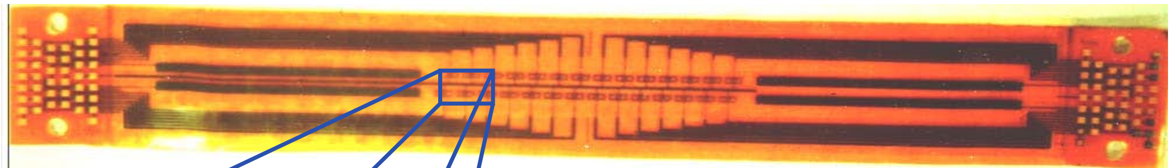
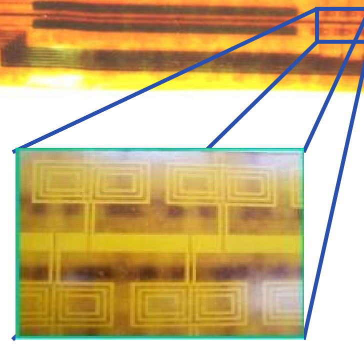
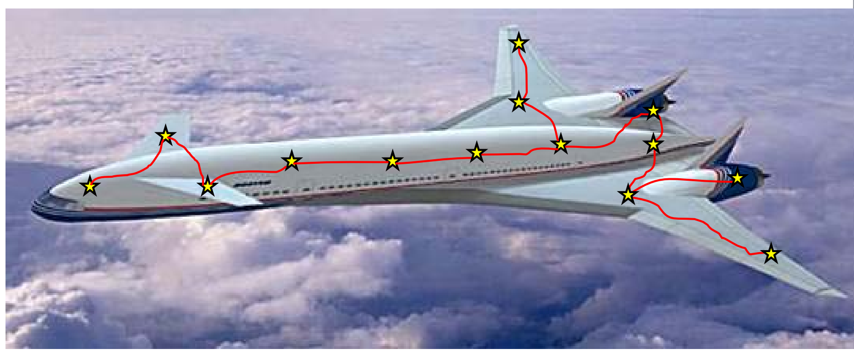
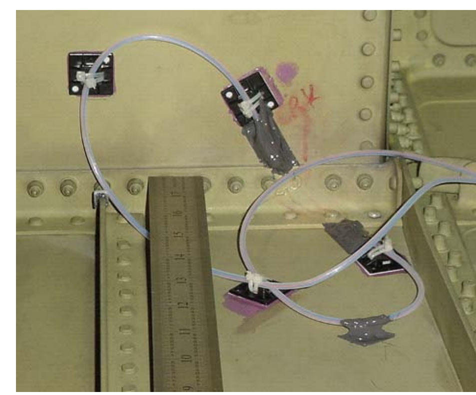
Does the Maturity of Structural Health Monitoring Technology Match User Readiness?

Aviation Industry View Regarding SHM Integration into Aircraft Maintenance Programs









Dennis Roach
Stephen Neidigk
Sandia National Labs
FAA Airworthiness Assurance Center

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

FAA Airworthiness Assurance Center (AANC) at Sandia National Laboratories

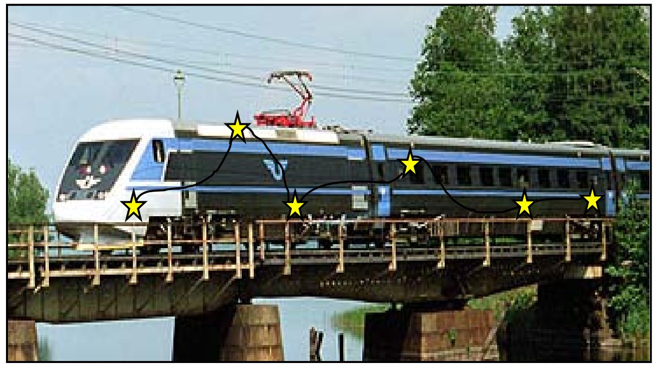
- **Initiated in 1988 under the Aviation Safety Act**
- **Provides a mechanism to develop, evaluate, and bring new aircraft technologies to market**
- **Partner with industry, academia, and government**
- **Develop and implement solutions to pressing problems**

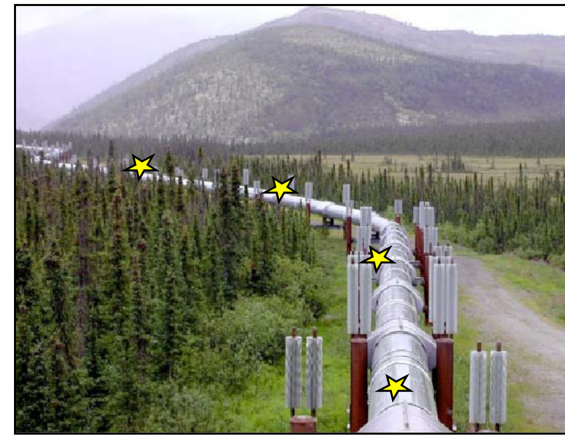
B737-200 Test Bed

Fairchild Metro II Test Bed

Distributed Sensor Networks for Structural Health Monitoring

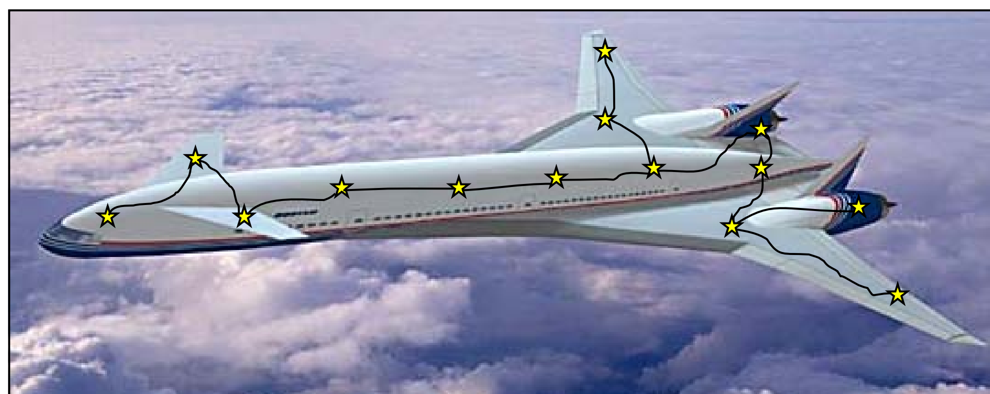
Smart Structures: include in-situ distributed sensors for real- time health monitoring; ensure integrity with minimal need for human intervention



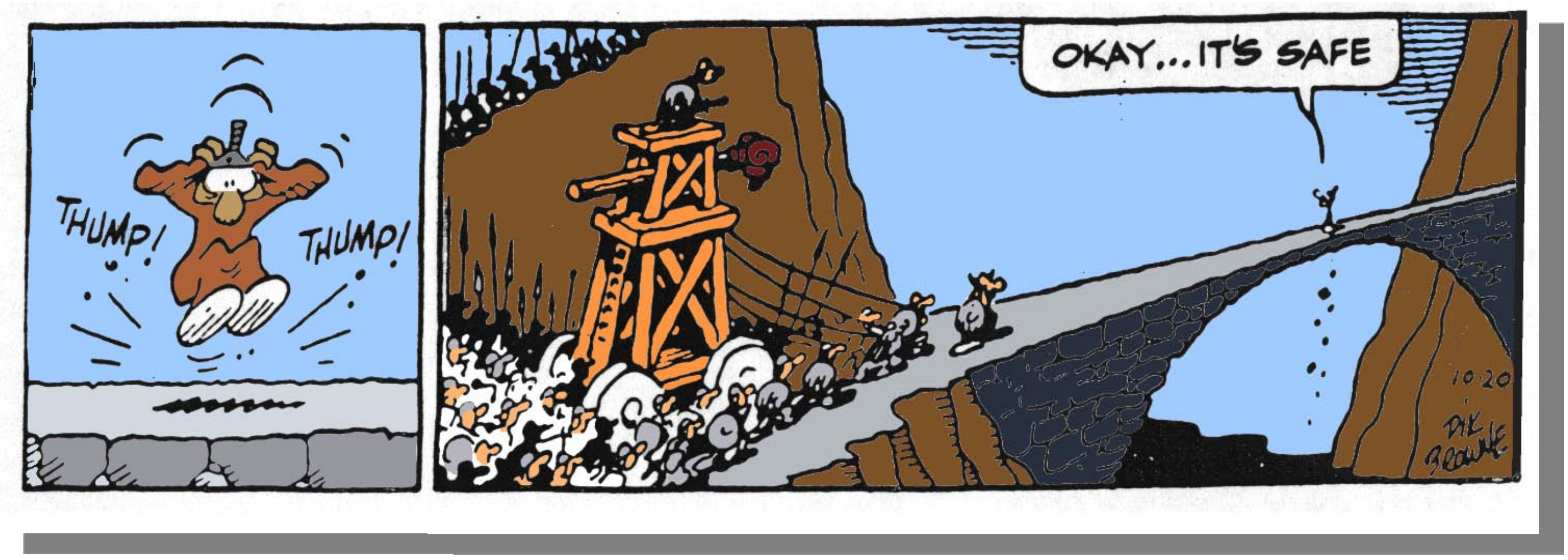


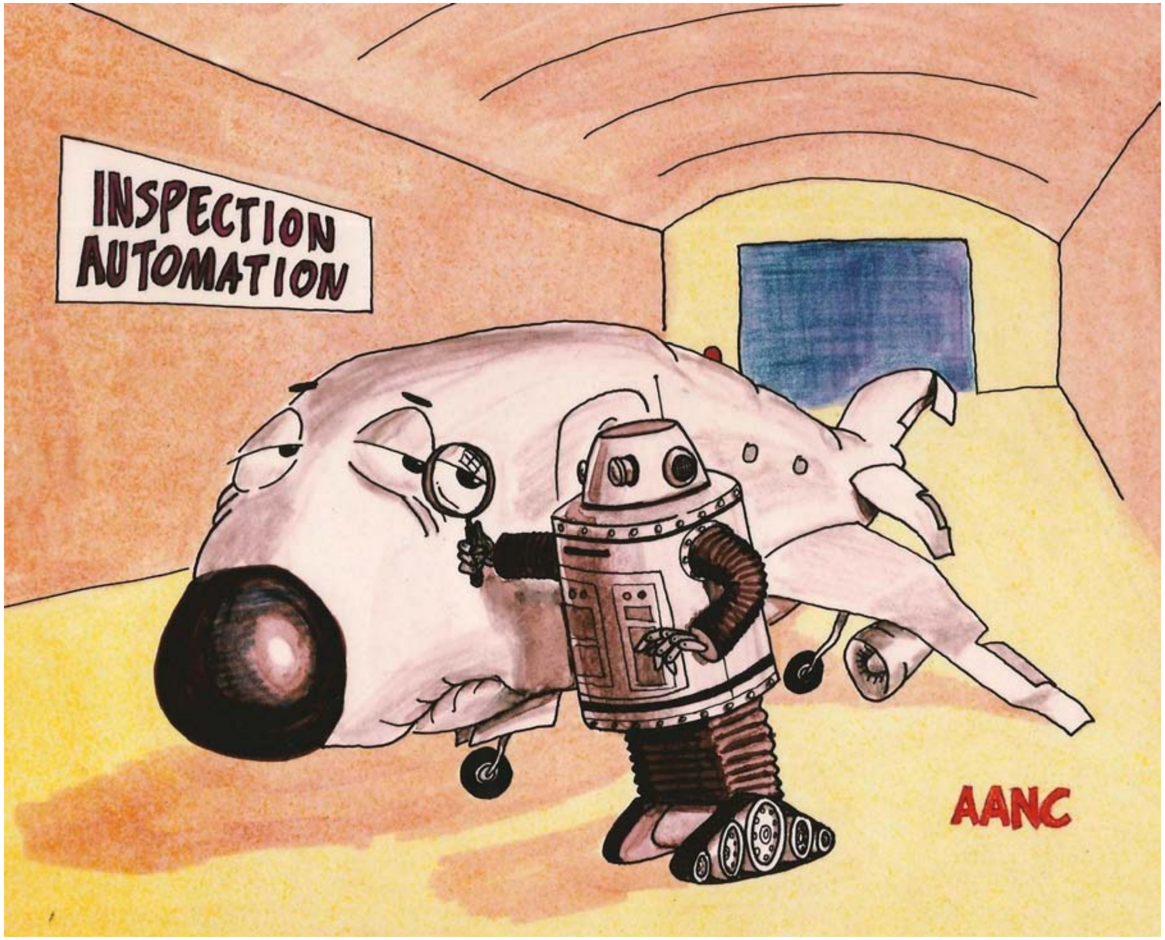
- Remotely monitored sensors allow for condition-based maintenance

- Automatically process data, assess structural condition, & signal need for maintenance actions



Structural Health Monitoring Dates Back Many Years





Definition is somewhat agreed upon. Usage and deployment covers a wide range of thoughts and options.

NDI vs. SHM – Definition

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

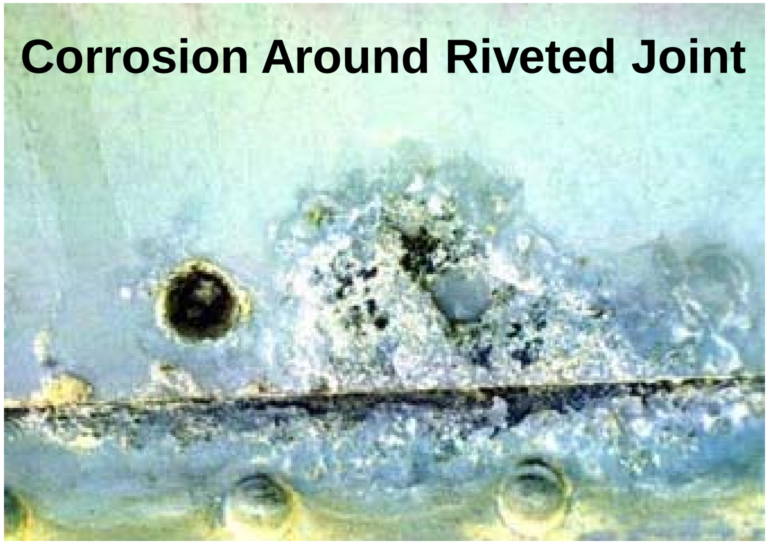
- High degree of human interaction
- Local, focused inspections
- Requires access to area of interest (applied at select intervals)

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

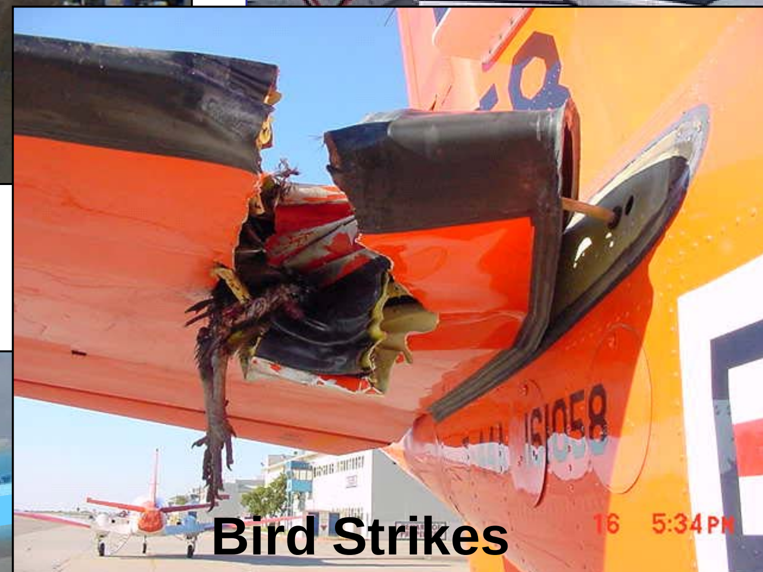
- Greater vigilance in key areas – address DTA needs
- Overcome accessibility limitations, complex geometries, depth of hidden damage
- Eliminate costly & potentially damaging disassembly
- Minimize human factors with automated data analysis

SHM: process of acquiring and analyzing data from on-board sensors to determine the health of a structure (AISC-SHM)

Typical Aircraft Flaw Scenarios

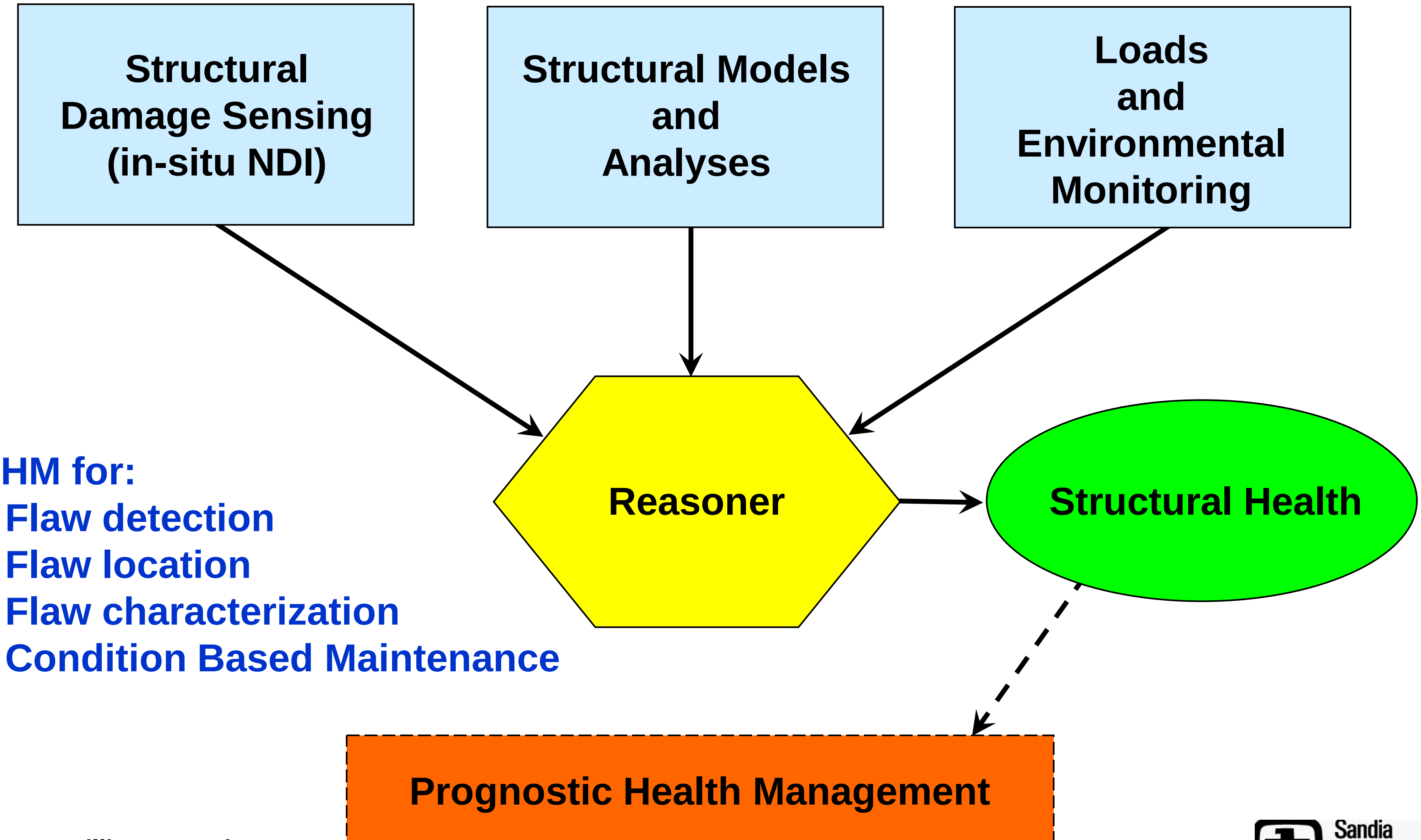



Ground Handling
Impact Damage


Bird Strikes

Structural Health Monitoring

- Courtesy of Eric Lindgren, AFRL

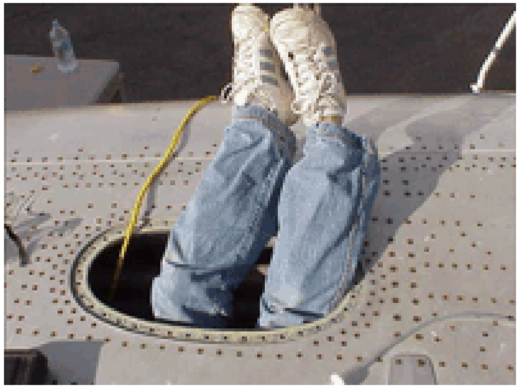


SHM for:
- Flaw detection
- Flaw location
- Flaw characterization
- Condition Based Maintenance

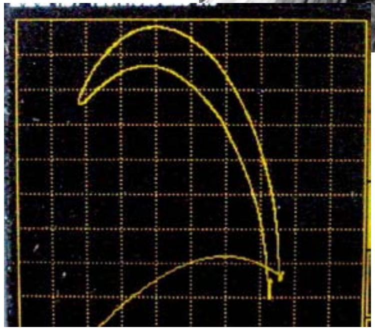
The Trouble with Math or…..
How do we calculate DT ??

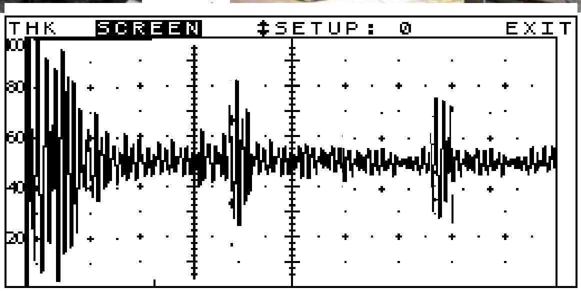
Difficulty in loads assignment, stress and fatigue calculations produces demands on NDI - "You want me to find a flaw where, and how small??"

Difficult Conditions



Lots of Rapid Data Interpretation





Benefits of SHM

Near-Term

- Elimination of costly & potentially damaging structural disassembly
- Reduced operating and maintenance costs
- Detection of blunt impact events occurring during normal airplane operations
- Reduction of inspection time
- Overcome accessibility & depth of flaw impediments
- Early flaw detection to enhance safety and allow for less drastic and less costly repairs
- Minimized human factors concerns due to automated, uniform deployment of SHM sensors (improved sensitivity)
- Increased vigilance with respect to flaw onset

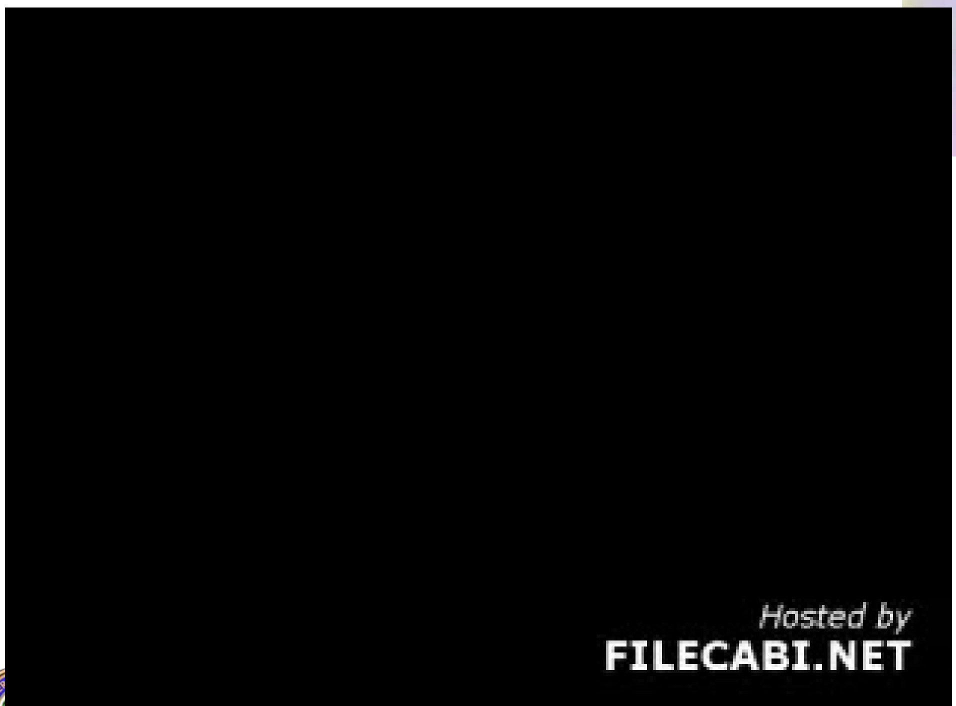
Long Term

- Optimized structural efficiency
- New design philosophies (SHM designed into the structure)
- Weight savings
- Substitution of condition-based maintenance for current time-based maintenance practices

SHM Impediments & Challenges

- Cost of sensors and sensor systems
- Ease of use and coverage area
- Need for rapid customization of sensors
- Need for substantial business case (cost-benefit analysis) – operators must realize benefits of multi-use
- OEMs may need to own technology
- Small-scale damage must be detected in large-scale structures
- Validation activities – general performance assessments needed; reliability of SHM systems must be demonstrated
- Validation activities – field trials on operating aircraft is necessary but time consuming
- Certification – need to streamline specific applications; technical, educational and procedural initiative (OEMs, operators, regulators)
- Standardization needed for validation and certification activities
- Technology transfer and implementation requires changes in maintenance programs

Desire to Account for the Unexpected



Off-design conditions and unexpected phenomena

FAA SHM R&D Roadmap

- SHM sensors have been demonstrated to reliably detect damage in laboratory environment and in a few commercial applications
- Need for an overarching plan that will guide FAA activities (regulatory needs) and comprehensively support the safe adoption of SHM practices (initial use and continued airworthiness)

SHM Survey of Aviation Industry

Goal: To solicit input from aircraft manufacturers, regulators, operators, and research organizations to identify the current status of SHM technology and the issues facing the aviation industry to safely adopt SHM practices.

- Used responses to 50 questions to obtain industry information on SHM deployment & utilization, validation & certification, SHM standardization, sensor evolution & operation, cost-benefit analysis, & SHM system description
- 455 responses obtained including relevant numbers from OEMs, operators, and regulators

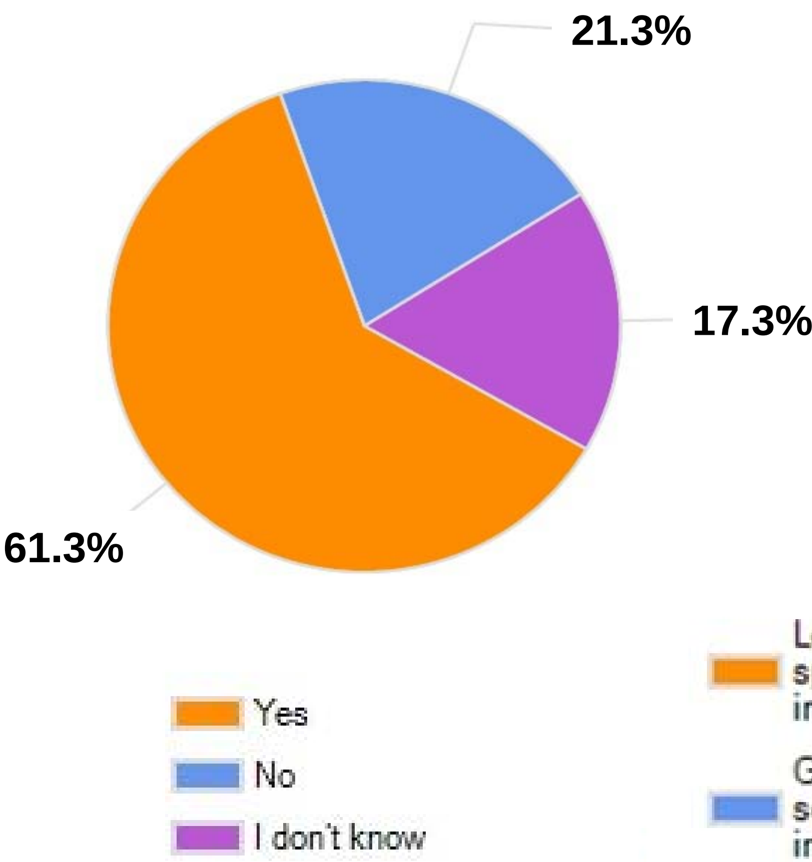
SHM Survey of Aviation Industry - Respondents

Owners/Operators	OEMs	Regulators	Maintainers
All Nippon Airways	Airbus	Air Transport Association	Aerotechnics Inc
American Airlines	Astronics-Adv. Electronic Systems	CAA - NL	Air New Zealand
Austrian Air Force	Avensys Inc.	CAA - Bra	China Airlines
China Airlines	BAE systems	EASA	Christchurch Engine Centre
Continental Airlines	Bell Helicopter Textron	FAA	Fokker Aircraft Services B.V.
Delta Air Lines	Boeing	NAVAIR	Fuji Heavy Industries, Ltd.
Federal Express	Bombardier Aerospace	NAWCAD	Jazz Air LTD
Finnair	Cessna Aircraft Company	Transport Canada (TCCA)	Lufthansa Technik AG
Hawaiian Airlines	Dassault Aviation	USAF	NASA
Japan Airlines	EADS Military Air Systems	US Army	Olympic Airways Services S.A.
Jazz Airlines	Embraer	USCG	SAA Technologies
Jet Blue Airways	Goodrich	US Navy	SR Technics Switzerland LTD
Kalitta Air LLC	Honeywell		Texas Aero Engine Services
NASA	Lockheed Martin Aeronautics		Timco / GSO
Qantas Airways	Messier-Dowty		United Airlines
Singapore Airlines	Mistras Group, Inc		USAF
Swiss Air	Polskie Zaklady Lotnicze Sp.		US Army
United Airlines	PZL Swidnik		USCG
US Airways	Rolls-Royce Corp		US Navy
USAF	Systems & Electronics, Inc.		
US Army	TecScan		
USCG			
US Navy			

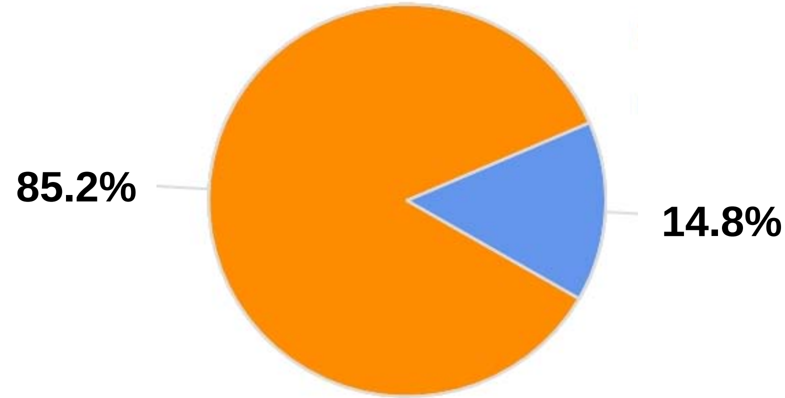
+ Over 100 SHM developers and research organizations

SHM Survey Results – Viability & Airline/OEM Usage

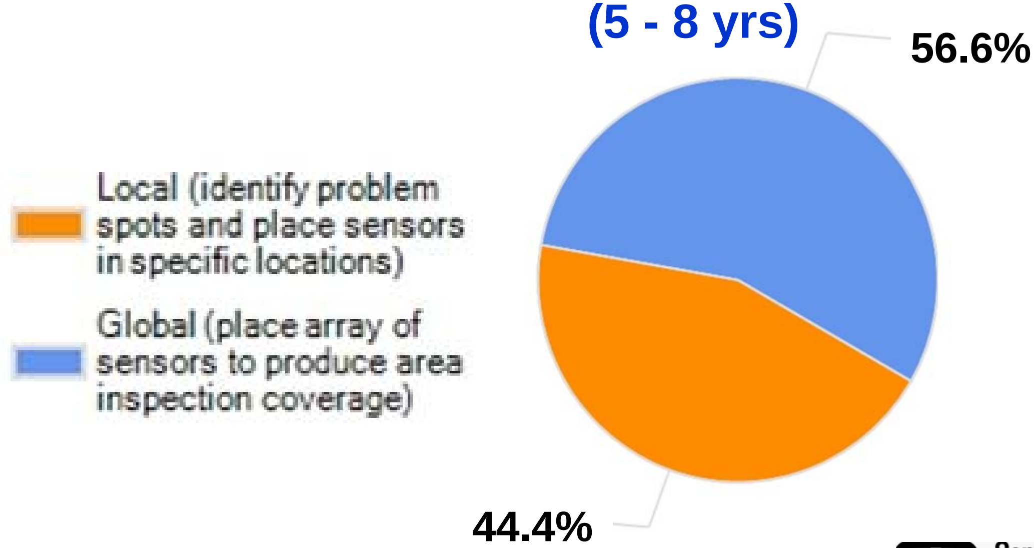
Viability of Using SHM as an Alternative Solution to NDT



SHM Anticipated in the Near-Term (Now - 5 yrs)

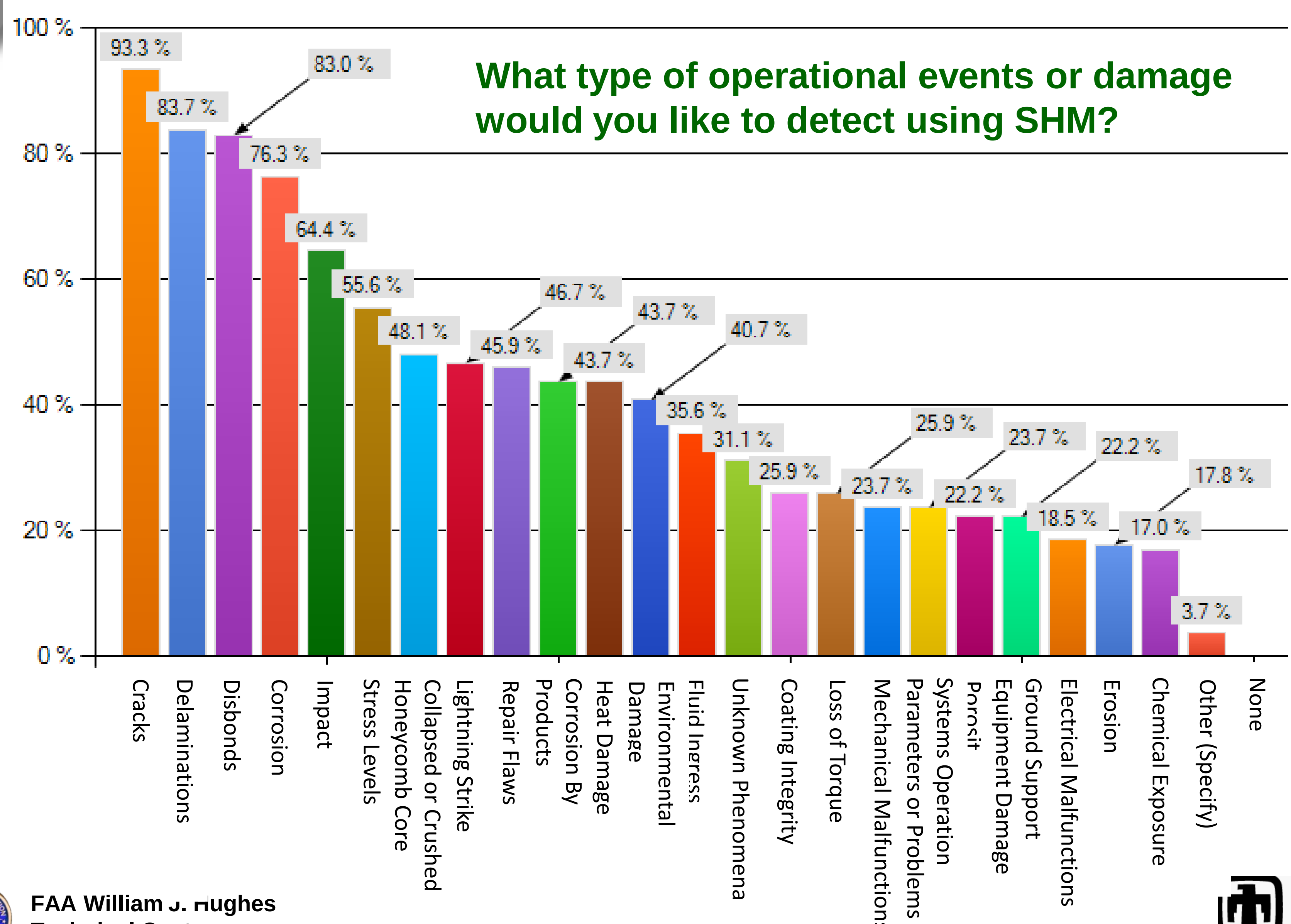


SHM Anticipated in the Long-Term (5 - 8 yrs)

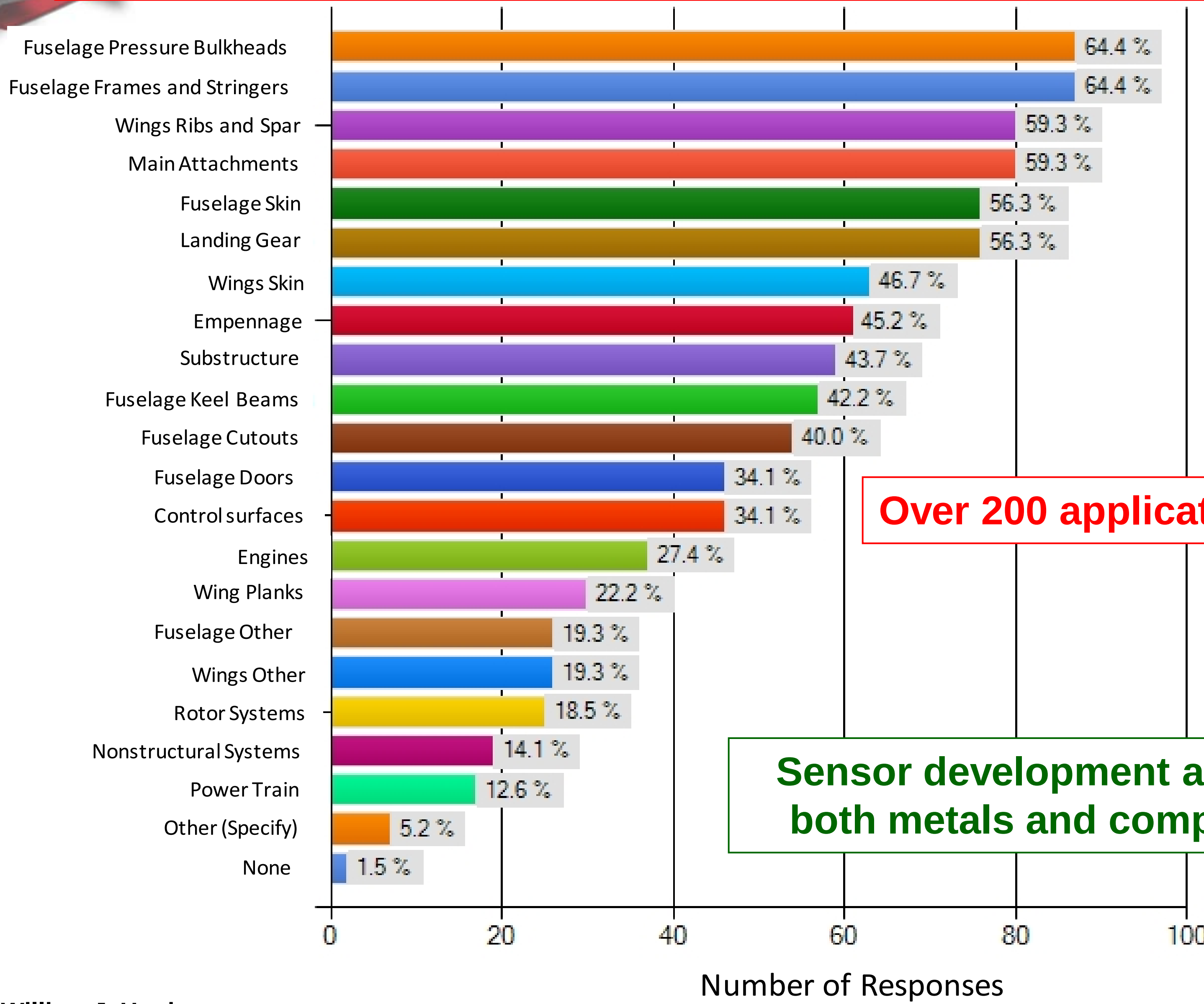


SHM Survey Results – Damage to Be Detected

What type of operational events or damage would you like to detect using SHM?



Areas Respondents Feel SHM Solutions are Viable



Over 200 applications listed

Sensor development agrees – both metals and composites

Top four perceived impediments to deployment of SHM on aircraft (OEMs, Operators, MROs)

1) Cost-benefit

2) Coverage area is small compared to size of structure

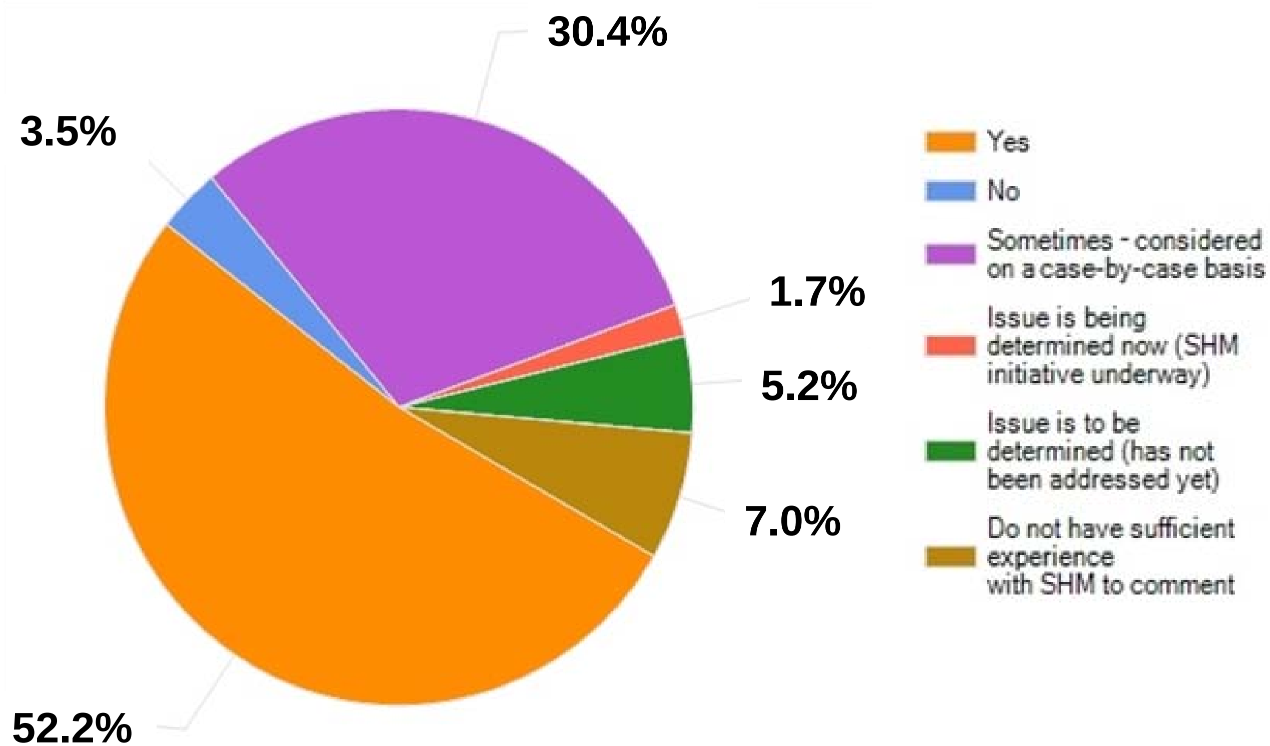
3) Overall performance assessment and validation of technology is needed

4) Certification for use

(installation, durability, adaptability, adoption, training)

Transitioning to SHM

Initially, would regulators and aircraft manufactures require SHM to run in parallel with existing NDI inspections?



SHM Industry Survey – Cost-Benefit & TRL

Top five cost-benefit considerations of an SHM solution:

1 Elimination of structural teardown to access regions to be monitored
2 Recurring cost of SHM sensors
3 Initial cost of SHM equipment
4 Time required for validation/qualification
5 Compliance requirements - existing or future needs

- **55% of aircraft operators, maintainers, and military personnel say that 5 years is a reasonable payback period for recouping the cost associated with using an SHM system**
- **31% say 2 years is reasonable**

Technology Readiness

- 43% have been through initial laboratory tests
- 37% had laboratory performance evaluation
- 9% have had field evaluation
- 7% have complete validation of SHM system
- 7% proven and ready for aircraft

Respondent's SHM System Costs

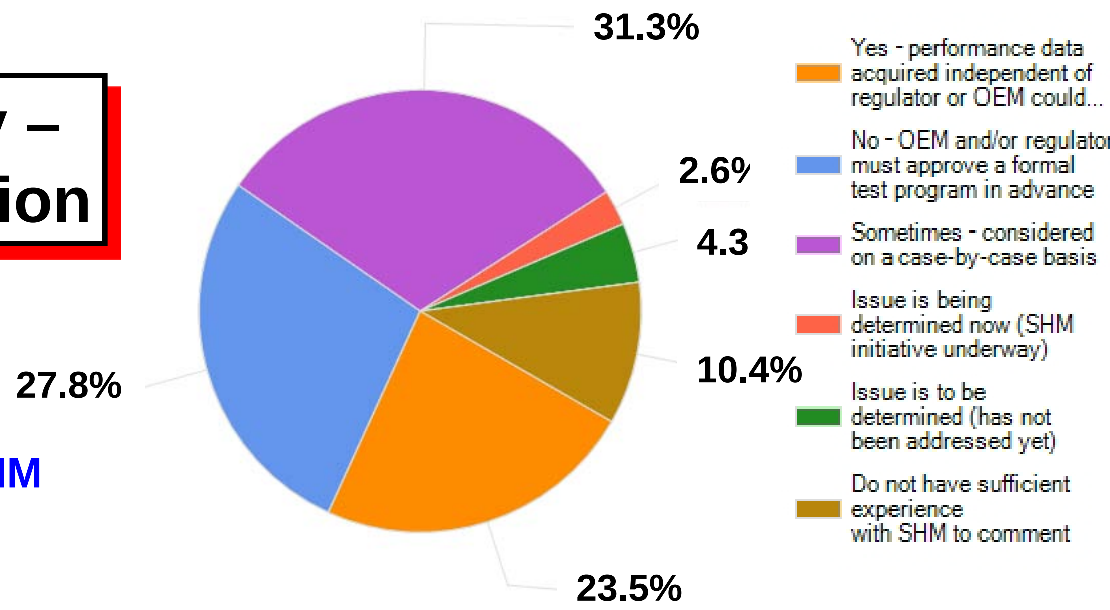
8% less than $1,000

28% between $1,000 and $8,000

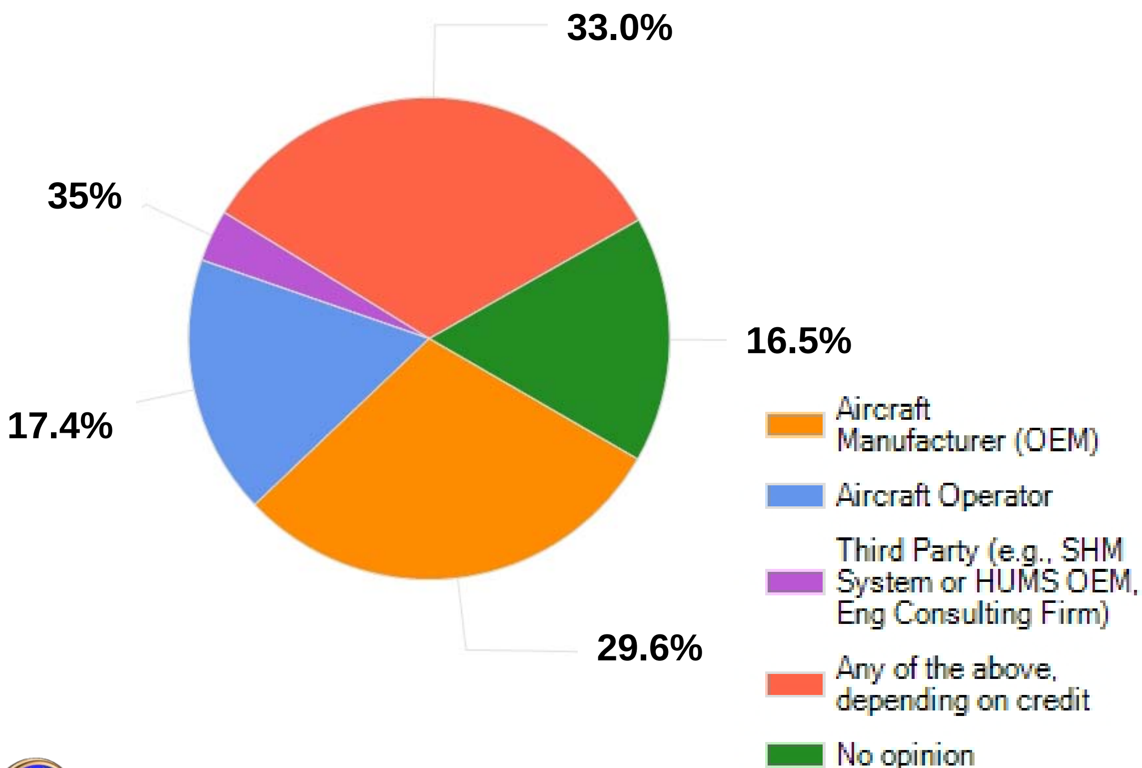
21% between $8,000 and $16,000

31% greater than $16,000

SHM Industry Survey – Operation & Certification

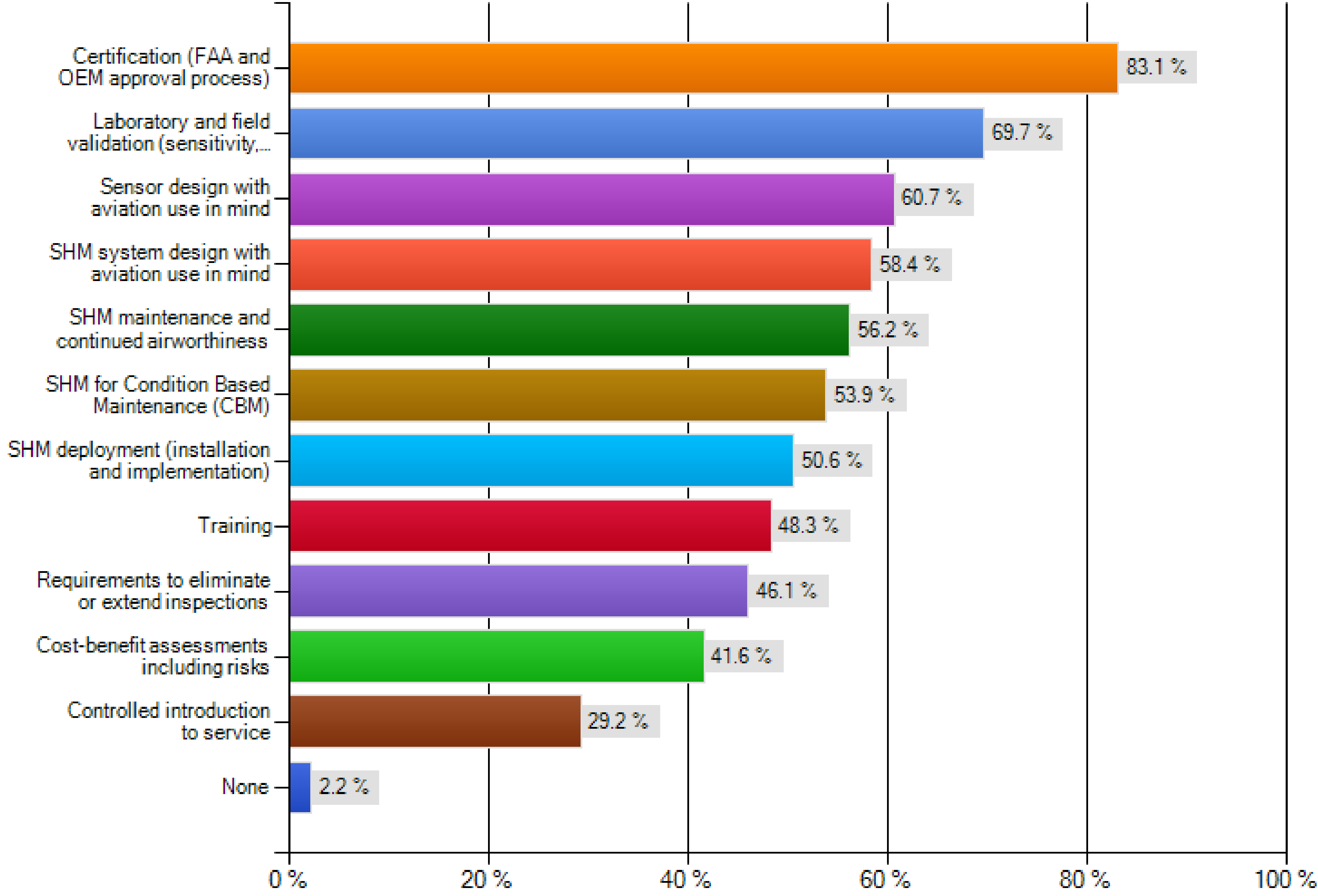


Who should apply for or own SHM based maintenance credits?

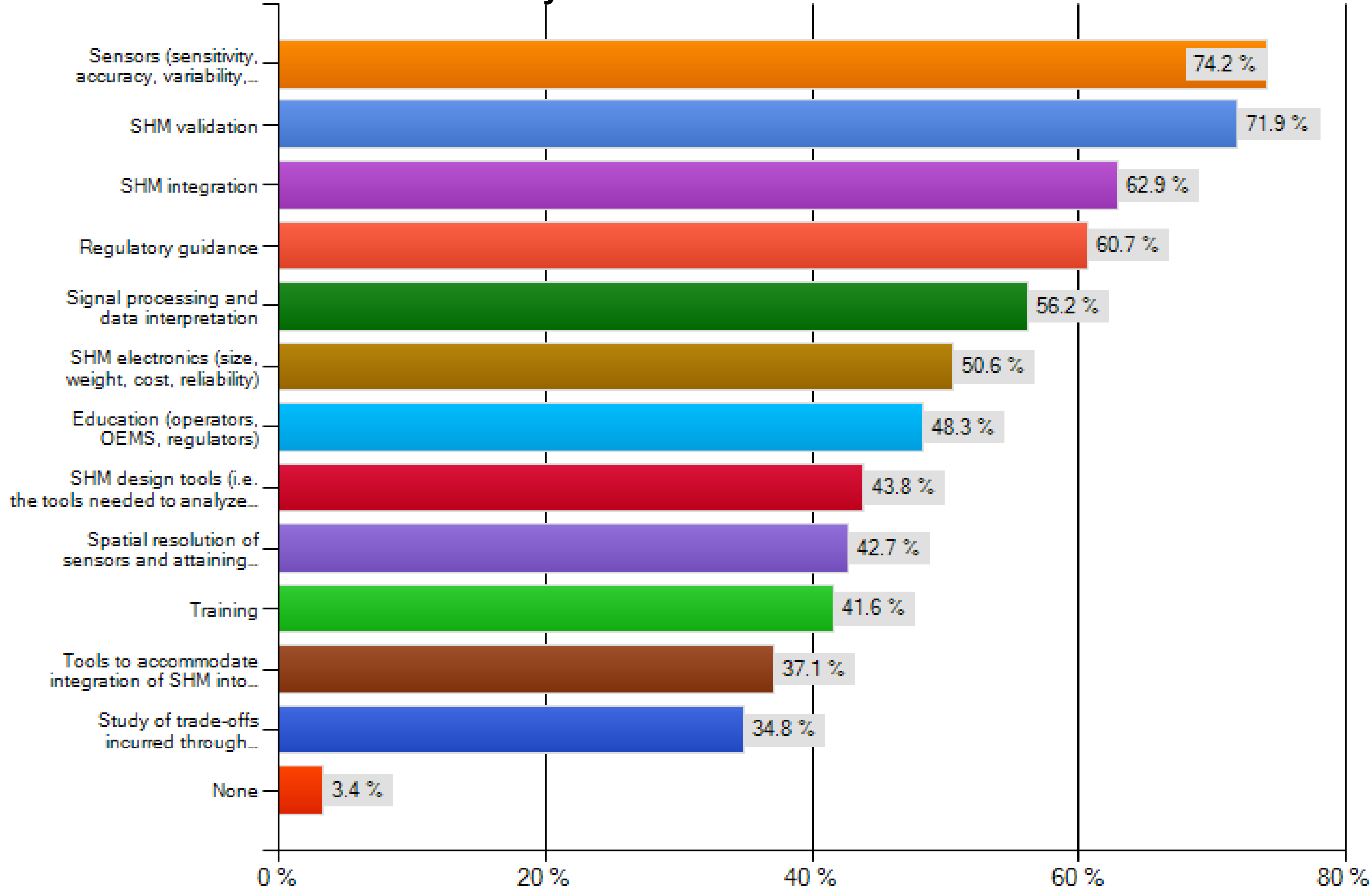


Would you accept performance data from operators/vendors /industry groups/military or require the regulatory agency/ OEM to be involved in a formal test program?

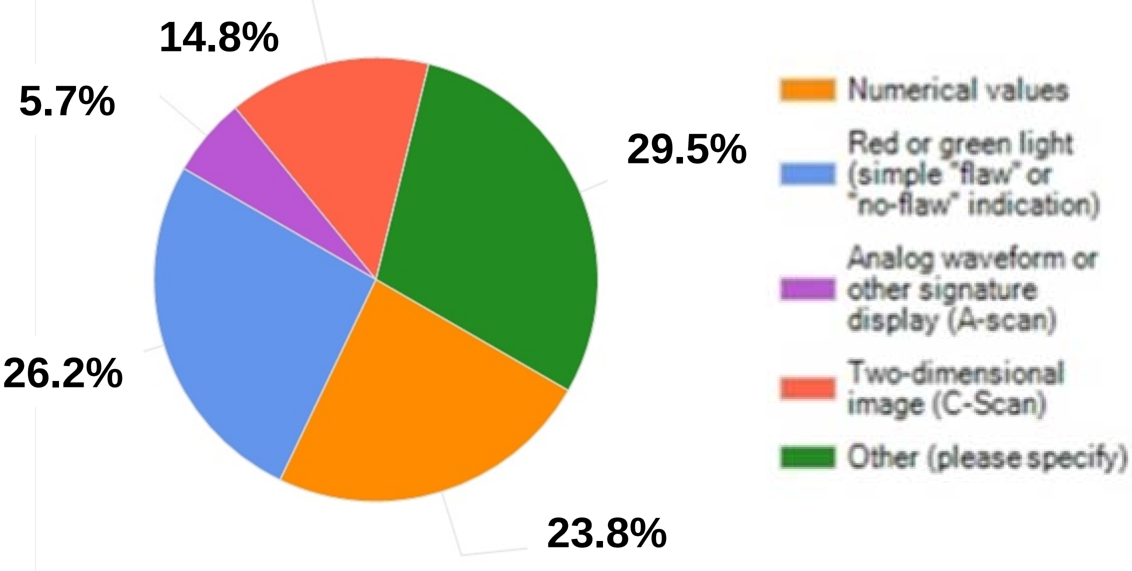
Where do OEMs and Owners/Operators think Standardization and Guidelines are Needed and Feasible?



What Type of Research and Development do OEMs and Owners/Operators think is needed to evolve SHM systems to where they can be used on aircraft?

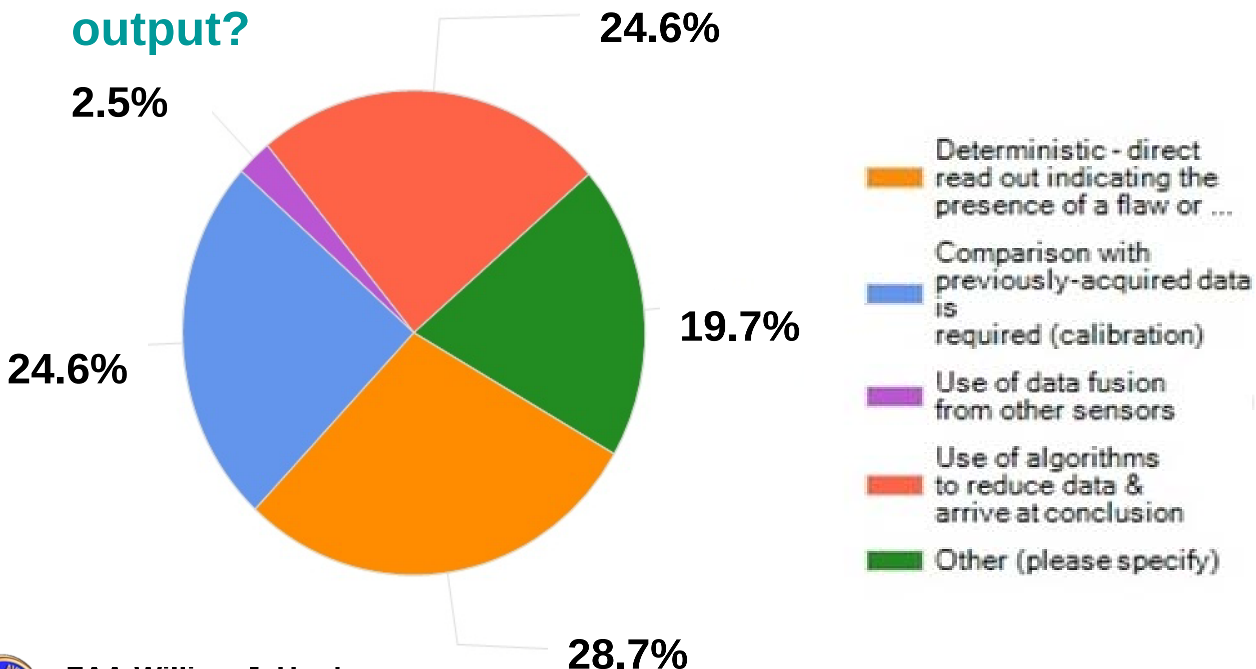


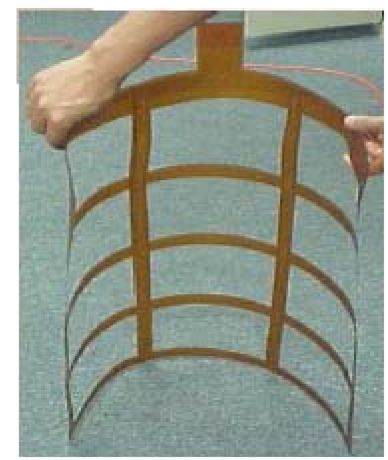
What the Industry Survey Revealed on Sensors



How much data interpretation is required of the sensor output?

How are the results presented to the operator?





Smart Patch Sensor System

Some Survey Results from Sensor Developers

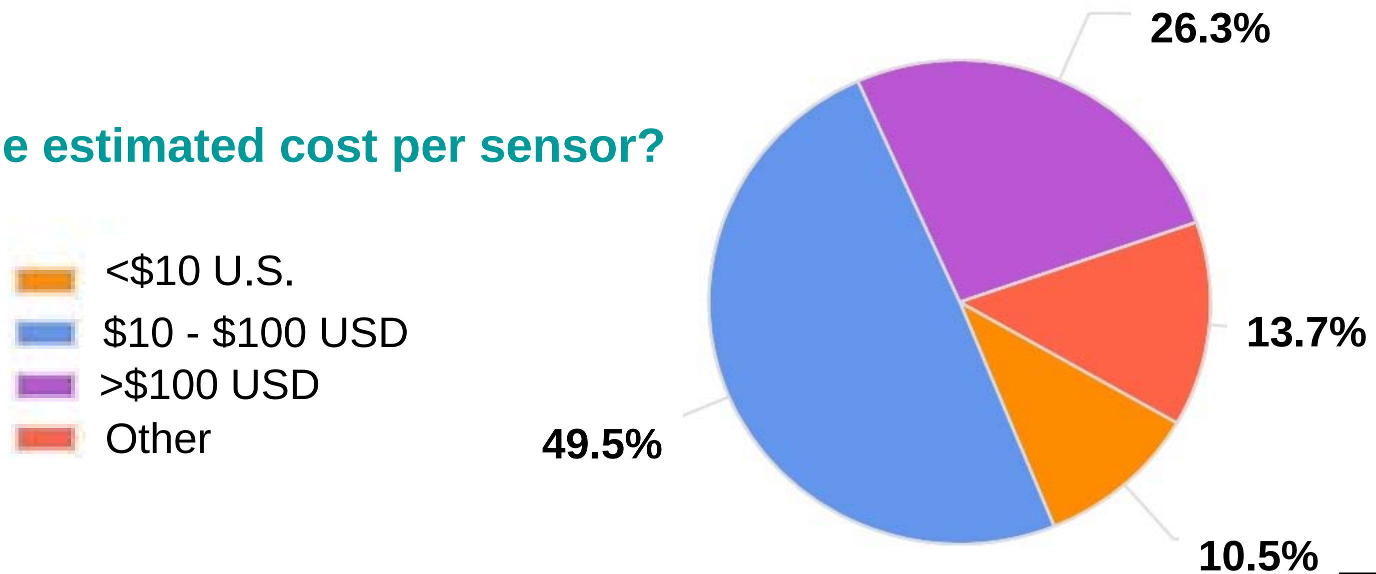
Does the sensor have a fail-safe feature which will prevent the acquisition of faulty data from a damaged or failed sensor?

52% Yes
48% No

Does the system contain a built-in self-diagnostic capability to automatically interpret the data?

60% Yes
40% No

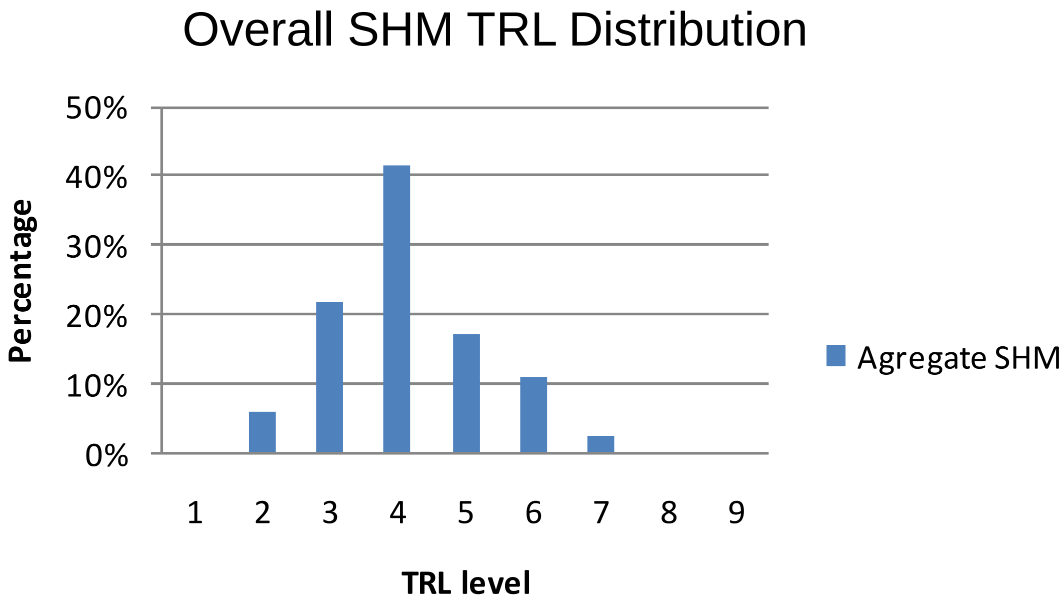
What is the estimated cost per sensor?

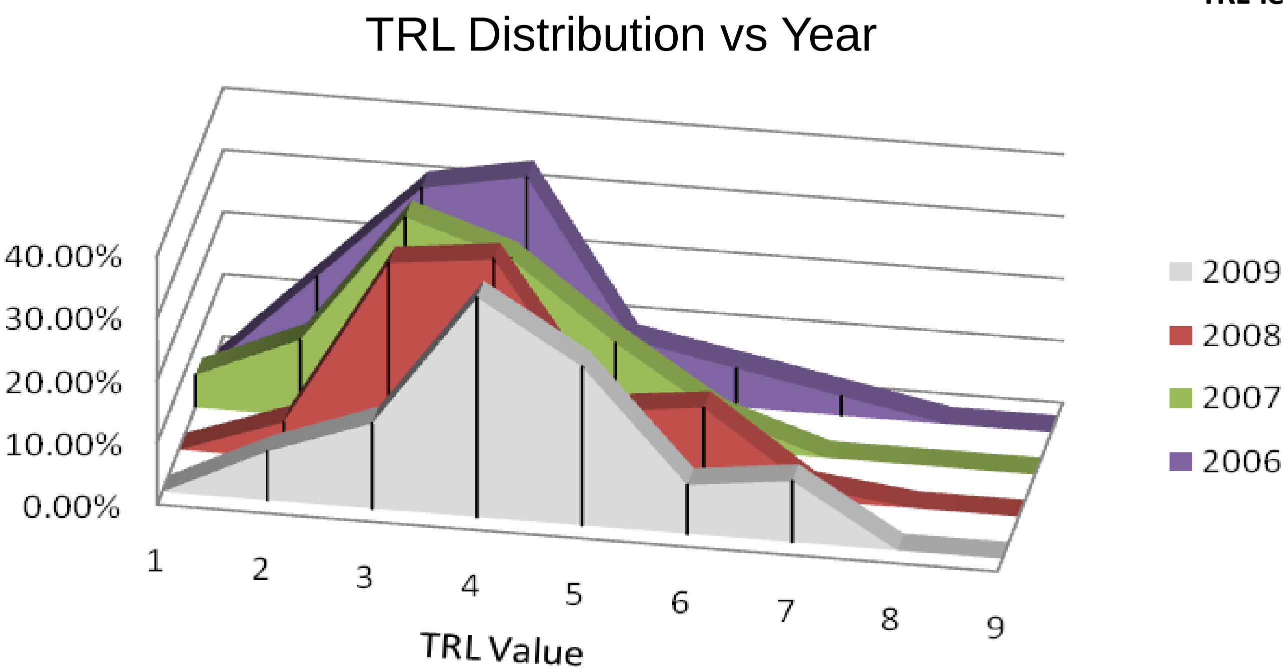


Technology Readiness Level (TRL)

- TRLs were adopted as a method for ranking technology/systems through the development stages
- Mimics TRLs used by NASA & military - this classification system clearly defines benchmarks, direction and maturity of emerging technologies
  - **TRL 1** - *Physical principles are postulated with reasoning*
  - **TRL 2** - *Application for physical principles identified but no results*
  - **TRL 3** - *Initial laboratory tests on general hardware configuration to support physical principles*
  - **TRL 4** - *Integration level showing systems function in lab tests*
  - **TRL 5** - *System testing to evaluate function in realistic environment*
  - **TRL 6** - *Evaluation of prototype system*
  - **TRL 7** - *Demonstration of complete system prototype in operating environment*
  - **TRL 8** - *Certification testing on final system in lab and/or field*
  - **TRL 9** - *Final adjustment of system through mission operations*

TRL currently peaks at 4 (centered around 3-6) - some technologies have reached full prototype systems designed for use on aircraft (7)

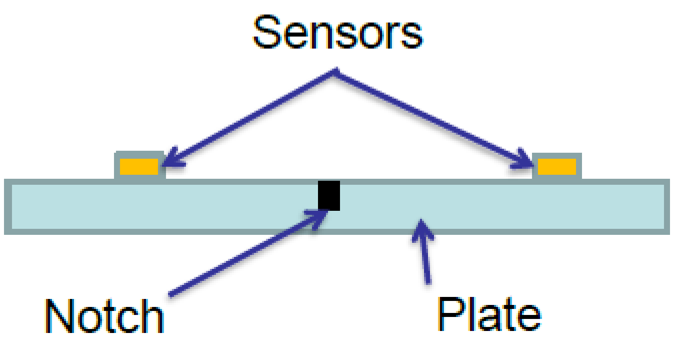




Shift in TRL (lft to rt) –shows advancing SHM technology; some should arrive at TRL 7-9 in the next 3-5 years

Validation with Representative Complexity

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



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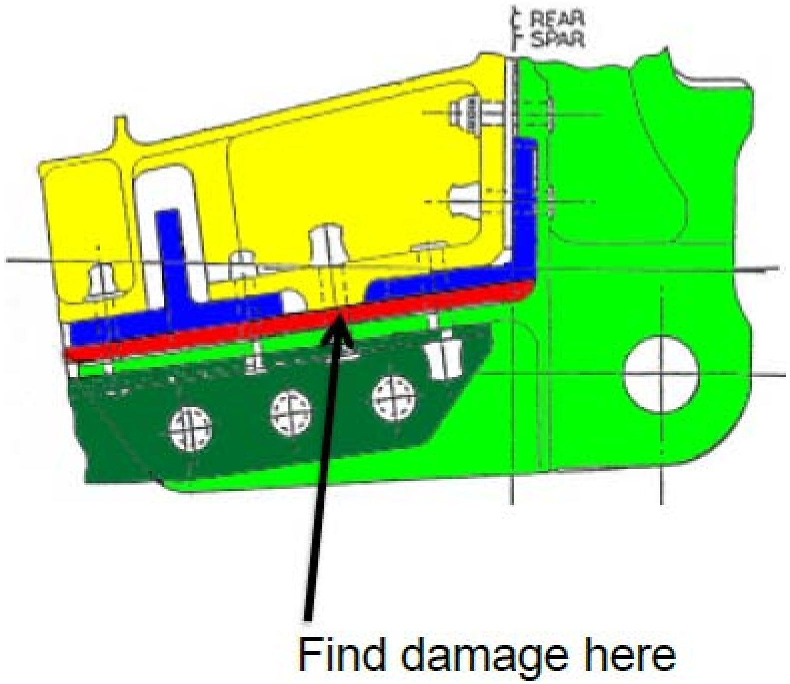
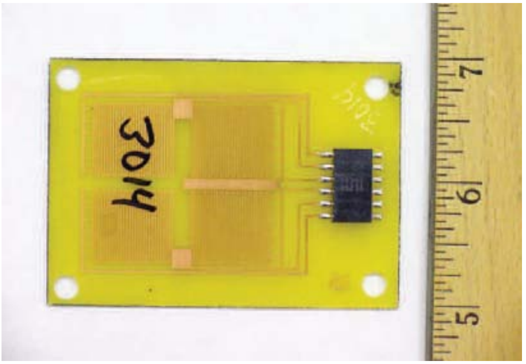
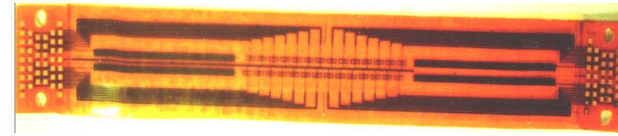


- Courtesy of Eric Lindgren, AFRL

Sampling of SHM Sensors

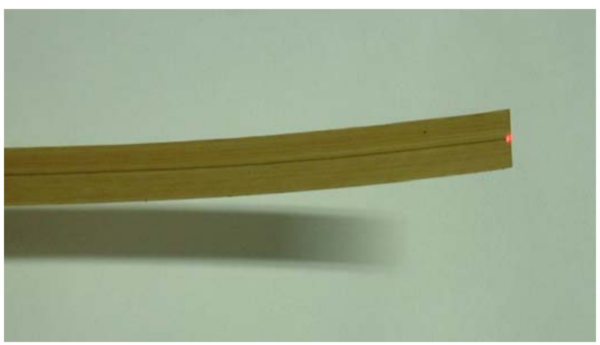


Cumulative Environmental Corrosion Sensor

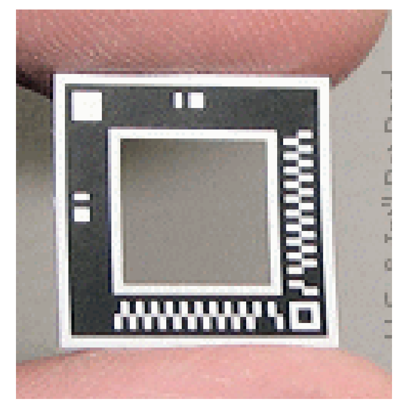


Flexible Eddy Current Array Probe

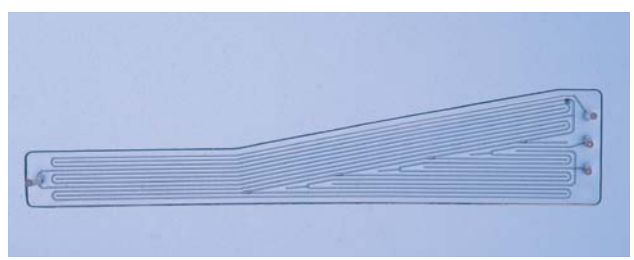
Vibro Fibre SHM Sensor



SMARTape Membrane Deformation Sensor

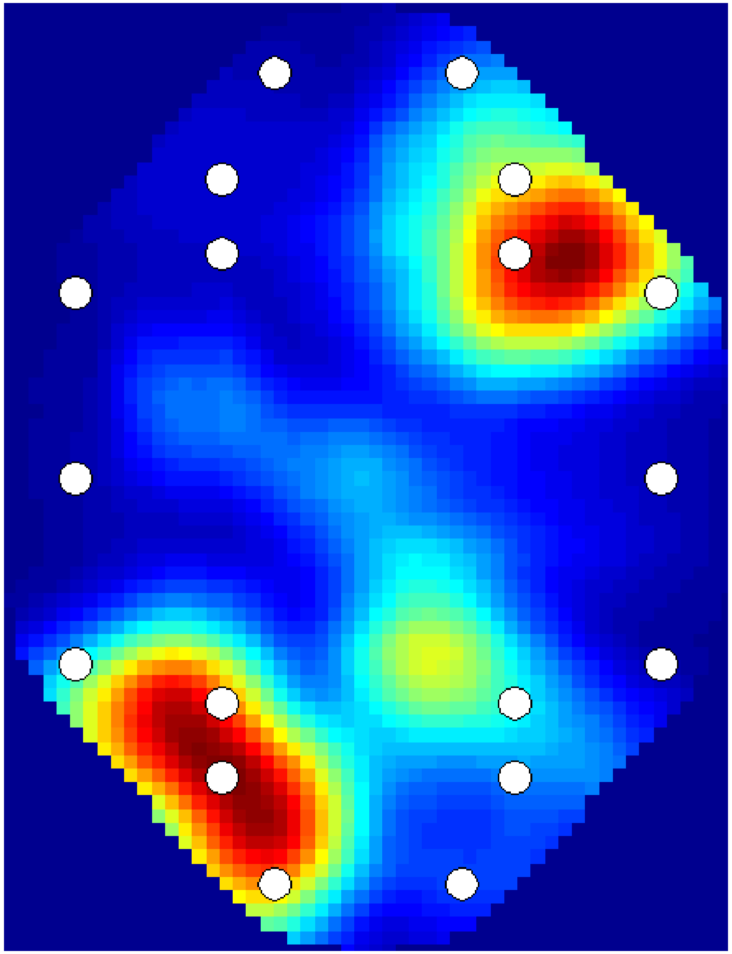


Direct Measurements Strain Sensor

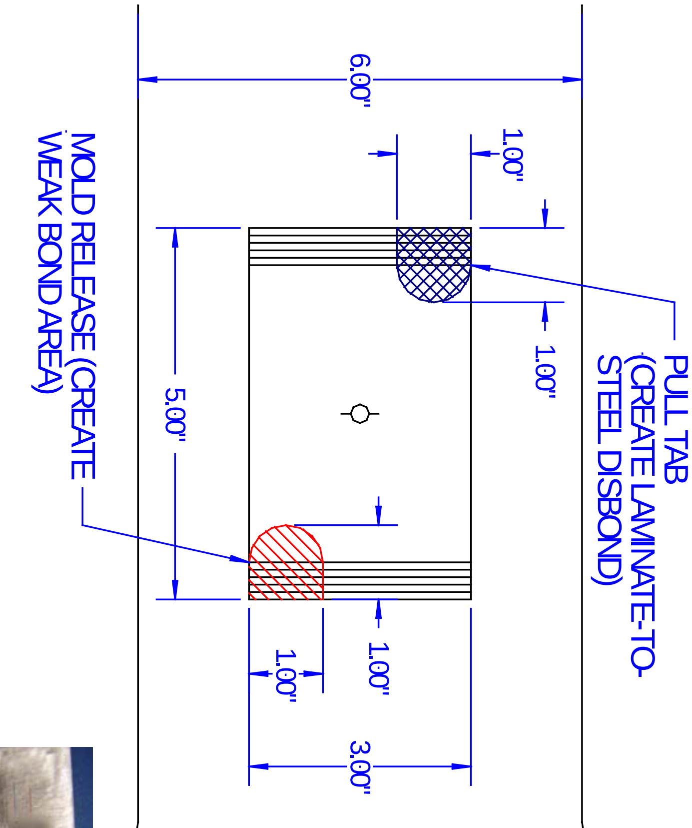


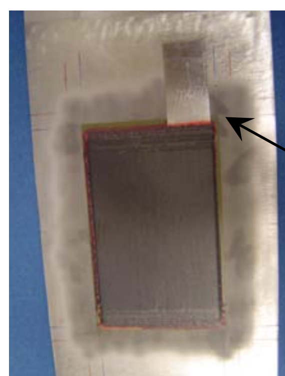
Comparative Vacuum Monitoring Sensor

Disbond Detection & Growth Monitoring with Piezoelectric Sensors



After mold release flaw growth
(50 KHz inspection)

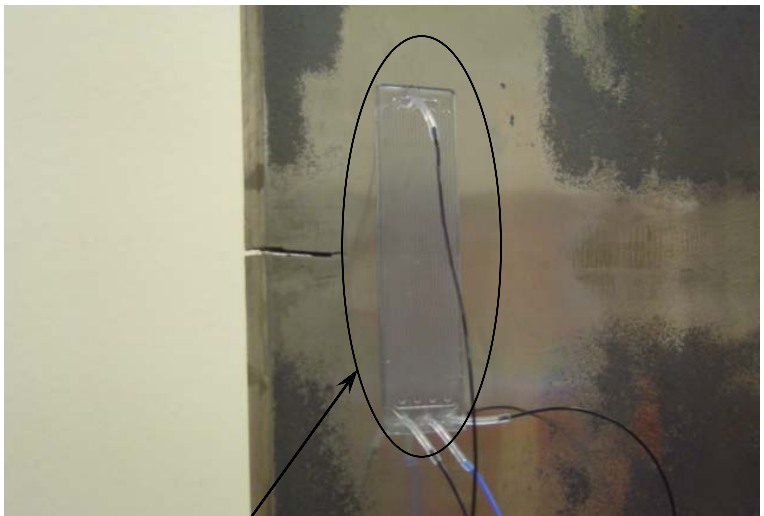




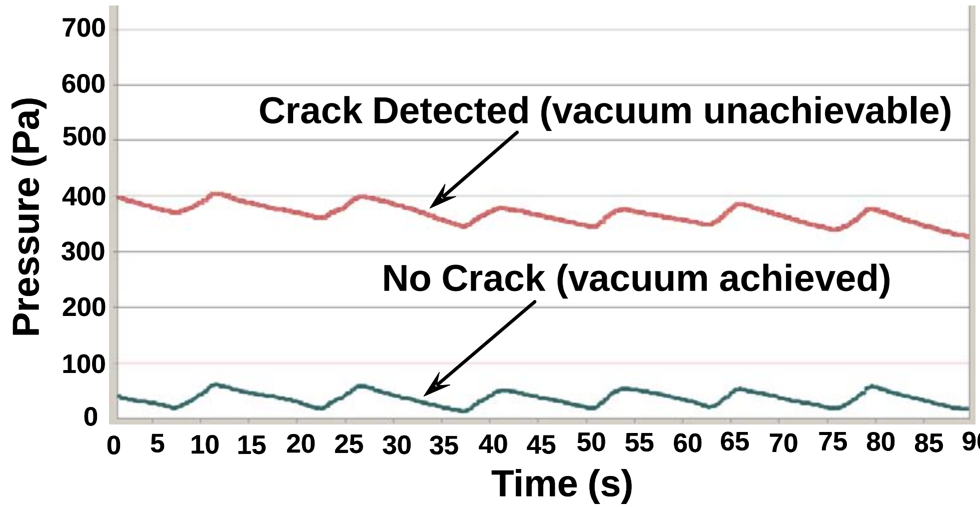
Pull tab flaw

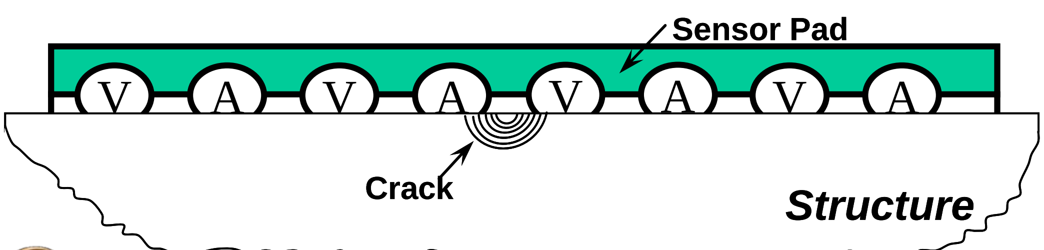
Comparative Vacuum Monitoring System

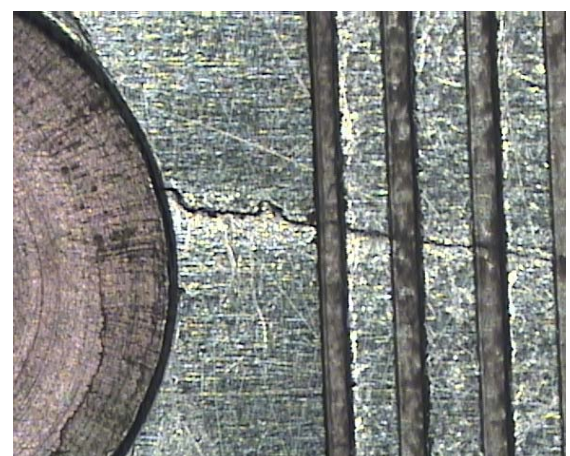
- Sensors contain fine channels - vacuum is applied to embedded galleries (crack detection < 0.1” for alum. < 0.1” th.)
- Leakage path produces a measurable change in the vacuum level
- Doesn’t require electrical excitation or couplant/contact



CVM Sensor Adjacent to Crack Initiation Site

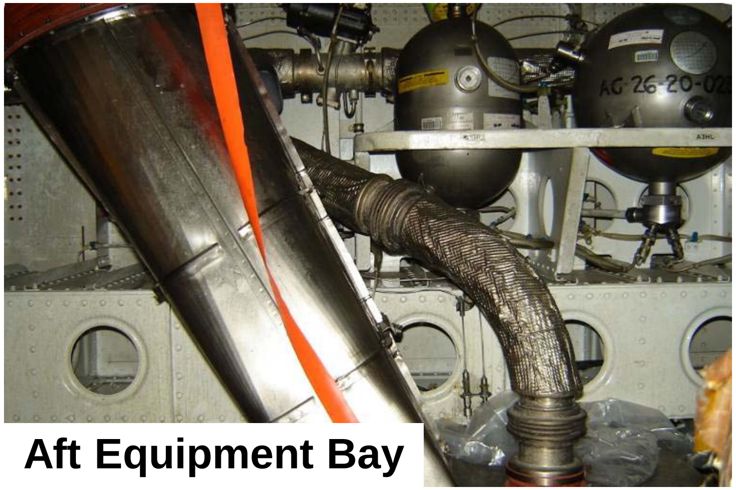


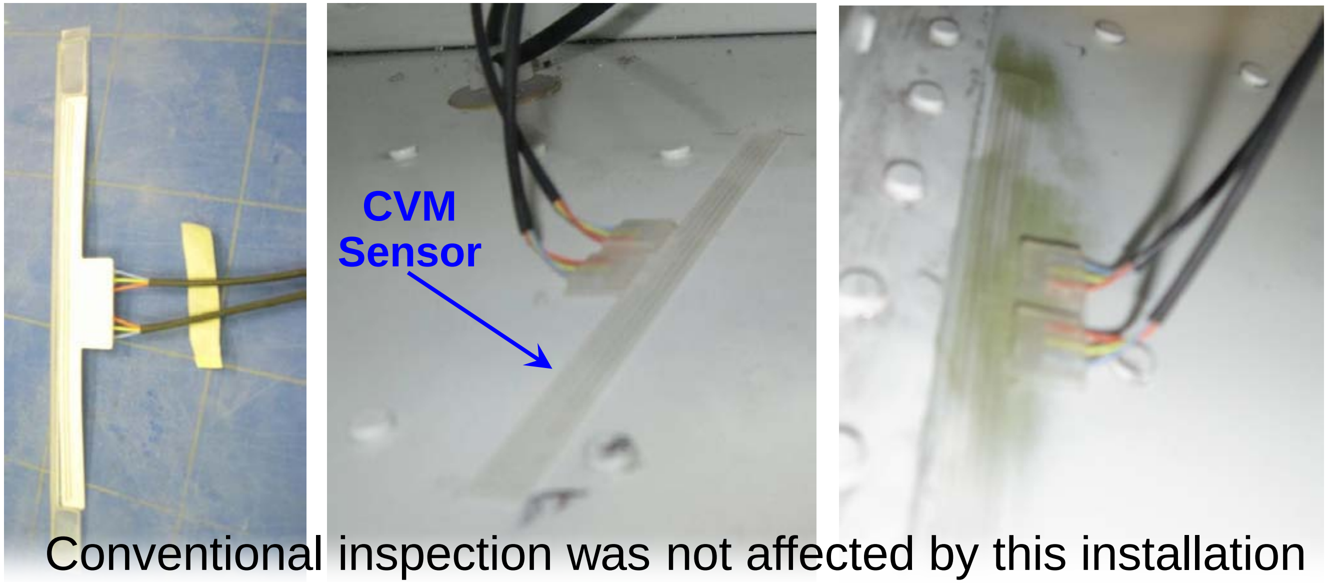




CVM Demonstration on an Operating Aircraft

2 CVM sensors were installed at possible cracking locations


Aft Equipment Bay



Sensor Issues:

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

Conventional inspection was not affected by this installation

Overview of SHM Readiness

- Overall, there is a strong interest in SHM – multitude of applications covering all aircraft structural, engine, and systems areas
- Industry's main concern with implementing SHM on aircraft is achieving a positive cost-benefit & time to obtain approval for SHM usage
- Research and development efforts should be focused on: global systems, sensor technology, system validation and integration, and regulatory guidance
- Standardization and guidelines are needed in certification, laboratory and field validation, and sensor design with aviation in mind
- SHM should run in parallel with current NDI inspections for a period of time
- Industry would use SHM to detect cracks, delaminations, disbonds, corrosion and impact among others
- There is a wide variety of SHM sensors currently developed that have shown potential in aircraft applications. SHM maturity has grown exponentially so desired usage and need for certification is expected to rise rapidly.

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