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Engineering, Test & Technology
Boeing Research & Technology

What We Want to Sense: Manufacturing and In-Service Aircraft Structure

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NDE for Manufacturing

NDE provides the “eyes” for the structural engineer to see that manufacturing has delivered what was asked for.

The Importance of NDE in Manufacturing

NDT Handbook : Robert McMaster : 1959

- **To ensure product reliability**
- **To prevent accidents and save human lives**
- **To make a profit for the user *(Add Value)***
  - **To ensure customer satisfaction and to maintain the manufacturer's "good name"**
  - **To aid in better product design**
  - **To control manufacturing processes**
  - **To lower manufacturing cost**
  - **To maintain a uniform quality level**

The Importance of NDE in Manufacturing

The Implementation of NDE Innovation provides a competitive advantage to the United States' interests, including:

- Defense
- Transportation
- Energy
- Oil & Gas
- Infrastructure
- Health Diagnostics

When is NDE Needed?

- **Fundamental Studies**
- **Manufacturing Development Support**
- **Structural Test Support**
- **In-Process Measurement**
- **Production NDE**

Manufacturing NDE

- Unplanned Event NDE
- Post-Production NDE (field, depot, PM)
- Damage Assessment & Repair NDE
- SHM Interface/Follow-up

In-Service NDE

Composites in Aerospace

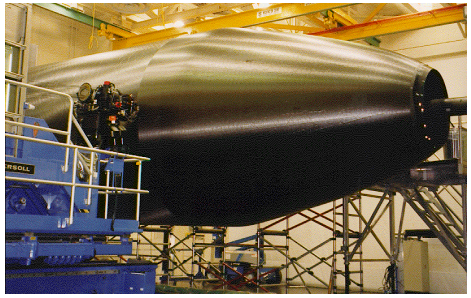
Composites

Form and Fabrication Influence NDE

Basic Fabrication Methods
- **Prepreg layups**
- **Tape or fiber placement**
- **Resin transfer molding**

Hand Layup

Automated Tape Layup



Fiber Placement

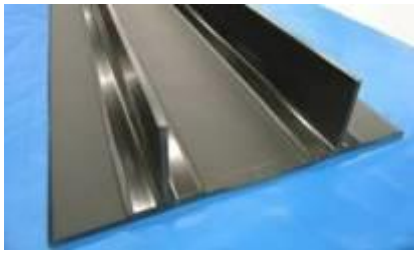
Resin Transfer Molding (RTM)

Composites

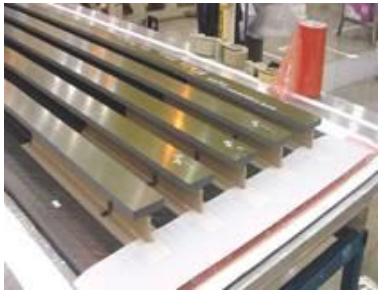
Form and Fabrication Influence NDE

- Solid Laminate
  - Flat and curved skins
  - C channel spars
  - I's, T's, Pi stringers
  - Hat stiffeners
- Sandwich Structure

Floor Beam

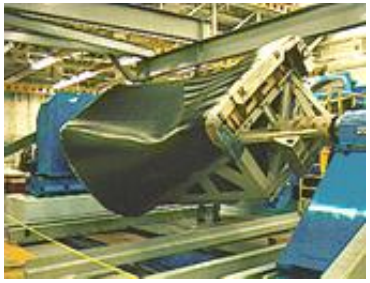


Blade Stringer on a Skin



T Stringer on a Skin

Hat Stiffeners on a Skin

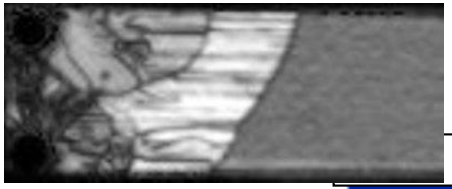


Fiber Placed Inlet Duct

Honeycomb core

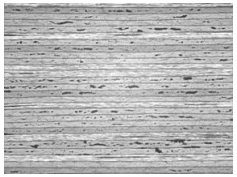
Typical Defects or Damage in Composites

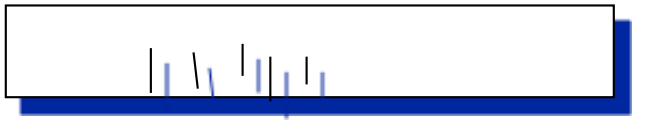
Delaminations



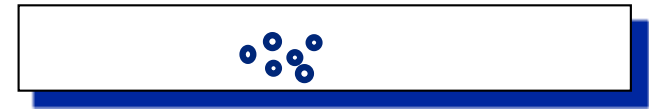
Disbonds

Cracking

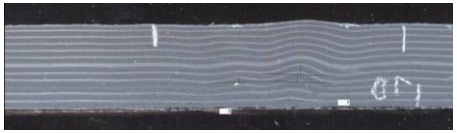


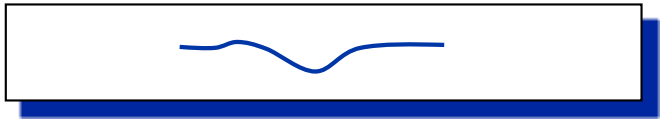


Porosity

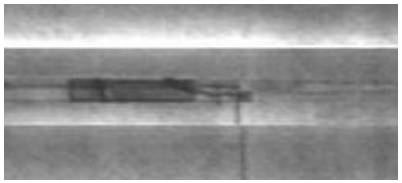


Wrinkles

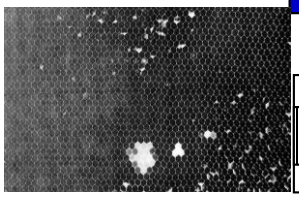




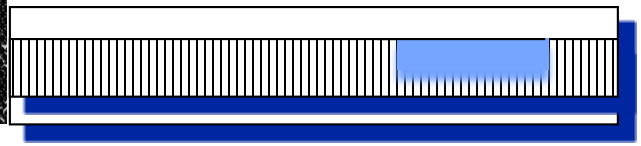
FOD



Heat Damage



Moisture Ingress



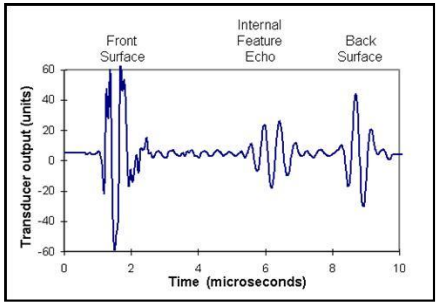
NDE for Composites: Methods

NDE Methods	Applicable to Composite Inspection
Visual	Always
Ultrasound	Predominate Inspection
Bond Testing	Usually In-service
Radiography and X-ray CT	Varied Applications
Thermography	Varied Applications
Shearography	Varied Applications
Acoustic Emission	Testing, SHM
Electromagnetics	Research

Ultrasonic Testing

Principle:

Mechanical wave propagation and reflection in materials.
Detects interfacial changes in wave propagation (planar defects).
Material property in terms of velocity of ultrasound ($E \sim kv^2$)

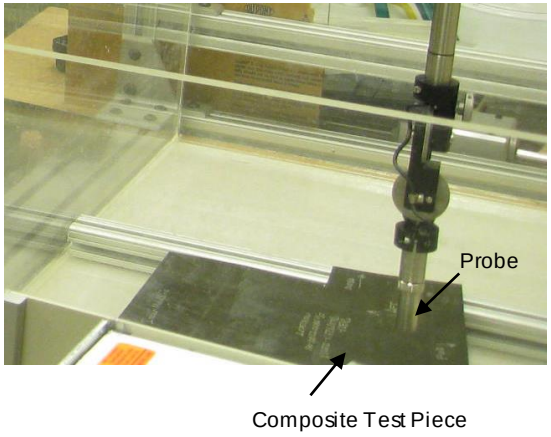


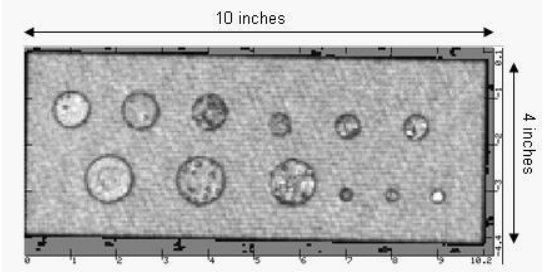
UT signal waveform

- Primary method specified for composite inspection
- Material allowables testing are based on this inspection

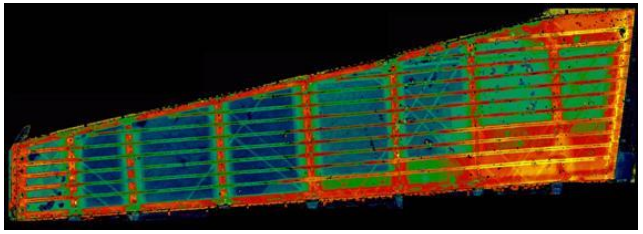
Large Thru Transmission Ultrasound Water Squirter System

Water Immersion Ultrasound Scanning Tank





Amplitude C-Scan of composite with flat bottomed holes



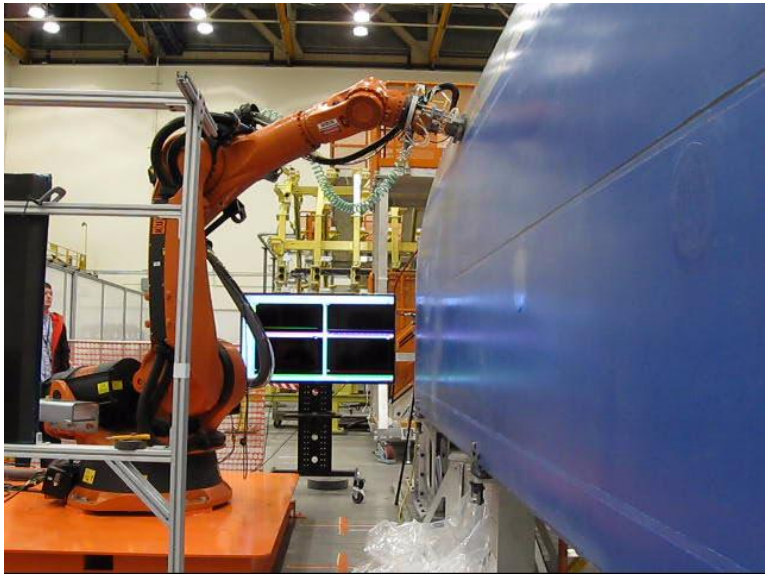
LaserUT™ TOF C-scan image of composite stabilizer

Flexible & Collaborative Robotic NDE

- Pedestal Robots with NDE end-effectors
- Programmable scanning paths
- Integrated with NDE – Ultrasonic Phased Array Systems

Agile, Reconfigurable Robotics for NDT

NDE for Composites: Robotic UT Inspections

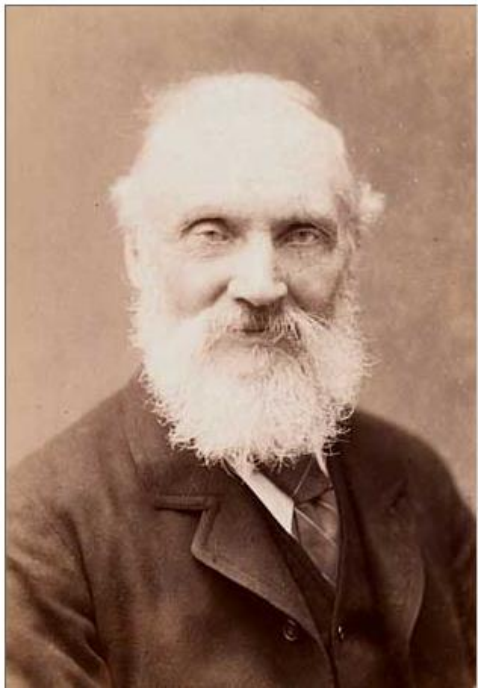


Robotic Scanner with UT Array

Multi-Array Pass Through System

In-Process Inspection/Data Analysis

You don’t inspect in Quality, you measure it.



“If you can’t put a number on it, you don’t know it.”

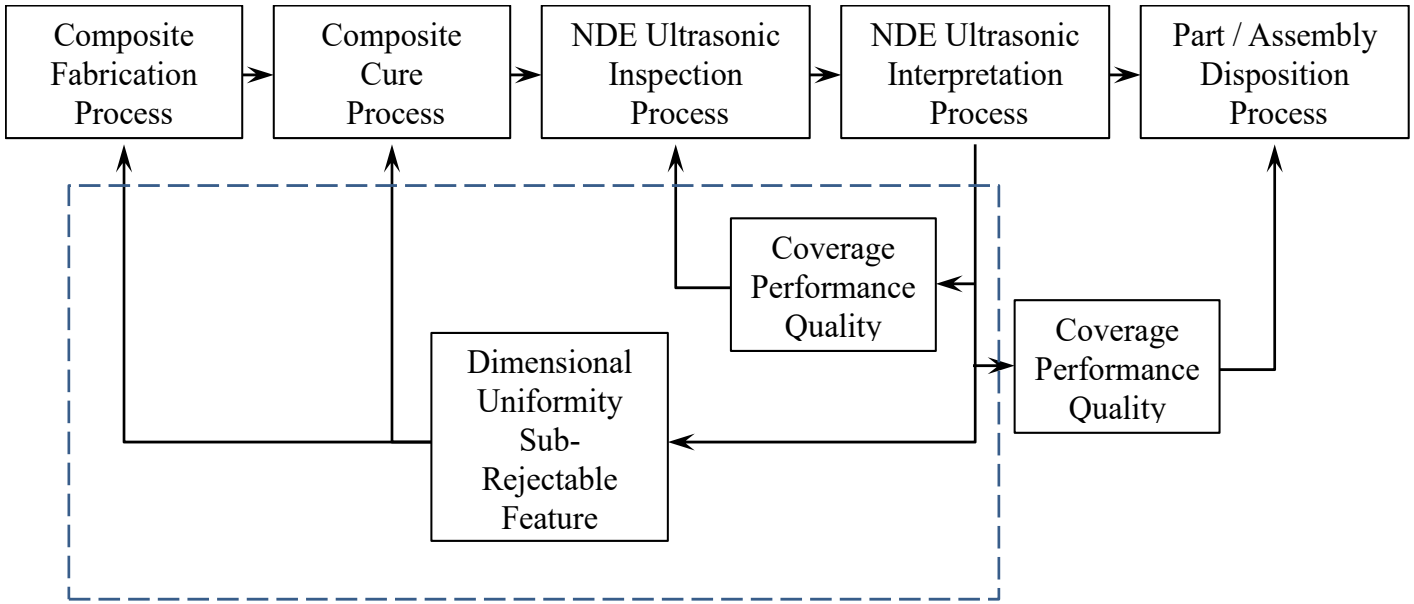
Paraphrased from Lord Kelvin

The Opportunity: Lots of Great Data!

- We collect a lot of NDE and Measurement data during manufacturing inspection.
- The data is generally used for defect detection and pass/fail decisions.
- The data is usually just archived temporarily or discarded.
- The data has valuable information that can correlated to upstream processes to understand causes and effects.
- We can reduce non-conformances, rework, and flow-time. *(Save Money!!!)*

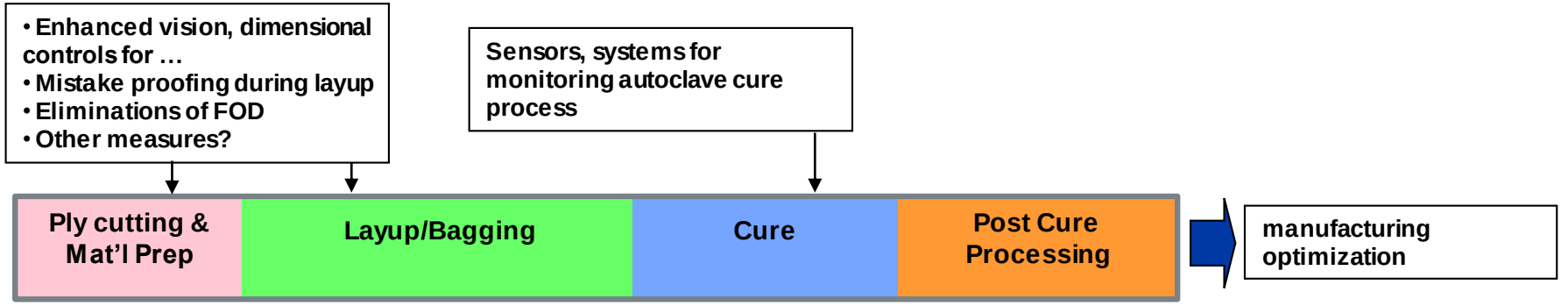
NDE for Manufacturing Process Monitoring

- **Process monitoring is fundamental to good manufacturing processes**
- **NDE data contains a wealth of information about a process**



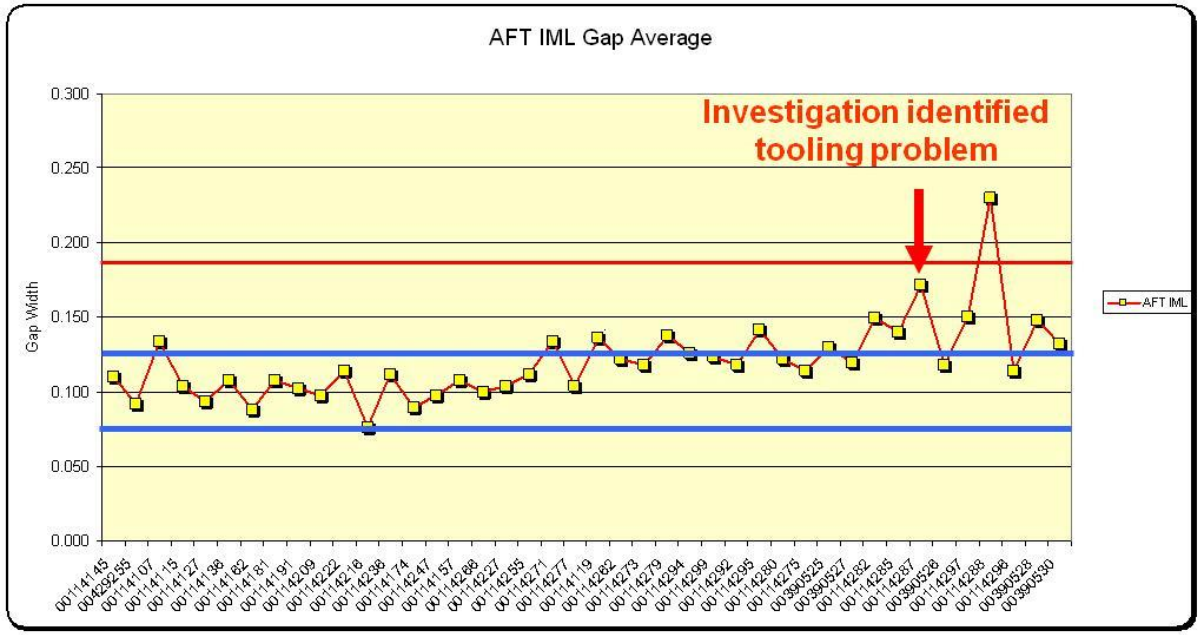
In-Process Inspection

- Monitor Key Processes During Fabrication
- Reduce Post Cure NDE Requirements

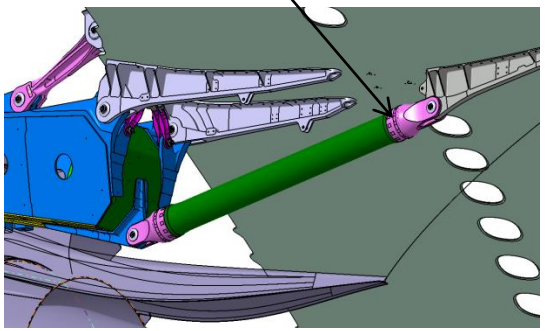


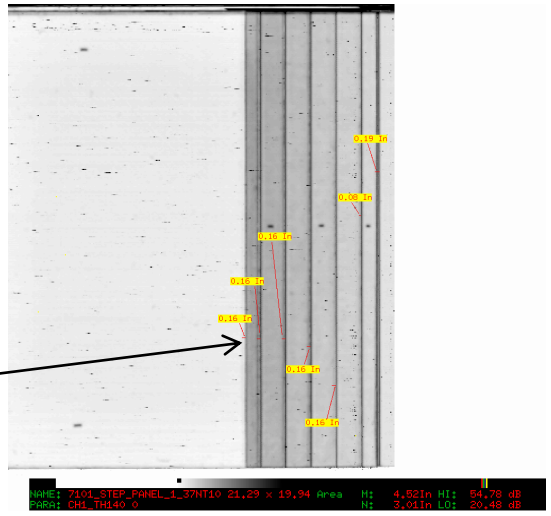
Tooling Degradation can be identified with NDE

- We need to be monitoring processes, so we can avoid rejecting product



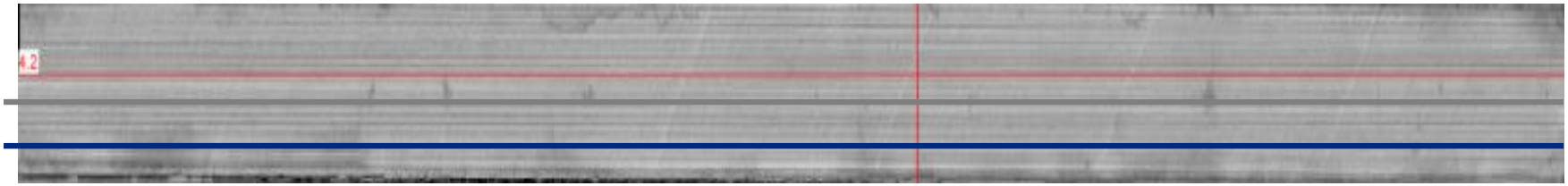
diagonal brace Ti fitting to composite tube bond

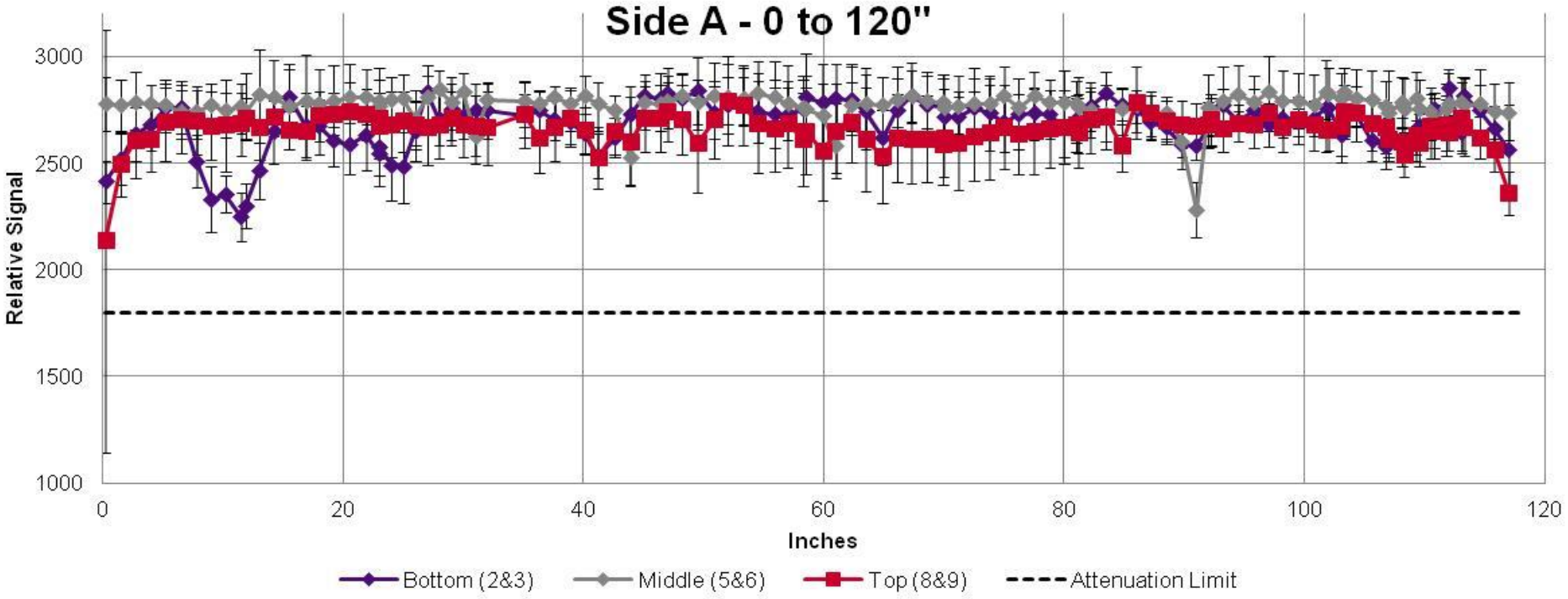




Ultrasonic scan for measuring step gap fitup

NDE Sub-Rejectable Data

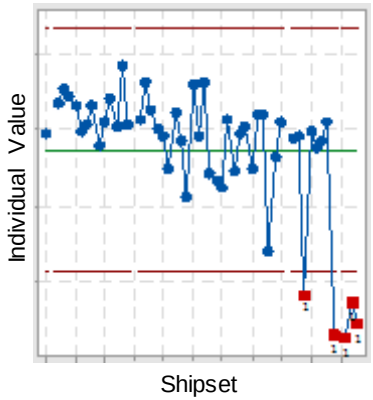




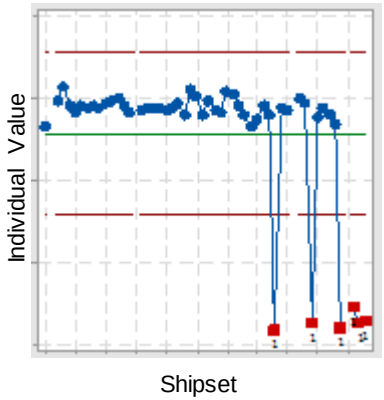
Process Control with NDE Standards

Data from selected flaw insert

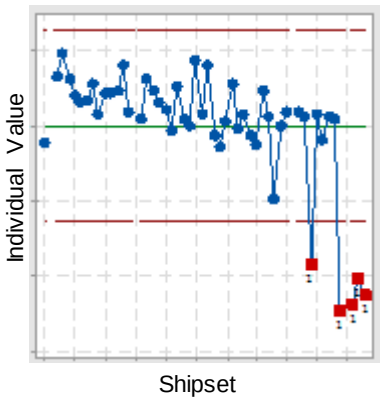
Measure A



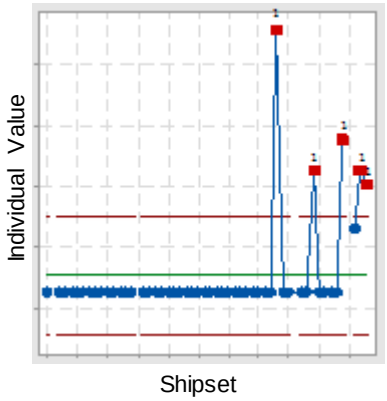
Measure B



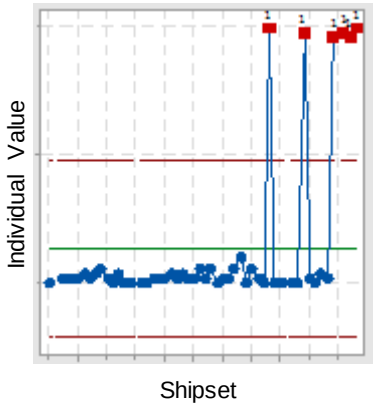
Measure C



Measure D

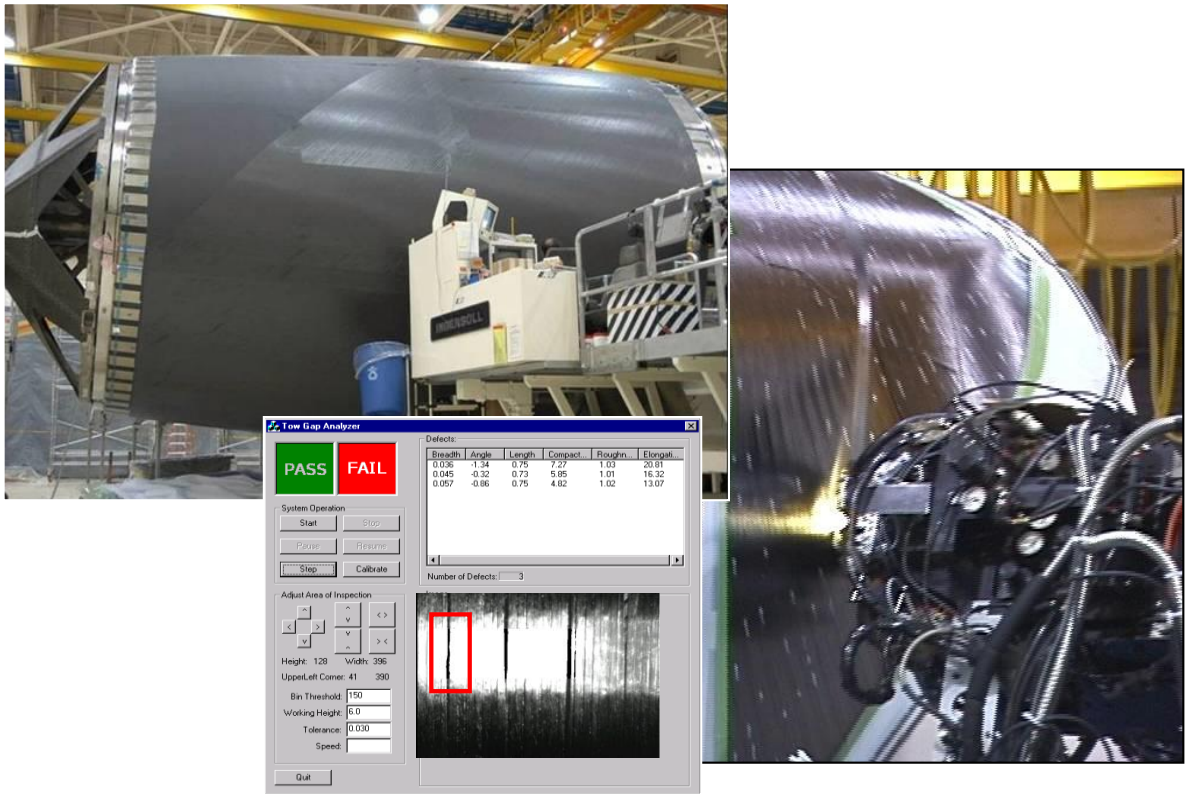


Measure E



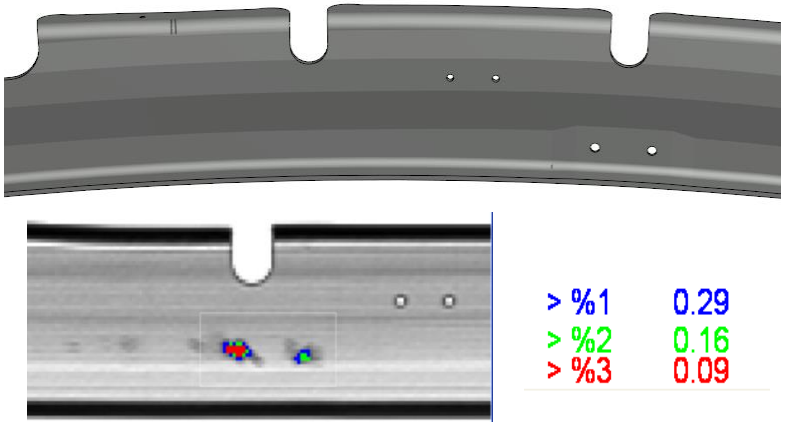
In-Process Inspection/Data Analysis

In-Process Inspection During Fiber Placement



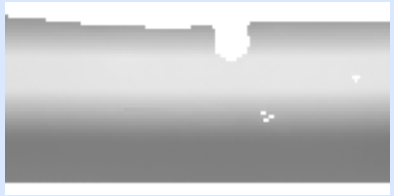
Assisted Data Analysis

- Computerized Analysis
- Defect Identification
- Quantitative Interpretation
- Monitoring of Sub-rejectables
- Fusion of NDE with the Structural Model



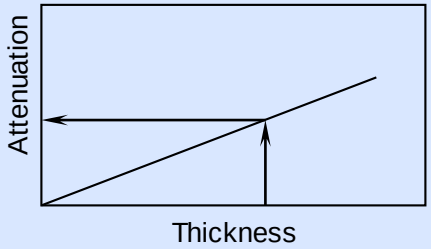
Real Time Porosity Characterization

Thickness

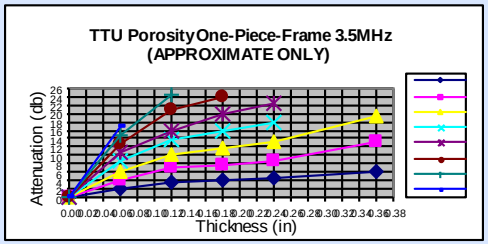


TOF Data or **Digital Master

Baseline



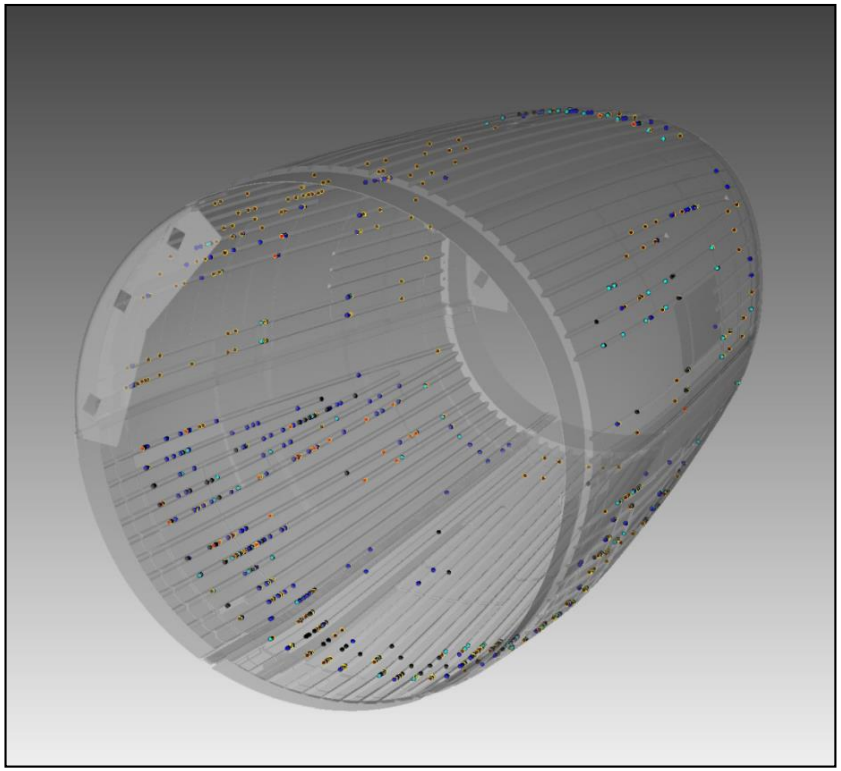
Porosity Curves

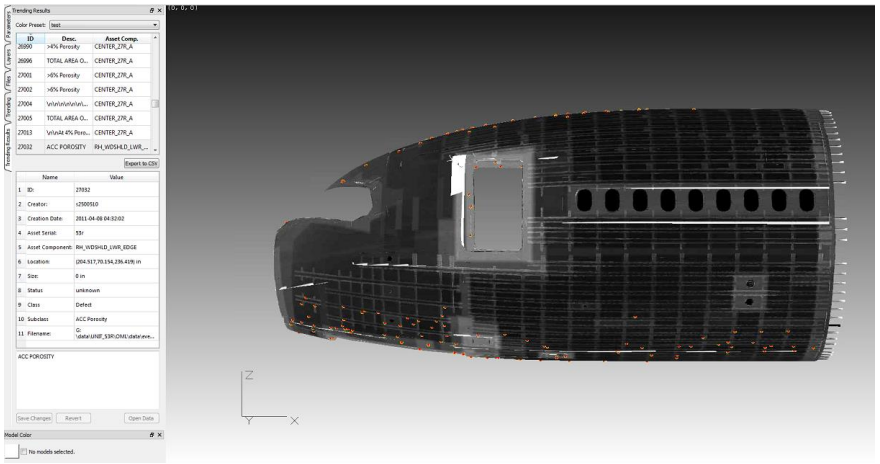


Blue -1%
Green - 2%
Red - 3%

Assisted Data Analysis

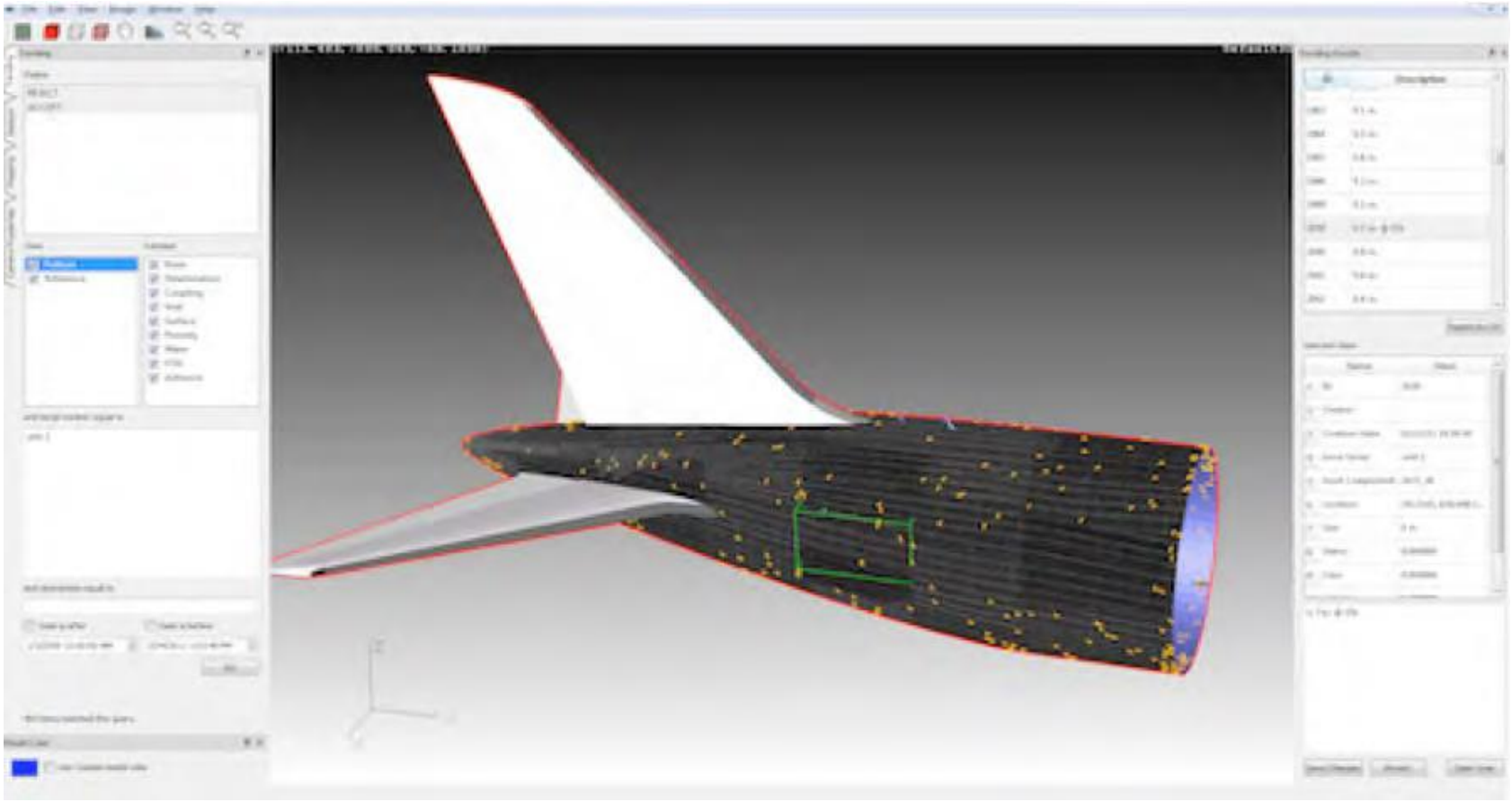
- Computerized Analysis
- Defect Identification
- Quantitative Interpretation
- Monitoring of Sub-rejectables
- Fusion of NDE with the Structural Model





Overlay of NDE Data on Structure

NDE data is overlaid onto the structural model
Data is accessible for coverage, SPC and review



The Need for Sensors in Manufacturing

We face many challenges in aerospace manufacturing:

- **Cost and Time for NDE** – needs to be reduced!
- **Design/Manufacturing/NDE** Correlation – siloed, sub-optimal, haphazard
- **Underutilization of NDE Data** -- single use, pass/fail, non-correlated
- **Much NDE is still manually intensive**
- **Human Factors Impacts** – differences in inspectors, fatigue, experience
- **Availability of Trained Techs** – we are getting behind the need!
- **Other Challenges!**

The Need for Sensors in Manufacturing

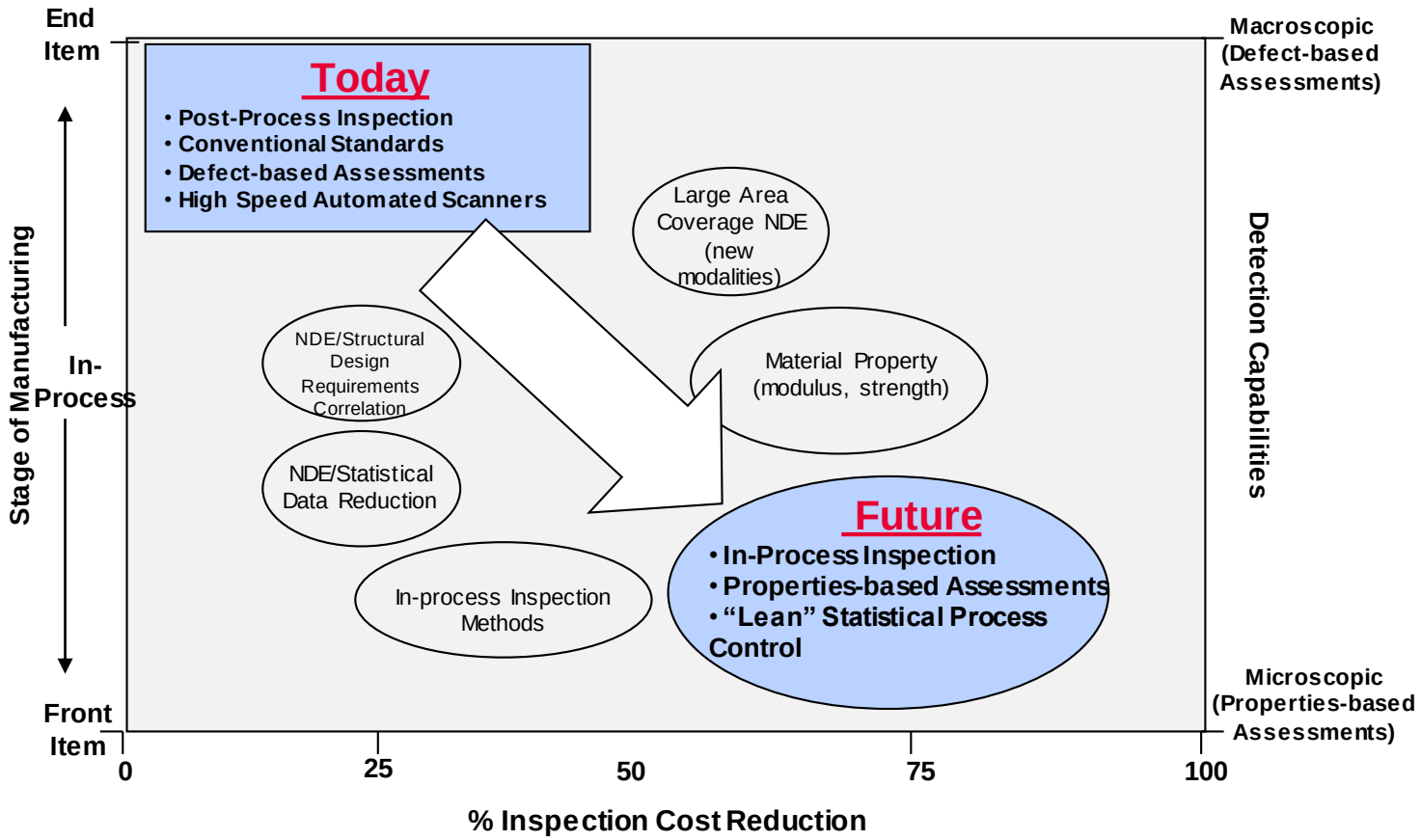
New Structure Related Challenges:

- **Composites NDE** – complexity, standards, correlation of NDE to performance
- **Additive Manufacturing** – a very complex structure/geometry; need for requirements and standards
- **Ceramics & Metals NDE** – complexity, process assessments, cost of inspections
- **Material Properties** – how do we validate new materials manufacturing/properties?

The Need for Sensors in Manufacturing

- In-Situ NDE methods for AM
- Automated Defect Analysis and Intelligence Augmentation
- Integration of NDE into manufacturing processes
- Process Monitoring & process Control with NDE
- Modeling of NDE for faster and better integration
- Rapid NDE-to-FEA based assessment capability

NDE – Opportunities in Manufacturing



Manufacturing and In-Service Digital Alignment

Changing environment presents opportunities

Inspection, manufacturing, and measurement data moving to digital

Automation and robotics growth continues

New materials and manufacturing processes

Attributes of Future Sustainment

Attribute		Major Success Characteristics	Attribute Owner/Co-Owner	Execution Group
	1. 100% Data Integration & Availability	All Data Sources are Digital (Digital Thread) Common Software Tools to Manipulate the Data Tail Number Weapon System/Commodity Digital Twins Data Fusion and Linkage to SME on Production Floor	AFSC/EN AFRL/RX	IEG
	2. 100% Parts Availability	100% On-Time, Cost-Effective Parts Availability Rapid Certification of New Parts & Sources Accurate Parts Forecasting Agile Local Manufacturing 3-D Reprocurement Packages	448 SCMW/DLA AFRL/RX/RQ	SCMEG
	3. Safe & Environmentally Compliant	Processes and Facilities That Are Inherently Safe Eliminate All Hazardous Materials from Processes Eliminate All Dangerous Tools & Working Conditions	AFSC/EN AFRL/RXS	DMEG
	4. Efficient Depot	One-Pass, Whole Weapon System NDI Assessment Perfectly Scheduled PDM Tailored to Individual Tail Extensive Robotics (Where Appropriate) Technology Enabled Reconfigurable Facilities Data Fusion of Digital WCDs	AFSC/EN AFRL/RXM	DMEG
	5. Effective Workforce	Clear Daily (8 hour) Work Expectations Training Aligned with Complex Mission/Goals/Objectives Less Intrusive & Capability Enhancing Personnel Protection Equipment	AFSC/DP AFRL/RH	DMEG
	6. 100% Process Control	All Processes Configuration Controlled & Managed Each Process Ideally Tuned: Statistical Process Control Processes as Good/Better Than Commercial Practices Balance of Quality Assurance & Quality Control	AFSC/EN AFRL/RX	DMEG
	7. Strategic Sustainment Management	Single AFSC Entry Point for Workload Common MRO Toolsets Across The ALCs Enterprise Loading of Common Production Capabilities Planning Tools That Optimize Workloads Among ALCs	AFSC/LGX AFRL/RX	SCMEG
	8. Resilient Mission-Ready Software Sustainment	Resilient software development, tools, and processes High fidelity WS simulations for val/ver/test/training Technology driven cross complex collaboration/innovation	AFSC/EN AFRL/RI	DMEG
	9. Energy Efficacy	Enabler in Meeting Air Force Energy Reduction Goals Energy Savings an Important Criteria for New Equipment Selection	Energy Consortium AFRL/RX	IISEG

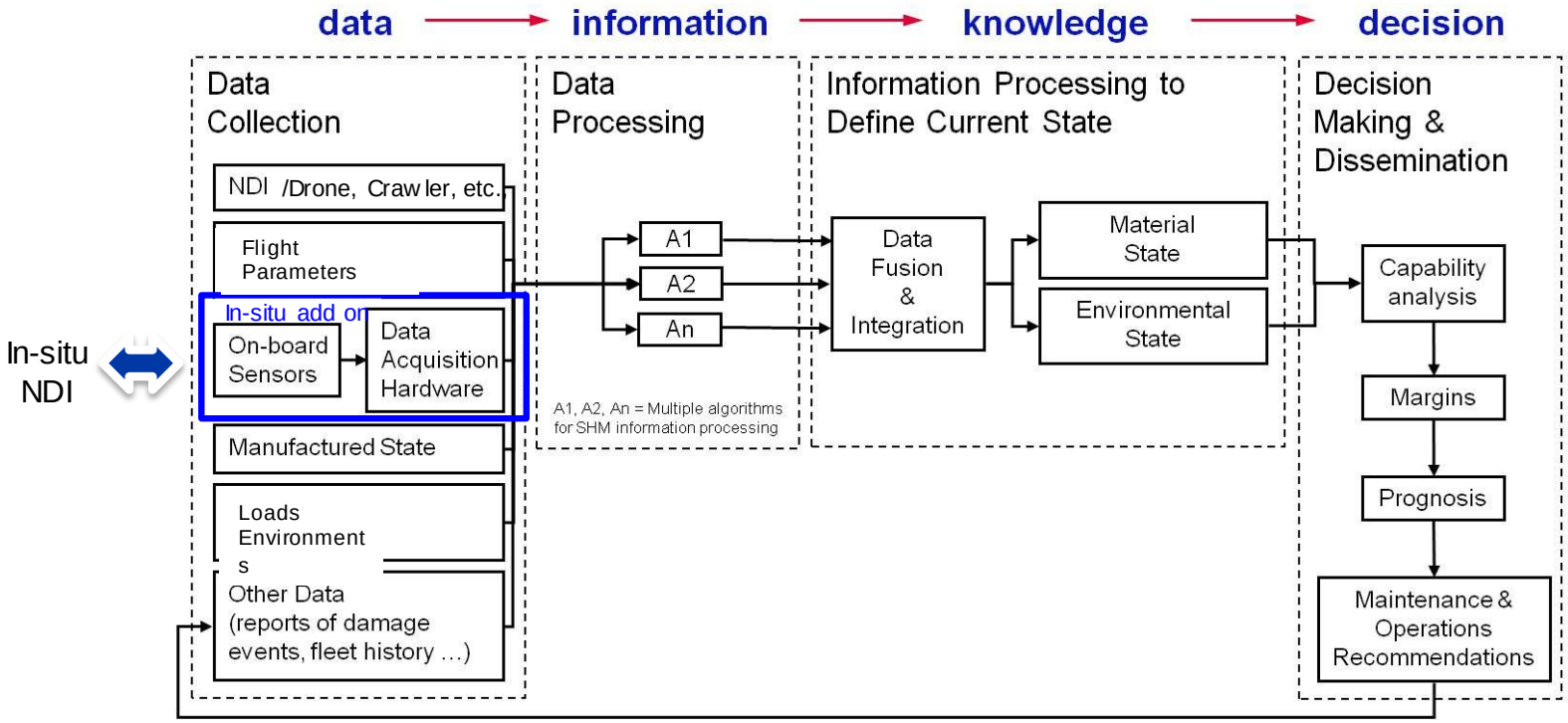
Table 1 – ***Logistics and Sustainment Enterprise 2040*** Attributes

Interests

- Factory automation
- Sensor development
- Inspection system digital transition
- Inspection, manufacturing, & measurement data:
  - Dynamically linked and integrated
  - Aligned to aircraft coordinates
- Feedback to manufacturing process & design tools
- Expanded mobile inspection capability
- Safety as an inherent design attribute

Focusing on cost, schedule, safety, quality, and aircraft availability

Boeing Structural Health Management System



- An *automated* and holistic process to determine airframe structure integrity and make timely and cost effective life cycle decisions
- → Affects ALL Phases of a Structure Life Cycle → "Digital Value Chain"

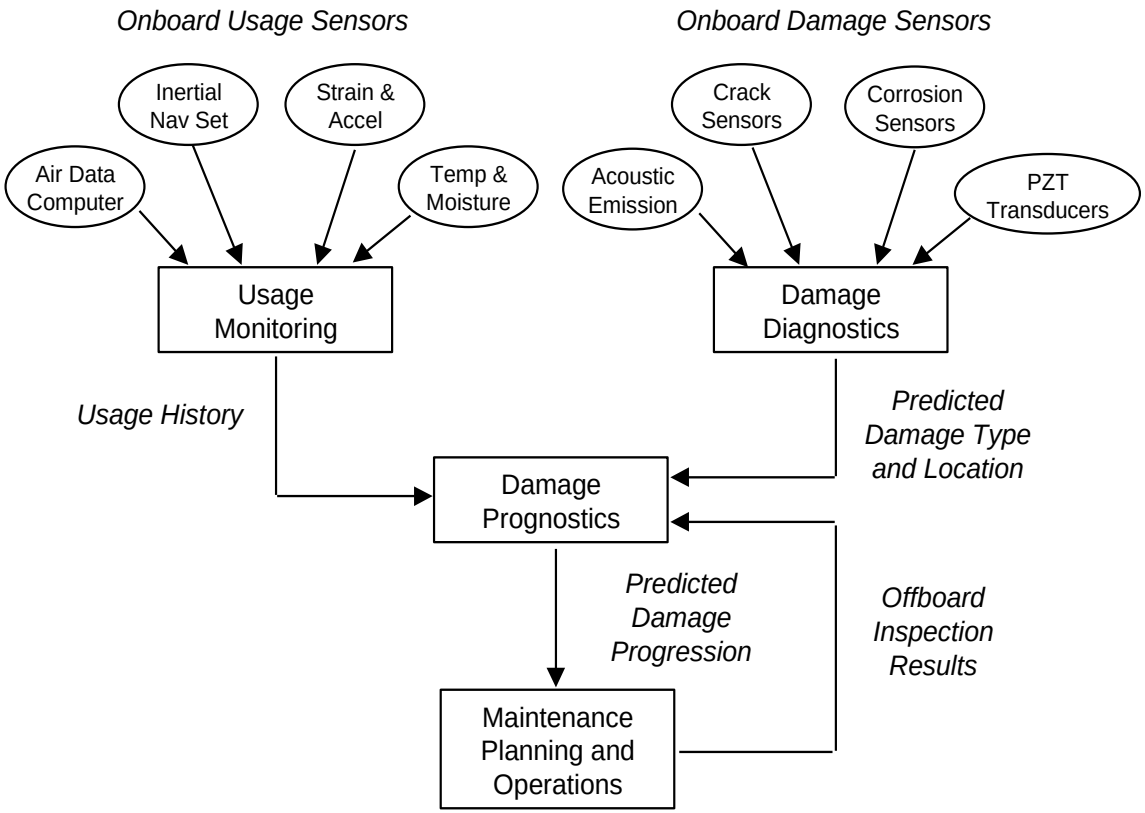
System Integration and Operation Options

Various system integration/operation options are traded for application objectives and costs

BR&T focused on Category I and II for near-term implementation opportunities

Category	Hardware		Monitoring Frequency	Reporting	Characteristics
	Sensor	DAQ			
I	**On-board**	**Off-board**	**Fixed intervals**	**Ground maintainers**	**No inference during flight, minimal system add-on, external plug in, easier certification path**
II	**On-board**	**On-board**	**Fixed intervals**	**Ground maintainers**	**No inference during flight, medium system add-on, no-external hardware required, easier certification path**
III	On-board	On-board	Real-time	Flight crews	Real-time alert, AHM integration, highest system reliability
IV	On-board	On-board	Real-time/ Optimized Intervals	Ground maintainers	Automated maintenance orders, No inference during flight
0	Off-board	Off-board	Fixed intervals	Ground maintainers	No inference during flight, same certification path as NDI

SHM Sensor System Architecture - Example



General Requirements for an Embedded Sensor System

Light weight

Durable

Reliable

Self-diagnostics

Self-powered

Wireless activation and data transmission

Thank You!