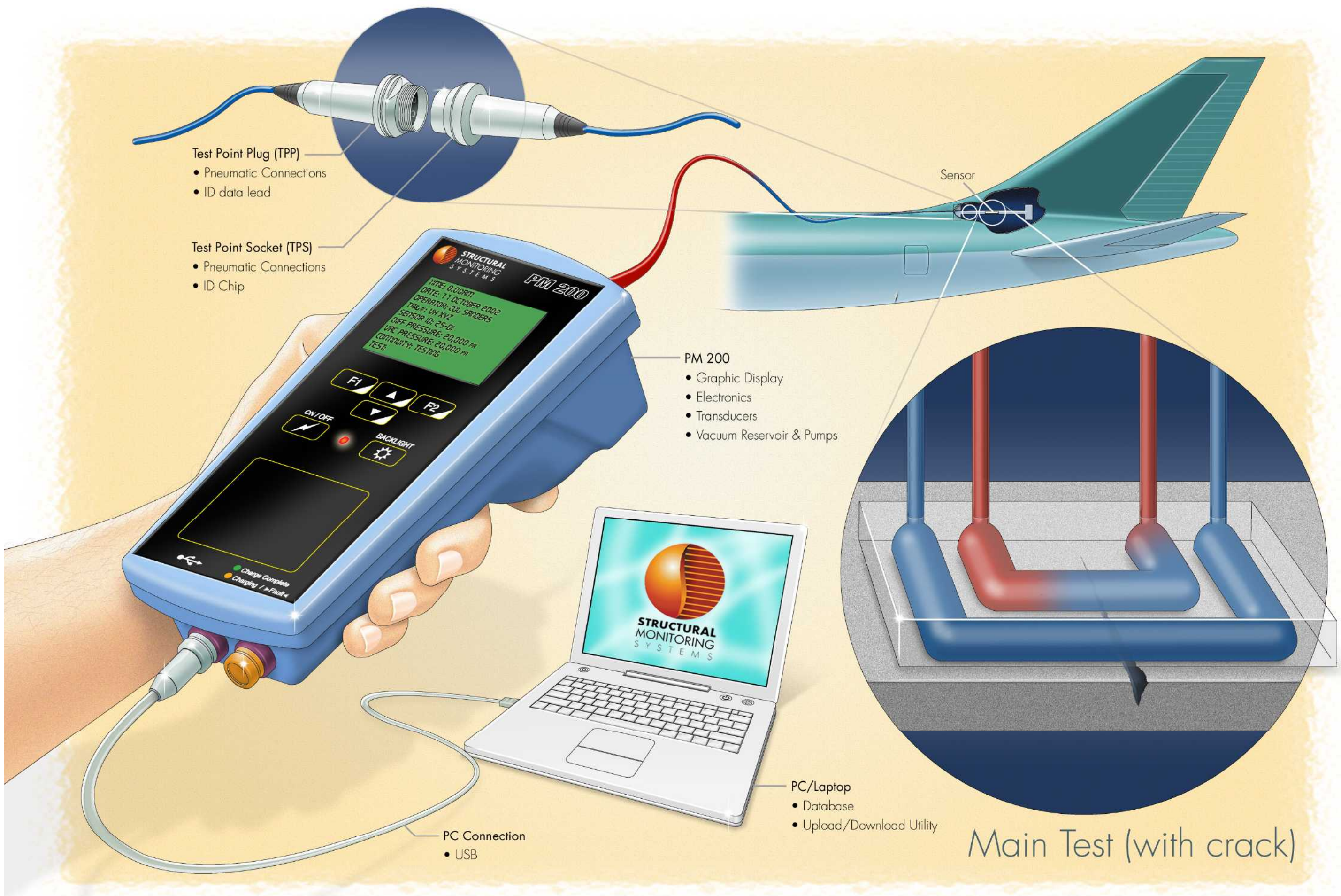
- Establishes no blockage in system
- CI should read high

Step 2: CVM test

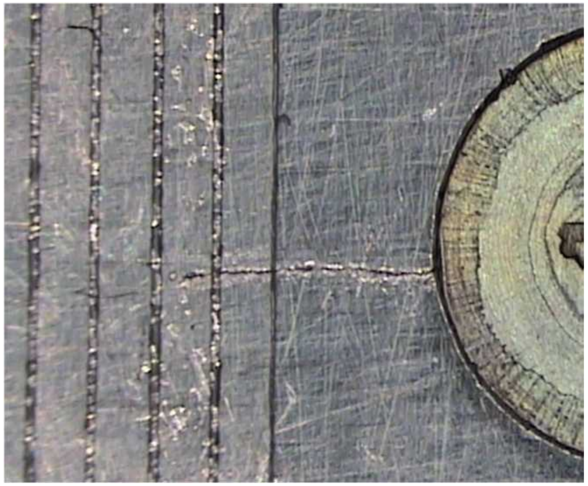
- Establishes no crack breaching sensor
- CI should read low (0.5 or less)

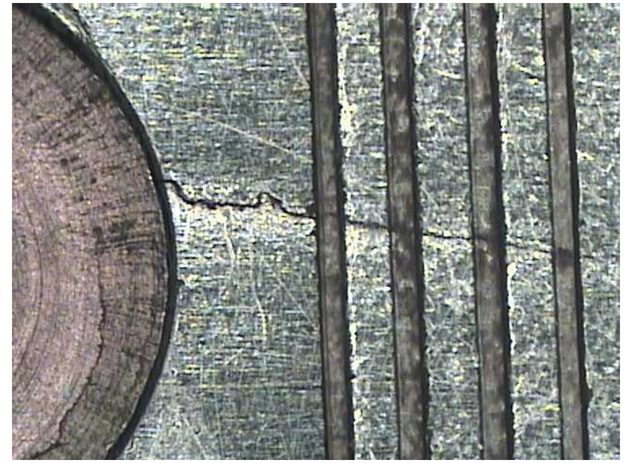
Step 2: CVM test

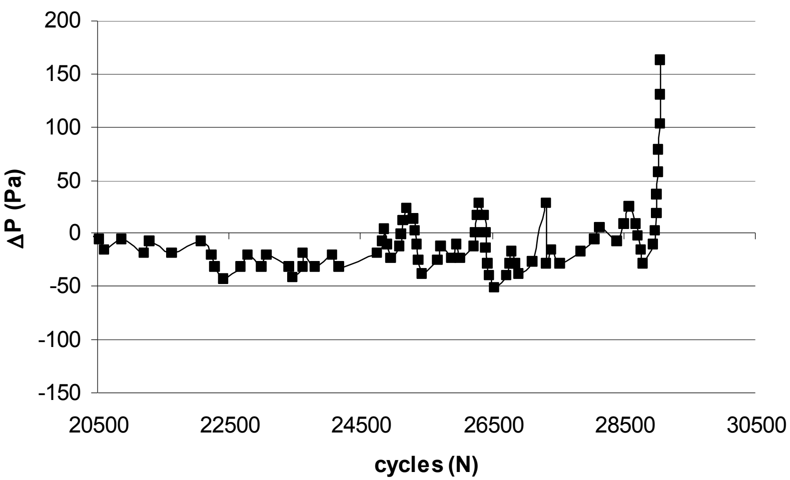
If crack breaches sensor……..
CI will read higher than 0.5 (usually much higher)

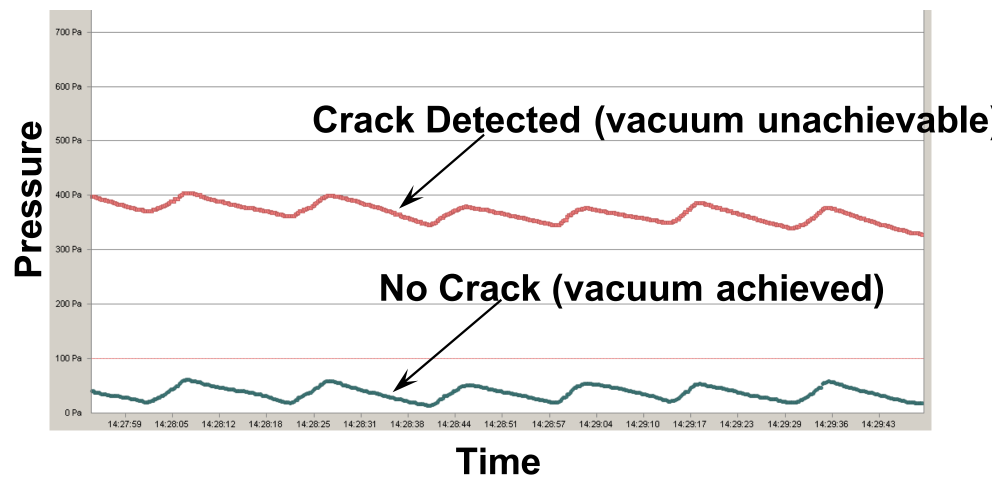


Comparative Vacuum Monitoring System









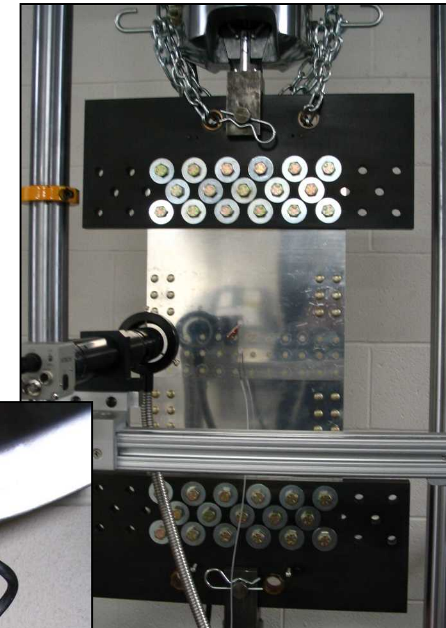
Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection

Part 2: Laboratory Validation and Determination of Statistically-Valid Probability of Crack Detection Values

Test Matrix to Quantify Probability of Crack Detection

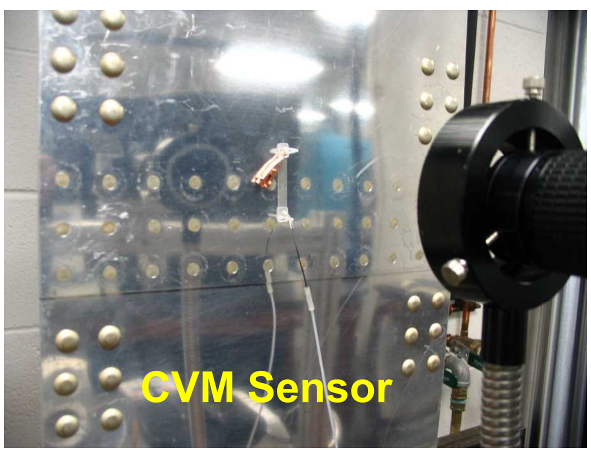
Test Scenarios:

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

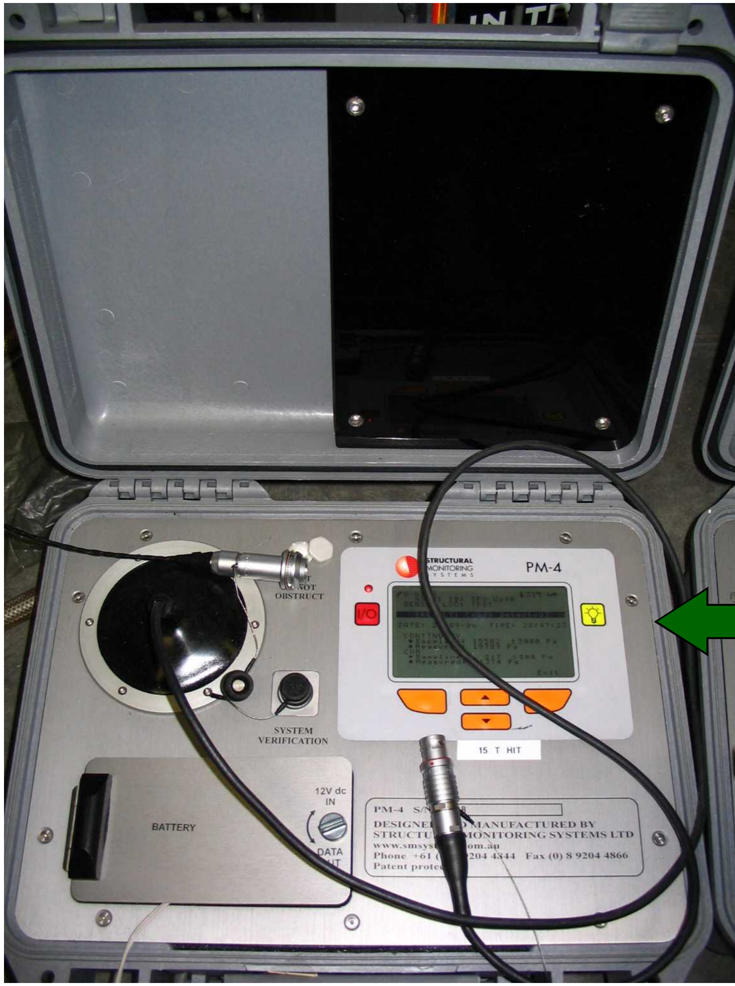


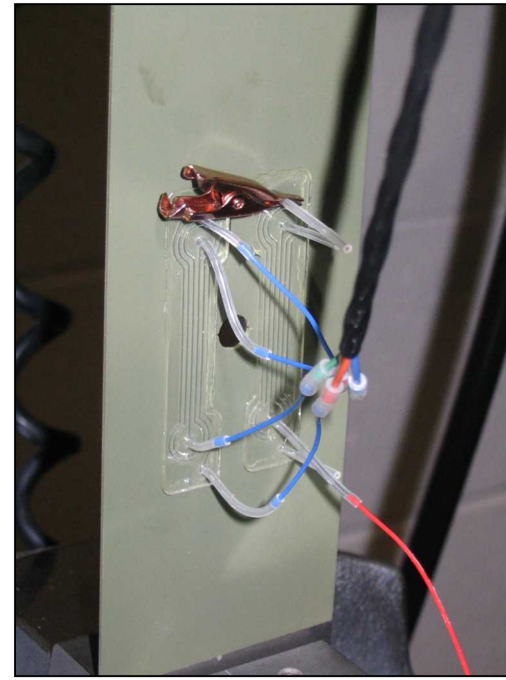
Test Procedure – Lab Monitoring with SIM-8 Followed by Check with Field PM-4 Device

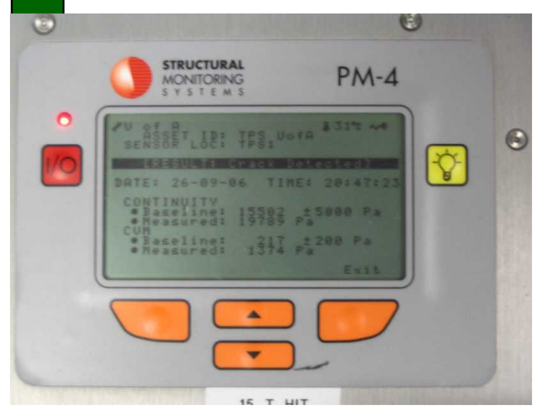
- Panels loaded into fixtures
- Baseline images of fasteners taken with optical microscope camera and USUT ultrasound
- Sample fatigued at R-ratio of 0.1 at 17 ksi until crack visually detected by CCD camera
- Sensor monitored to check for crack detection
- Crack growth closely measured while CVM sensors are periodically monitored to determine <u>permanent</u> alarm threshold

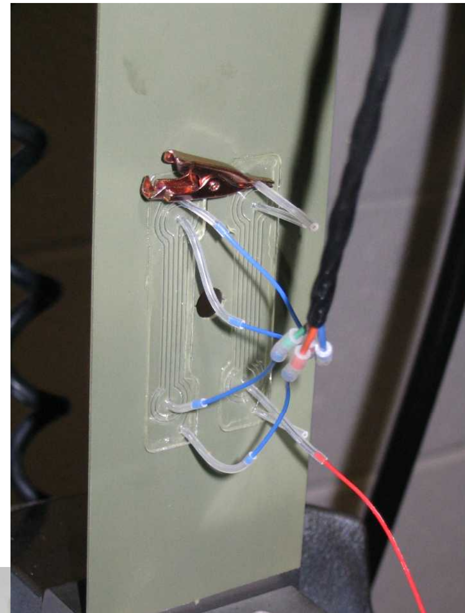


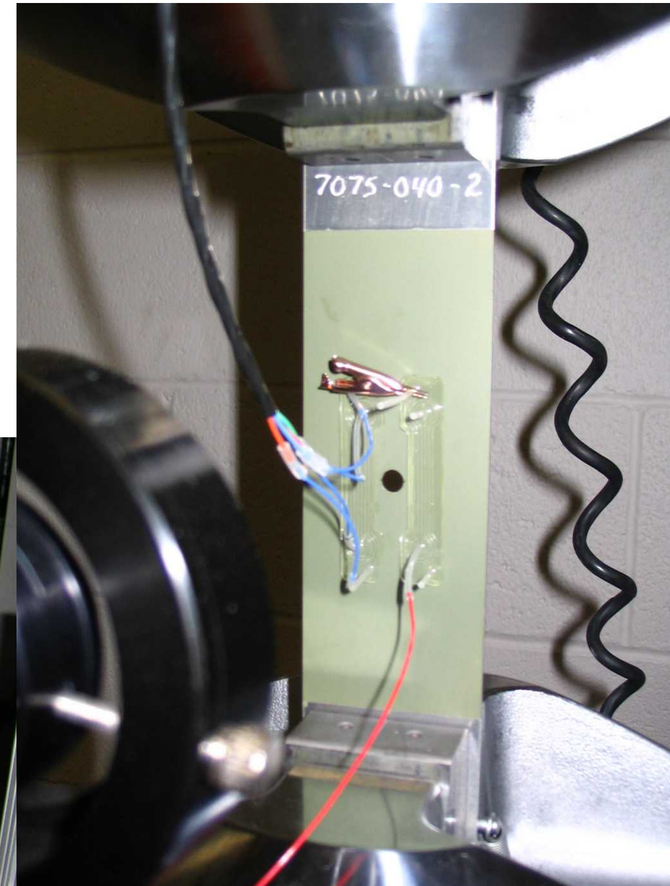
Monitoring CVM Sensors in the Field with a PM-4 Device










7075-040-2

$\overline{X}$

CVM Validation – Data Analysis Using One-Sided Tolerance Intervals

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

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

X = Mean of detection lengths

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

S = Std. deviation of detection lengths

n = Sample size

1- α = Detection level

CVM Validation - Crack Detection Results

All POD levels listed are for 95% confidence

2024-T3 Alum.

Description: 0.040 inch thick panel (primer surface)

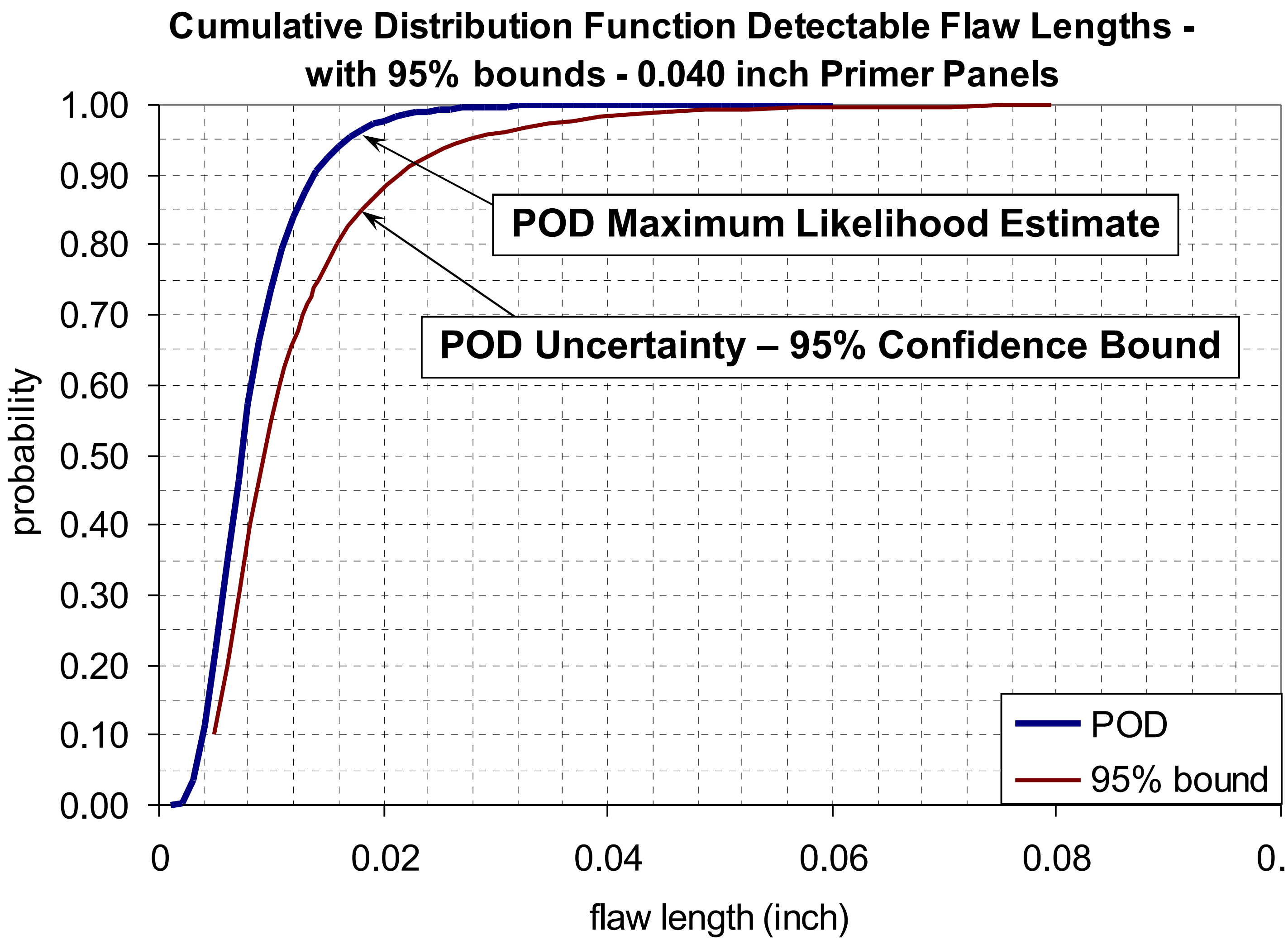
PHASE 2 TESTS						
Panel	**Fastener Crack Site**	**Distance from Fastener (inches)**	**Crack Length at CVM Detection (growth after install in inches)**	**SIM-8 Reading ΔPa (Pasm)**	**PM-4 Read-out**	**PM-4 Indicate Crack (Y or N)**
4018	5R	0.040	0.002	400-500	1607	Y
4018	6R	0.014	0.007	1700-1800	2847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

90% POD Level	False Calls
0.021"	0

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

Sample Probability of Detection Curves for CVM

2024-T3 Alum.



CVM Validation - Crack Detection Results (cont.)

All POD levels listed are for 95% confidence

Description: 0.071 inch thick panel (primer surface)

2024-T3 Alum.

PHASE 3 TESTS				
Panel	**Sensor**	**Crack Length at CVM Detection (growth after install in inches)**	**PM-4 Read-out**	**PM-4 Indicate Crack (Y or N)**
1	1-R	0.043	1507	Y
1	1-L	0.019	1535	Y
1	2-L	0.020	1639	Y
1	2-R	0.021	1673	Y
1	3-L	0.019	2332	Y
1	3-R	0.007	1469	Y
2	1-R	0.015	1335	Y
2	1-L	0.007	1441	Y
2	2-L	0.009	1526	Y
2	2-R	0.012	1424	Y
2	3-L	0.009	1390	Y
2	3-R	0.012	1311	Y
3	1-L	0.035	1339	Y
3	1-R	0.015	1376	Y
3	1-L	0.012	1388	Y
3	1-R	0.008	3405	Y

90% POD Level	False Calls
0.0423"	0

PM-4 device

[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)

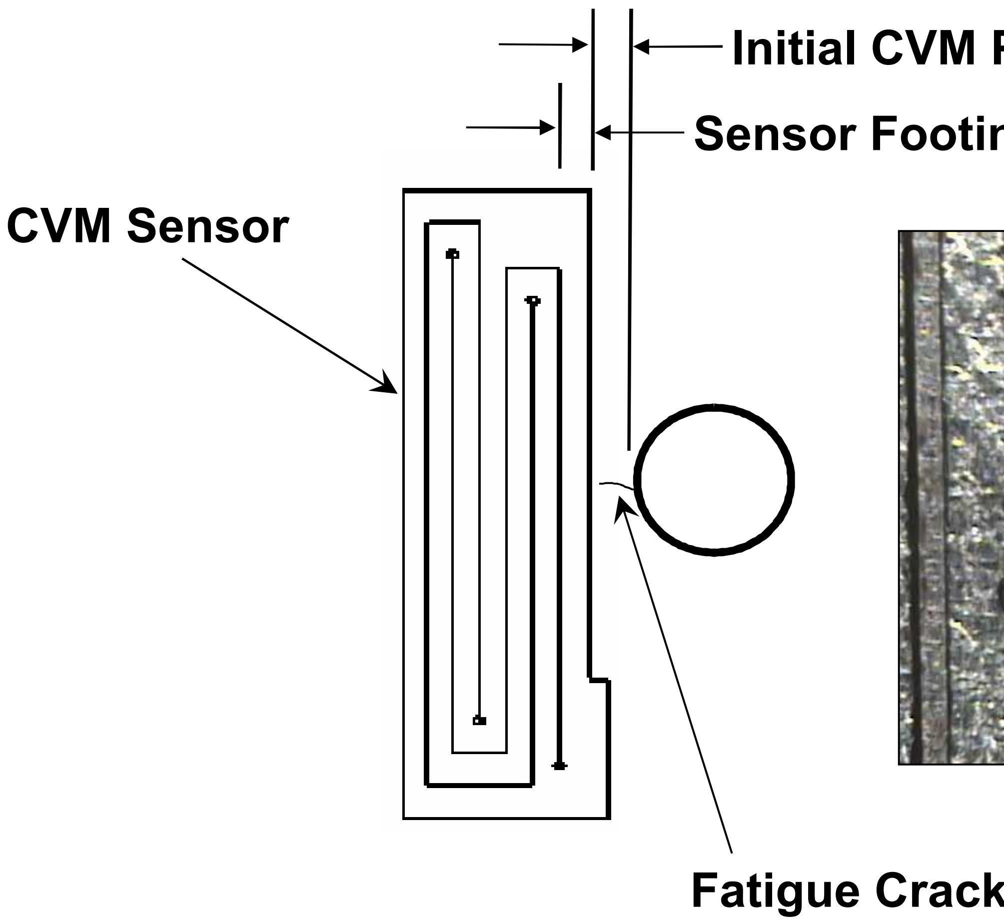
2024-T3 Alum.

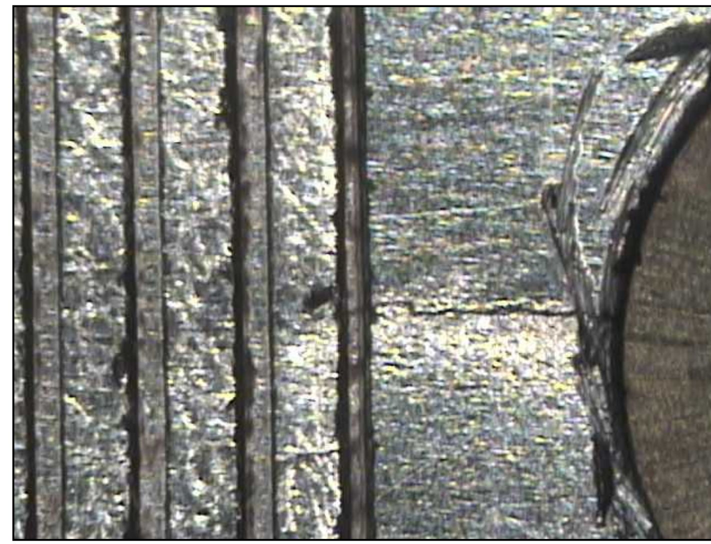
PHASE 2 TESTS						
Panel	**Fastener Crack Site**	**Distance from Fastener (inches)**	**Crack Length at CVM Detection (growth after install in inches)**	**SIM-8 Reading ΔPa (Pasm)**	**PM-4 Read-out**	**PM-4 Indicate Crack (Y or N)**
1001	5L	0.350	0.065	773-825	1713	Y
1001	7R	0.206	0.054	697-722	1768	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]

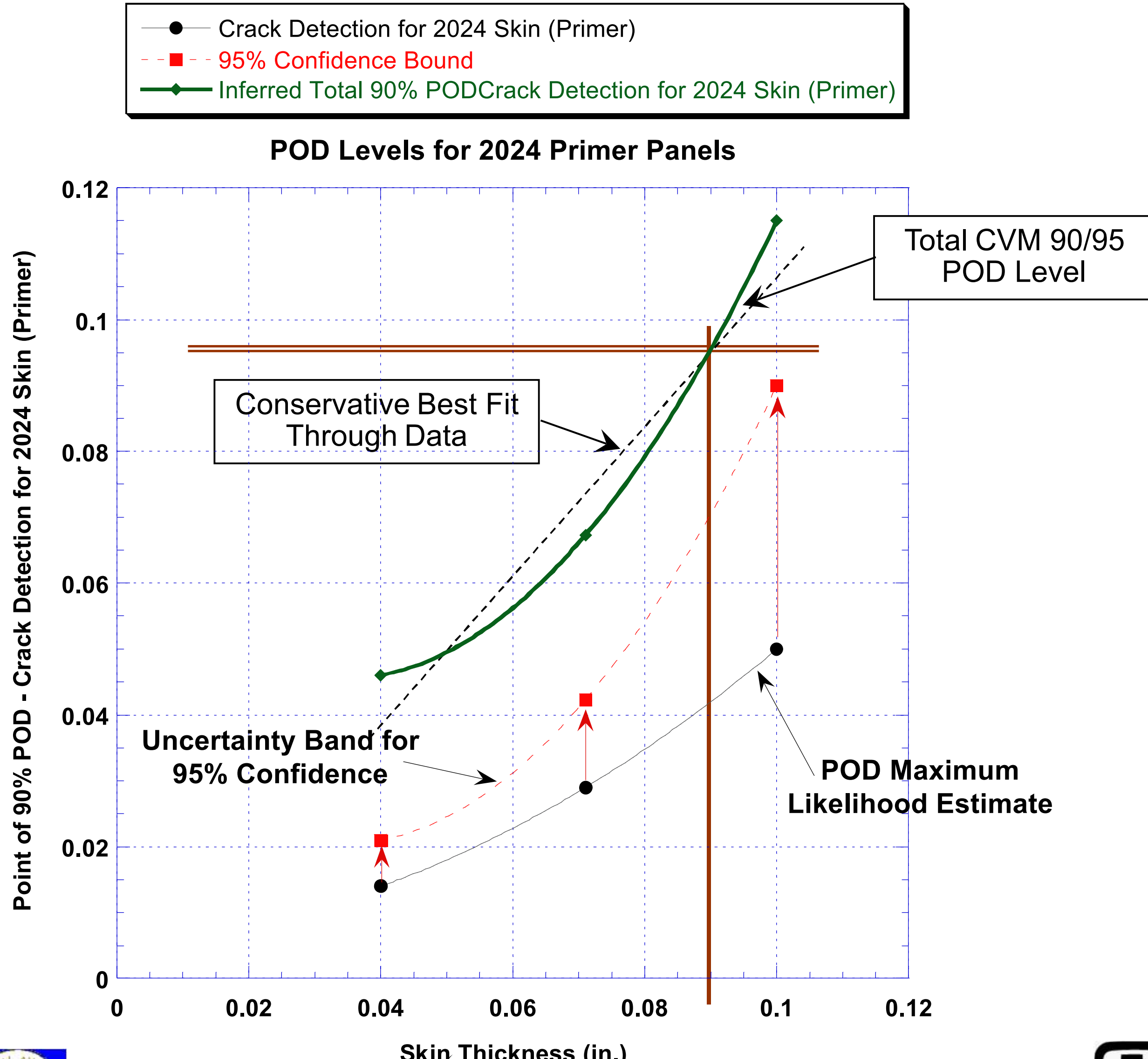
Determining Final CVM Crack Detection Level from Crack “Lag” Values





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

Overall Probability of Detection Values as a Function of Material Thickness



CVM Validation - Crack Detection Results (cont.)

All POD levels listed are for 95% confidence

Description: 0.040 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	3400	0.009	1738	Y
1	1-R	2400	0.011	1706	Y
1	2-L	6200	0.013	2109	Y
1	2-R	6000	0.014	2415	Y
1	3-L	6702	0.015	2346	Y
1	3-R	6702	0.004	1680	Y
2	1-R	3200	0.010	1611	Y
2	2-R	4850	0.006	1658	Y
2	3-L	5450	0.014	2506	Y
2	3-R	5450	0.018	4058	Y
3	1-L	3725	0.012	1731	Y
3	1-R	2925	0.006	1679	Y
3	2-L	4800	0.004	1833	Y
3	2-R	4600	0.008	1750	Y
3	3-L	5325	0.016	2946	Y
3	3-R	5230	0.005	2150	Y

90% POD Level	False Calls
0.0255"	0

7075-T6 Alum.

[all panels are 7075-T6 alum.]

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.]

CVM Validation - Crack Detection Results (cont.)

All POD levels listed are for 95% confidence

Description: 0.100 inch thick panel (primer surface)

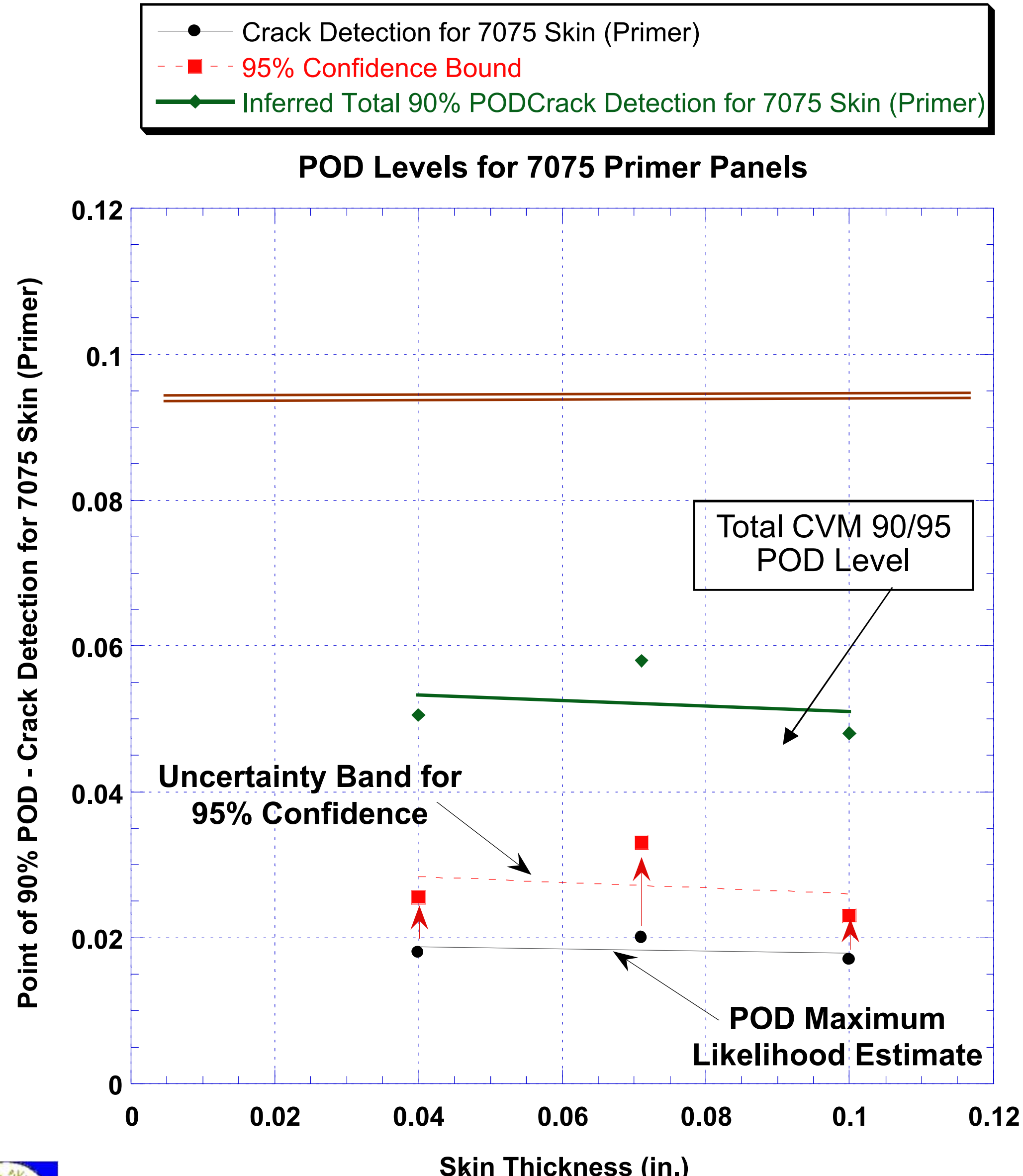
PHASE 3 TESTS					
Panel	**Fastener Crack Site**	**Number of Fatigue Cycles**	**Crack Length at CVM Detection (growth after install in inches)**	**PM-4 Read-out (Pasm)**	**PM-4 Indicate Crack (Y or N)**
1	1-L	3505	0.007	2123	Y
1	1-R	3205	0.007	1938	Y
1	2-L	5350	0.010	2251	Y
1	2-R	5550	0.011	1954	Y
1	3-L	6650	0.009	4526	Y
1	3-R	7099	0.016	7099	Y
2	1-L	3100	0.011	1786	Y
2	1-R	3400	0.014	1707	Y
2	2-L	5300	0.005	2383	Y
2	2-R	5300	0.016	2204	Y
3	1-L	4475	0.019	1790	Y
3	1-R	4825	0.013	1904	Y
3	2-L	7025	0.008	2100	Y
3	2-R	7878	0.010	4302	Y

90% POD Level	False Calls
0.023"	0

7075-T6 Alum.

[all panels are 7075-T6 alum.]

Overall Probability of Detection Values as a Function of Material Thickness



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

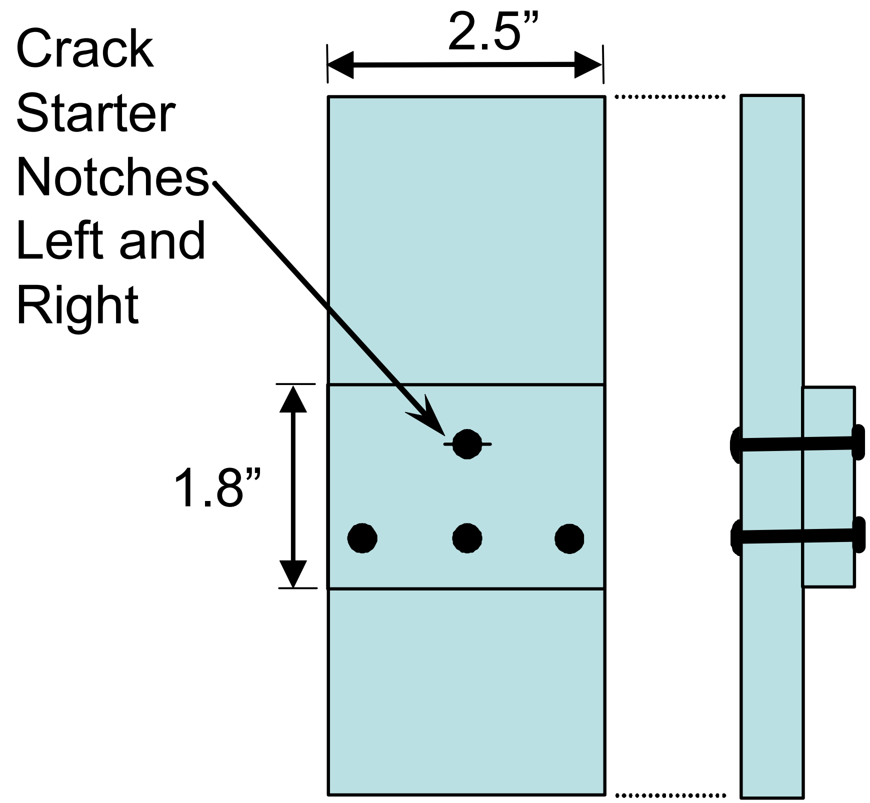
Objective: Provide confidence in the performance of CVM in the presence of CICs during crack growth

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.

Study to Assess the Effects of CIC on the Performance of CVM

Test Specimen: **2.5" wide plate with a doubler plate riveted to the back (7075-T6); two rows of rivets; upper rivet row is only the single center hole in order to ensure controlled crack growth (highest center stress); single rivet also provides more space for CVM sensors as cracks grow so that more data can be acquired from each specimen**

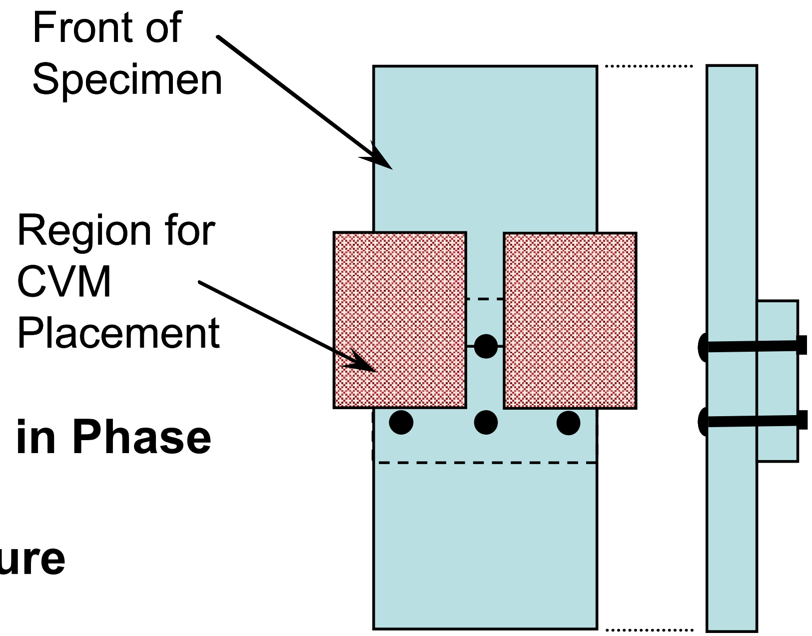


Schematic of Test Specimen to Assess CIC Affects on CVM

Study to Assess the Effects of CIC on the Performance of CVM

Test Procedure:

- Coupon plate and doubler plate will both be coated with primer
- No sealant will be placed beneath the doubler to allow for maximum fluid ingress
- Fatigue crack will be initiated in the specimen from the starter notches; cracks will range in length from 0.050” to 0.100” as this is the length that we don’t expect crack detection. In other words, such a crack could exist in the field and be coated with CIC prior to CVM application.
- CIC will be applied in normal spray fashion with no intent to avoid nor excessively inject CIC between the faying surfaces; CIC is applied to the front and back side of the test specimens; upper left and right regions of doubler plate in schematic above will be clamped to eliminate any excessive gaps between the two plates (abnormal CIC ingress)
- CIC will be allowed to cure as per manufacturers specifications
- The area for CVM application will be prepped as per normal field installation procedures: sand surface, clean surface, apply primer. A CVM sensor will be placed adjacent to each crack tip (i.e. no CVM detection or engagement at this point). The area marked with a red crosshatch in schematic will be prepped for the application of several CVM sensors.
- Fatigue loads will continue to grow the crack until permanent alarm detection is achieved



CVM Detection: (same data acquisition as in Phase I-III tests)

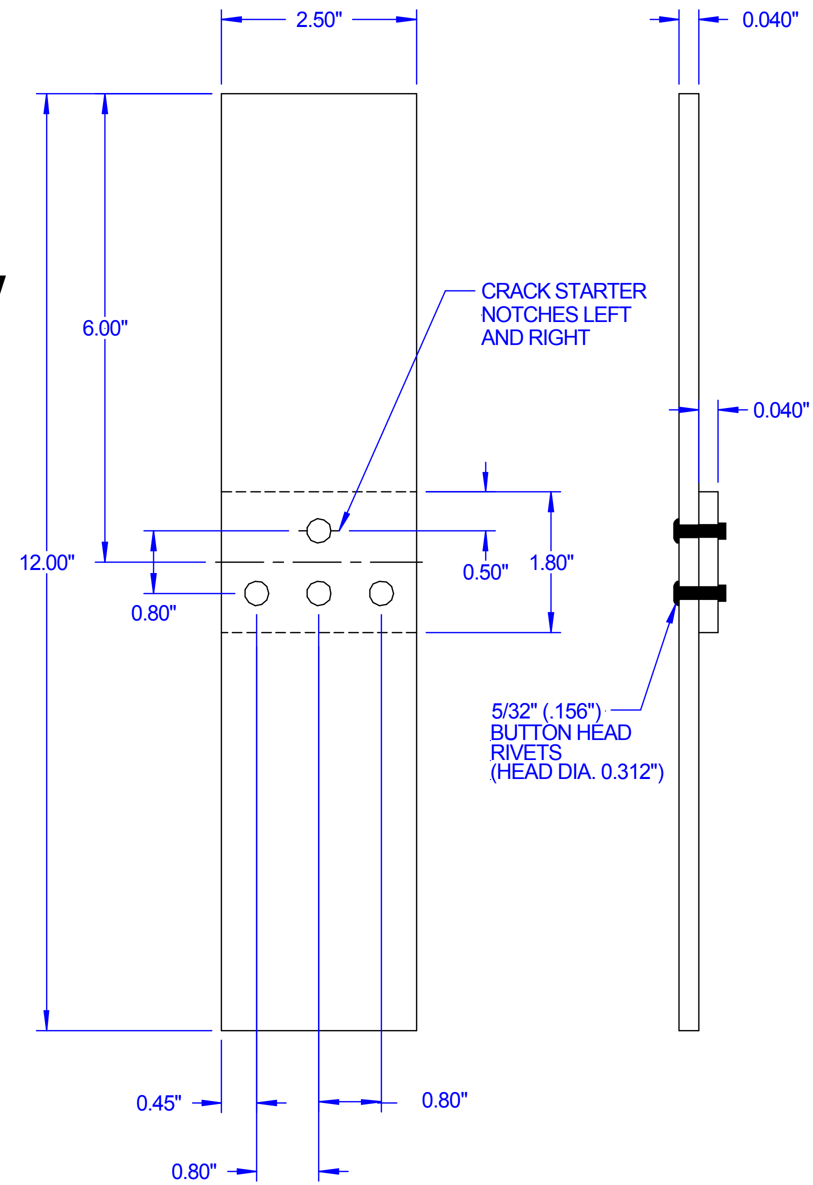
- Apply CVM to primer surface and measure baseline pressure levels
- Use SIM-8 (13 Tpasm) for real-time crack detection with max sensitivity
- Apply PM-4 to determine similar detection; grow crack additional length if needed for PM-4 detection (permanent alarm in unloaded specimen)
- Measure crack lag, as before, for CVM detection length

Data:

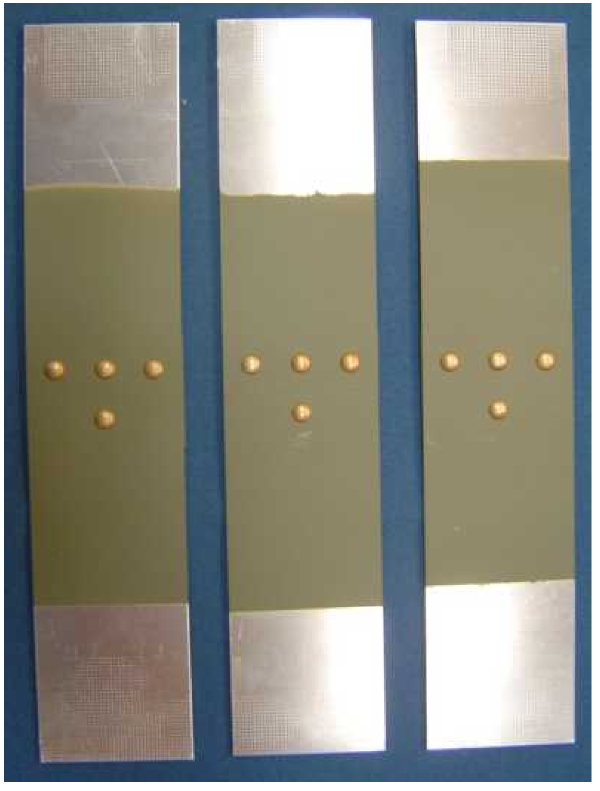
- Acquire 8-16 data points to, ideally, show no affects from presence of CIC.
- Repeat entire test series using both identified CIC compounds

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

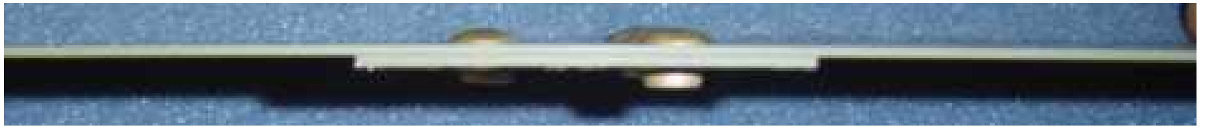


Study to Assess the Effects of CIC on the Performance of CVM



Primed Coupons (front)

Primed Coupons (back)



Primed Coupons (side view)

Application of CIC to Test Specimens

Application of CIC Compounds (Corban-35 and AV-8) to Test Specimens Prior to Fatigue Crack Growth [starter notch in place]

Results - CVM Performance in the Presence of CIC Compounds

Description: 0.040 inch thick panel (primer surface)

7075-T6 Alum.

PHASE 3 TESTS			
Panel	Fastener Crack Site	Number of Fatigue Cycles	Crack Length at CVM Detection (growth after install in inches)
1	1-L	3400	0.009
1	1-R	2400	0.011
1	2-L	6200	0.013
1	2-R	6000	0.014
1	3-L	6702	0.015
1	3-R	6702	0.004
2	1-R	3200	0.010
2	2-R	4850	0.006
2	3-L	5450	0.014
2	3-R	5450	0.018
3	1-L	3725	0.012
3	1-R	2925	0.006
3	2-L	4800	0.004
3	2-R	4600	0.008
3	3-L	5325	0.016
3	3-R	5230	0.005

Avg. = 0.011”

No CIC Present

CVM Results in Presence of CIC (Corban-35 CIC)		
Panel	Sensor	Lag (inch)
3C	1-R	0.012
4C	1-L	0.016
3C	2-R	0.010
4C	2-L	0.009
4C	3-L	0.019
3C	3-R	0.012
3C	4-R	0.026
4C	4-L	0.013
2C	1-L	0.010
2C	2-L	0.006
Average Lag		0.013

Results - CVM Performance in the Presence of CIC Compounds

Description: 0.040 inch thick panel (primer surface)

7075-T6 Alum.

PHASE 3 TESTS			
Panel	Fastener Crack Site	Number of Fatigue Cycles	Crack Length at CVM Detection (growth after install in inches)
1	1-L	3400	0.009
1	1-R	2400	0.011
1	2-L	6200	0.013
1	2-R	6000	0.014
1	3-L	6702	0.015
1	3-R	6702	0.004
2	1-R	3200	0.010
2	2-R	4850	0.006
2	3-L	5450	0.014
2	3-R	5450	0.018
3	1-L	3725	0.012
3	1-R	2925	0.006
3	2-L	4800	0.004
3	2-R	4600	0.008
3	3-L	5325	0.016
3	3-R	5230	0.005

Avg. = 0.011”

No CIC Present

CVM Results in Presence of CIC (AV-8 CIC)		
Panel	Sensor	Lag (inch)
1D	1-L	0.007
1D	2-L	0.014
2D	1-R	0.030
1D	1-R *	0.074
2D	2-R	0.020
2D	3-R	0.017
2D	4-R	0.018
Average Lag		0.026
Average Lag Without *		0.018

* Panel had no detection on right side then crack propagated rapidly and jumped to detection at 0.075”

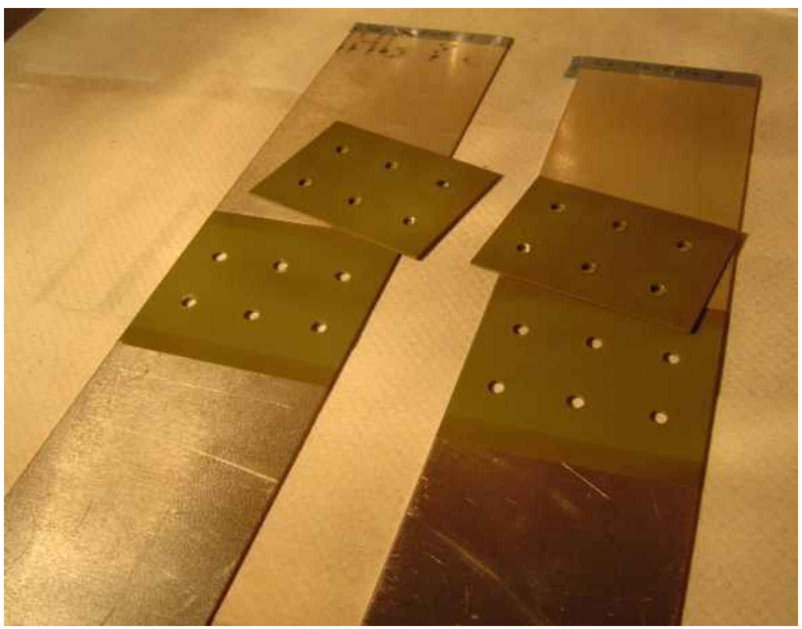
Side Study – Level of Cure for CIC Compounds Over Time

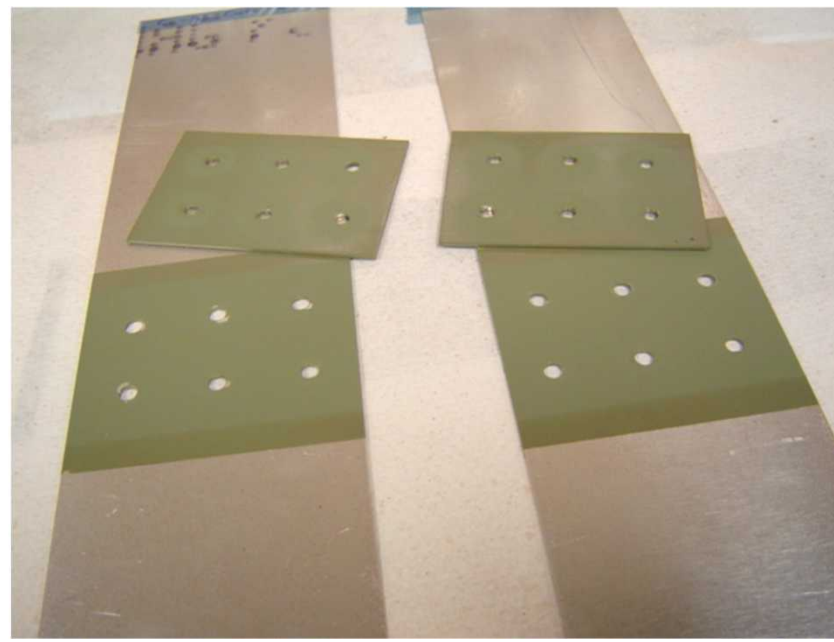
Photos of cure assessment coupons with Clecos at rivet points

Trial 1 - CIC Cure (Corban-35)

CIC applied as per specifications: 3 to 4 passes at a distance of 8 – 10 inches on specimens Cor-35-Cure-1 thru Cor-35-Cure-4

Result: with normal clamp-up spacing, CIC did not penetrate far into faying surface (wicking at edges); all CIC cured to a hardened coating in 24 hours





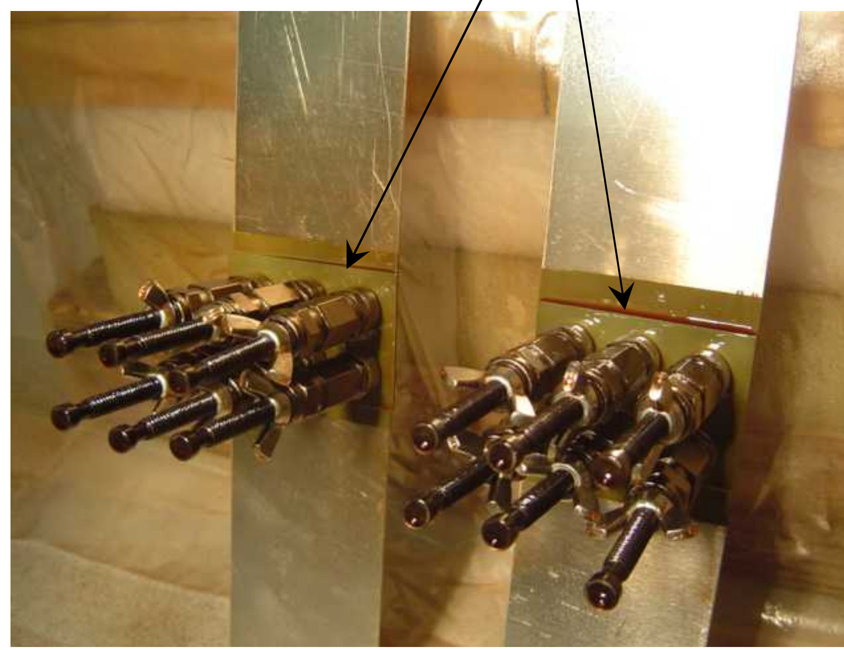
Trial 2 - CIC Cure (Corban-35)

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)

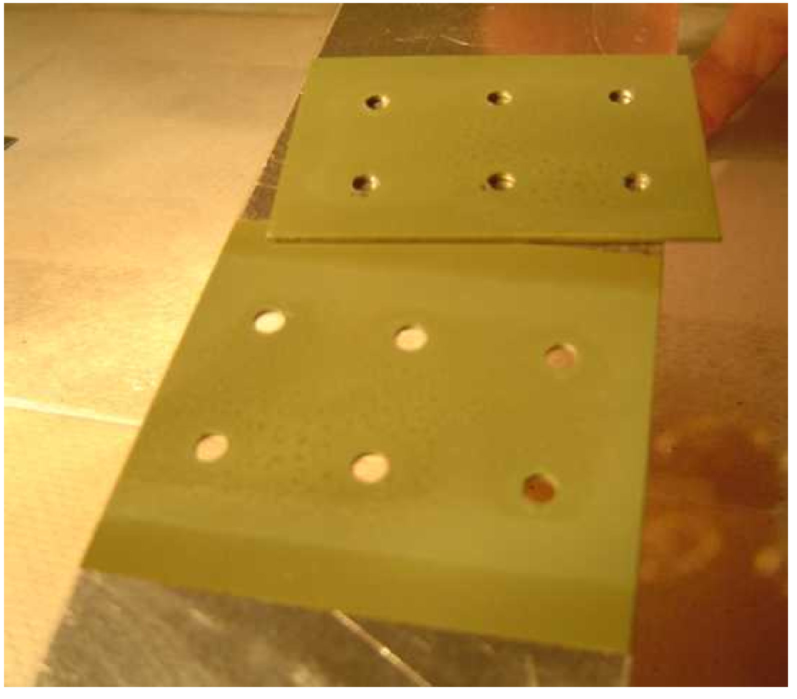


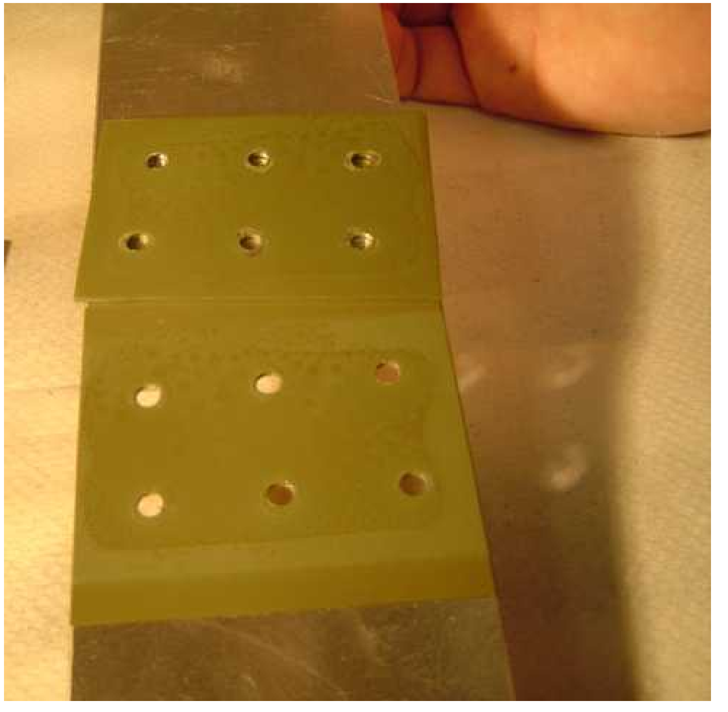
(b)

Trial 2 - CIC Cure (Corban-35)

CIC applied to extreme levels: **Spray <u>inside</u> of faying surface directly**

Result for Cor-35-Cure-1 thru Cor-35-Cure-3: After 24 hrs. - outside dry; inside very tacky; will not flow or wipe off; After 48 hrs. – hardened coating like nail polish



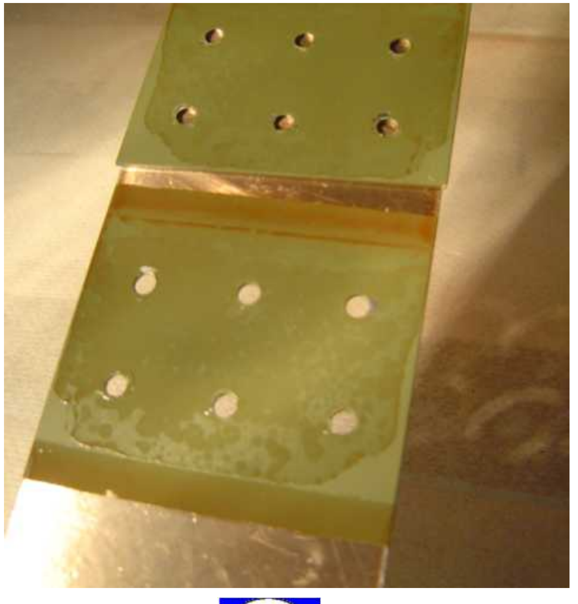


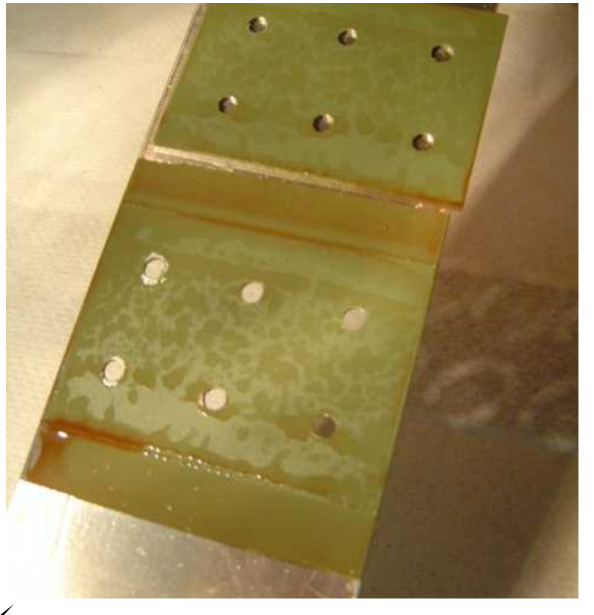
Cor-35-Cure-1 with excessive spray; still mostly cured in 24 hrs.

Trial 2 - CIC Cure (Corban-35)

CIC applied to extreme levels

Result for Cor-35-Cure-4 thru Cor-35-Cure-5: excessive pooling of CIC inside; After 24 hrs. - outside dry; inside tacky to the point of not flowing except at accumulation areas along the edge (will wipe off with cloth; could possibly flow); After 48 hrs. - inside mostly hardened coating like nail polish except at accumulation areas along the edge which were tacky to the point of not flowing (would not wipe off with cloth; would not flow); After 96 hours – same, accumulation areas even more tacky and hardened; After 120 hours – hardened coating

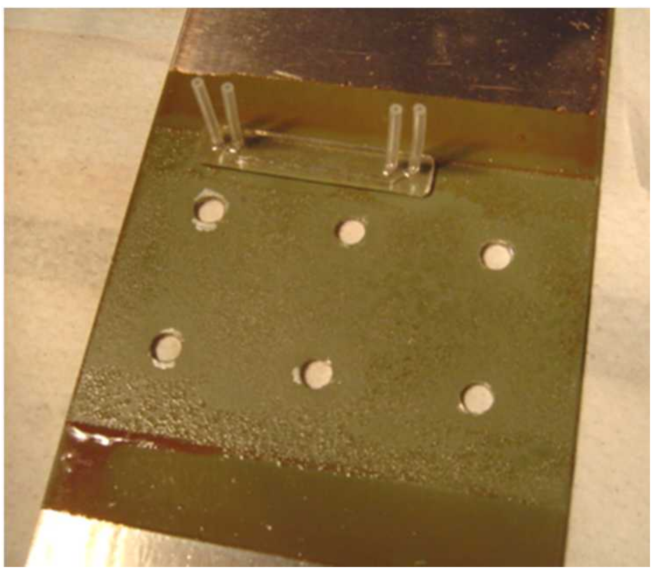


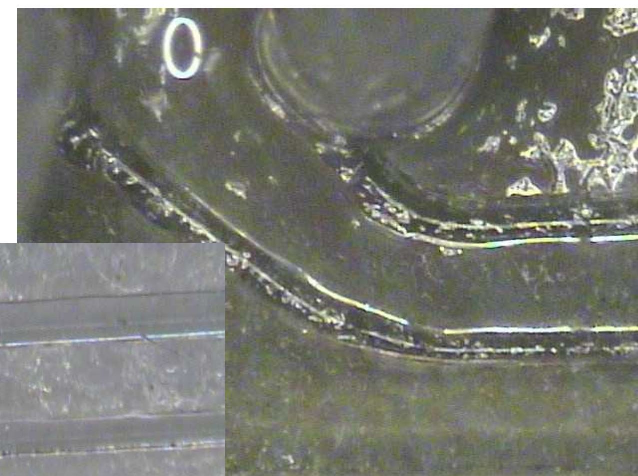


Trial 3 - CIC Cure (Corban-35)

CIC applied to extreme levels: Cor-35-Cure-5: Spray CIC to excess until it is flowing [10 passes with liquid accumulation at plate edge and inside]

Result for CVM Applied on Faying Surface of Cor-35-Cure-5: excessive pooling of CIC inside; **After 96 hours** – inside mostly hardened coating like nail polish except at accumulation areas along the edge which were tacky to the point of not flowing (would not wipe off with cloth; would not flow); **CVM applied directly to tacky inside surface at CIC accumulation point – no CIC drawn into CVM after two hours at full vacuum (530 Pa)**





Close-Up of CVM Mounted Over "Tacky" CIC

Trial 4 - CIC Cure (Corban-35)

CIC applied to extreme levels:

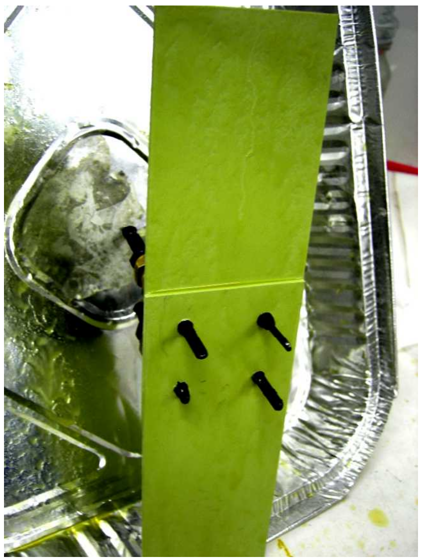
Cor-35-Cure-1 thru Cor-35-Cure-3: Spray inside of faying surface directly and then assemble panel; [5 passes used to produce thick coating]

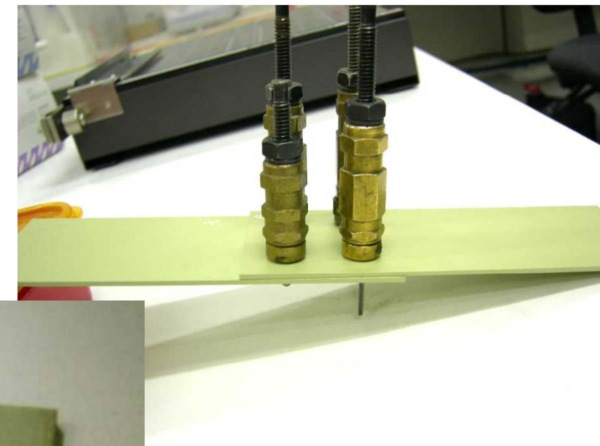
Result for Cor-35-Cure-1 thru Cor-35-Cure-3: After 24 hrs. – inside hardened & dry in spots; tacky but could possibly flow in accumulation areas (will wipe off); accumulation not concentrated in pools (striation pattern); After 48 hrs. – mostly dry; all accumulation areas tacky & most not flowing (would not wipe off); only one accum. area (Cure-1) would possibly flow; After 72 hrs. – same as 48 hrs.; After 96 hrs. – all areas hardened cure or very tacky (will not flow)

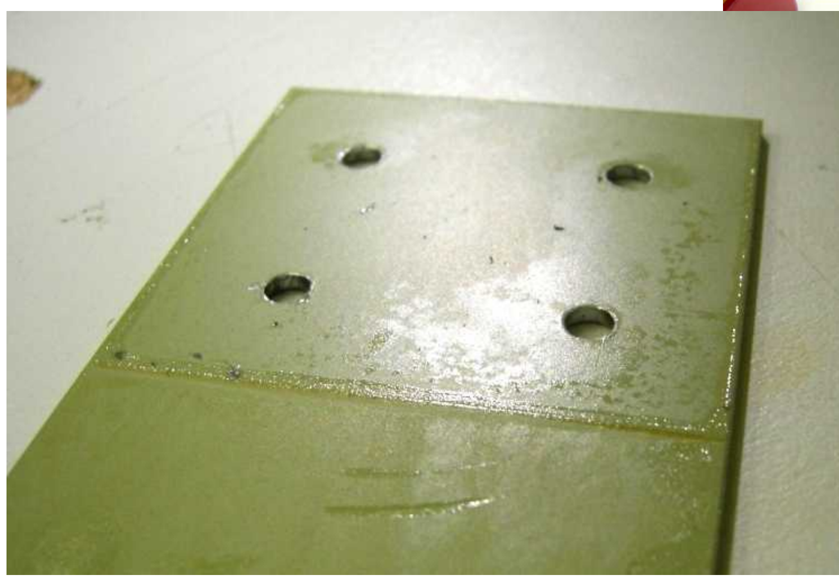
Trial 5 - CIC Cure (AV-8) at SMS

CIC Application: applied when the overlapping plate was facing upwards to allow the CIC to pool & wick into the faying surfaces

Result: After 48 hrs. – mostly hardened; all accumulation areas tacky & will not flow or wipe off







Conclusions on CIC Affects on CVM

- CIC compounds had no significant affect on CVM performance
- CIC cure was achieved in less than 4 days even with excessive sprays and large accumulation of CIC in faying surfaces
- CVM sensors applied directly on top of tacky CIC compound did not draw CIC into the CVM galleries when vacuum was applied for over two hours; noraml time to reach the tacky state is 1 to 3 days
- For a conservative, safe approach, the Boeing NDT Common Practices Manual states that CVM sensors should not be applied with 30 days of CIC application.

Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection

Part 3: Field Durability Tests on Operating Aircraft

Field Evaluation of Sensor Applications

To assess the long-term viability of CVM sensors in an actual operating environment, sensors have been installed on the following civil aircraft for functional evaluation:

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

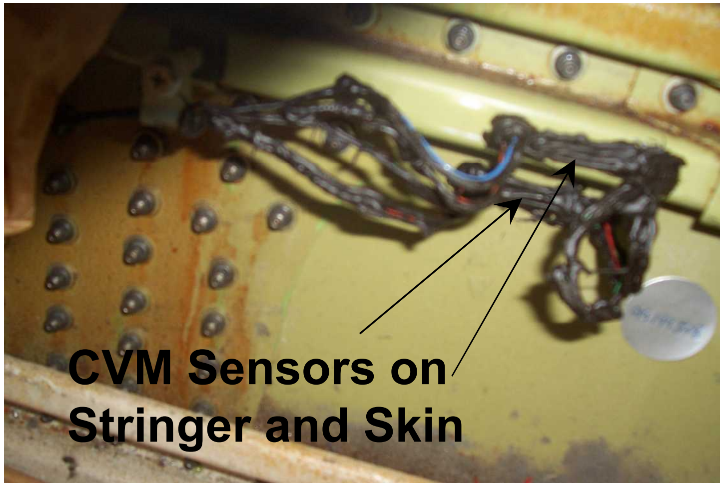
Field Evaluation of Sensor Applications

Environmental Durability Testing

- Project requires long-term sensor flight trials
- First sensors were MFA/TRI fuel tank sensors installed in DC-9 empennage in Feb 2004
- Installations conducted at NWA and Delta in April 2005
- 22 sensors installed and connected on 4 aircraft
- Delta and NWA indicate good data from connected sensors on AC thus far

DC-9 Lower Wing Spar

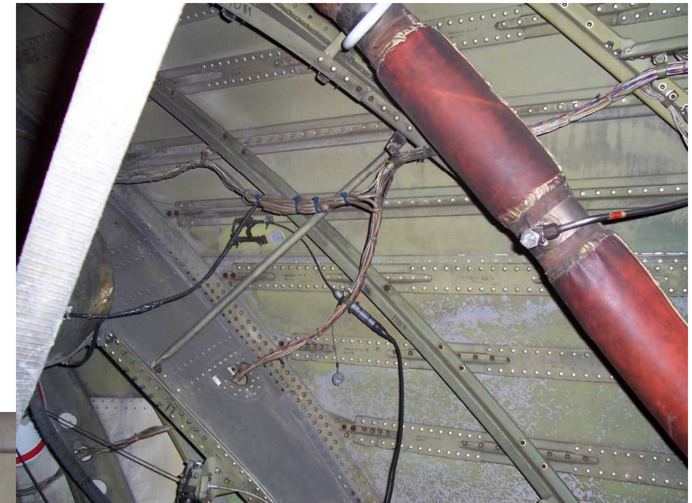
NWA Aft Baggage Compartment Sensor (A/C 9968)

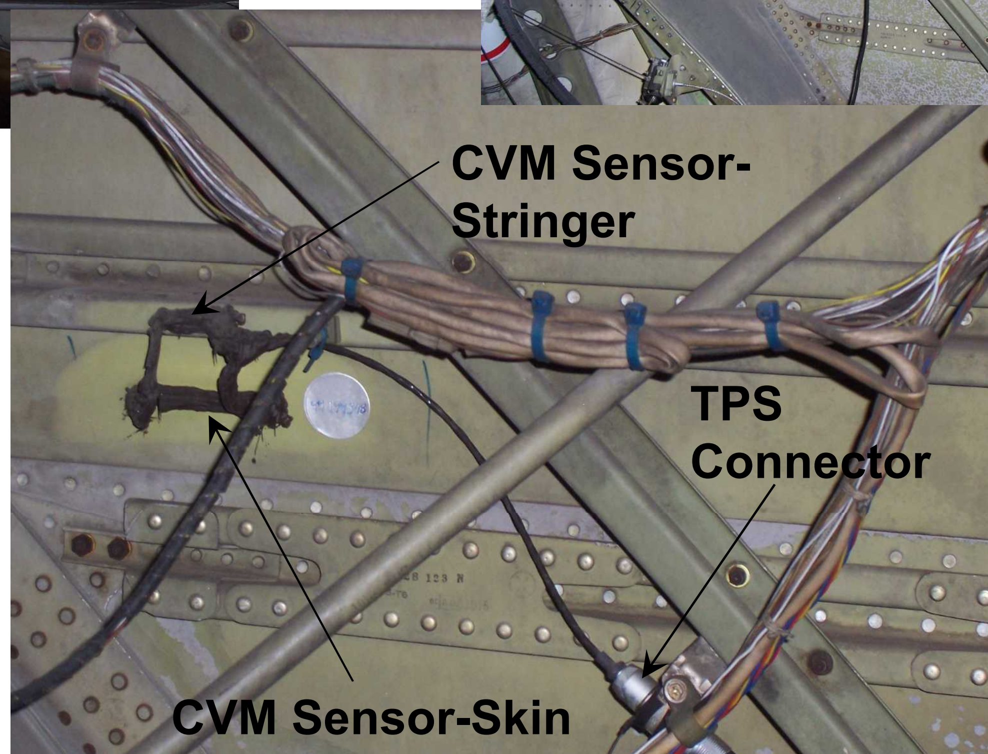


TPS connector routed to access panel

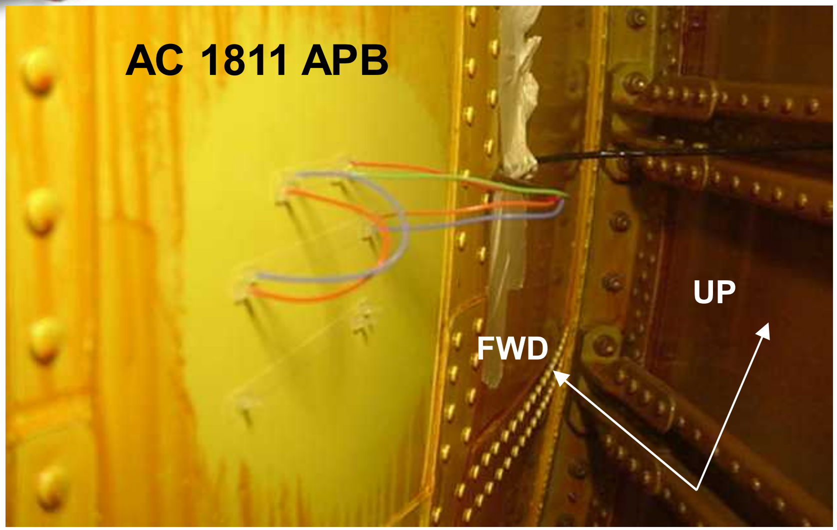
Monitoring CVM with PM-4 device

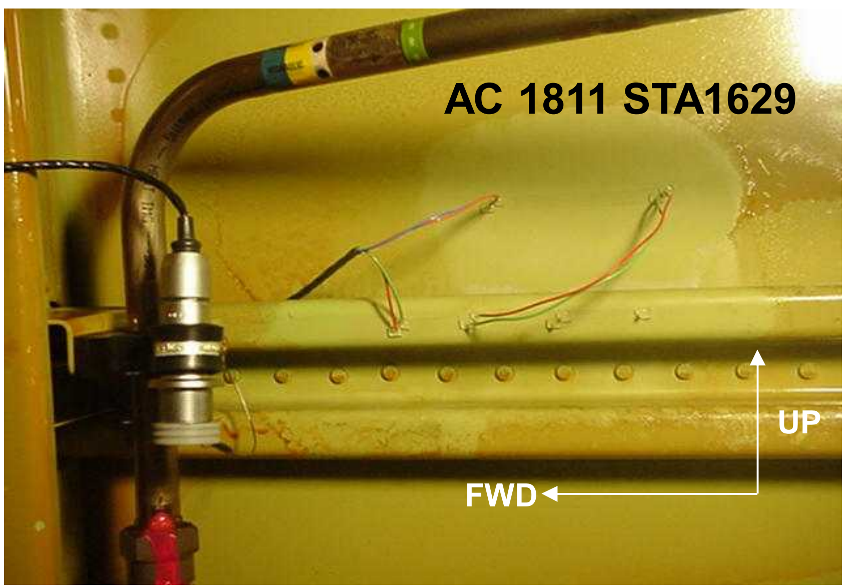
NWA Empennage Sensor (A/C 9968)

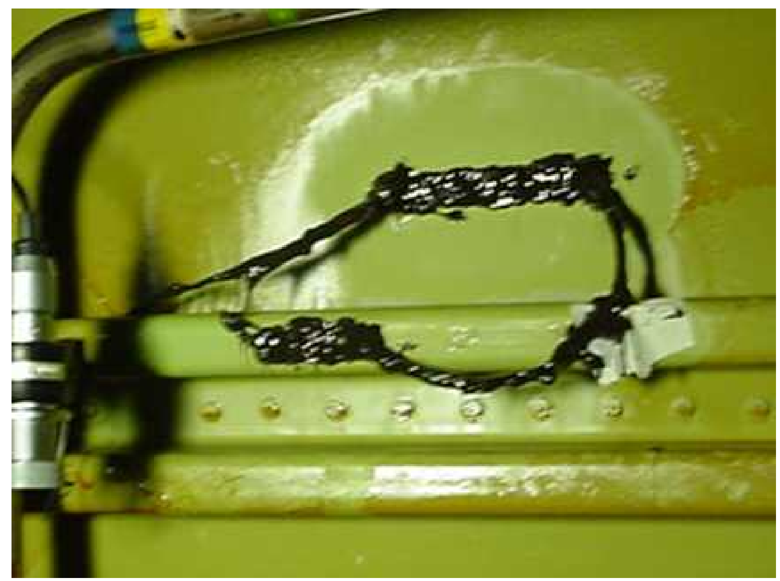




Delta Air Lines Field Installations







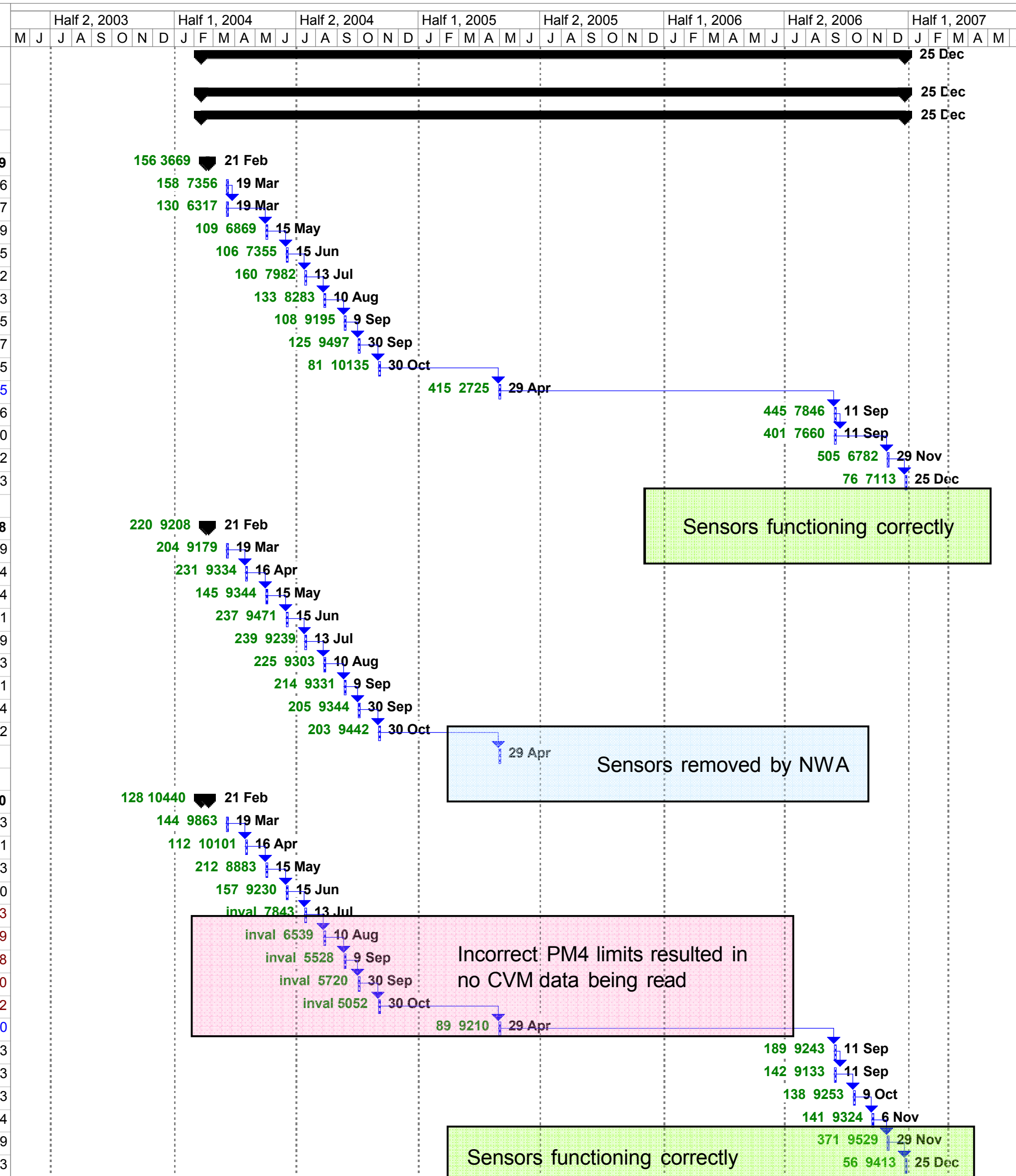
Field Evaluation of Sensor Applications

Environmental Durability Testing

- Project specifies 2 year sensor flight trials required – sensors will reach 3 years of operation in April 2008
- First sensors were MFA/TRI fuel tank sensors installed in DC-9 empennage in Feb 2004
- Installations conducted at NWA and Delta in April 2005
- 22 sensors installed and connected on 4 aircraft so far
- Delta and NWA indicate good data from connected sensors on AC thus far

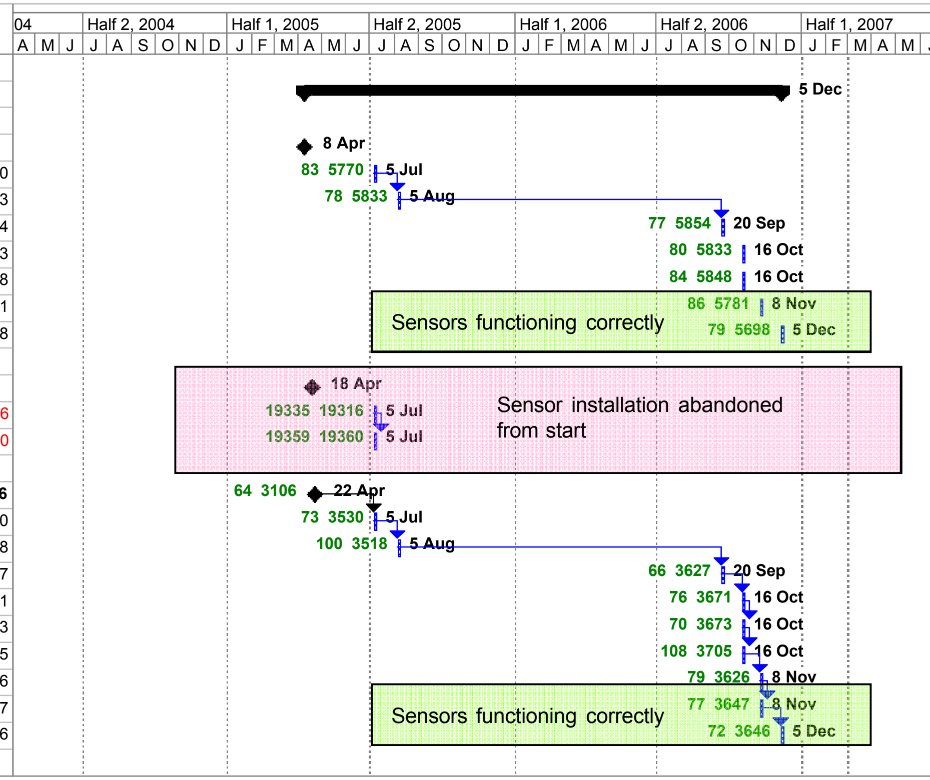
Aircraft Installation and Monitoring Summary (1)

ID	Task Name	PM4 SN	CVM CTY
1	**SPM Program Aircraft Environmental Durability Installations**		
2	**NWA installations**		
3	**NWA DC9 AC9961 (Sensor Type 1)**		
4			
5	**NWA 9961 APU install**	**0004**	**156 3669**
9	NWA 9961 APU checked	0004	158 7356
10	NWA 9961 APU checked	0004	130 6317
11	NWA 9961 APU checked	0004	109 6869
12	NWA 9961 APU checked	0004	106 7355
13	NWA 9961 APU checked	0004	160 7982
14	NWA 9961 APU checked	0004	133 8283
15	NWA 9961 APU checked	0004	108 9195
16	NWA 9961 APU checked	0004	125 9497
17	NWA 9961 APU checked	0004	81 10135
18	NWA APU renamed sta 1121 checked	0016	415 2725
19	NWA 9961 sta 1121 checked	0016	445 7846
20	NWA 9961 sta 1121 checked	0016	401 7660
21	NWA 9961 sta 1121 checked	0016	505 6782
22	NWA 9961 sta 1121 checked	0016	76 7113
23			
24	**NWA 9961 r baggage install**	**0004**	**220 9208**
28	NWA 9961 r baggage checked	0004	204 9179
29	NWA 9961 r baggage checked	0004	231 9334
30	NWA 9961 r baggage checked	0004	145 9344
31	NWA 9961 r baggage checked	0004	237 9471
32	NWA 9961 r baggage checked	0004	239 9239
33	NWA 9961 r baggage checked	0004	225 9303
34	NWA 9961 r baggage checked	0004	214 9331
35	NWA 9961 r baggage checked	0004	205 9344
36	NWA 9961 r baggage checked	0004	203 9442
37	NWA 9961 r baggage removed by NWA	0016	
38			
39	**NWA 9961 flt recorder install**	**0004**	**128 10440**
48	NWA 9961 flt recorder checked	0004	144 9863
49	NWA 9961 flt recorder checked	0004	112 10101
50	NWA 9961 flt recorder checked	0004	212 8883
51	NWA 9961 flt recorder checked	0004	157 9230
52	NWA 9961 flt recorder checked	0004	inval 7843
53	NWA 9961 flt recorder checked	0004	inval 6539
54	NWA 9961 flt recorder checked	0004	inval 5528
55	NWA 9961 flt recorder checked	0004	inval 5720
56	NWA 9961 flt recorder checked	0004	inval 5052
57	NWA 9961 flt recorder renamed voice rcd checked	0016	89 9210
58	NWA 9961 voice rcd checked	0016	189 9243
59	NWA 9961 voice rcd checked	0016	142 9133
60	NWA 9961 voice rcd checked	0016	138 9253
61	NWA 9961 voice rcd checked	0016	141 9324
62	NWA 9961 voice rcd checked	0016	371 9529
63	NWA 9961 voice rcd checked	0016	56 9413



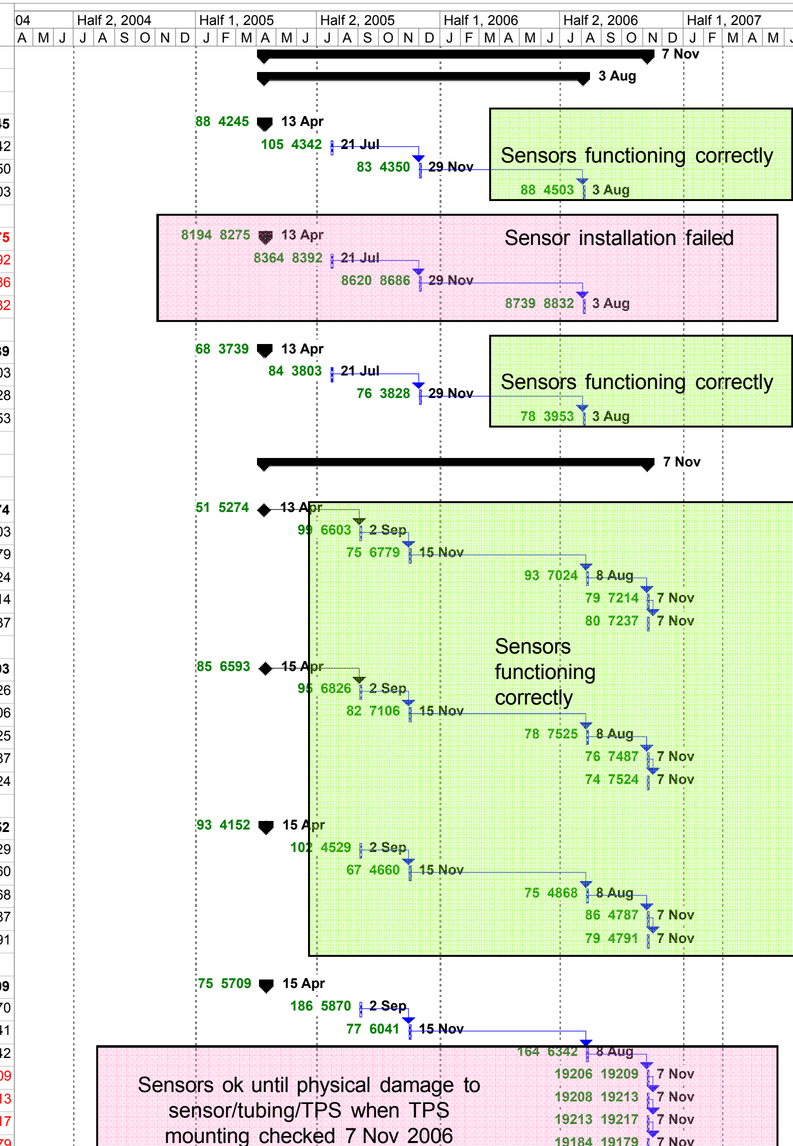
Aircraft Installation and Monitoring Summary (2)

ID	Task Name	PM4 SN	CVM CTY
65			
66	**NWA DC9 AC9968 (Sensor Type 2)**		
67			
68	**NWA 9968 St1104lt installed**		
69	NWA 9968 St1104lt checked	0016	83 5770
70	NWA 9968 St1104lt checked	0016	78 5833
71	NWA 9968 St1104lt checked	0016	77 5854
72	NWA 9968 St1104lt checked	0016	80 5833
73	NWA 9968 St1104lt checked	0016	84 5848
74	NWA 9968 St1104lt checked	0016	86 5781
75	NWA 9968 St1104lt checked	0016	79 5698
76			
77	**NWA 9968 canted 1046lt installed**		
78	NWA 9968 canted 1046lt installed	0016	19335 19316
79	NWA 9968 canted 1046lt abandoned	0016	19359 19360
80			
81	**NWA 9968 Aft crgo V/Rcdr installed**	**0016**	**64 3106**
82	NWA 9968 Aft crgo V/Rcdr checked	0016	73 3530
83	NWA 9968 Aft crgo V/Rcdr checked	0016	100 3518
84	NWA 9968 Aft crgo V/Rcdr checked	0016	66 3627
85	NWA 9968 Aft crgo V/Rcdr checked	0016	76 3671
86	NWA 9968 Aft crgo V/Rcdr checked	0016	70 3673
87	NWA 9968 Aft crgo V/Rcdr checked	0016	108 3705
88	NWA 9968 Aft crgo V/Rcdr checked	0016	79 3626
89	NWA 9968 Aft crgo V/Rcdr checked	0016	77 3647
90	NWA 9968 Aft crgo V/Rcdr checked	0016	72 3646
91			

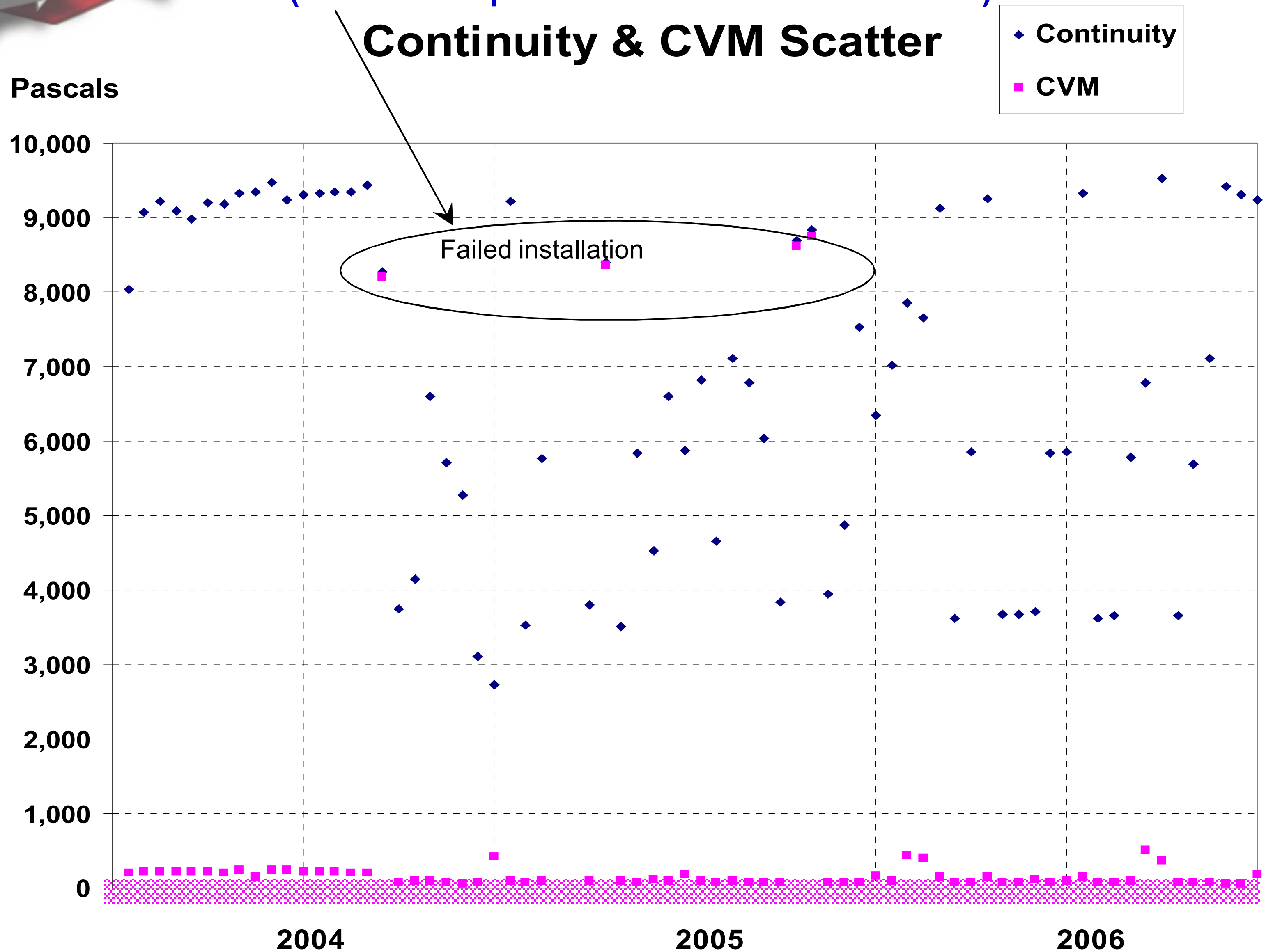


Aircraft Installation and Monitoring Summary (3)

ID	Task Name	PM4 SN	CVM CTY
92	**Delta Installations**		
93	**Delta B767 AC1811 (Sensor Type 2)**		
94			
95	**Delta AC1811 AFT PRESSURE BLK install**	**0017**	**88 4245**
98	Delta AC1811 AFT PRESSURE BLK checked	0017	105 4342
99	Delta AC1811 AFT PRESSURE BLK checked	0017	83 4350
100	Delta AC1811 AFT PRESSURE BLK checked	0017	88 4503
101			
102	**Delta AC1811 APBCenter install - not completed**	**0017**	**8194 8275**
104	Delta AC1811 APBCenter checked	0017	8364 8392
105	Delta AC1811 APBCenter checked	0017	8620 8686
106	Delta AC1811 APBCenter checked	0017	8739 8832
107			
108	**Delta AC1811 STA 1629 install**	**0017**	**68 3739**
113	Delta AC1811 STA 1629 checked	0017	84 3803
114	Delta AC1811 STA 1629 checked	0017	76 3828
115	Delta AC1811 STA 1629 checked	0017	78 3953
116			
117	**Delta B757 AC669 (Sensor Type 2)**		
118			
119	**Delta AC669 STA1750 install**	**0017**	**51 5274**
120	Delta AC669 STA1750 checked	0017	99 6603
121	Delta AC669 STA1750 checked	0017	75 6779
122	Delta AC669 STA1750 checked	0017	93 7024
123	Delta AC669 STA1750 checked	0017	79 7214
124	Delta AC669 STA1750 checked	0017	80 7237
125			
126	**Delta AC669 Stn 1720 upr lft install**	**0017**	**85 6593**
127	Delta AC669 Stn 1720 upr lft checked	0017	95 6826
128	Delta AC669 Stn 1720 upr lft checked	0017	82 7106
129	Delta AC669 Stn 1720 upr lft checked	0017	78 7525
130	Delta AC669 Stn 1720 upr lft checked	0017	76 7487
131	Delta AC669 Stn 1720 upr lft checked	0017	74 7524
132			
133	**Delta AC669 Stn 1720 lwr rgt install**	**0017**	**93 4152**
137	Delta AC669 Stn 1720 lwr rgt checked	0017	102 4529
138	Delta AC669 Stn 1720 lwr rgt checked	0017	67 4660
139	Delta AC669 Stn 1720 lwr rgt checked	0017	75 4868
140	Delta AC669 Stn 1720 lwr rgt checked	0017	86 4787
141	Delta AC669 Stn 1720 lwr rgt checked	0017	79 4791
142			
143	**Delta AC669 Stn1768 install**	**0017**	**75 5709**
145	Delta AC669 Stn1768 checked	0017	186 5870
146	Delta AC669 Stn1768 checked	0017	77 6041
147	Delta AC669 Stn1768 checked	0017	164 6342
148	Delta AC669 Stn1768 checked	0017	19206 19209
149	Delta AC669 Stn1768 checked	0017	19208 19213
150	Delta AC669 Stn1768 checked	0017	19213 19217
151	Delta AC669 Stn1768 checked	0017	19184 19179



Poor or deteriorated installation can be detected via continuity check and sensor can be replaced (i.e. will not produce false or missed calls)

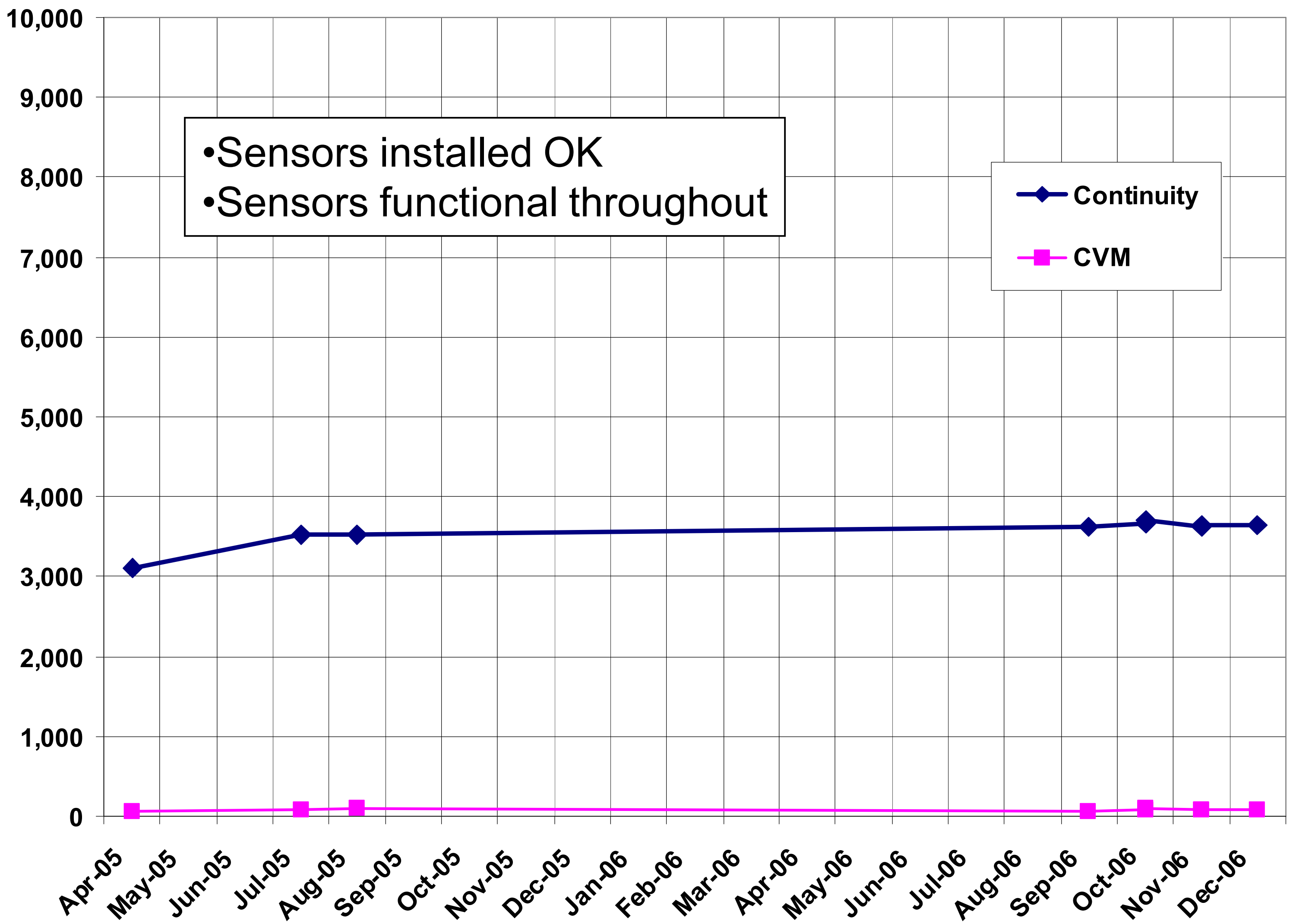


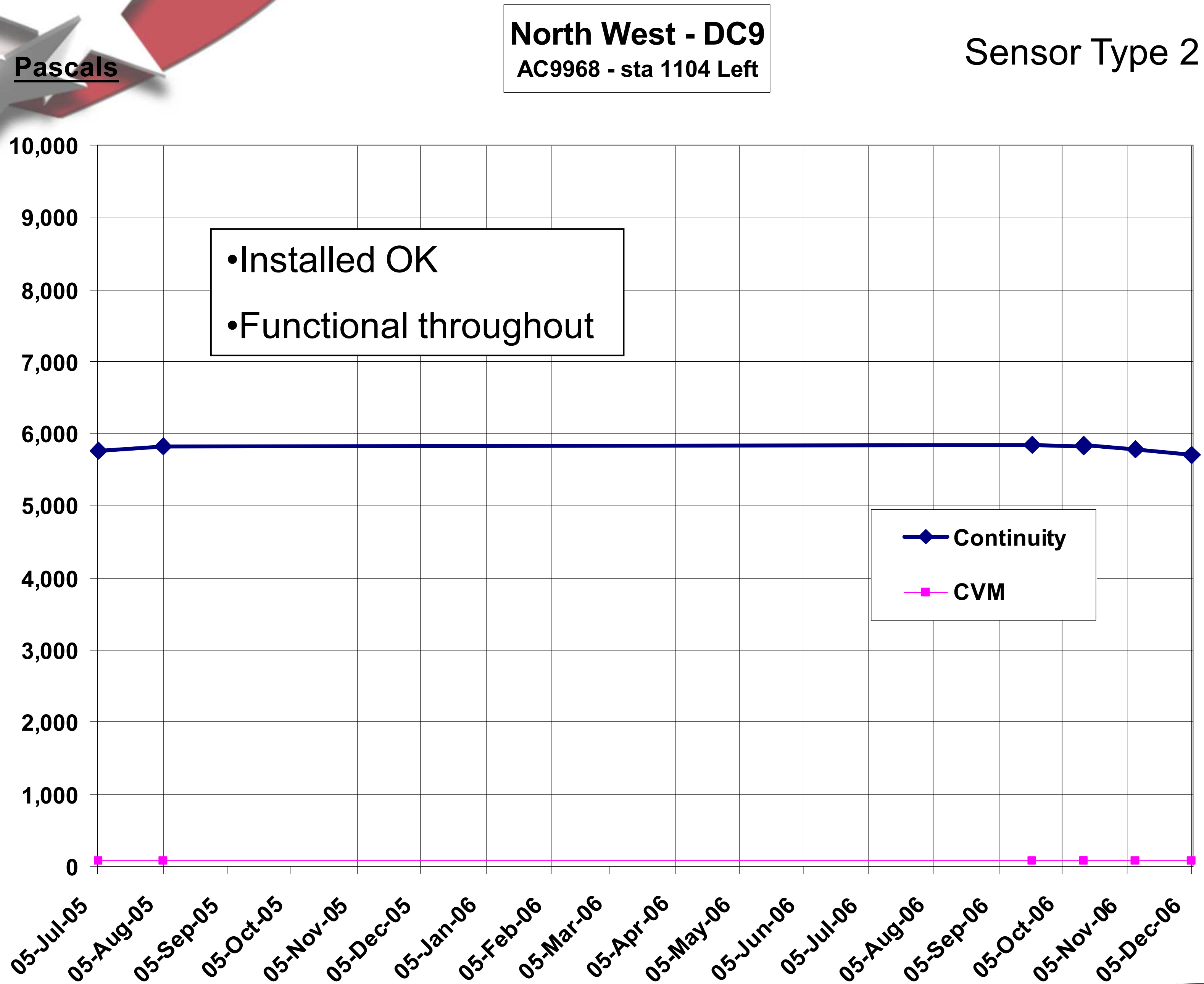
FAA Hughes Technical Center

North West - DC9
AC9968 - Aft Cargo Voice Recorder

Sensor Type 2

Pascals





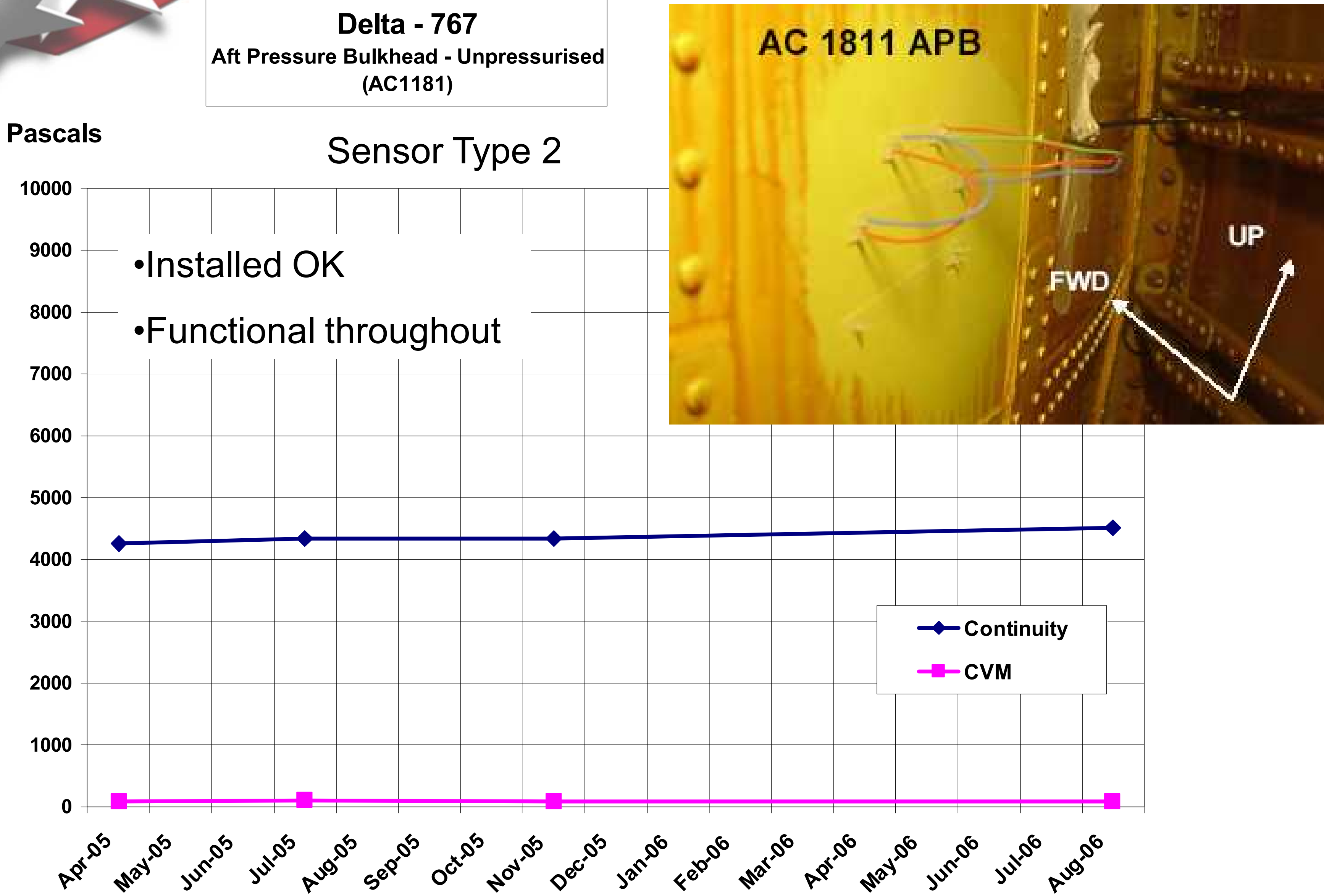
North West - DC9
AC9968 - sta 1104 Left
Sensor Type 2
Pascals
•Installed OK
•Functional throughout
Continuity
CVM
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
05-Jul-05
05-Aug-05
05-Sep-05
05-Oct-05
05-Nov-05
05-Dec-05
05-Jan-06
05-Feb-06
05-Mar-06
05-Apr-06
05-May-06
05-Jun-06
05-Jul-06
05-Aug-06
05-Sep-06
05-Oct-06
05-Nov-06
05-Dec-06

Delta - 767

Aft Pressure Bulkhead - Unpressurised (AC1181)

Sensor Type 2

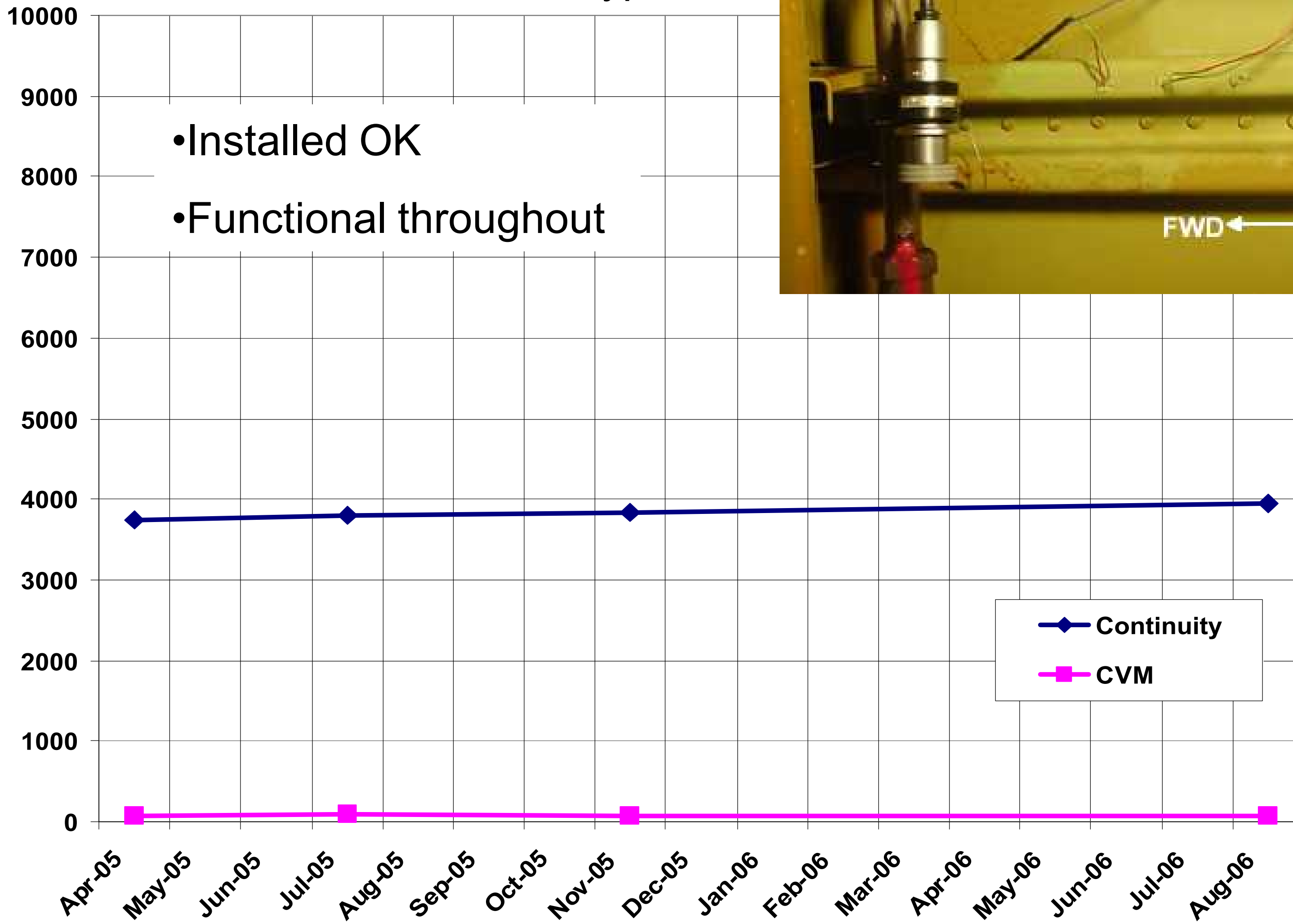
- Installed OK
- Functional throughout

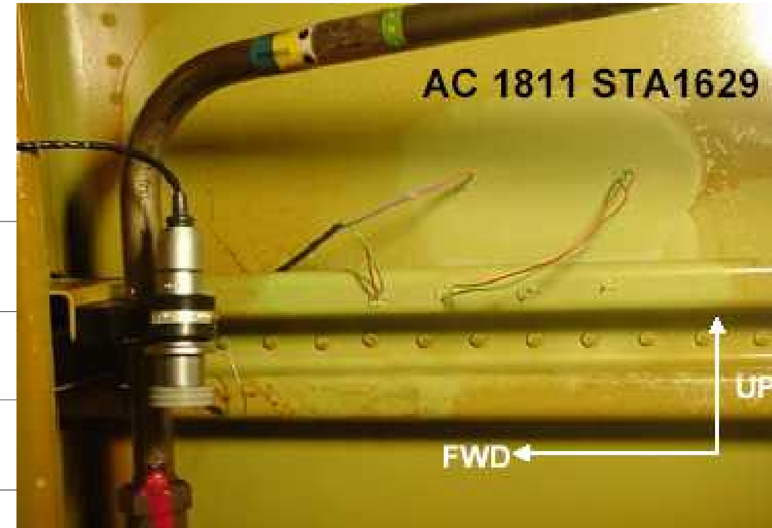


Delta - 767
Empennage - Unpressurized
(AC1181 - STA 1629)

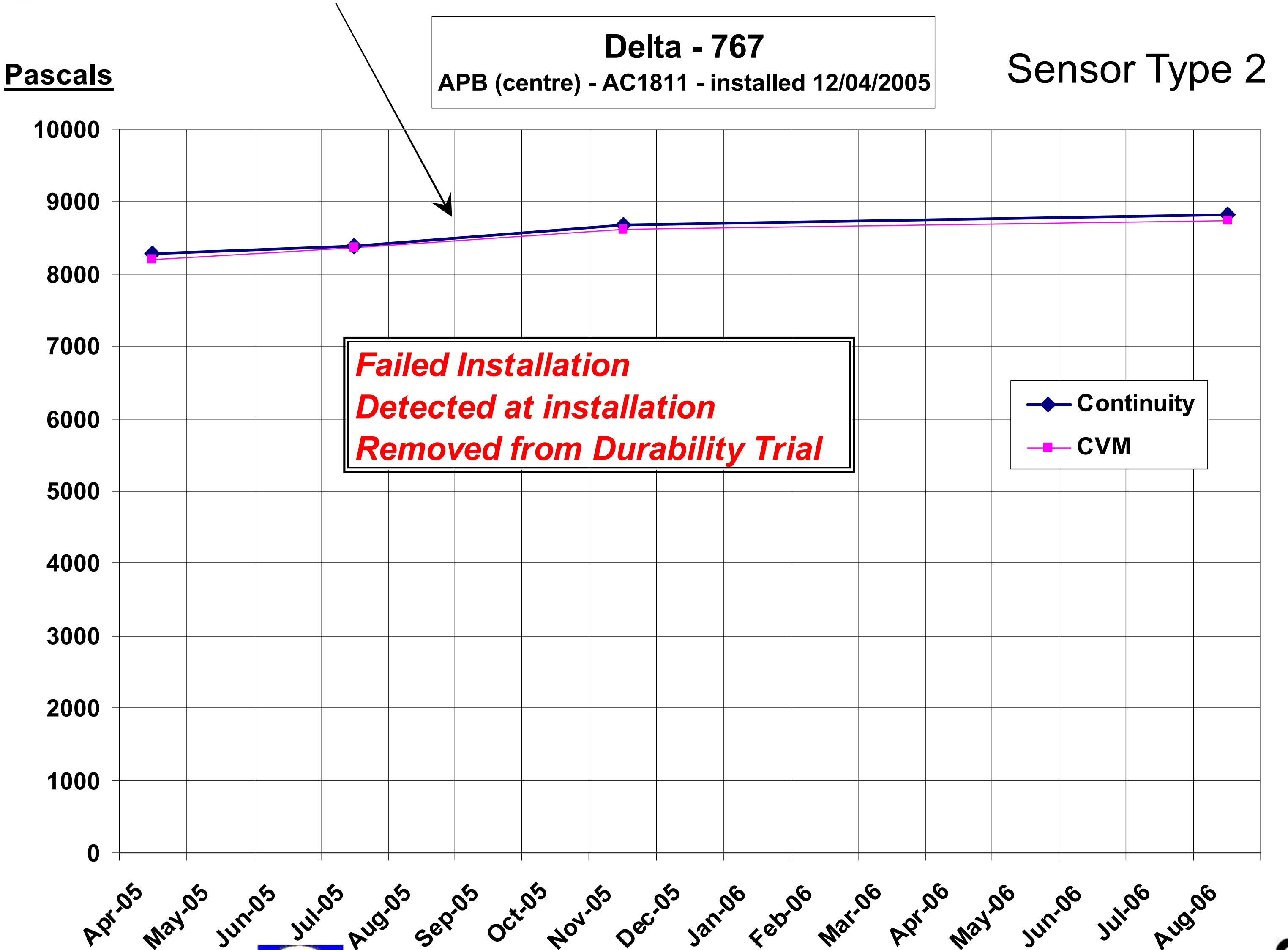
Sensor Type 2

- Installed OK
- Functional throughout

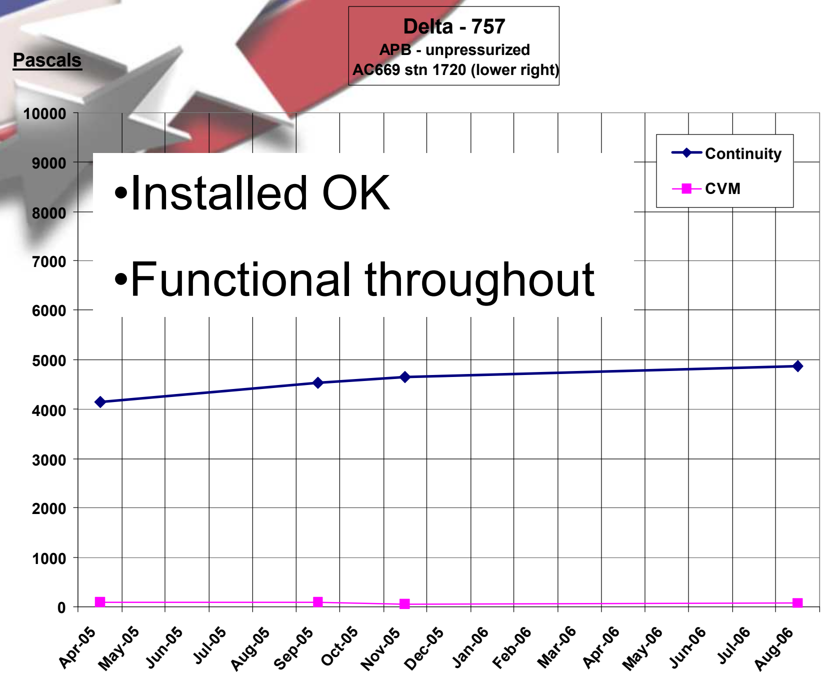


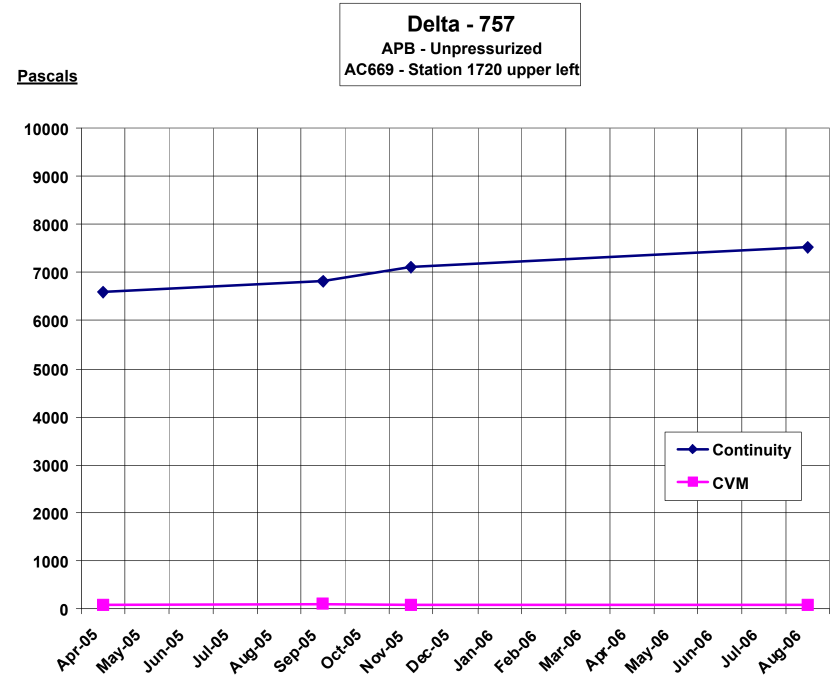


Fail-Safe Feature – poor installation (cannot pull vacuum) is detectable prior to use for monitoring and sensor can be replaced (i.e. will not produce false or missed calls); this sensor was left in place and monitored but would be replaced in a real application

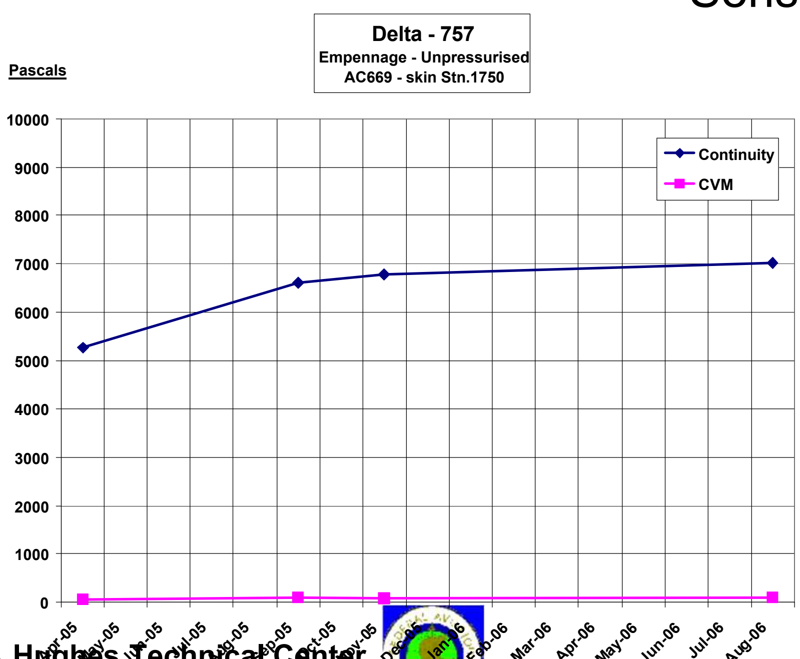


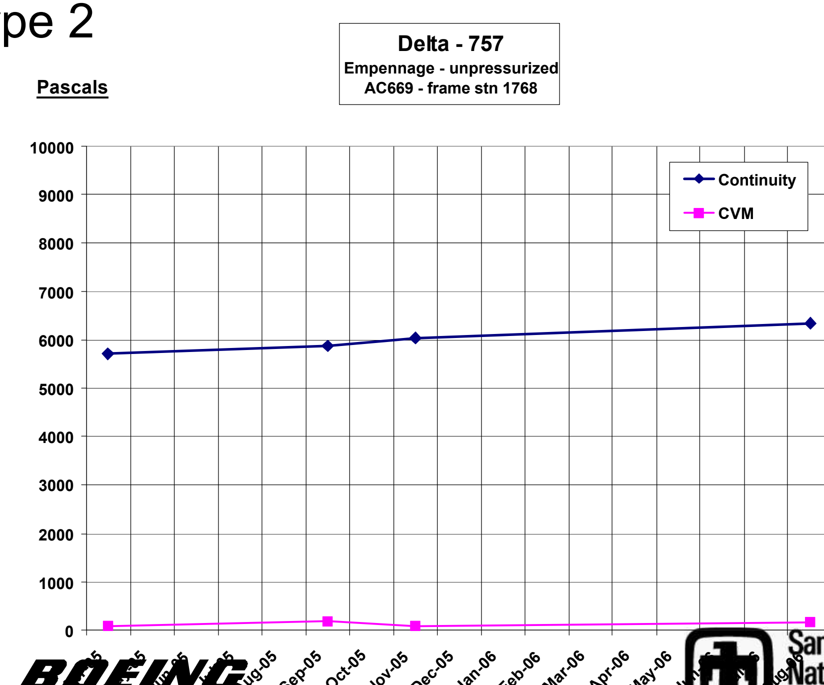
- Installed OK
- Functional throughout





Sensor Type 2



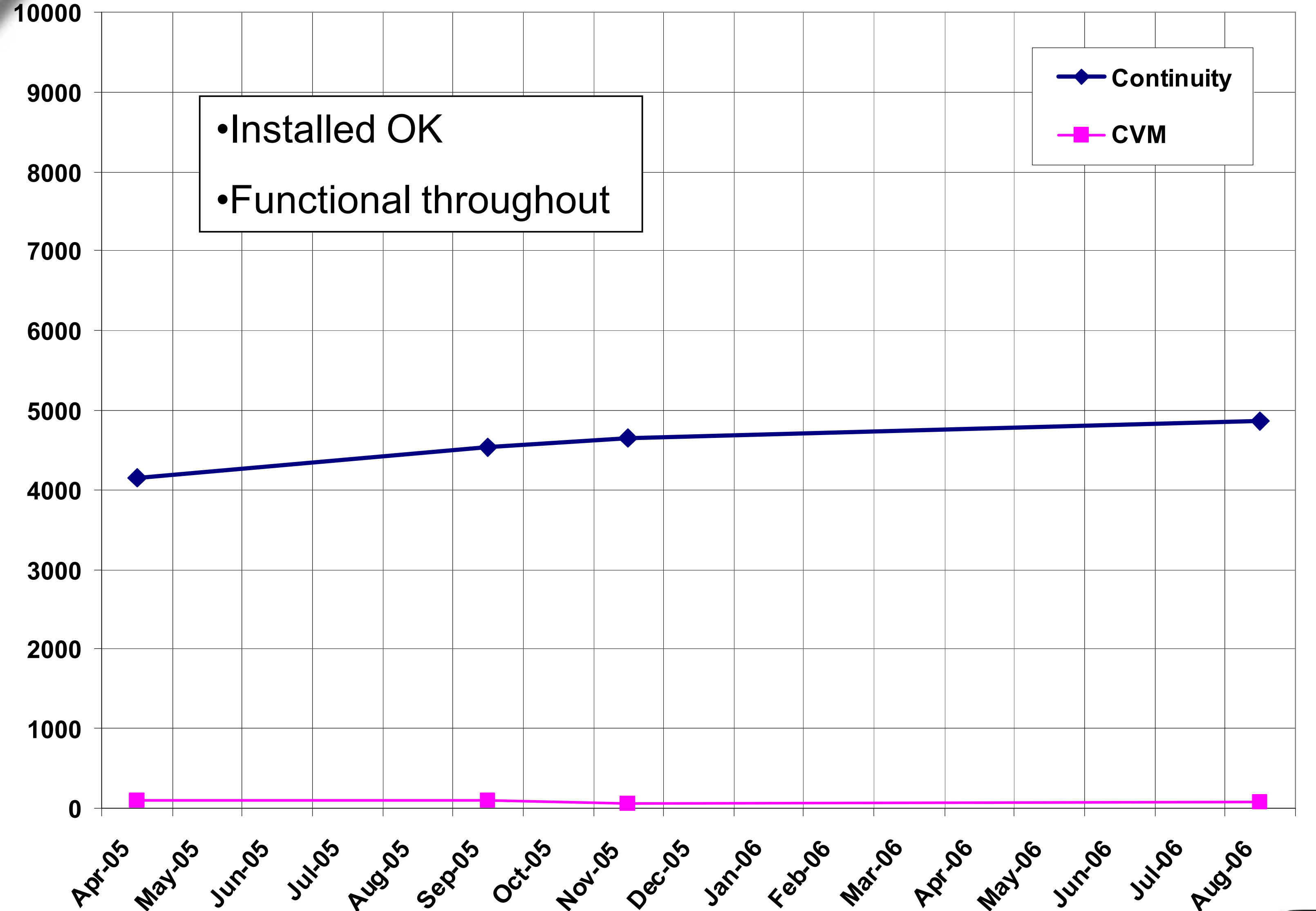


Delta - 757

APB - unpressurized

AC669 stn 1720 (lower right)

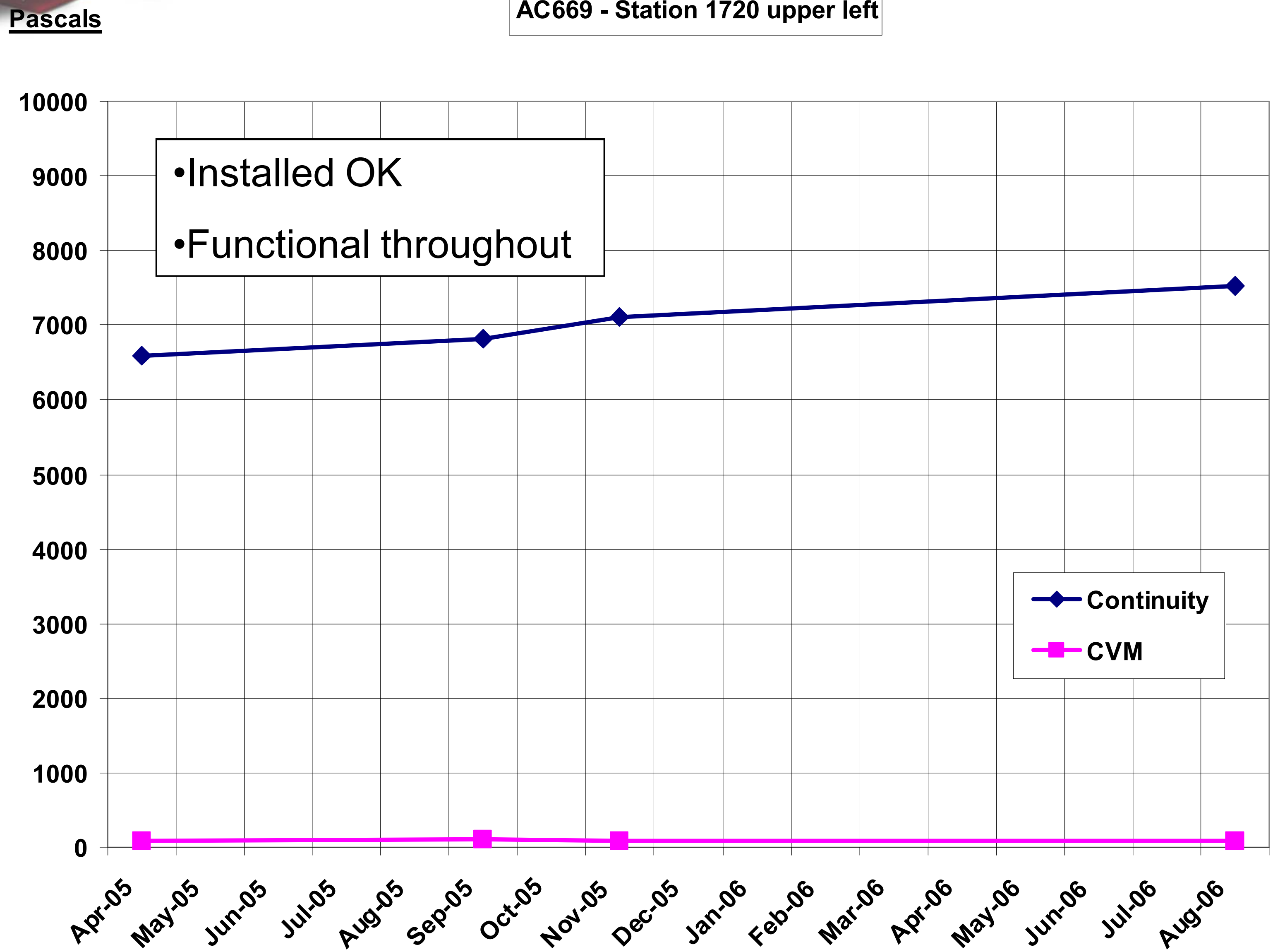
Pascals



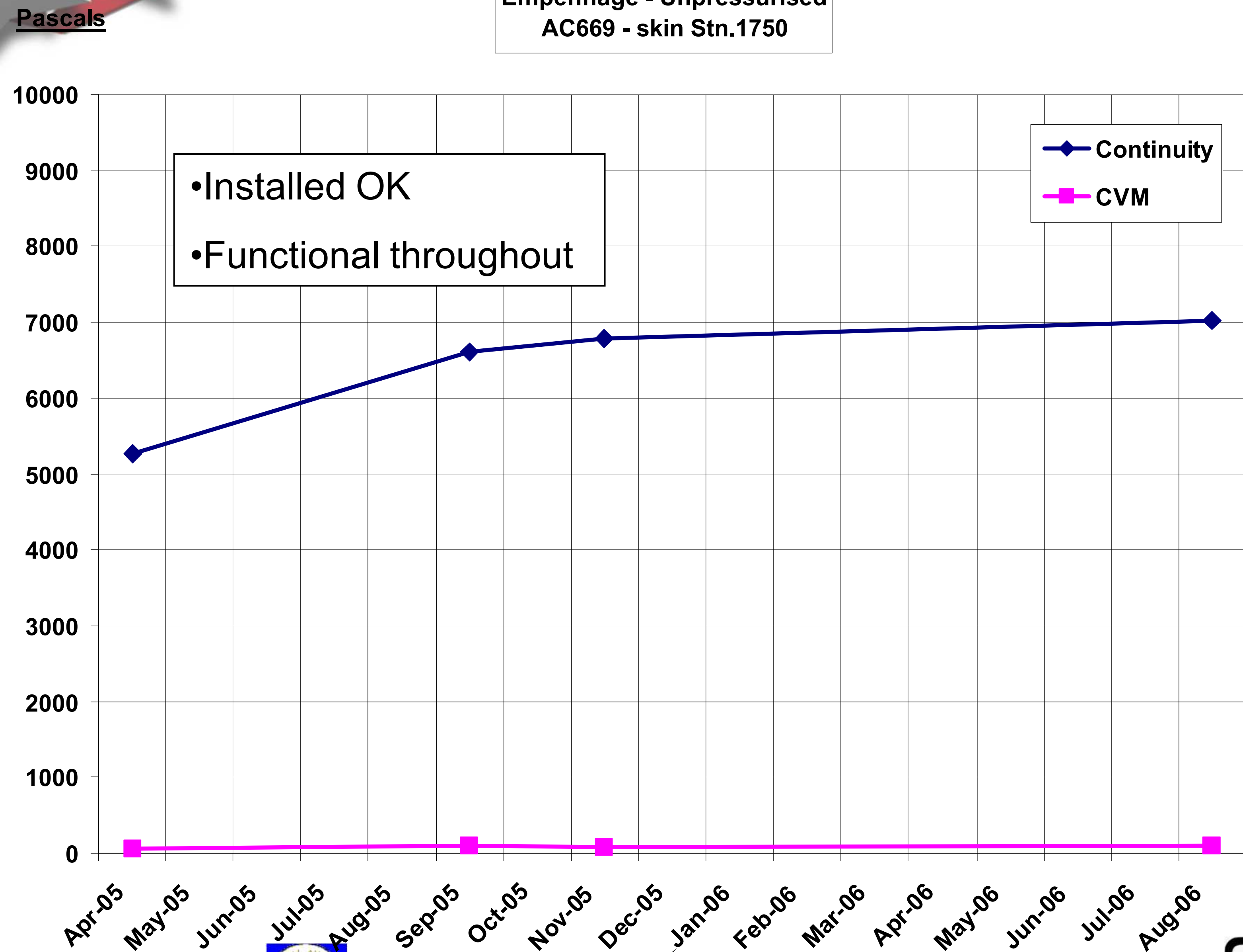
Delta - 757

APB - Unpressurized

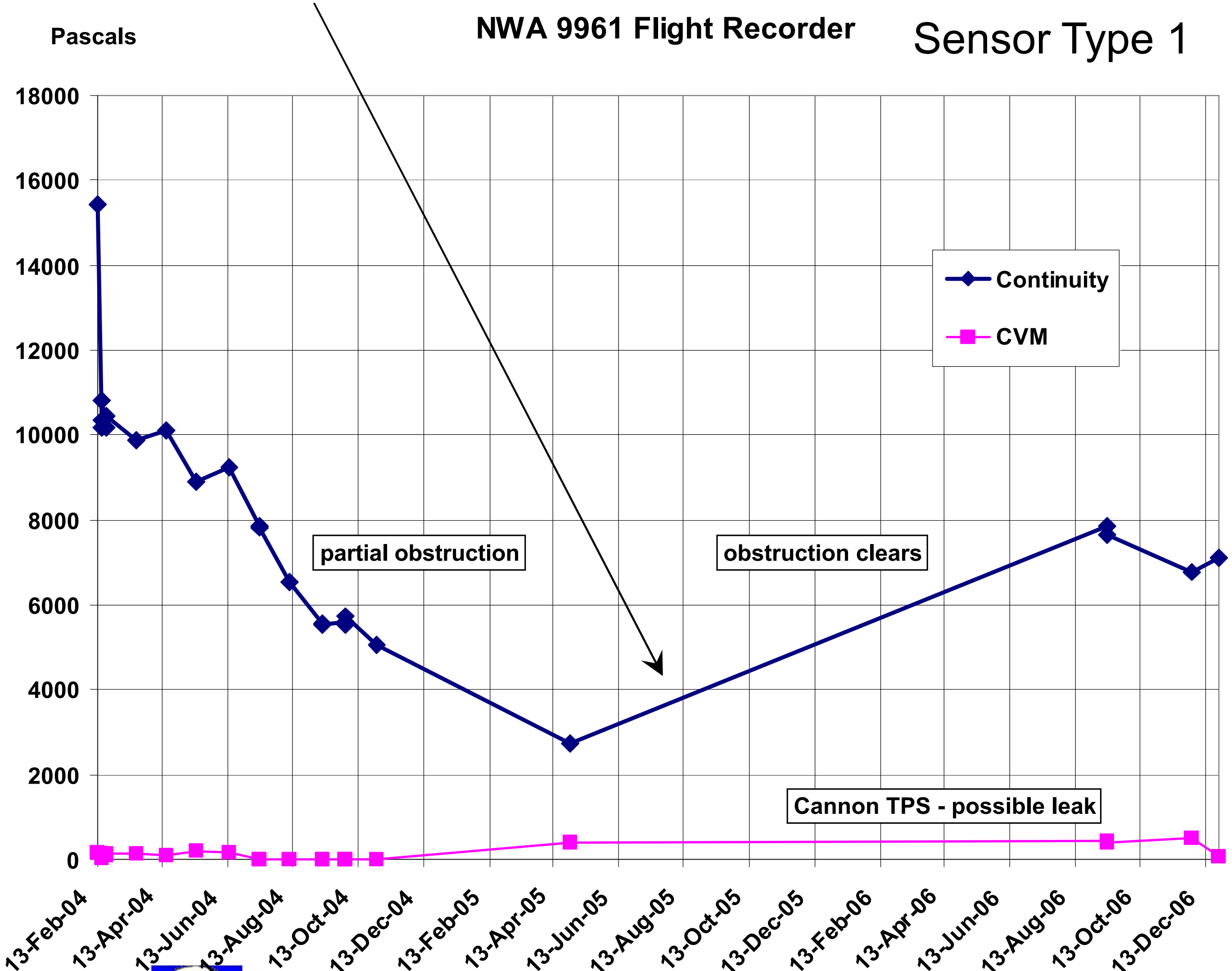
AC669 - Station 1720 upper left



Delta - 757
Empennage - Unpressurised
AC669 - skin Stn.1750



Fail-Safe Feature – blockage in sensor is detectable prior to monitoring and sensor can be replaced (i.e. will not produce false or missed calls); this sensor had some blockage which caused it to fail continuity check; it was left in place and monitored but would be replaced in a real application

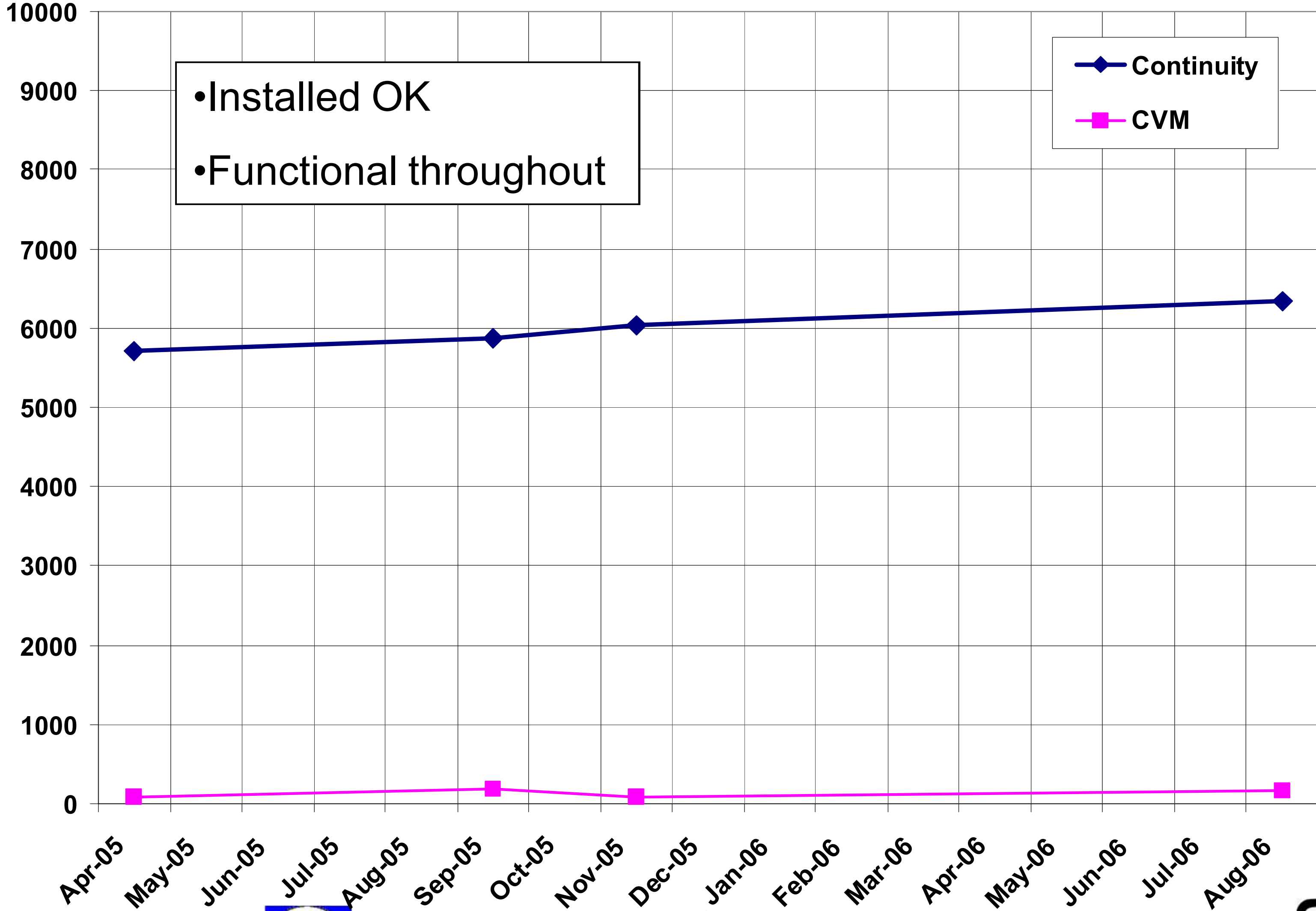


Pascals

Delta - 757

Empennage - unpressurized

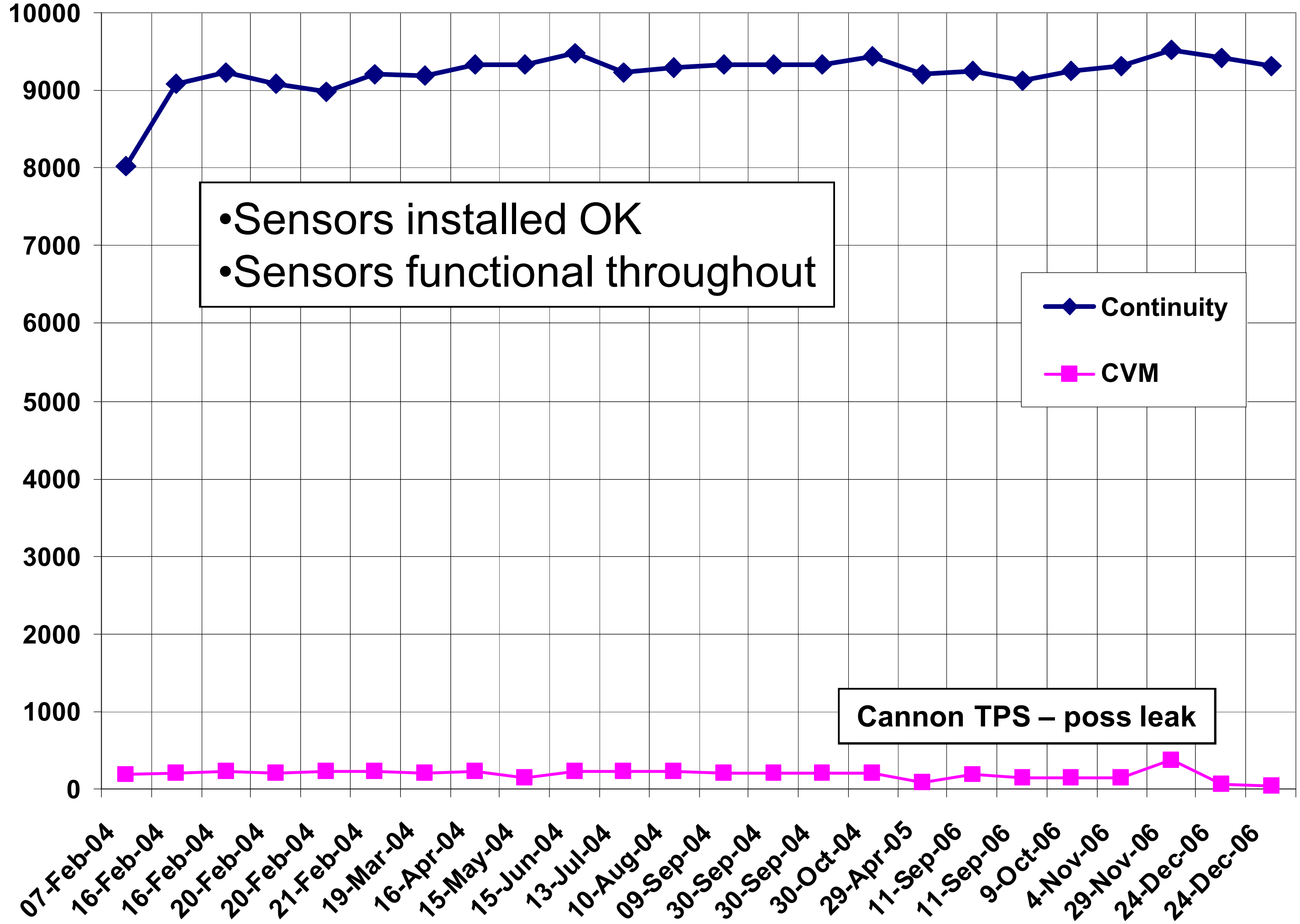
AC669 - frame stn 1768



Pascals

North West - DC9
AC 9961 - (rear baggage) voice recorder

Sensor Type 1



Application and Certification of Comparative Vacuum Monitoring Sensors For In-Situ Crack Detection

Part 4: Sample of Requests for CVM Usage on Aircraft

DC9/MD80 APB T Cap Inspection

North West Airlines Request

- [Description:NWA has been working with Structural Monitoring Systems (SMS) to develop a new NDI method for the Aft Press. Blkhd. (APB) Tees inspection as alternate to Ref /A/ and Ref /B/ detailed visual and LFEC inspections.
- The new NDI method utilize a Comparative Vacuum Monitoring (CVM) sensors system installed with adhesive on the APB tees at typical crack locations.
- During the last two years, NWA NDT dept and SMS have been working together to verify the durability of the CVM sensors hardware installation at different locations on the DC-9 aircraft pressurized and unpressurized areas.
- Two in-service aircraft were used for the evaluation. The evaluation was completed with good results at the end of 2006. Most of the CVM sensors were found intact and in good working condition during the evaluation period. In June 2007, NWA engineering attended a presentation given by SMS to demonstrate the CVM sensors system performance on a section of the APB tee with a crack. NWA NDT dept provided the APB tee section which it was removed from an in-service a/c after crack finding. The crack was hardly visible and it was discovered using LFEC inspection during REF /B/ inspection. The demonstration went well and the crack was immediately detected by the CVM sensor system.
- NWA believe that the new CVM sensors NDI technology would be beneficial, more reliable and it will provide improvement to the current DC-9 APB tee inspection from a human factors perspective. REF /A/ and /B/ detailed visual and LFEC inspections are susceptible to human error due to limited accessibility of inspection areas, quality of surface preparation for inspection and application of inspection methods in constrained areas.
- Please note that NWA NDT dept has provided information about SMS new NDI
- method to Boeing's NDT dept in Long Beach.
- Action Requested: 1. NWA is requesting Boeing engineering and NDT dept to evaluate the new CVM sensors NDI technology for Ventral and Non-Ventral APB Tees inspection.
- 2. NWA is requesting Boeing engineering to perform a comparison study of the new CVM sensors NDI method to current methods of inspection on REF /A/ and /B/ Ventral and Non-Ventral APB Tees for use as an alternate inspection method and to adjust current inspection intervals to normal maintenance check at 3,500 cycles.
- 2. NWA is requesting Boeing engineering and NDT dept to set up a meeting in
- Long Beach with NWA engineering and NDT dept to discuss our request.
-]
-
- Ramiro J Castro
- 612-726-0748
- ramiro.castro@nwa.com
- NWA
-
- Jul 18, 2007 13:14 PDT / Jul 18, 2007 20:14 GMT

DC9/MD80 APB T Cap Inspection

American Airlines Request

- **REFERENCES:**
- **/A/ SB DC9-53A232**
- **/B/ AD 96-16-04**
-
- **DESCRIPTION:**
- **NWA has been working with Structural Monitoring Systems (SMS) to develop a new NDI method for the Aft Press. Blkhd. (APB) Tees inspection as alternate to Ref /A/ detailed visual and LFEC inspections. AAL has been made aware of this technology as an alternate inspection method on the bulkhead tee. SMS has demonstrated their sensors on a cracked tee section from NWA showing its effectiveness.**
-
- **AAL interested in the SMS system pertains to its use for the lower tee inspection, L-20 ? L-20, at intervals of 3,500 cycles. The inspection required for this section is a detailed visual inspection.** <u>This inspection requires the removal of the APU and APU shroud, making the aircraft being out of service for 2 days. The use of the SMS system will eliminate this out of service time for AAL.</u> **SMS has proposed installing their sensors on the aft side of the bulkhead tee to take the place of the DVI for this area.**
-
- **Action:**
-
- **1 AAL is requesting Boeing to evaluate the new CVM sensors NDI technology for APB Tees inspection from L-20 to L-20 lower section, aft side.**

DC9/MD80 APB T Cap Inspection

ABX Air Request

- **Gentlemen, I would like to take a moment and express ABX AIR's support of Northwest and American Airlines position with regard to substituting High Frequency Eddy current Inspection requirement of SB DC9A53-232 with Comparative Vacuum Monitoring (CVM).** CVM NDI will save our airlines a significant amount of time and money without jeopardizing safety**. As I understand, Andrew Chilcott of Structural Monitoring System has already presented the supporting data to Boeing. We appreciate it if you give priority to this issue and we are available to provide information if needed.**

  Thanks and best regards.

Mary Arabi

Engineering Manager
ABX AIR, INC.
P 937-366-2558
C 937-725-2462
F 937-366-3073
mary.arabi@abxair.com

767 Frame Inspection

Delta Airlines Request
(AMOC for HFEC in 0.15” th. Member)

FROM: THE BOEING COMPANY
TO: DAL [MESSAGE NUMBER:1-685090904-2] 14-Dec-2007 10:30:27 US PACIFIC TIME
Boeing Response

This message is sent to the following:

David Piotrowski, at Delta Air Lines

SERVICE REQUEST ID: 1-685090904
PRIORITY: Routine
ACCOUNT: Delta Air Lines (DAL)
DUE DATE: 14-Dec-2007
PROJECT: BFSATL-DAL-Atlanta, Georgia-United States
PRODUCT TYPE: Airplane
PRODUCT LINE: 767
PRODUCT: 767-300
ATA: 5300-00

SUBJECT: BS 903.5 Frames - Investigation of alternate NDT inspection systems //PIOTROWSKI//

REFERENCES:
/A/ Fleet Team Digest 767-FTD-53-07001

DESCRIPTION:
Delta requests assistance in determining the feasibility of using the CVM sensors as an inspection option for the SB mentioned in the ref /A/ FTD article. If agreed that the application is feasible, Delta would like to volunteer to work with Boeing in obtaining approvals for inclusion in any proposed Service Bulletin (and AD). This includes using Delta aircraft as a prototype.

Delta Airlines Request
(AMOC for HFEC in 0.063” th. Member)

REFERENCES:
/A/ SB 737-53A1248
/B/ AD 2005-21-06

> From: Howard, Quincy
> Sent: Friday, January 04, 2008 10:44 AM
> To: 'david.piotrowski@delta.com'
> Cc: Kollgaard, Jeffrey R; Linn, John R; Bangsund, John K; 'Jeff
> Register'
> Subject: Use of CVM sensors on a Boeing airplane
>
> David,
>

We have two requests from you regarding the possibility of applying CVM sensors - one on the 737 aft pressure bulkhead and one on the 767 BS 903.5 frame. We have been discussing this amongst ourselves here and would like to concentrate our efforts on the 737 application for several reasons as follows:

We are very comfortable with our validating data, including the Pod, on structures 0.10 inch thick and less. The 737 application fall into this range, the 767 does not. As you are aware, our initial general procedure will be limited to structures 0.10 inch thick and less. We get into more of a gray area in structures > 0.10 inch thick.

There has already been discussions with the 737 AR regarding CVM and the 737 people have seen demos of CVM. We want to be careful. We all want the first in-service application of CVM to be a success. We think the 737 application provides the best chance for this to happen. Once we have a successful application, the second and third will come much easier.

Based on the above, I'd like to send a reply to your 767 request stating that we're planning to concentrate our efforts on the 737 application. I'd appreciate and am open to your comments before I send the message.

Thanks and Best Regards,
>
> Quincy Howard
> The Boeing Company
> Service Engineering
> Structures, NDT

Application and Certification of Comparative Vacuum Monitoring Sensors for In-Situ Crack Detection

Dennis Roach 1, Jeff Kollgaard 2, Steve Emery 3, Jeff Register 4, Kyle Colavito 5, Dave Galella 6
1 FAA Airworthiness Assurance Center at Sandia National Laboratories, 2 Boeing Commercial Aircraft, 3 Structural Monitoring Systems, 4 Aerotechnics, 5 University of Arizona, 6 FAA

ABSTRACT

Current aircraft maintenance operations require personnel entry into normally-inaccessible or hazardous areas to perform mandated, nondestructive inspections. To gain access for these inspections, structure must be removed, sealant must be removed and restored, fuel cells must be vented to a safe condition, or other disassembly processes must be completed. These processes are not only time consuming but they provide the opportunity to induce damage to the structure. The use of in-situ sensors, coupled with remote interrogation, can be employed to overcome a myriad of inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage. Furthermore, prevention of unexpected flaw growth and structural failure could be improved if on-board health monitoring systems are used to more regularly assess structural integrity. The Airworthiness Assurance NDI Validation Center (AANC) at Sandia Labs, in conjunction with Boeing, the University of Arizona, Structural Monitoring Systems, and interested airlines is currently conducting a research program to develop and validate Comparative Vacuum Monitoring (CVM) Sensors for crack detection. CVM sensors are permanently installed to monitor critical regions of a structure. The CVM sensor is based on the principle that a steady state vacuum, maintained within a small volume, is sensitive to any leakage. Vacuum monitoring is applied to small galleries that are placed adjacent to a second set of galleries maintained at atmospheric pressure. If a flaw is not present, the low vacuum remains stable at the base value. If a flaw develops, air will flow from the atmospheric galleries through the flaw to the vacuum galleries. A crack in the material beneath the sensor will allow leakage resulting in detection via a rise in the monitored pressure. The test specimens include those designed to simulate the Boeing aircraft lap joint and others with single crack origination sites. The test matrix studied the affects of surface coating, skin thickness, and material type on the performance of the CVM sensors. Statistical methods using one-sided tolerance intervals were employed to derive Probability of Detection (POD) levels for each of the test scenarios. The result is a series of flaw detection curves that can be used to propose CVM sensors for aircraft crack detection. Complimentary, multi-year field tests were also conducted to study the deployment and long-term operation of CVM sensors on aircraft. This paper presents the quantitative crack detection capabilities of the CVM sensor, its performance in actual flight environments, and the prospects for structural health monitoring applications on commercial aircraft.