Federal Aviation Administration

Emerging Technologies and Risk Mitigation – *Additive Manufacturing*

Presented to:

REDAC Subcommittee on Aircraft Safety

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for Fatigue and Damage Tolerance

Disclaimer

- *The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration rules interpretation or policy*

Outline

- **Emerging technologies considerations**
- ***Additive Manufacturing* – new “disruptive” technology**
- **Technology transition and risk mitigation**
- **“State of Industry” overview**
- **Summary**

Emerging Technology Considerations

AM →

- ❑ **New material systems**
- ❑ **New manufacturing technologies**
- ❑ **…**

"Since its emergence 25 years ago, additive manufacturing has found applications in industries ranging from aerospace to dentistry and orthodontics… and is poised to exceed $3B by 2016 …" (Wohlers 2011).

Motivation

From the FAA Priority Initiatives

"Risk-Based Decision Making: build on safety management principles to proactively address emerging safety risks…"

What Causes Failures?

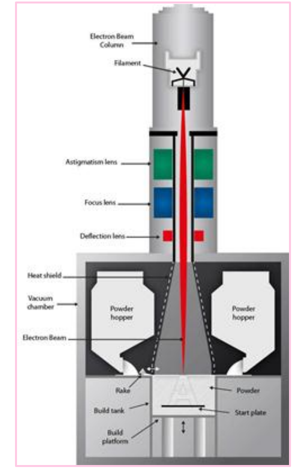
Frequency of Failure Mechanisms *)

Failure Mechanism	% Failures *(Aircraft Components)*
Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%

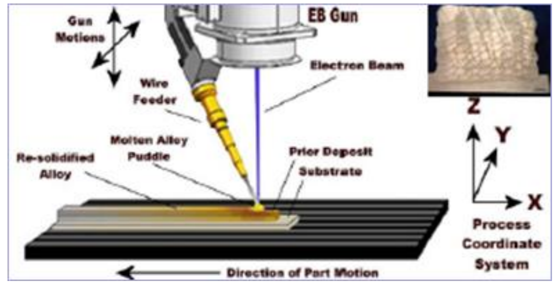
*) *Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- **Fatigue is the Predominant Failure Mode in Service**
- ***Expect this trend to continue for metallic materials***
- ***Some of the most challenging requirements for new material systems are Fatigue and DT***

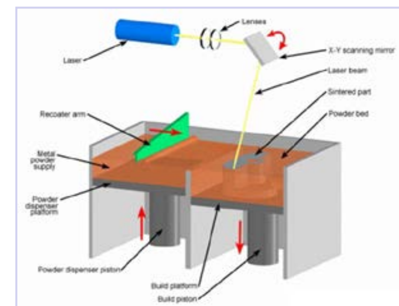
Types of AM Processes and Application Domains



By Source of Material:
Powder vs. Wire

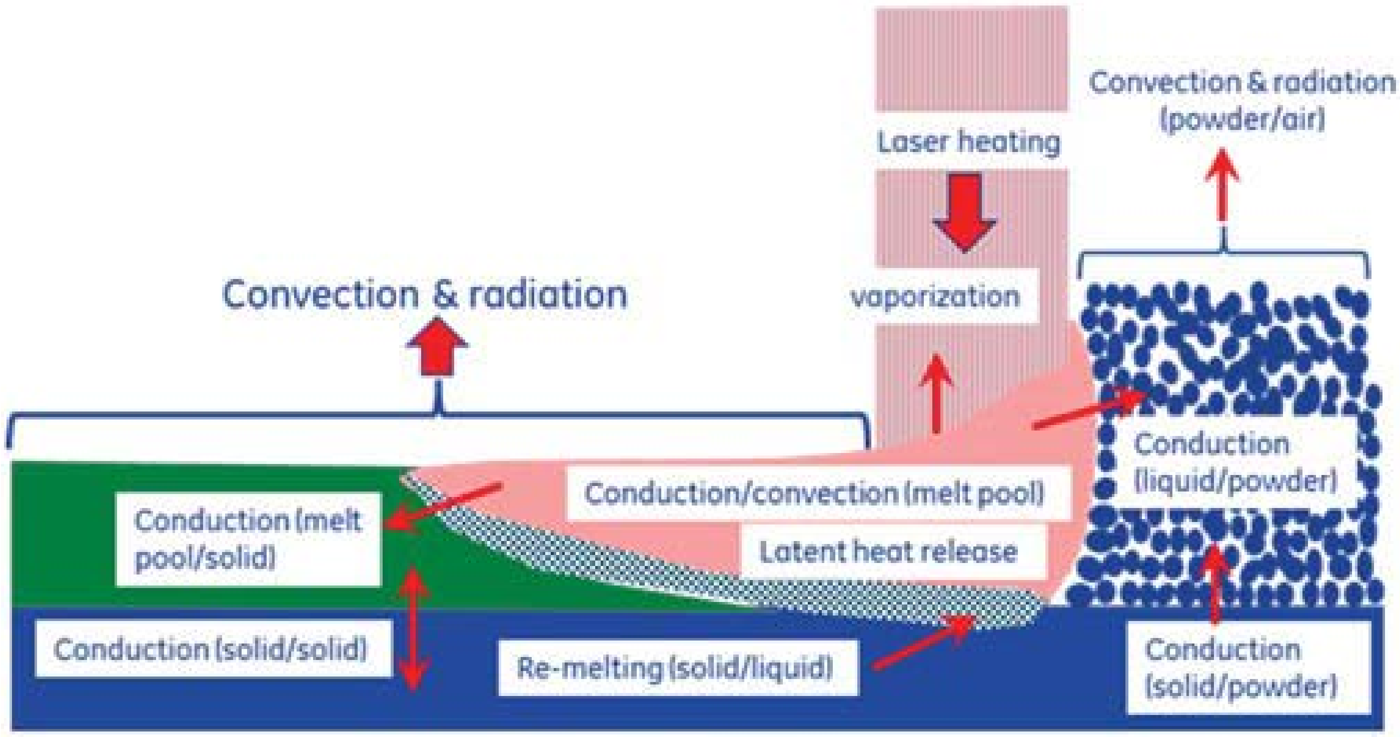


By Source of Energy:
Laser vs. E-Beam



New Type and Production Certificates	Repair and Overhaul (MROs)	Aftermarket Parts (PMAs)

Example: Powder Bed AM – Process Physics



- ***Complex physics***
- ***Significantly different*** **from conventional manufacturing processes (cast, wrought)**

State of Industry

“Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas…”

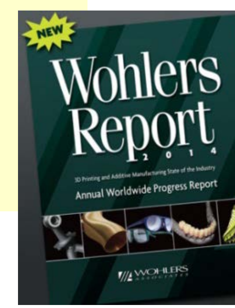
Mr. David Joyce, GE Aviation President and CEO

<u>Source</u>: Aviation Week, July 15, 2014

"Metal parts from <u>some</u> AM systems are *already on par with their cast or wrought counterparts*. As organizations qualify and certify these and other materials and processes, the industry will grow very large. In fact, additive manufacturing is poised to become the most important, the most strategic, and the most used manufacturing technology ever."

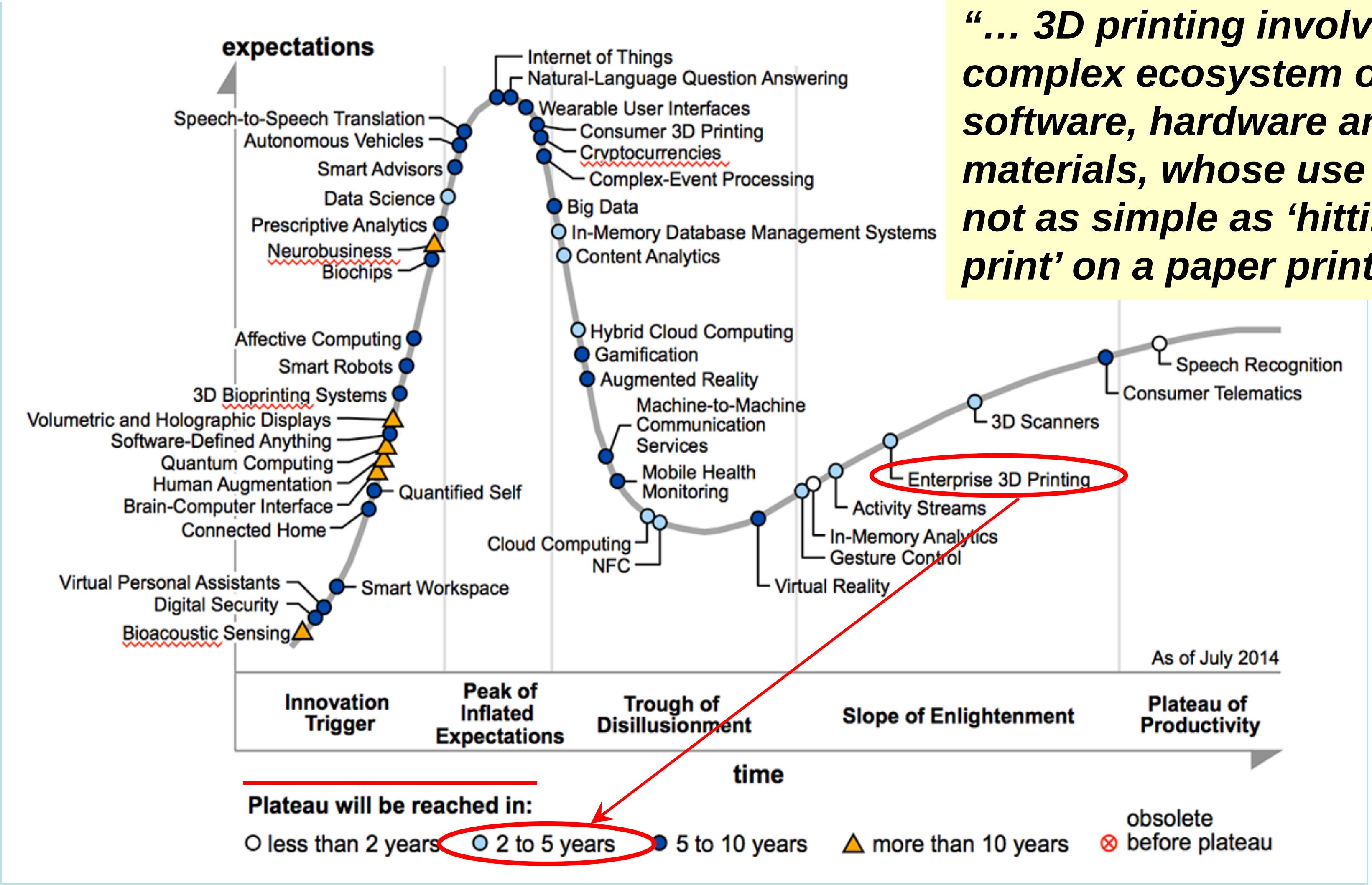
(highlights are added)

<u>Source</u>: Wohlers Report 2012



The 2014 Gartner Hype Cycle Chart

***Source*: "Divining Reality from the Hype", The Economist, Aug. 27, 2014**



"… 3D printing involves a complex ecosystem of software, hardware and materials, whose use is not as simple as 'hitting print' on a paper printer…"

Federal Aviation Administration

Business Drivers for AM

- **Part count reductions**
- **Producibility / machinability issues**
  - ***e.g. thin-wall castings***
- **More complex geometric designs**
  - ***Weight reduction***
  - ***Design optimization***
- **Single Source alternatives**
- **Production of low volume / legacy parts**
- **PMA business model (reverse engineering)**
- **Low barrier to entry for smaller businesses**

Important to Understand Business Drivers as Predictors of Technology Trends

Engine OEMs Are Becoming Early Adopters of AM Technology

- ***"Each LEAP engine has inside 19 3D-printed fuel nozzles…"*** http://www.gereports.com/post/80701924024/fit-to-print

- ***"The world's first 3D-printed jet engine — a breakthrough for aerospace manufacturing and beyond — took the spotlight Thursday at the Avalon Airshow in Australia…"*** http://www.avweb.com/avwebflash/news/First-3D-Printed-Jet-Engine-Made-In-Australia-223622-1.html

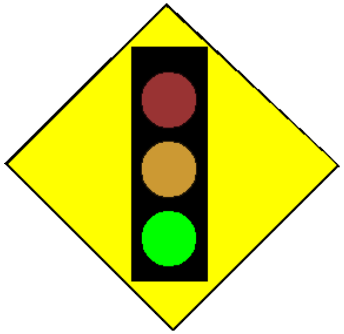
Benchmarking Government Efforts in AM

- **Most major US government agencies have been involved in AM roadmaps development and R&D *over the past 5-10 years***
  - **NSF, ONR, DARPA, NIST, NIH, USAF, NavAir, NASA, FDA etc.**
  - ***FAA was not a part of these activities***
- **Examples of funded activities (DoD) – *partial list***
  - **Metallic AM Inspection Benchmarking for AF**
  - **Manufacturing Variability Quantification for Aerospace**
  - **DARPA Open Manufacturing**
  - **Metallic AM for Liquid Rocket Engines**
  - **AM of Ceramic Cores for Airfoils**
  - **Direct Part Mfg of HT Thermoplastic Composites**
  - **Sustainment Opportunity Assessment & Risk-based Decision Tree**
  - **Etc.**

> $50M R&D Investment

Technology Transition Criteria

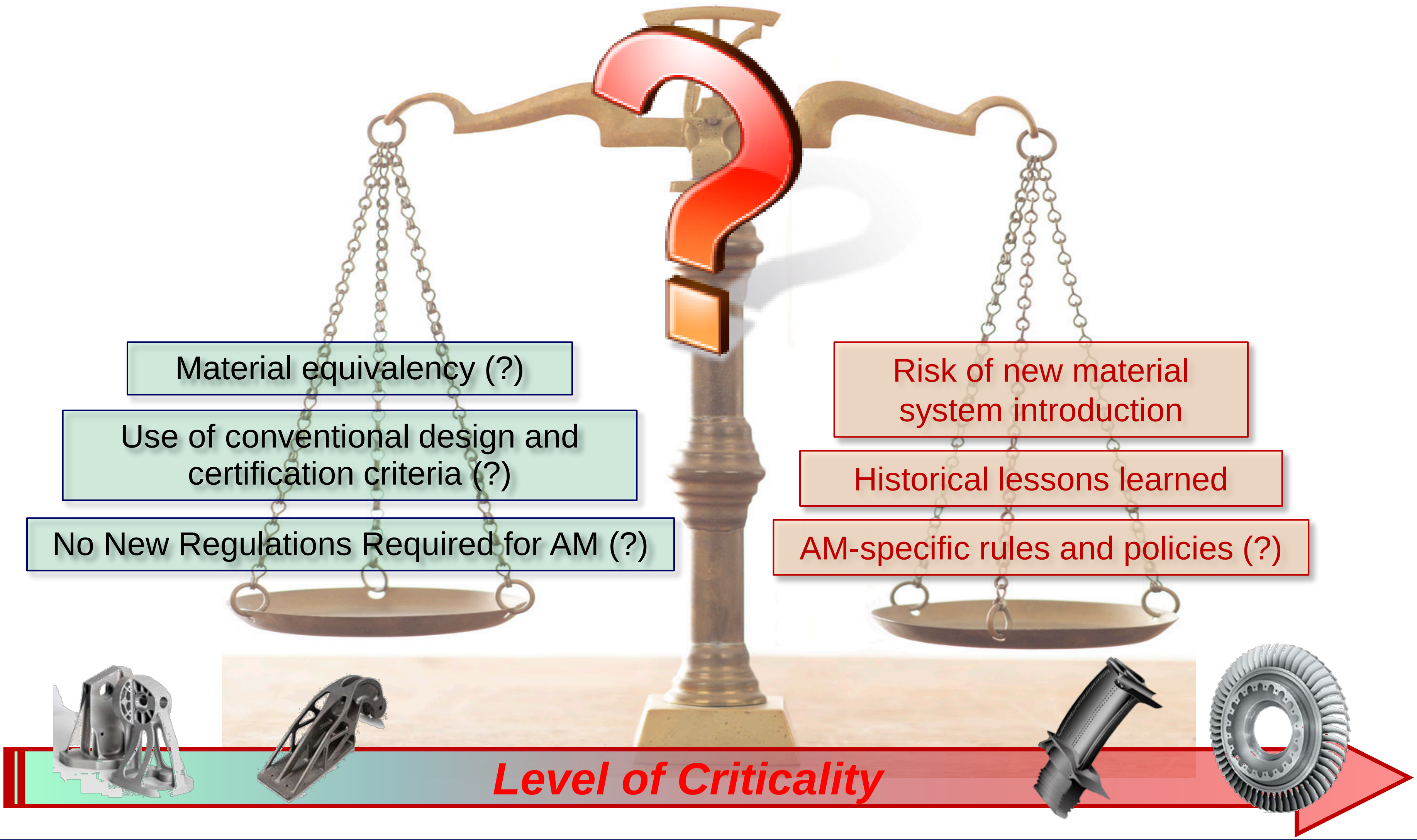
- **USAF performed a *study of the successful transitions of structural technologies* from the laboratory to EMD**
  - *EMD = Engineering and Manufacturing Development*
- **It was found that *five factors constituted a common thread* among these successes:**
  - **Stabilized material and/or material processes**
  - **Producibility**
  - **Characterized mechanical properties**
  - **Predictability of structural performance**
  - **Supportability**



"A deficiency in any one of the factors could constitute a fatal defect "

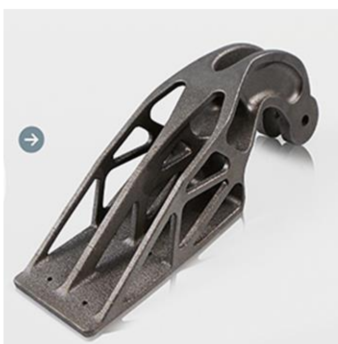
Source: Dr. Jack Lincoln, Structural Technology Transition to New Aircraft, USAF.

Finding The Right Balance…



So, How Much Time Do We Have?

“Amazon gets FAA approval for drone testing…”



?

The world’s first 3D-printed jet engine

From Non-Critical to Critical

- **Typical new aerospace alloy development and introduction timeline – *10 to 15 years***
  - **However**

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural component	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

Criticality Considerations

- **Consequence of failure to operational safety**
- **Certification requirements depend on the type of product (e.g. commercial transport, rotorcraft, engine)**
  - **Additional challenge for AM (in comparison with PM) due to the breadth of applications**

- **Example – definition of *hazardous engine effects* in CFR Title 14 §33.75** (*partial list*):

(i) **Non-containment of high-energy debris;**

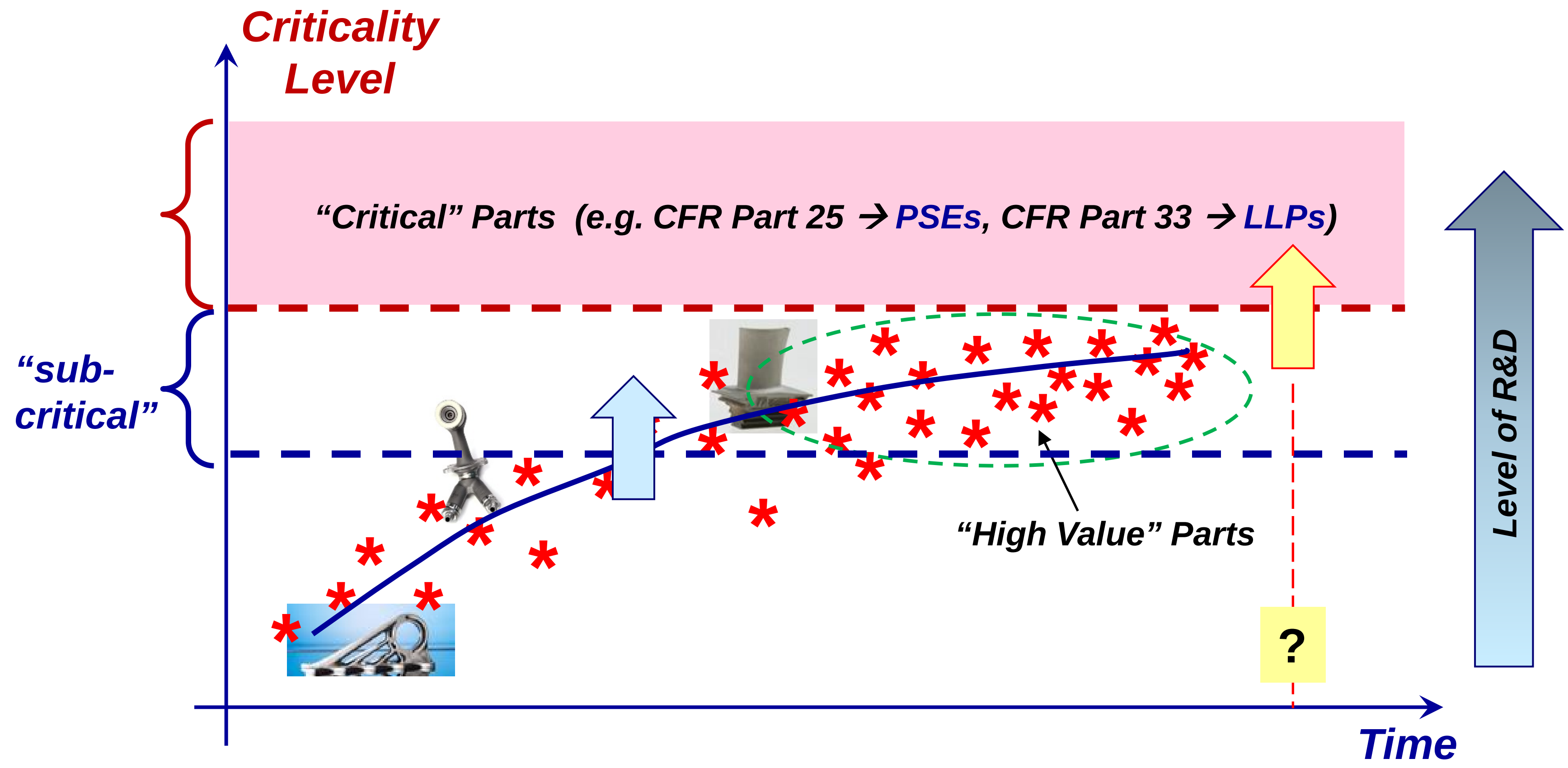
(iii) **Significant thrust in the opposite direction to that commanded by the pilot;**

(iv) **Uncontrolled fire;**

(v) **Failure of the engine mount system leading to inadvertent engine separation;**

(vi) **Release of the propeller by the engine, if applicable**

Evolution of Criticality of AM Parts



Aggregation of parts at "sub-critical" levels may result in non-trivial *cumulative* risk impact

AM Challenges To Be Addressed

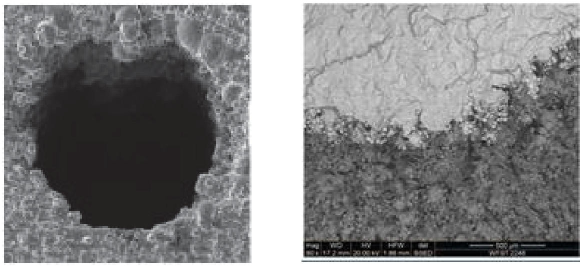
"top five"

- **Variation in the types of AM equipment / processes and lack of standardization**
- **Limited understanding of acceptable ranges of variation for key manufacturing parameters**
- **Limited understanding of key failure mechanisms and material anomalies**
- **Lack of industry databases / allowables**
- **Development of capable NDI methods**

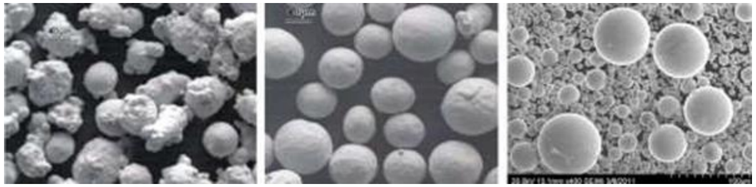
Other considerations

- ***Lack of robust powder supply base***
- ***OEM-proprietary vs. commodity type technology path***
- ***Level of criticality for initial applications***
- ***Low barrier to entry for new (inexperienced?) suppliers***
- ***Potential export control considerations***

Examples of Risk Factors for AM



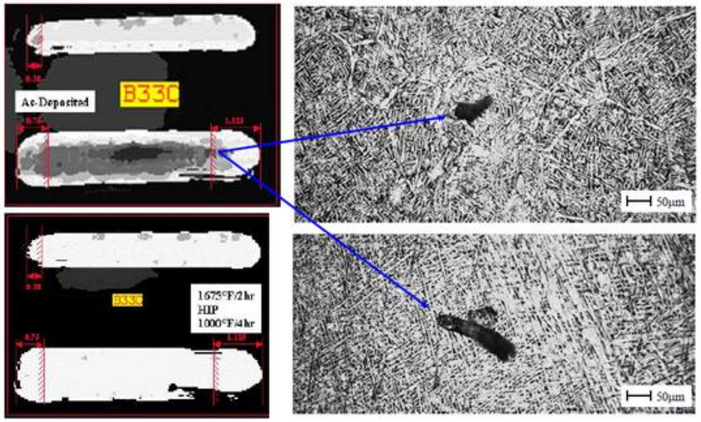
Surface Quality



Powder Control

Powder feed rate (g/min)
Laser Power (W)
Scan speed (in/min)
Laser spot size (in)
Substrate temp (ºF)
Hatch spacing (% of calculated)

Process Controls



HIP Effectiveness

Many More Identified by Experts…

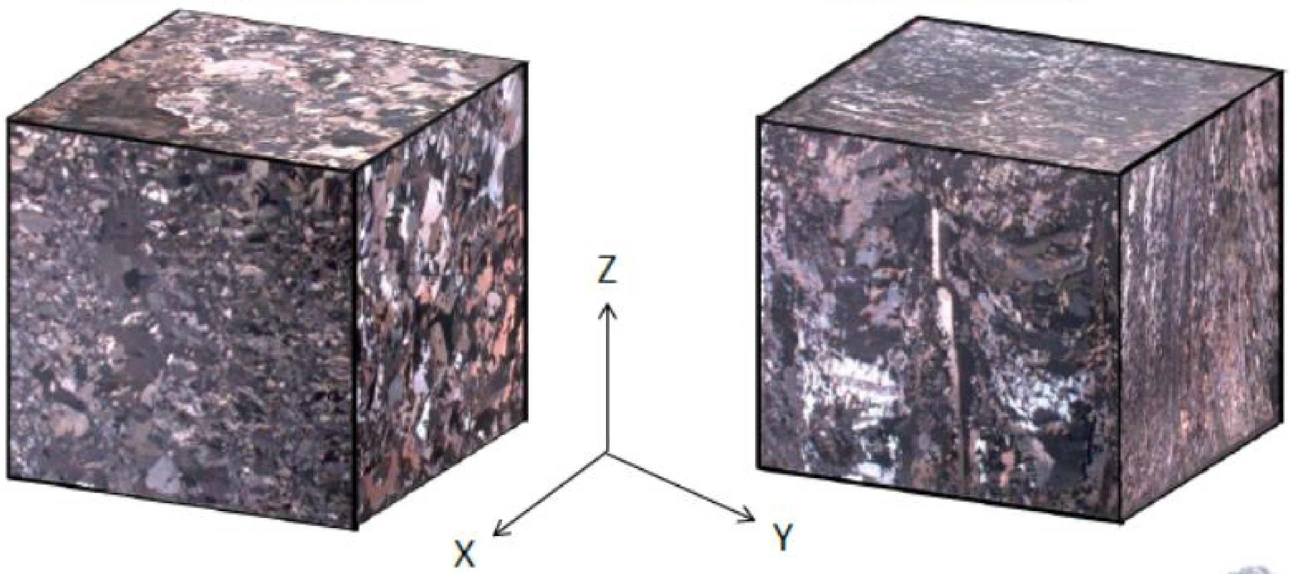
Example – *Microstructure Variability*

Microstructure Variation in Ti64 EBAM:

Same Material, Process, and Heat Treat!

- Drastically different microstructure for same material chemistry, deposition and heat treat
- Cause of microstructure variance not well understood

Course Equiaxed Beta | Course Columnar Beta



Distribution A: Approved for public release; distribution unlimited (88ABW-2015-0669)

AFRL 18

<u>Reference:</u> USAF Perspective on Additive Manufacturing, presented at 3-03-15 MMPDS Meeting.

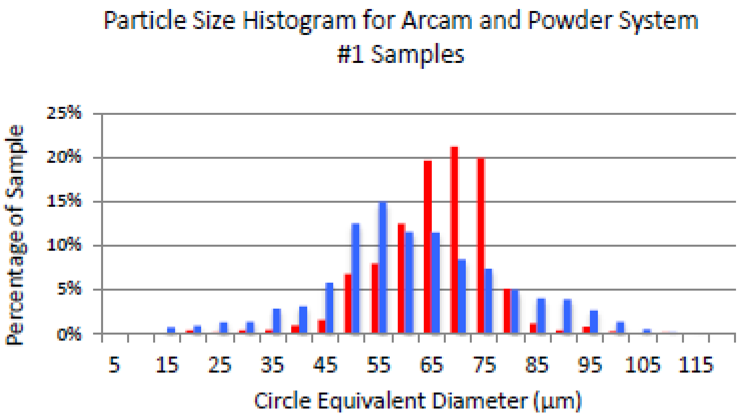
Example - *Powder Quality Control*

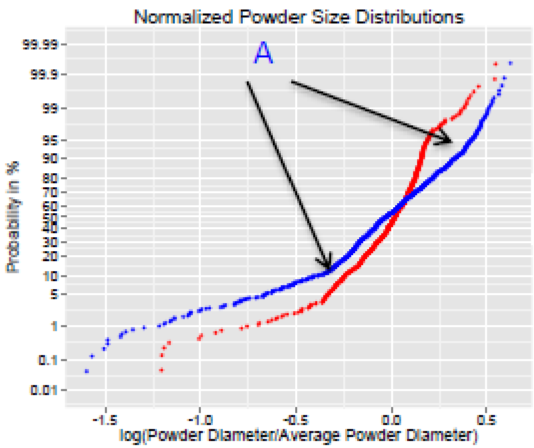
Powder Characteristics:

- Size distribution
  - Upper and lower spec limits
  - Distribution shape
- Cleanliness / inclusions
- Sphericity
- Powder reuse
- Other…?

Questions:

- Which parameters are critical?
- What are acceptable ranges?
- How do they effect properties?





Reference: "A Database Relating Powder Properties to Process Outcomes for Direct Metal AM", Prof. J. Beuth, CMU, America Makes PMR, Sept. 2014.

Courtesy of Mr. Kevin Jurrens, NIST

Uncertainties in Additive Manufacturing

Powder	Process	Part
		
Uncertainties in the Input Materials	Uncertainties in Equipment and Process Performance	Uncertainties in the Final Parts

Powder + Process = Part

Effective Use of Probabilistic and Uncertainty Quantification (UQ) Methods is Needed to Address These Risks

Formation of FAA AM Steering Group

- **Management review meetings – Dec'14 / Jan'15**
- **Development of team charter and memo to ACOs**
- **Main *initial* focus is on developing agency's roadmap in Additive Manufacturing**
  - **Including R&D plans…**
- **Includes representatives of four Directorates, Tech Center, Chief Scientists and H/Q**
- **Ramping up interaction with other government agencies and academia**
- **Benchmarking of major OEMs**

R&D Topics for AM → *DRAFT*

- **Identification of how AM process variability (including parameters and thresholds) influences the creation of anomalies**
- **Identification and characterization of life-limiting material anomalies (intrinsic vs. "rogue")**
- **Determination of effect of anomalies on material properties, including fatigue and damage tolerance**
- **Evaluation of effectiveness of NDI methods (production and in-service) for above anomalies**
- **In-situ process monitoring methods (IPQA)**
- **Guidelines for development of material and process specifications / standards for AM**
- **Guidelines for developing design values for AM materials**
- **Development of acceptance standards for material variation and material substitution**

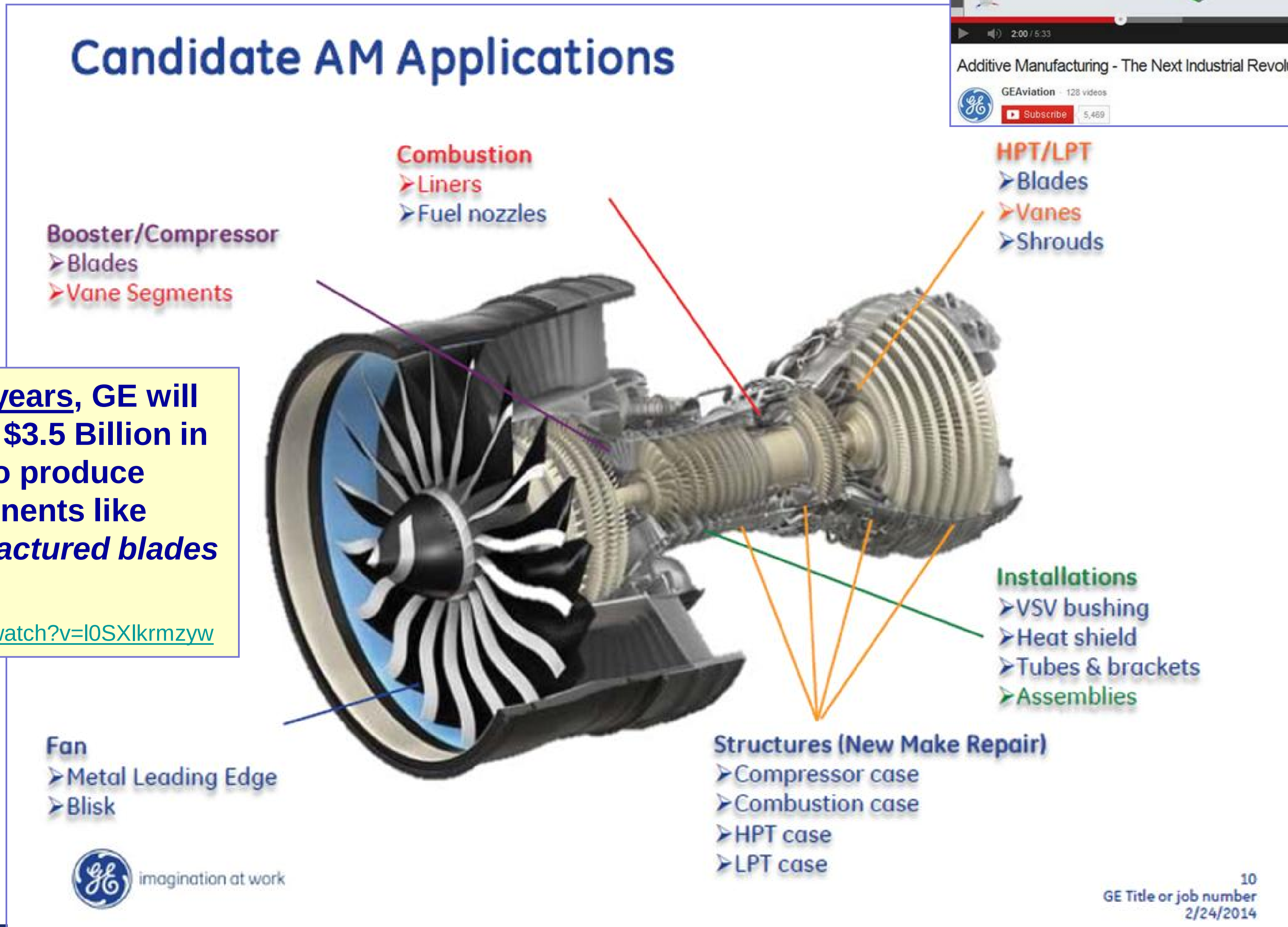
> ➢ **Focus on risk mitigation and Safety Continuum**
> ➢ **Coordination / synergies across product types**

“State of Industry” Overview

- OEMs

- Government Agencies

GE Aviation



"… <u>In the next 5 years</u>, GE will invest more than $3.5 Billion in new equipment to produce advanced components like *Additively Manufactured blades and blisks …*"

http://www.youtube.com/watch?v=l0SXlkrmzyw

GE Aviation (cont.)

- **GEA has revealed plans to develop the aerospace world's first large, dedicated additive manufacturing facility for jet engine parts in Auburn, Alabama.**
- **The site … will make complex fuel nozzles for the CFM Leap using a series of 3-D printing machines.**
- **The Auburn site will also have the capability to take on *additional components* when these are added to the GE-CFM design suite … these components … are also expected to feature in larger numbers on the GE9X engine…**


3D PRINTING / BUSINESS

GE Considers 3D Printing Turbine Blades for Next Generation Boeing 777X's GE9X Engines

BY BRITTNEY SEVENSON · AUGUST 6, 2014

Certification* of AM fuel nozzle for LEAP engine is *in progress

Pratt & Whitney

- **GTF family will be the first P&W introduction of production hardware using powder-bed additive manufacturing.**
- **P&W *will incorporate more than 25 additively made parts into the PW1500G engine* for the Bombardier C-series at entry into service.**
- **"While additive manufacturing for metal parts will no doubt change the MRO landscape, it is not clear how quickly the nascent technology will take over, particularly for safety-critical parts *where certification hurdles remain*."**

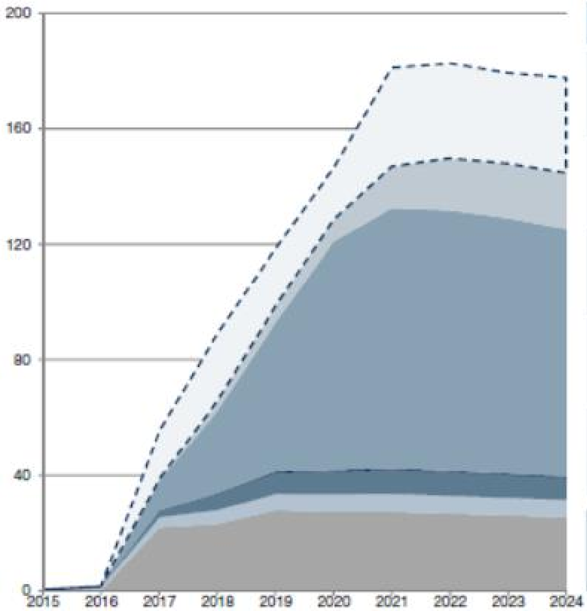
MTU

MTU Aero Engines

Additive Manufacturing (AM) Challenges Conventional Production

Further industrialisation steps

Future AM parts volume (mach. hrs x 10^3)



2015 2024

Expected introduction dates for serial production

	2014	2015	2016	2017	2018	2019	2020	2021
Strut								▲
Bearing case							▲	
Seal carrier rings				▲				
Air cooling bosses				▲				
Bores-cope bosses	▲							

Increasing quality requirements
Further investigations and development needed for critical applications

Boeing

- **Technology transition**
  - **In 2003 … Phantom Works transitioned programs and technologies to the business units that were worth more than $14 billion. Among them were *laser additive C-17 pylon panels*…**
  - ***The Boeing Company's Additive Manufacturing R&D group in St. Louis, Missouri***
- **A *partial list* of critical technologies and processes involved in advanced manufacturing:**
  - **Friction stir joining**
  - **Advanced metal processing, *including laser AM***
  - **Direct digital manufacturing, *including data streaming to AM equipment***

Additive Mfg. Boeing Application History

Engineering, Operations & Technology | **Boeing Research & Technology**

Speed brake Hinge
Deposited on 36” x 8” x 2.5” Plate
First Flying LAM Part

41 C-17 Pylon Panel Production Articles Machined and Installed

Juno Satellite Components
Launched August 5th, 2011

Pylon Rib
Flying in 10 or More Aircraft

NanoSat Component
Currently in Orbit

Strong History in Additive Metals

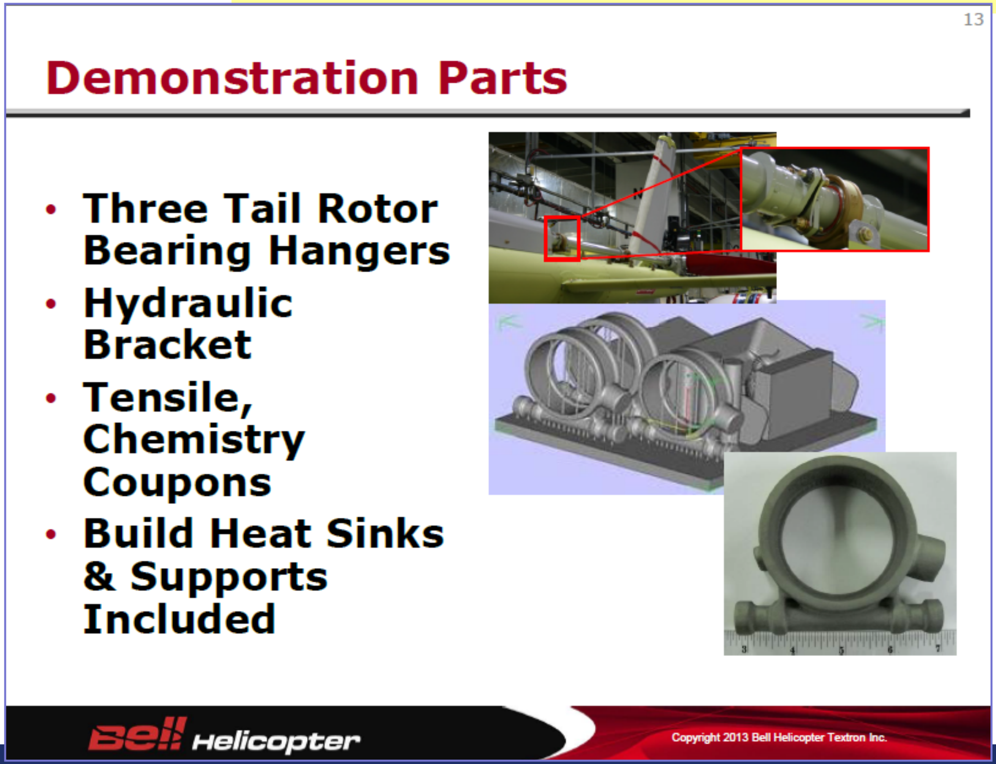
Presented by Mr. R. Cochran at the 26th MMPDS Meeting

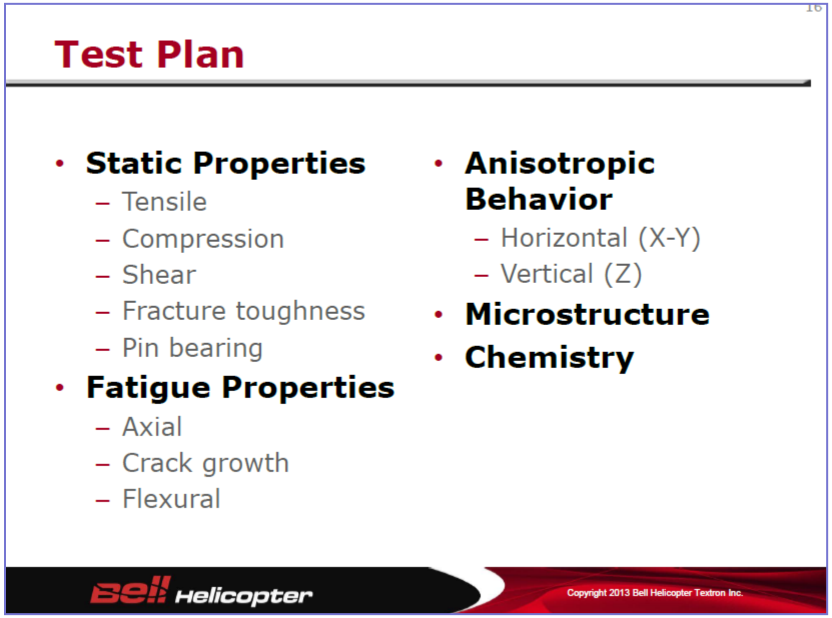
Airbus

- **Parts produced with this method (i.e. AM) are beginning to appear on a range of the company's aircraft – from the next-generation A350 XWB to in-service jetliners…**
- **"We are on the cusp of a step-change in weight reduction and efficiency – producing aircraft parts which weight 30 to 55 %, while reducing raw material used by 90 % …" - *Peter Sander*, Airbus.**
- **Airbus is also working toward spare part solutions with this technology … for producing cost-effective out-of-production aircraft spare parts on-demand.**

Bell Helicopter

- **Powder-Based AM Technology**
  - **Arcam EBM**
- **Materials**
  - **Ti 6Al-4V**
  - **Cobalt-Chrome**



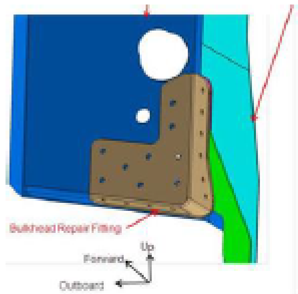


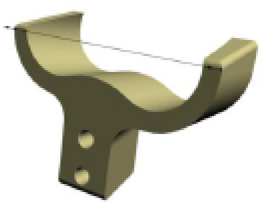
NavAir Roadmap

AM Roadmap Initiatives

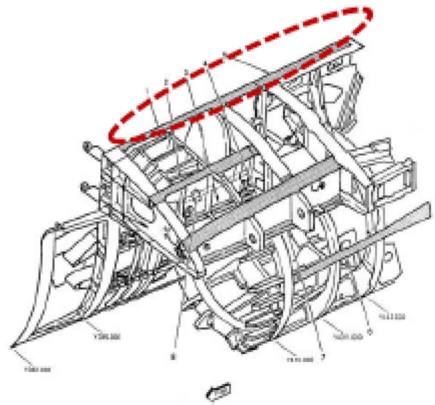
Additive Manufacturing Structural Repair/Replacement

Near Term

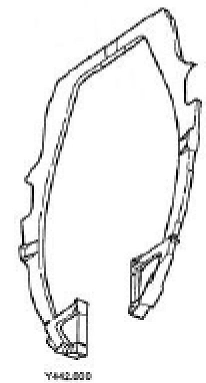


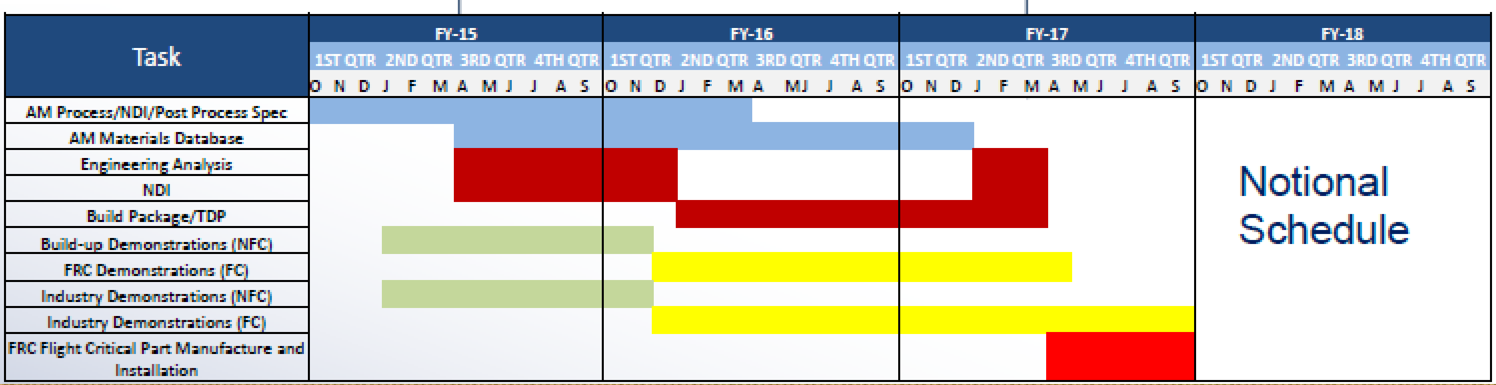


Mid Term



Long Term



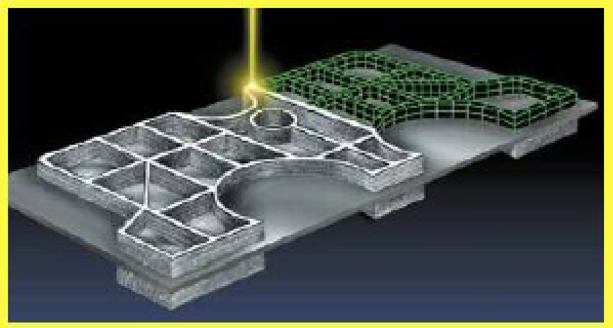


Air Force

Big focus on risk mitigation

Potential Aerospace Applications

- **Primary Application Is Manufacture / Repair of:**
  - Rib-web Structural Components
  - Turbine Engine Cases
  - Turbine Blades & Vanes



- **<u>Potential</u> AM Advantages Are:**
  - Reduced Raw Material Usage
  - Reduced Raw Material Stock Size
  - Reduced Machining Operations
  - Reduced Hard Tooling Requirements

- **<u>Potential</u> AM Benefits Are:**
  - Reduced Procurement Lead Time
  - Reduced Acquisition Cost
  - Salvaging of Damaged High-value Components

REALIZATION OF AM BENEFITS IS HIGHLY COMPONENT-, PROCESS-, AND MARKET-DRIVEN

Air Force (cont.)

Why AM Implementation Is a Challenge

- Structures Bulletin: Substitution with AM
  - NOT RECOMMENDED without significant testing and AFRL/RX support

- Considerations for Implementation of AM
  - Demonstrated Process Controls
  - Nondestructive Evaluation & Quality Assurance
  - Post-Deposit Processing & Residual Stress Management
  - Statistically-Based Mechanical Property Database

<u>**Reference:**</u> **USAF Perspective on Additive Manufacturing, presented at 3-03-15 MMPDS Meeting.**

How to statistically ensure material integrity for design with

1. Continually-changing, local processing environment with changes in geometry and process parameters (similar to welding)
2. Lack of *constrained* process controls
3. Stochastic formation of difficult to inspect weld-type defects
4. Post-deposit distortion and residual stress
5. Undefined post-processing requirements, lack of POD for NDI

NASA Research

MSFC Tasks and Objectives

Flight Certification

1. Part Classifications
2. Part performance qualification
3. Governing process controls
4. NDE requirements
5. Lot acceptance requirements
6. Fracture control requirements
7. Machine and Operator cert and re-cert

MSFC Interim Spec

Reference*:** ***"JANNAF: Additive Manufacturing for Propulsion Applications", Kristin Morgan, MSFC, 3-9-14.

NIST Roadmaps

Figure 2-3. Roadmap Action Plan: Metals Design Allowables Database

Barrier: No public database exists to derive materials properties for design allowables for specific processes. Acquiring data is difficult due to the number of AM machine manufacturers, the evolution of machine control software/ hardware versions, and the lack of standard protocols for AM materials (e.g., x-y-z specimen preparation).

Approach Summary: Undertake collaborative effort to test specific materials and processes and establish databases. Three aspects of this activity are (1) Feedstock (e.g., powder, wire); (2) Manufacturing Platform (i.e., Electron Beam (ARCAM S-12, A-1, A-2, A-2x, A-2xx) or Laser Beam (EOS – M270, M280; Concept laser – M2, M2ab; Renishaw – AM125, AM2510; ; Phoenix Systems - PXL, PXM, PXS, PXS & PXM dental; SLM Solution – SLM 280, SLM 250 Realizor) (3) Testing Protocol

	Roadmap Action Plan	Milestones and Results	Overarching Targets
1-2 years	• Feedstock ○ Identify alloy testing priorities ○ Develop material specification for each machine • Manufacturing platforms ○ Prioritize processes/materials ○ Develop standards for initial machine metrics ○ Identify parameters that significantly affect material properties ○ Determine upper and lower limits for parameters that affect properties • Testing Protocol ○ Design testing protocol (i.e., x, y, z build location); begin testing on high priority pairs (materials/processes) ○ Identify facilities where specimen building will occur ○ Qualify machines	• General ○ Documentation on data reporting ○ Initial database/repository established • Feedstock ○ Materials/alloys identified ○ Alloys acquired ○ Material specification published • Manufacturing Platforms ○ ASTM standard published for initial machine metrics ○ Process parameters identified for priority platforms • Testing Protocol ○ Test specimens built and tested for top 2 alloy types	• Low cost, flexible database that can be updated as technology changes • Industry acceptance of data • Greater use of AM • Feedstock ○ Standardized feedstock properties • Manufacturing Platforms ○ Published standard for determining machine platforms suitable for processing materials • Testing Protocols ○ Robust testing protocol that can accommodate the various technological differences
3-5 years	• Testing Protocol ○ Produce test specimens ○ Test specimens and analyze results ○ Expand materials testing to cross process barriers ○ Compare results for models ○ Incorporate flexibility (database changes as more information becomes available from sensors)	• Feedstock ○ Alloys acquired • Manufacturing Platforms ○ Machine standard to which machine manufacturer must comply • Testing Protocol ○ Test specimens built and tested for top 10 alloy types	

NIST Roadmap (cont.)

Figure 4-2. Roadmap Action Plan: Standard Guidelines and Methods for Qualification and Certification

Barrier: Standard guidelines for qualification and certification are lacking. Challenges include the ability to define the type and quantity of guidelines and wide variations in machines and end users. ASTM qualification and certification guidelines for AM machine components are currently lacking or inadequate.

Approach Summary: Develop uniform standards and a taxonomy that encompasses all AM methods and is flexible to accommodate new technologies as they emerge.

	Roadmap Action Plan	Milestones and Results	Overarching Targets
1–2 years	• Collect existing worldwide standards and guidelines currently in use for AM • Develop common baseline and taxonomy • Coordinate with AM process models and properties development (see Figure 5-2) • Develop and apply standard validation procedures to computational tools (e.g., process models and design tools, see Figure 5-2)	• Framework begun for ASTM standard document • Modularity incorporated into the standard • Established database (standards, supporting data, and generalized process models) is available to the AM community	• ASTM standard for qualification and certification • Layer by layer qualification of parts
3–5 years	• Draft standards framework documents • Develop standard methods for rapid qualification of processes • Incorporate data from models and control systems	• Revised draft standards framework document • Validated models that support qualification and certification (see Figure 5-2)	
5+ years	• Write ASTM standard for AM process qualification, ensure the standard is flexible and supports new technology development • Integrate virtual testing standards with experimental testing standards	• Revised standards as technology progresses • Rapid qualification of processes and parts	

Industry and Government Collaboration on AM is Rapidly Expanding …

America Makes

ASTM F42

Additive Manufacturing Consortium

RTAM (SME)

CIMP-3D

AMUG

DMDII

ACAMM

MAMC

RAPID

SAMPE

…

…

Vision of Several Organizations is to Develop a National Strategy for Additive Manufacturing

Summary

- **Most of the engine and aircraft OEMs are evaluating / developing / implementing AM technology**
- **FAA is starting to work on developing AM roadmap**
- **Most major OEMs and agencies support risk-based decision making approach, including "system-level" considerations:**
  - **Manufacturing process controls and specs development**
  - **Identification and characterization of key failure modes and anomalies**
  - **Lifing system and certification criteria**
  - **IPQA and NDI methods**
- **Longer term – push for model-based "rapid" qualification**
- ***Significant opportunities for industry and agencies collaboration***
  - ➢ **Should be leveraged to effectively manage risks of AM introduction across Aerospace**
  - ➢ **<u>However</u>, most agencies also executes their own R&D programs *tailored to agencies' objectives***

Discussion

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