Federal Aviation Administration

Additive Manufacturing Roadmap Update

Presented to:

REDAC Subcommittee on Aircraft Safety

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Oklahoma City, OK

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for Fatigue and Damage Tolerance

Acknowledgements

- ***Thanks to J. Bakuckas and K. Stonaker of the FAA Tech Center for providing detailed research tasks description referenced in this presentation***

1-25-17 SAS Recommendations and FAA Response

<u>**Recommendation (2)**</u>: The FAA should share the draft roadmap and accompanying R&D plan with the Subcommittee for review and comment.

<u>**FAA Response**</u>: **The FAA concurs with the Committee's recommendation on Additive Manufacturing (AM) with the noted exceptions and clarifications and intends to undertake the following actions to address the recommendation.** The strategic FAA AM roadmap is due to the FAA Aircraft Certification Service (AIR) management by September 2017, in accordance with the official Additive Manufacturing National Team (AMNT) charter. The roadmap is being developed and matured, however will only be available in a draft form by the time of the next SAS meeting (early March of 2017), and will not be reviewed by the FAA management at that time. Therefore, the roadmap will not be presented to SAS *in its entirety*. Instead, the information to be presented at the next SAS meeting will include the outline of the roadmap and its key elements necessary to provide sufficient context for the multi-year AM Research and Development (R&D) plan that will be presented as well.

Presentation Framework:

Progress since Sept. 2016 and Schedule

- **Roadmap Development Framework and Process**
  - **Six "swimlanes" (4+2) → *see next page***
  - **Draft content being developed by sub-teams (concurrently)**
    - ➢ ***Current percent completion (average) > 50%***
  - **Templates deployed to ensure consistency**
- **F2F roadmap working meeting (AMNT) → *April 2017***
- **Interim review with FAA Management → *May 2017***
- **Feedback from other government agencies and industry (as feasible) → *June-July 2017***
  - **CSTA AM Workshop → *August 2017***
- **AM Roadmap "Ver. 1.0" delivered to management → *Sept. 2017***
  - ➢ **To be revisited and updated annually**

AM Roadmap – Main Focus Areas (“swimlanes”)

(1) *Certification Process*

(2) *Production / QA*

(3) *Maintenance / MROs*

(4) *COS*

Enablers

(5) *Workforce Education (FAA + Designees + Industry)*

(6) *R&D*

Key Elements of the AM Roadmap Content

(4 regulatory swimlanes)

- **Key Risk Factors**
- **Regulatory gap analysis**
- **Proposed new or revised documents (policies, ACs, …)**
  - *No rule changes expected*
- **Key Tasks and Project Plan**
- **“Inter-dependencies” between the 4 swimlanes**
- **Input into R&D and Training swimlanes**

Note:

- ***It is recognized that we may not currently have enough internal knowledge and experience to address some of the items above →***

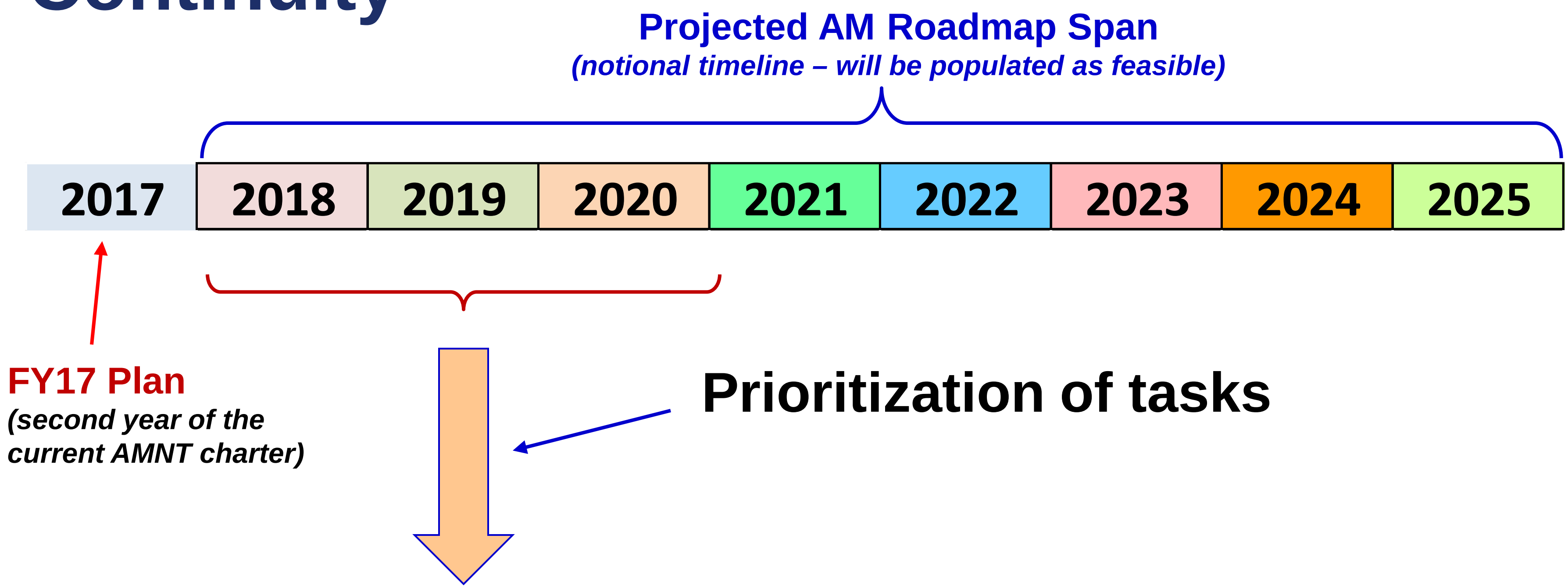
see next page

Options to Address Current Knowledge Gaps

- **Industry engagement (AIA, GAMA, MARPA, other..?)**
- **Engagement with SDOs (SAE, ASTM, AWS, …)**
- **Government engagement (USAF, NAVAIR, NASA, NIST, America Makes…)**
- **R&D (internal / external)**
- **CSTA and other targeted workshops (e.g. DER conferences, ARSA, …)**
- **FAA AM certification projects benchmarking**
- ***Manufacturing surveillance***
- **AMNT site visits to production facilities (outreach)**
- **Coordination with NAAs**

Most of these mechanisms are already engaged

Tie-in Between the Multi-year Roadmap and 2-year AMNT Project Plan Will Ensure Continuity



FY18-20 **“tactical” project plan**

(part of the next AMNT charter – subject to management approval)

Benchmarking of Composites ACs

- **Three ACs from the "Early Days" of Composites**
  - Composite aircraft structure → **AC 20-107A** (1984)
  - Composite manufacturing quality control → **AC 21-26** (1989)
  - Repair Stations for Composite and Bonded Aircraft Structure → **AC 145-6** (1996)

These and Similar Documents are Being Considered by the AM Roadmap Team

Benchmarking of AVS Composite Plan

A. Hybrid Fatigue & Damage Tolerance Substantiation

Fatigue and damage tolerance engineering protocol for composite aircraft structures differ significantly from metal engineering practices. These issues must be considered for the substantiation of most modern structures that include a combination of composite and metallic parts and assemblies. Some issues with hybrid structural testing include thermal stresses that are generated between metal-composite interfaces and the higher cyclic loads for composites, which can cause yielding and crack growth retardation that invalidates the test results for the metallic structure. Composite analysis methods are not as mature as those applied to metals and composite damage is far more difficult to simulate than metal cracks.

“What”

Problem/Issue: Title 14 CFR part 25 requires a revision to account for hybrid metallic/composite structures.

Sponsor	Deliverable	Milestones
ANM-115	Policy on interpretation of 25.571 for existing rule	Publish policy in coordination with ARAC • Create white paper documenting FAA position 9/2016
ANM-115	A new rule defining damage tolerance requirements for the certification of composite transport aircraft.	Publish NPRM for a modified § 25.571 or new subpart to part 25 FY15-FY19[4]
ANM-115	Associated guidance for new part 25 rule.	Publish final AC with rule • Complete draft AC FY15-FY19

“How” and “When

External Benchmarking


National Aeronautics and
Space Administration

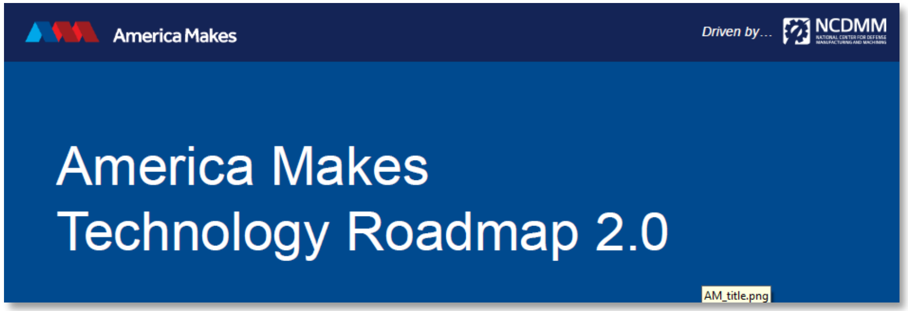
MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard
for Additively Manufactured
Spaceflight Hardware



Prioritization Considerations

(Draft – being further developed by AMNT)

- **Safety impact**
  - Expected increase in criticality of applications
    - “minor effect” → “major effect” → “safety-critical” / timeline?
  - Various industry segments (e.g. OEMs, Tier 1, PMAs, MROs…)
- **Certification process**
  - Breadth of application (e.g. multiple categories of parts / multiple product types)
  - Industry deployment timeline (e.g. current TRL / MRL levels)
  - Regulatory gaps (applicability of current policies / advisory materials)
  - Current experience level (development / full-scale production / field)
- **Other considerations**
  - Availability of industry specs and standards (materials, processes)
  - Availability of industry design / properties data

NAVAIR News Release
NAVAIR Headquarters
Patuxent River, MD

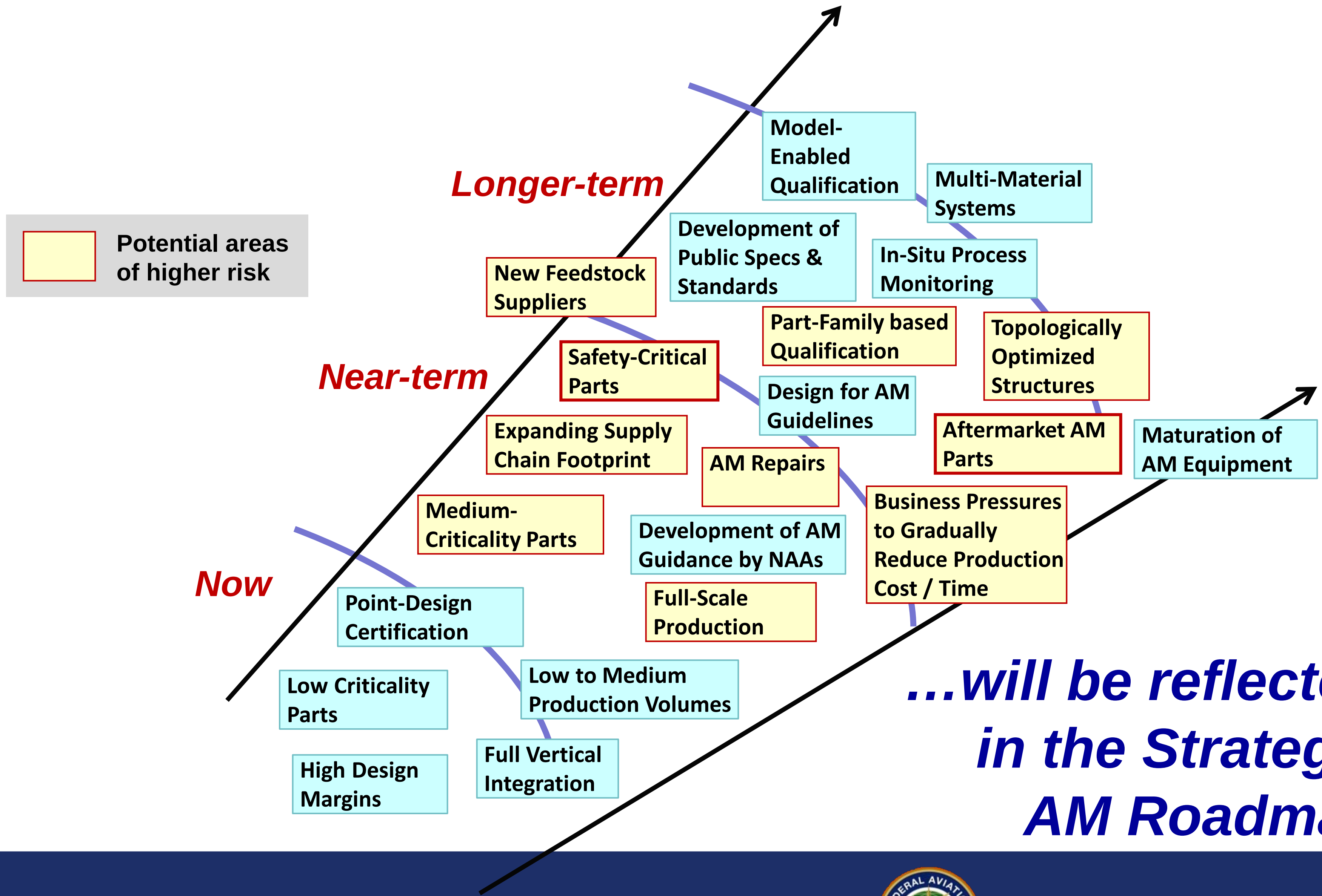
July 29, 2016

NAVAIR marks first flight with 3-D printed, safety-critical parts

Safety-Critical AM Parts are Coming…

An MV-22B Osprey equipped with a 3-D printed titanium link and fitting inside an engine nacelle maintains a hover as part of a July 29 demonstration at Patuxent River Naval Air Station, Maryland. The flight marked Naval Air System Command's first successful flight demonstration of a flight critical aircraft component built using additive manufacturing techniques. (U.S. Navy photo)

Expected Evolution of AM Landscape…



…will be reflected in the Strategic AM Roadmap

Current AMNT Research Plan (FY16-22)

(see Appendix for detailed Tasks description)

- **Task 1: Partner with AM Consortia - ongoing research with KART and CMU (FY15-FY19)**
  - *Roadmap tie-in: development of R&D plans; training / education*
- **Task 2: Static Special Factors (FY16-FY19)**
  - *Roadmap tie-in: Policy on AM Special Factors*
- **Task 3: Powder Reuse for Static Strength Applications (FY16-FY19)**
  - *Roadmap tie-in: Policy on Static Strength Allowables*
- **Task 4: Sensitivity Study for Fatigue Behavior of Anomalies and Assessment of NDI Methodologies (FY19-FY21)**
  - *Roadmap tie-in: F&DT Policy and/or AC Modifications*
- **Task 5: Evaluation of Life Prediction Methodologies for AM (FY17-FY22)**
  - *Roadmap tie-in: F&DT Policy and/or AC Modifications*

AM Research Topics at a Glance

Phase 1

Topic: Static Special Factors
Scope: Wire Fed, Ti-6-4 and PBF, Ti-6-4, powder reuse
Goal:
Approach: Task 1 - Develop Empirical testing approach. Task 2 – Conduct testing, Task 3 - Use data from Task 2 to develop draft methodology; Task 4 - characterize a third material/system using empirical approach first, Task 5- use this data to "calibrate" the methodology

Output: Support Issue paper/policy

→

Phase 2

Topic: Static Design Value Methodologies
Scope: Phase 1 materials and tech.
Goal: Capture the variability of as-purchased feedstock and as-processed final product
Approach: Task 1 - Define test matrix, Task 2 – Define the statistical methods, Task 3 – Test…, Task 4 – Assess the use of Phase 1 special factors in conjunction with design values.

Output: Support Issue paper/policy

→

Phase 3

Topic: Powder reuse for static strength applications
Scope: Feedstock – contaminants from reuse – (process and handling)
Goal: Understand the effect of powder characteristics
Approach: Investigation of each cycle reuse,

Output: Support Issue paper/policy

→

Phase 4

Topic: Generation of AM Induced Anomalies
Scope: PBF, Ti-6-4 and Inconel 718
Generate coupons with artificially induced anomalies.
Goal: Investigate fatigue and NDI
Approach: Task 1 - Use P-V maps to identify process parameters that consistently produce anomalies; main focus gas porosity and lack of fusion.

Output: Support Issue paper/policy

→

Phase 5

Topic: Assess NDI methodologies
Scope: Current and emerging NDI including CT and Laser Ultrasonic
Goal: Validate NDI methodologies for detection of anomalies
Approach: Task 1 – Use specimens fabricated in Phase 4 to conduct validation assessments, Task 2 - Use the data generated in Task 1 to develop POD estimates for most promising NDI methods and for key classes of material defects.

Output: Support Issue paper/policy/AC

→

Phase 6

Topic: Mechanical Testing
Scope: PBF, Ti-6-4 and In718
Goal:
Approach: Task 1 - Conduct mechanical testing of the specimens produced in Phase 4 and characterized in Phase 5, for both baseline specimens and with artificial (seeded) defects, Task 2 - Quantify debit in mechanical properties associated with a specific population (and distribution) of defects.

Output: Support Issue paper/policy/AC

→

Phase 7

Topic: Sensitivity study for threshold behavior of anomalies
Scope:
Goal:
Approach: Task 1 - Conduct iteration of Phase 4 and 6 to establish a threshold on the key attributes (frequency of occurrence, size distribution) of defect populations for each major defect class, by generating batches of specimens with artificial anomalies of various severity (Phase 4), Task 2 - quantifying their impact on properties through mechanical testing (Phase 6).

Output: Support Issue paper/policy/AC

→

Phase 8

Topic: Evaluation of Predictive Modelling
Scope:
Goal:
Approach: Evaluate the feasibility of using predictive models to understand the results, and to enable development of the quantitative acceptance criteria based on the data generated in Phases 6 and 7, for Task 1 - static and Task 2 - fatigue

Output: Support Issue paper/policy/AC

Potential Topics for Future Research in Support of AM Roadmap → up to FY25

(Draft – content being developed by AMNT)

- **AM Process Control and Monitoring (linked to Qualification Requirements)**
- **In-Service NDI**
- **In-situ Process Monitoring**
- **Fatigue and DT Methods for AM Parts**
- **Use of ICME *) and Process Modelling / Simulation for Model-based Qualification**
- **Development of AM Forensic Failure Analysis Handbook**
- **Development of Industry "Lessons Learned" Database**

*) ICME = Integrated Computational Materials Engineering

Leveraging R&D Resources of Other Agencies

DARPA-SN-16-27
Open Manufacturing Transition Study: Qualification for Additively Manufactured Aircraft Components Call for Full Proposals

Full Proposals Requested by: 4:00 p.m. (Eastern) on April 18, 2016
Point of Contact: Mick Maher, Program Manager, DARPA/DSO
Email Address: DARPA-BAA-15-39@darpa.mil
URL: http://www.darpa.mil/work-with-us/opportunities

The Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office (DSO), invites full proposals for an Open Manufacturing Transition Study to explore qualification for additively manufactured aircraft components. All full proposals are requested in response to DARPA-BAA-15-39, DSO's Office-wide Broad Agency Announcement (BAA).

Specifically, submissions should propose a study focused on additively manufactured (AM) structural parts in military and commercial aircraft applications. The study should be designed to explore and identify implementation challenges and risk reduction strategies – in the context of qualification and certification requirements. These challenges include complexity of manufacturing process controls, applicability of conventional non-destructive examination methods, lack of industry standards, design allowables, etc. It is anticipated that successful proposals will exhibit thorough understanding of system requirements, Federal Aviation Administration (FAA) regulatory processes, manufacturing variability, and quality assurance impact.

Participating Companies:

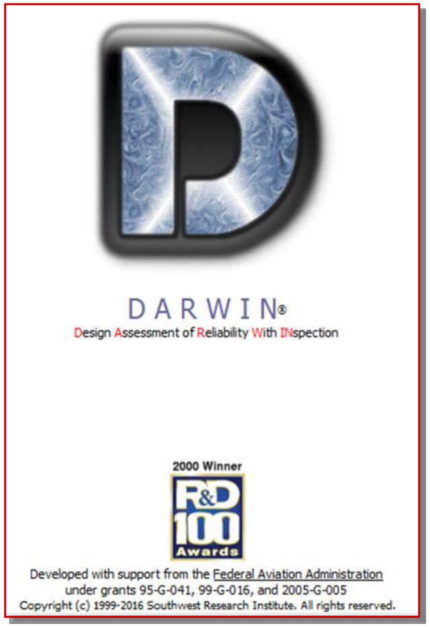
- ***Boeing***
- ***General Electric***
- ***GKN Aerospace***
- ***Honeywell***
- ***Northrop Grumman***
- ***Sikorsky***

~ $400K value

Reference: M. Gorelik, "Additive Manufacturing in the Context of Structural Integrity", *International Journal of Fatigue 94 (2017) 168–177*

Leveraging *Prior* FAA Investments

- **Analysis framework (and software code) that can assess a component with a known population of anomalies and location-specific properties.**
- **Represents *~20 years of R&D and over $25M of investment* by the FAA**
- **Has the following attributes:**
  - **Validated by industry**
  - **Accepted by multiple companies and regulators**
  - **Commercial grade software**
  - **Can account for *location-specific* properties:**
    - **Various populations of anomalies**
    - **Inspectability / POD**
    - **DT attributes**
    - **Residual stresses**
    - **Material properties**
    - **Risk threshold / targets**



Features Can Be Customized For AM With Relatively Moderate Incremental Investment (specific plan is being discussed)

APPENDIX

Task 1: Partner with AM Consortia (FY15-19)

This task will partner with industry and other government agencies through new and existing AM consortiums. The FAA will leverage resources and become a contributing partner in AM consortiums allowing the FAA to assess several key issues including use of process maps, effect of material reuse, evaluation of introducing special factors (similar to castings), the effectiveness of several NDI in detecting flaws in parts being produced, design for AM, fatigue and damage tolerance evaluation of AM parts, powder spreading, surface properties and finishing, and process modeling for process/material property relationships. The data generated will be used in developing policy and regulatory guidance. The targeted consortia are as follows:

- Kansas Aviation Research & Technology (KART) Consortium: Static, Fatigue, and Damage Tolerance Qualifications of AM
- Carnegie Mellon University *NextManufacturing* Consortium: AM process controls, defects formation, microstructural characterization

Task 1 Deliverable: A report summarizing key technical findings and observations from the first year of research including recommendations for the longer-term FAA research in AM, and a partial input for the FAA AM Roadmap. Due July 2017. Consortia are currently funded with FY15 money. Following years (beyond 2016) membership feasibility will be evaluated based on benefits of the first year membership.

Task 2: Static Special Factors (FY16-19)

This task will evaluate the potential for developing methodologies to produce a set of conservative static strength special factors and static design values for AM parts. The special factors being considered may be similar to casting factors as outlined in existing regulations (e.g. 14 CFR part 25.621) and correspond with inspection, test techniques, and sampling rates. These special factors may be applied to design values for both generic and point design applications similar to those published in CMH-17 for composites. The initial focus will be on titanium alloy (Ti-6Al-4V) for both wire-fed and powder bed AM technology. Test articles will be made to publicly available specifications, inside a defined process map (Task 1), which are currently under development. The following phases are planned:

- Phase 1: Draft empirical testing approach for a specific material/AM technology combination around a publicly available specification, FY16
- Phase 2: Build specimens, perform NDI, and conduct tests on Ti-6Al-4V powder bed material/technology systems, FY17-18
- Phase 3: Use data from Phase 2 to develop draft methodology for creating special factors, FY18
- Phase 4: Characterize Ti-6Al-4V direct energy deposition and additional material/technology system(s) using empirical approach drafted in Phase 3, FY18-19
- Phase 5: Use data from Phase 4 to refine the special factors methodology, FY19
- Phase 6: Define statistical methods for generating static strength generic and point design values, FY18-19
- Phase 7: Assess the use of special factors in conjunction with design values, FY19

Task 2 Deliverable: An FAA report summarizing the experimental procedure and methodology defined for developing special factors and design values for static strength properties of AM parts.

Task 3: Powder Reuse for Static Strength Applications (FY17-19)

This task will evaluate the effects of material reuse for AM powder bed systems and define the requirements that should be placed on the powder, process and part to allow powder reuse for static strength applications. Data from the powder bed portions of Task 1 and 2 will be used as a baseline for this Task. The following phases are planned:

- Phase 1: Draft test plan and identify material reuse procedure, FY17
- Phase 2: Collect unused powder from builds conducted in Task 2. Perform chemical and spreadability analysis of powder after each use, FY17-19
- Phase 3: Build specimens with reused powder, perform NDI, and conduct tests, FY17-19
- Phase 4: Compare the data to specimens tested in Task 2, FY18-19
- Phase 5: Collect unused powder from build in Phase 3 and repeat Phase 2 thru 5 as necessary, FY18-19

Task 3 Deliverable: An FAA report summarizing the experimental procedure and requirements defined for powder reuse for building AM parts designed to static strength regulations.

Task 4: Sensitivity Study for Threshold Behavior of Anomalies and Assessment of NDI Methodologies (FY19-21)

This task will identify the types and characteristic of defects/anomalies generated by AM (including frequency and size distributions), validate current and emerging NDI capabilities to detect them and determine their effect on static, fatigue and fracture properties. The process maps (Task 1 & 2) of AM powder bed systems using titanium (Ti-6Al-4V) and Inconel 718 will be evaluated to identify the process parameters that consistently produce anomalies, specifically gas porosity and lack of fusion. Traditional and emerging NDI, such as computed tomography (CT) and laser ultrasonic, will be used to validate the methodologies for detection of the created anomalies. Once identified, a sensitivity study will be conducted to identify the thresholds on the key attributes (frequency of occurrence, size distribution, etc.) of defect populations for each major defect class. The specimens built throughout this task will then be tested to quantify the debit on material properties associated with a specific population (and distribution) of defects. The following phases are planned:

- Phase 1: Build specimens using process maps to identify process parameters that consistently produce anomalies, FY19-20
- Phase 2: Use specimens fabricated in Phase 1 to conduct validation assessments of current and emerging NDI, FY19-20
- Phase 3: Use the data generated in Phase 2 to develop probability of detection (POD) estimates for the most promising NDI methods and the key classes of material defects, FY20-21
- Phase 4: Generate batches of specimens with artificial anomalies of various severity as mapped in Phase 1 and identified in Phase 3 to establish the thresholds of defect populations, FY20-21
- Phase 5: Conduct mechanical testing of specimens built in Phase 4 to quantify the debit on mechanical properties (static, fracture and fatigue) associated with a specific population of defects at various levels of severity, FY20-21

Task 4 Deliverable: A series of FAA reports summarizing the experimental procedure and significant findings including: identification of a process map for each material system, anomaly distribution and material property debits, and validated NDI method for detection with POD data and correlated to fatigue test results

Task 5: Evaluation of Life Prediction Methodologies for AM (FY17-22)

This task will evaluate the feasibility of using predictive models to understand the results, and to enable development of the quantitative acceptance criteria based on data generated in the previous tasks. The modeling approach may be based on probabilistic damage tolerance frameworks (such as the one codified in the FAA-funded DARWIN software code), probabilistic fatigue prediction framework similar to the ones currently used for design and certification of Powder Metallurgy (PM) safety-critical parts, or other similar methods.

The following phases are planned:

- Phase 1: Evaluation of probabilistic damage tolerance framework where frequency and size distribution of defects are used as the key input variables, with other inputs including directional and location-specific material properties, NDI POD curves etc. FY17-FY19
- Phase 2: Correlation of the outcome of Phase 1 with experimental data obtained in Task 4. FY20-FY21
- Phase 3: Evaluation of zoning approach for AM parts, based in part on the outcome of Phase 1. FY18-FY19
- Phase 4: Evaluation of F&DT models suitable for assessment of AM safety-critical parts. FY19-FY22

Task 5 Deliverable: An FAA report summarizing the modeling methods, their correlation with experimental data, feasibility assessment of the potential F&DT methodology for AM parts, and other significant findings.