ASTM INTERNATIONAL
Additive Manufacturing Center of Excellence

Progress in inspection methods for aerospace and routes to certification

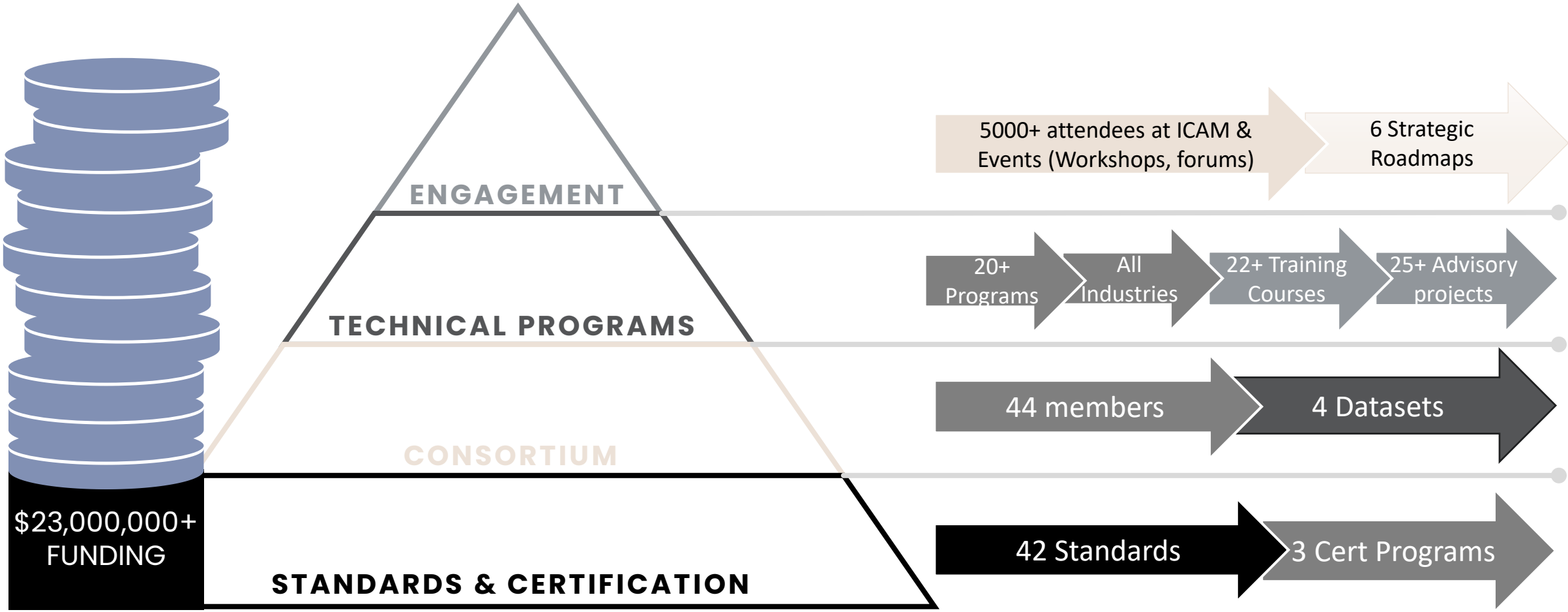
Dr. Martin White

Director – Technical Operations, Global Advanced Manufacturing Programs, *Bristol UK.*

October 1st 2024
Additive Manufacturing for Aerospace, BINDT.

www.amcoe.org

ASTM AMCoE – IMPACT



What is the status in the UK currently?

- Roadmap now released:
- [Additive-Manufacturing-Strategy-Roadmap-Sept-2024-Final.pdf (ati.org.uk)]

Why has this group been brought together?

- Bring together AM experts from the UK aerospace sector in a collaborative forum
- Minimise duplication of effort, address common challenges once for wider benefit
- Create an aligned vision and roadmap for the sector
- Support the update of the ATI aerospace AM technology strategy

This group will be the leadership team – as key industry organisations that represent the primary routes to exploitation

- However, the scope of the group is the end-to-end value chain
- We will need the support of the rest of the UK sector – materials suppliers, machine manufacturers, supply chain organisations etc.

10 ATI Aerospace AM Roadmap

Main R&D activity, significant and targeted R&D in this timeframe is expected

Transition does not mean a phase out of R&D, however a change of R&D empasis

R&D significantly matured, expect industry lead approach until superseded

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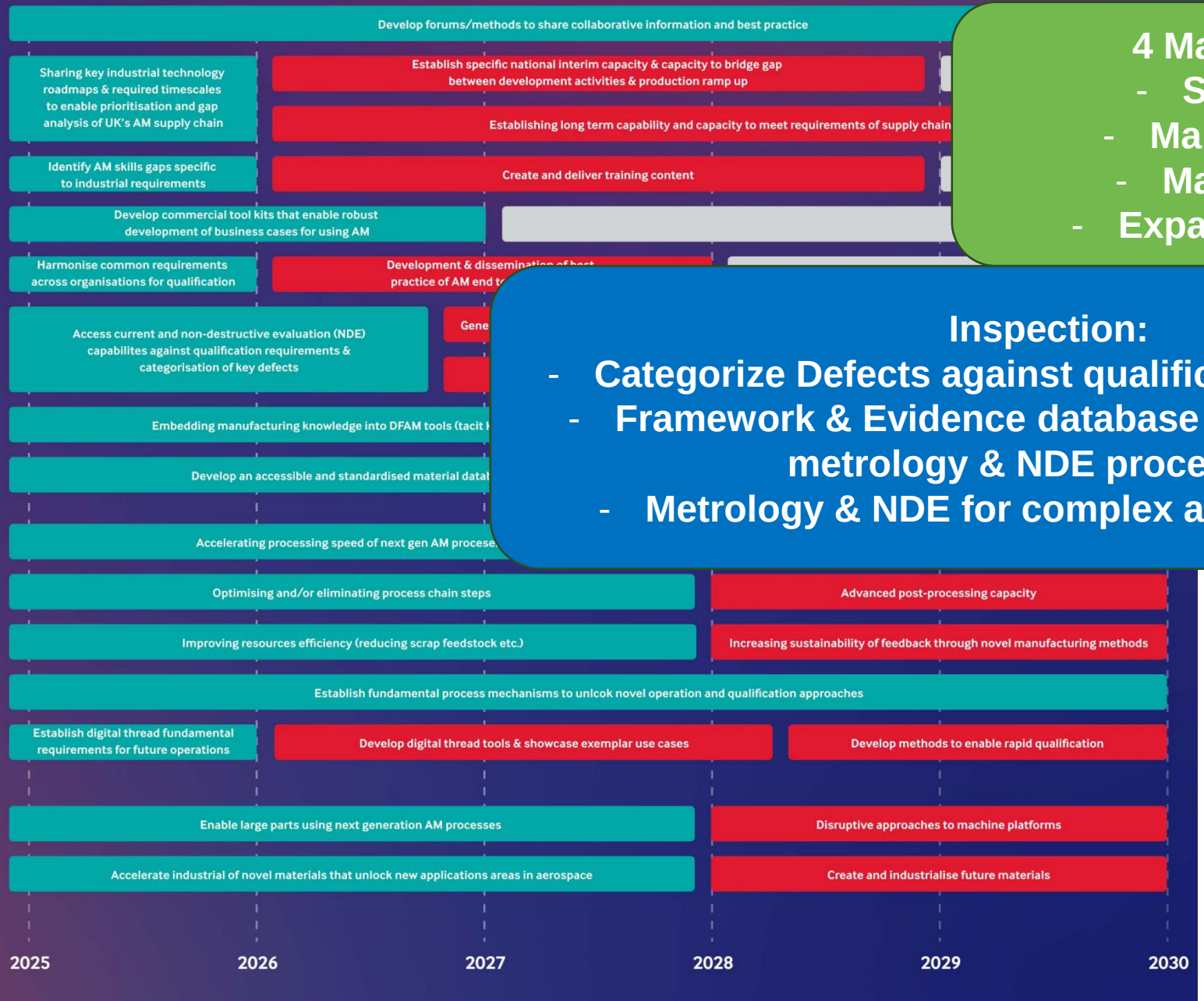
Utilising current technology

- Developing a resilient and cohesive supply chain
- Improving efficiency of qualification and certification of AM parts for aerospace

Maturing future technology

- Drastically reducing cost of AM parts
  - Improving M/C Speed
  - Optimising AM Process Chain
  - Digital Qualification
- Expand the possible application areas for utilising AM
  - Enabling Technologies
  - Novel Materials



4 Major Strands:

- Supply Chain
- Make Q&C easier
- Make it cheaper
- Expand Applications

Inspection:

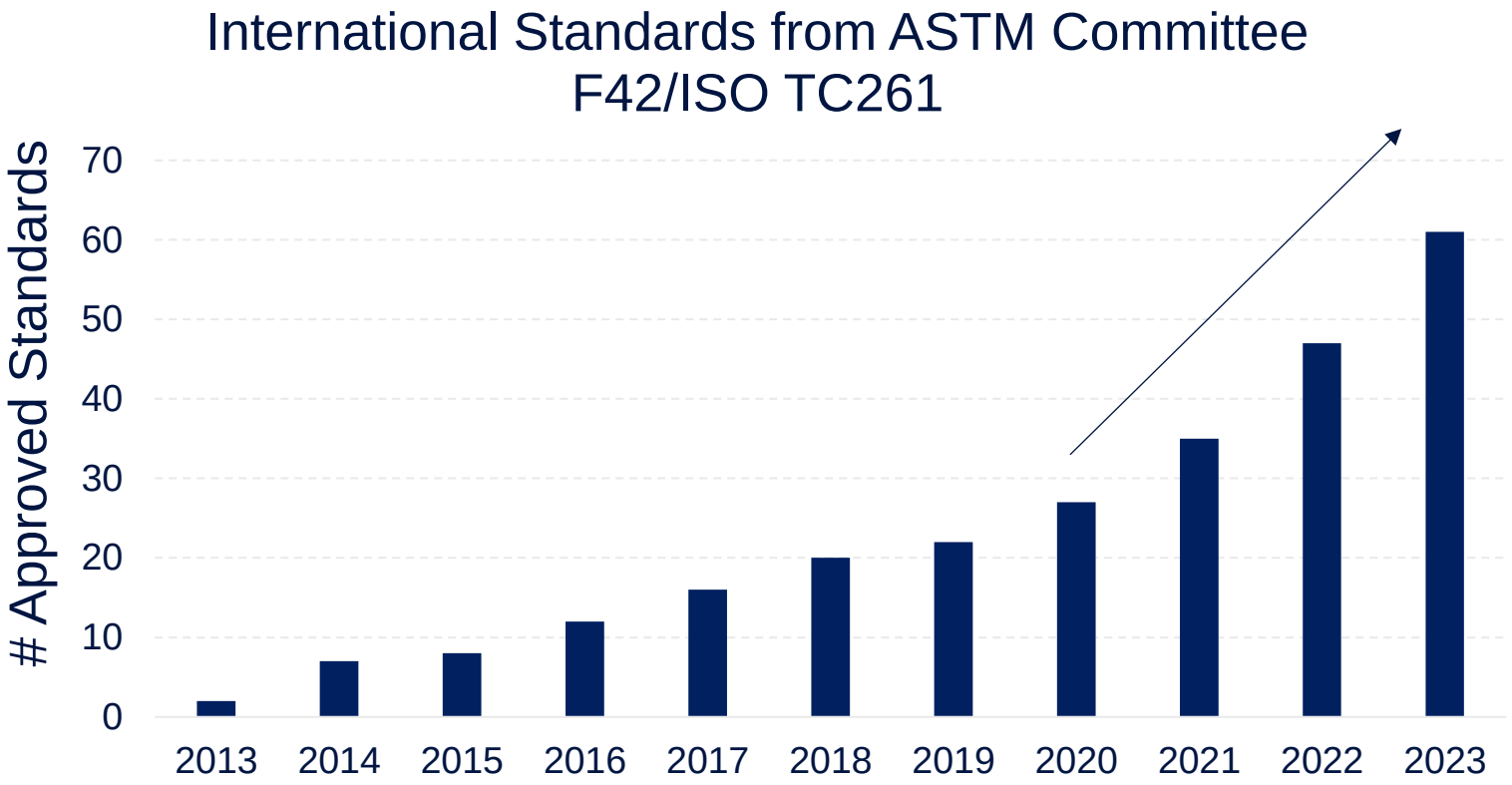
- Categorize Defects against qualification requirements
- Framework & Evidence database to enable reduced metrology & NDE process steps
- Metrology & NDE for complex and/or large parts

The Landscape of Standards

We are Accelerating…

ASTM CoE Research to Standards

Conducts R&D identified and prioritized by the top minds in the field to significantly accelerate standards development.



Context – Inspection & Structural Integrity

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We have an extensive toolbox of approaches to support Safe operation

Safe Operation

Regulations

The way to meet a regulation can very greatly based on:

- Type of material and process (traditional metal, composite, additive manufacturing, etc.)
- Criticality of the application* (transport aircraft versus ultralight glider)
- Criticality of the part within the application (wing spar versus non-structural external fairing)

"*Societally Accepted Risk*"
Requirements will remain the same

*Safety Continuum based on Application

November 2021 Part Criticality and Associated Degree of Rigor Federal Aviation Administration 11

Ref Cindy Ashforth, FAA Senior Technical Specialist for Composites. 'Criticality and the Associated Degree of Rigor in Certifying AM Parts', ICAM November 2021

- In-Service → Health Monitoring, Inspection, MRO
- Structural Lifing → *"Certification by Analysis, supported by Test"*
- Component Validation → Inspection – Part in hand
- Manufacturing Process
  - PFMEA
  - Understand and manage likelihood of process escape
  - In Situ Monitoring
  - PoD… Adaptive Manufacturing

NASA-ASTM Cooperative Agreement

Cooperative Efforts

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Qualification

Design, test, and standardize a qualification schema for laser beam powder bed fusion (PBF-LB).

Defects & Inspection

Define types & sources of process escape in AM, Develop a PFMEA for AM Defects, Probabilistic analysis methods for likelihood of defect occurrence and detection

Monitoring

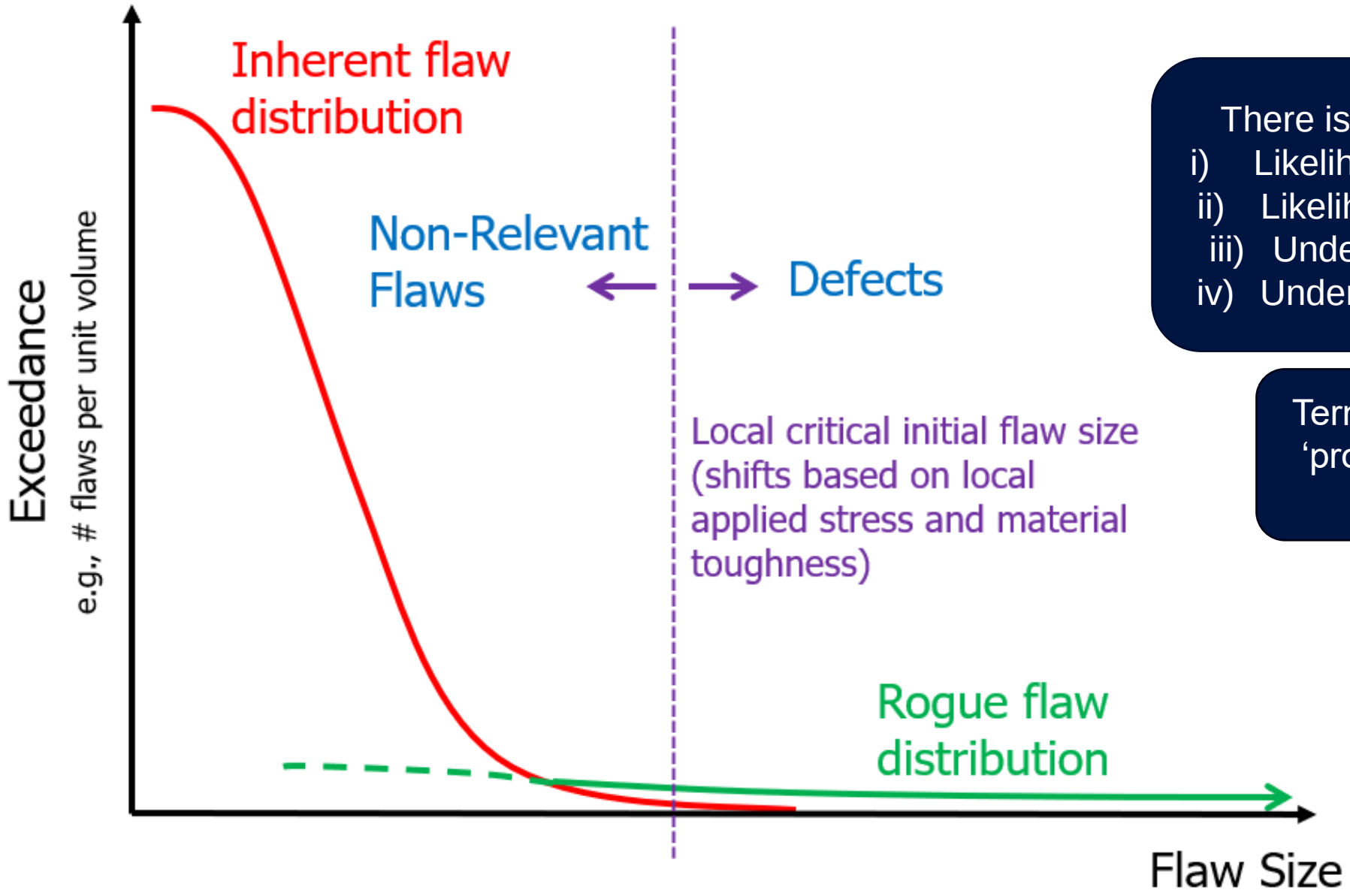
Assess current status of *in-situ* monitoring technologies and develop a roadmap for prioritization moving forward.

Literature Review | Targeted Surveys | Expert Interview | Technical Workshop | Brainstorming Sessions

Strategic Guides & Roadmaps

https://amcoe.org/research-development/publications/

Definition – Flaw & Defect Distributions



There is uncertainty with respect to:

i) Likelihood of a rogue flaw occurring
ii) Likelihood of a flaw being detected
iii) Understanding why a flaw occurs
iv) Understanding the effects of a flaw

Terminology still being debated… ‘process escape flaw’ vs ‘Rogue flaw

Holistic Approach To AM Quality & Inspection

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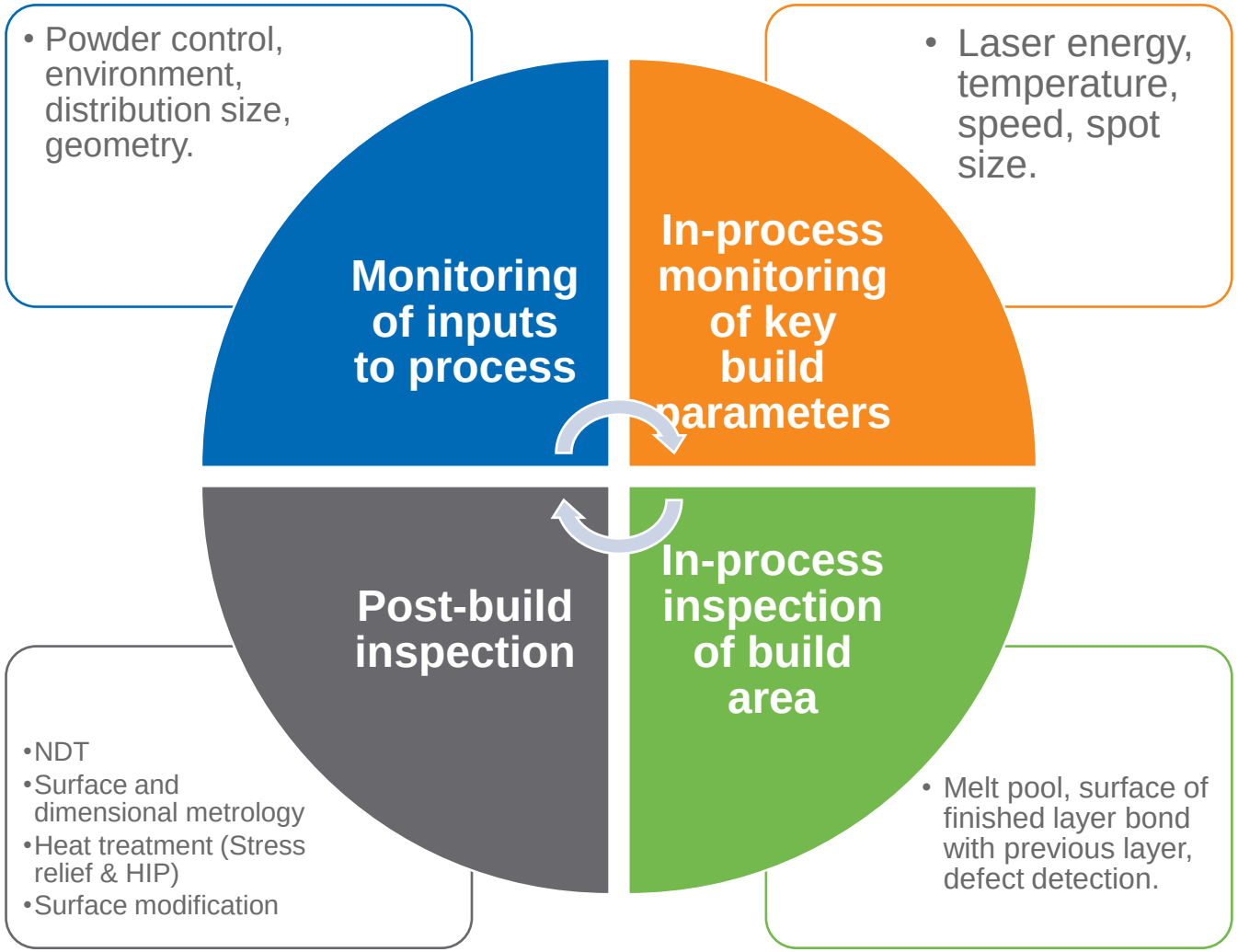

Slide presented by Dr Ben Dutton, MTC at the ICAM 2023 Introduction to Quality Assurance Course

State of the Art & Technical Maturation – In Situ Monitoring

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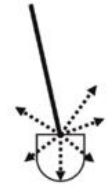
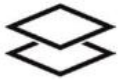
Three general regimes of ISM in AM Systems

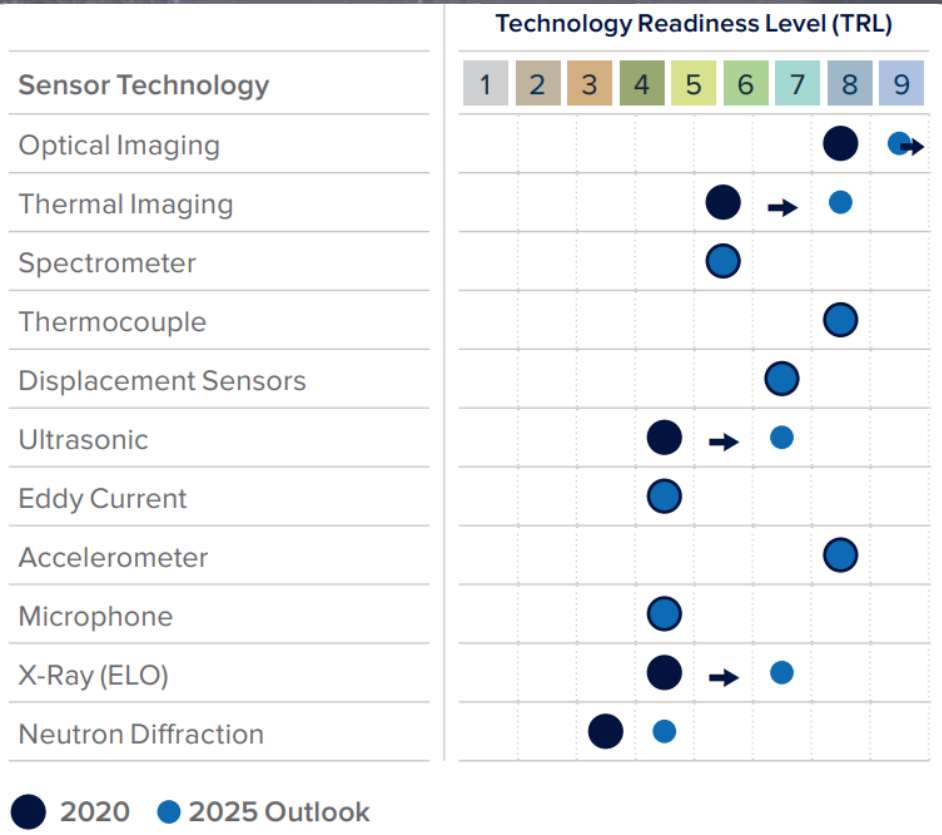
AM Machine Condition monitoring (system health monitoring)



Melt process monitoring



Deposited Material monitoring

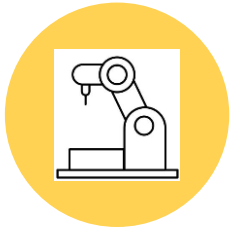


Sensor technologies evaluated on ability to replace or reduce ex-situ inspection for critical application

PBF

-Layer Imaging likely to be Standard for detection of recoater or part distortion

- In-Situ defect detection is expected with development work



DED

- Auto height control is necessary for normal operation

- Methods also implemented for process monitoring with potential for in-situ defect detection

- Increased surface roughness of DED relative to PBF may be a challenge

Types of Detectable Defect States

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High Detectability

- Lack of fusion
- Spatter
- Geometric/dimensional defects
- Powder Spreading Quality

Medium Detectability

- Porosity(Keyhole)
- Stress-induced crack (internal)
- Delamination

Low Detectability

- Microstructure, Chemical Composition(Chemistry)
- Contamination
- Subsurface defects

Limits of Detectability

- Measurement speed is slow
- Cost & Difficult to integrate
- Lack of Causal Correlation
- Sensor Resolution
- Interaction with previous layer
- Registration
- Equipment Access

- **Wish List:**
  - Data Stream to be used to *characterize the severity of the anomaly*
  - *Defect Library* to be developed with size/shape, cause, minimum critical flaw size for each specific size
- **What if…**
  - Defects could be characterized by using ‘inferable’ rather than ‘detectable’?
  - *Detection intensity was related to the potential size/impact*?

Status of Standardisation (‘*Classic*’ NDE & IPM)

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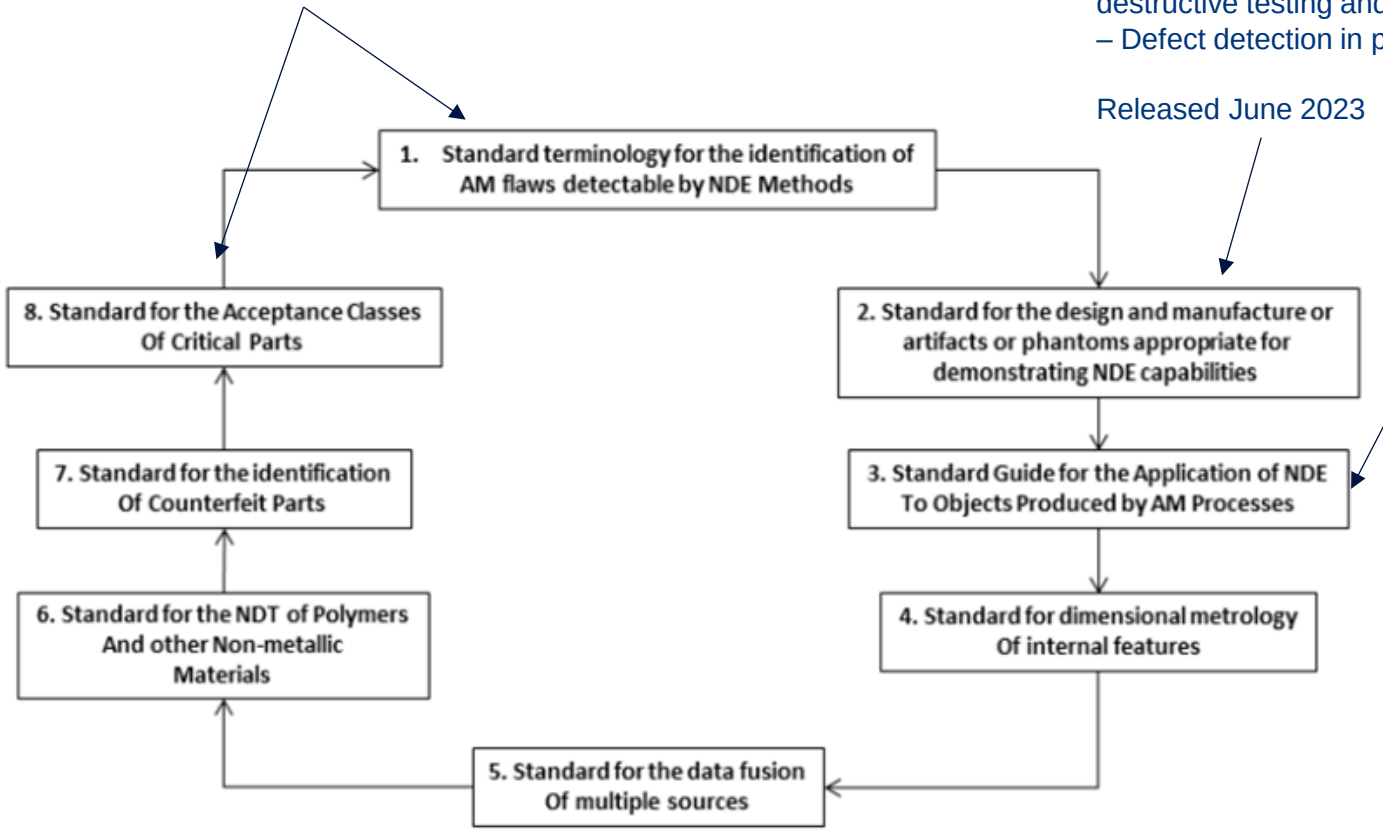
WK75329 - Nondestructive Testing (NDT), Part Quality, and Acceptability Levels of Additively Manufactured Laser Based Powder Bed Fusion Aerospace Components

ISO/ASTM 52905:23 – Additive Manufacturing of Metals – Non-destructive testing and evaluation – Defect detection in parts.

Released June 2023

ASTM E3166 Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build



Taken from AMSC roadmap Gap report

- IPM can leverage the existing NDE Standards landscape
- Many of the workshop topics are replicated for traditional NDE methods

IPM Standards Activities

ASTM WK73978: General Principles – Registration of Process-Monitoring & Quality-Control Data for data registration

ISO/ASTM 52958: AM of Metals – PBF – Best Practice for In-Situ Flaw Detection and Analysis for Laser-based PB

Inspection Acceptance Criteria

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- **WK 75329**
- specifies the NDE and acceptance criteria for parts manufactured via PBF-LB
- This work item applies to radiographic examination and liquid penetrant

Discontinuity	Level 1	Level 2
Surface or Internal		
Propagating discontinuities - cracks, solidification cracks, delamination cracks, Lack of Fusion or Incomplete Fusion - build layer separations, lateral, vertical, hatch, connected porosity, keyhole porosity, through wall separations	0	0
Voids	2.5% of the material thickness in its longest dimension.	0.060"
Inclusion	2.5% of the material thickness in its longest dimension	0.060"
Contamination	0	0
Trapped Powder	0	N/A
Sub Surface Porosity		
Individual distinguishable from cracks – keyhole, gas porosity	2.5% of the material thickness in diameter.	N/A
Group more than two distinguishable from cracks – keyhole, gas porosity	3 individual pores greater than 2.5% of the material thickness in diameter	N/A
	separated by 3 times the diameter of the largest pore.	
Surface Porosity		
Individual	0.060"	0.060"
Group	3 individual pores greater than 2.5% of the material thickness separated by 3 times the diameter of the largest pore.	7 individual pores greater than 2.5% of the material thickness separated by 3 times the diameter of the largest pore

Latest updates to Work Item will align the criteria against F3572 for Part Criticality

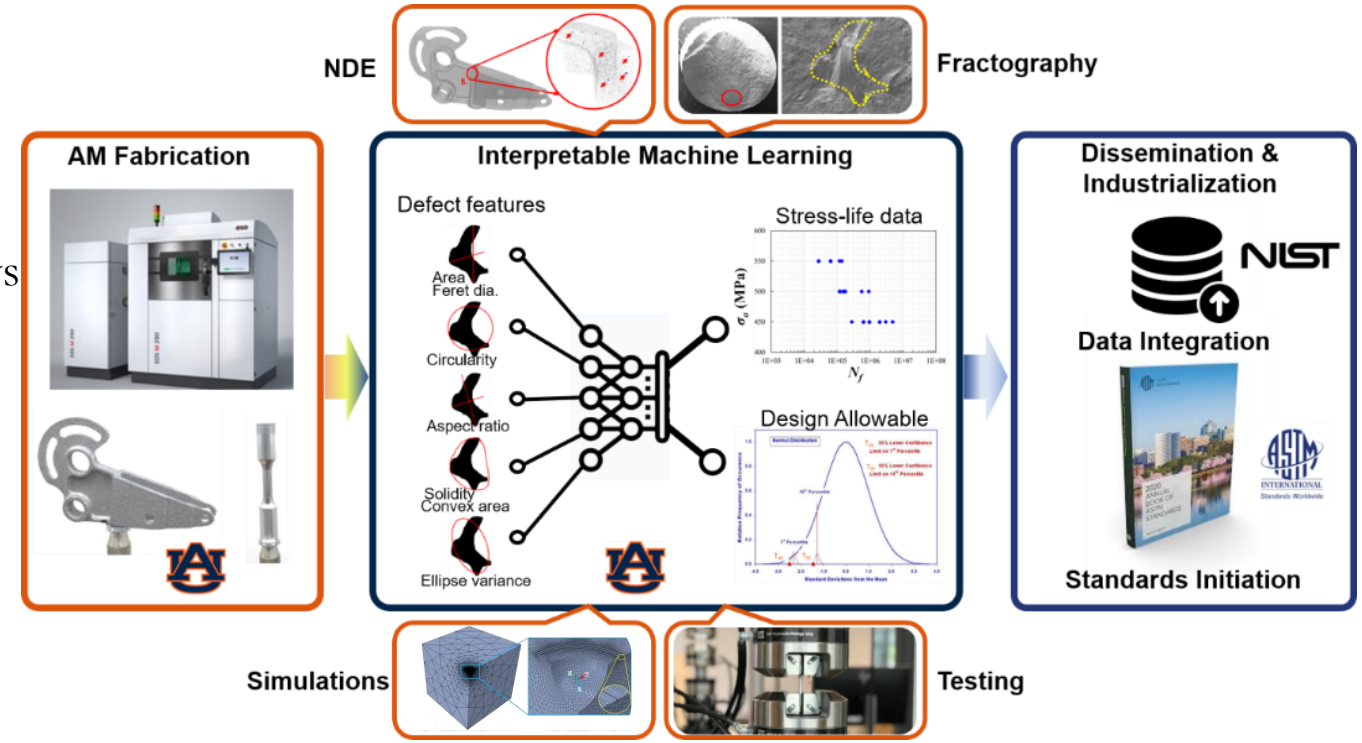
NDE-Based qualification (Innovative Approaches to Qualification)

Determine the **criticality of AM defects** on the **fatigue performance** of AM materials

Develop a **data-driven framework** using computer vision and machine learning to model the effect of defects in support of non-destructive qualification

Initiate new **standards** and/or improve current standards for mechanical testing, non-destructive evaluation (NDE), data collection, and qualification

❖Correlation study
- Low and high res CT scan data
- Defects features in 2D and 3D views
- Defects and fatigue behavior



– Collaborative effort

– Sponsored by:

Data Management Initiatives – one of the key hurdles

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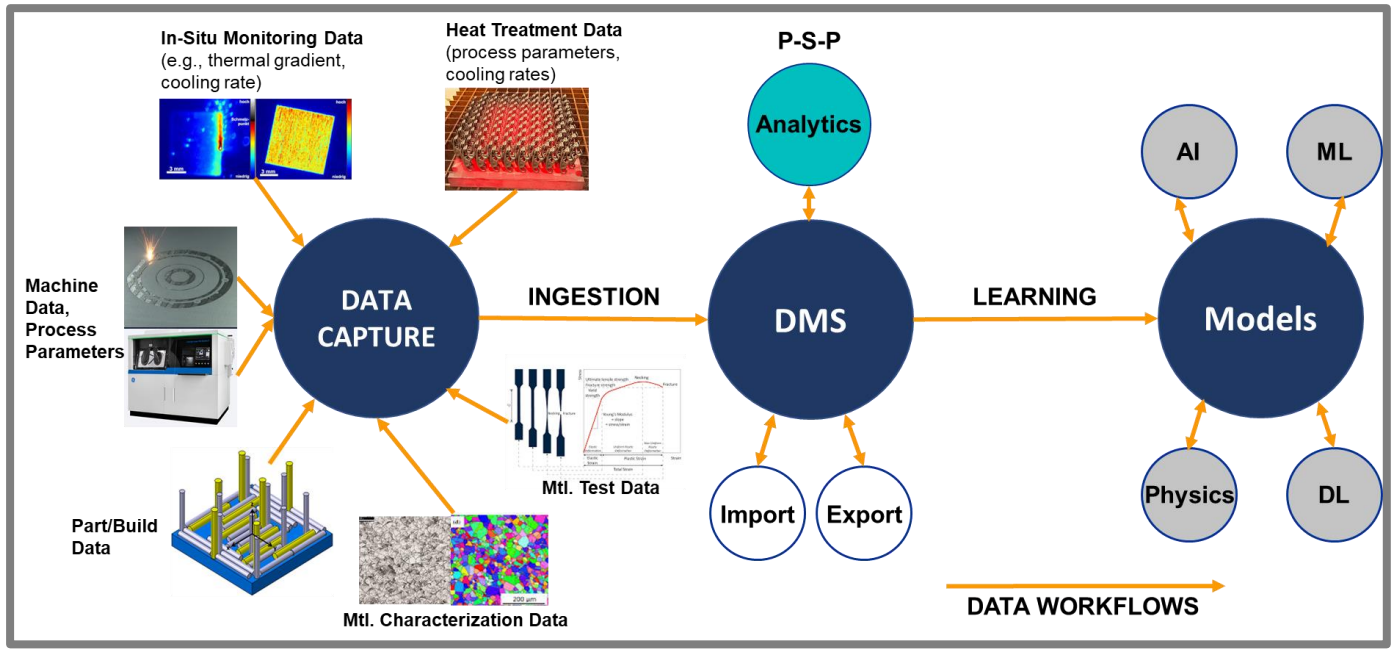
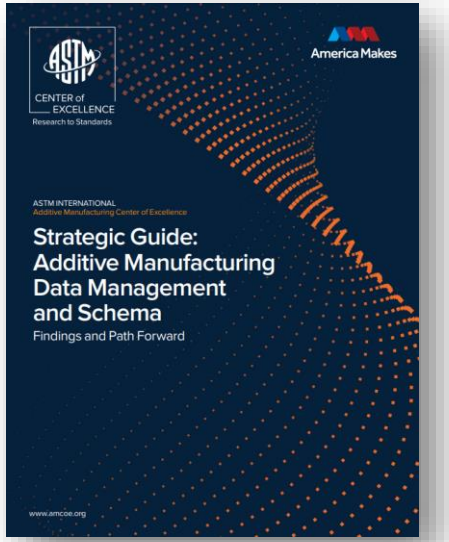
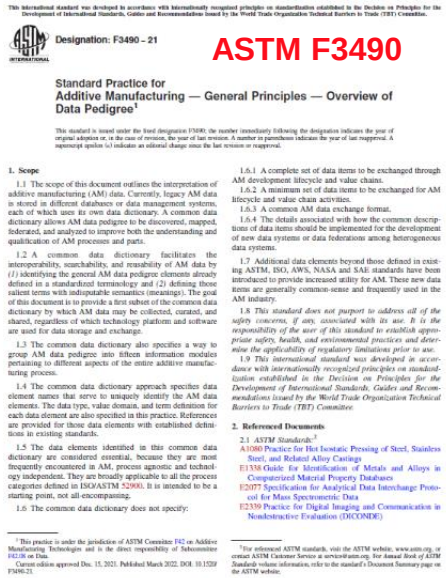
– Supporting various programs, to generate **high-pedigree data**

– A pre-requisite for the development of high-quality simulation and machine learning packages for AM.



~700 data elements are being collected by **Common Data Dictionary (CDD); ASTM F3490**.
~1700 data elements are being collected by **CMDS's Data Acquisition Template**.





Download now!

Supported Programs

- ASTM INTERNATIONAL — **CMDS**
- National Institute of Standards and Technology — **NDE-based Qualification**
- America Makes — **GAMAT**

Final thoughts

IN PROCESS MONITORING

Great potential to support Structural Integrity for AM Applications but work still needed.

STANDARDS

'A rising tide lifts all boats…'

Consensus through Standards will lead to best practices.

COLLABORATION

Alignment on the key topics will reduce duplication – allowing the research community to solve the problems

ASTM

Continue to:

- Close Standards gaps
- Solve difficult technical problems
- Actively participate in funded calls

ASTM INTERNATIONAL UK

ASTM ICAM 2024 – Global Ecosystem Gathering

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- 6 days
- 4 short courses
- 26 symposia
- 8 keynotes
- 10 panels
- 700+ presentations

The ASTM AM Division Product Pyramid

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ICAM – Research to Application Through Standardization

ASTM Advisory Services

Product

Getting an AM part into Critical Applications can be built on all the layers below
Classification of Product – Mechanical Testing – Manufacturing Process

Q&C

Control **Feedstock**, **Machine**, **Process**, **Inspection**, and IQ/OQ/PQ leveraging ISO/ASTM Stds
Advanced Methods – Part Family Q&C, Probabilistics, In-Process Monitoring

Materials & Data

Consortium for Materials Data & Standardization (CMDS)
High caliber datasets based on P-S-P, **powered by members,** driven by Standardization

Facility

Control facility, operations, safety – all through ISO/ASTM Standards
Demonstrate - ASTM Additive Manufacturing Qualification (AMQ), PTP

People

Enable workforce through advanced training based on Standards & experience. *Demonstrate* - ASTM Qualifications, *Operators, Safety*

Fundamentals

ASTM Funded Research to Standards Program
Closing Gaps identified by Industry

How to leverage standards– Mapping of ASTM/ISO Standards

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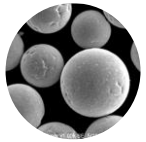


- B212-17 Standard Test Method for Apparent Density of Free-Flowing Metal Powders Using the Hall Flowmeter Funnel
- B213-20 Standard Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
- B214-16 Standard Test Method for Sieve Analysis of Metal Powders
- B215-20 Standard Practices for Sampling Metal Powders
- B243-20 Standard Terminology of Powder Metallurgy
- B329-20 Standard Test Method for Apparent Density of Metal Powders and Compounds Using the Scott Volumeter
- B417-18 Standard Test Method for Apparent Density of Non-Free-Flowing Metal Powders Using the Carney Funnel
- B527-20 Standard Test Method for Tap Density of Metal Powders and Compounds
- ISO/ASTM52925-22 Additive manufacturing of polymers Feedstock materials Qualification of materials for laser-based powder bed fusion of parts
- ISO/ASTM DIS 52924 Additive manufacturing of polymers — Feedstock materials — Qualification of materials for laser-based powder bed fusion of parts

Feedstock Characterization

- F3001-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
- F3055-14a Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
- F2924-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
- F3056-14 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
- F3184-16 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion

Materials Properties

- ISO/ASTM 52910-18 Additive manufacturing — Design — Requirements, guidelines and recommendations
- ISO/ASTM 52911-1-19 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals
- ISO/ASTM52911-2-19 Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers
- ISO/ASTM TR 52912:2020 Additive manufacturing — Design — Functionally graded additive manufacturing
- ISO/ASTM52915-20 Specification for additive manufacturing file format (AMF) Version 1.2
- ISO/ASTM52950-21 Additive manufacturing — General principles — Overview of data processing
- ISO/ASTM52922-19e1 / F3413-19 Guide for Additive Manufacturing Design Directed Energy Deposition
- ISO/ASTM TR 52916:2022 Additive manufacturing for medical — Data — Optimized medical image data

Design

Safety

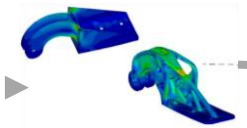
- F3546-2022 Guide for Additive manufacturing -- Environment, health and safety -- Standard guideline for use of metallic materials
- WK66473 New Test Method for Additive Manufacturing Environment, Health, and Safety Test Method for Determination of Particle and Chemical Emission Rates From Desktop 3D Printer Material Extrusion
- NEWSTD(Z9801Z) WK70918 Test Method for Additive manufacturing -- Environment, Health, and Safety - Test method of hazardous substances emitted from ME- type 3D printers in the AM workplace
- NEWSTD(Z0422Z) WK73227Guide for Investigation for Additive Manufacturing (AM) Facility Safety Management
- ISO/ASTM DIS 52931 Additive manufacturing of metals — Environment, health and safety — General principles for use of metallic materials

Materials Data & Mechanical Properties

DfAM

F3572-22 Standard Practice for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation

Part Classification



ISO/ASTM 52930 Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment

Part Qualification Build Setup

Equipment OEM

Factory Acceptance Test

- ISO/ASTM 52941-20 Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application

Shipping

Machine Calibration

- ISO/ASTM 52941-20 Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application

Site acceptance test

- ISO/ASTM 52941-20 Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application

Machine qualification

- ISO/ASTM 52930 Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment

Process control

- ISO/ASTM52904-19 Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications

ISO/ASTM 52942-20 Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications

- Part dimension
- Witness coupon
- Test artifacts
- Monitoring

Thermal treatment

- F3301-18a Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion

Machining

NDT evaluation

- E3166-20e1 Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build
- ISO/ASTM DTR 52905 Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts

Final inspection

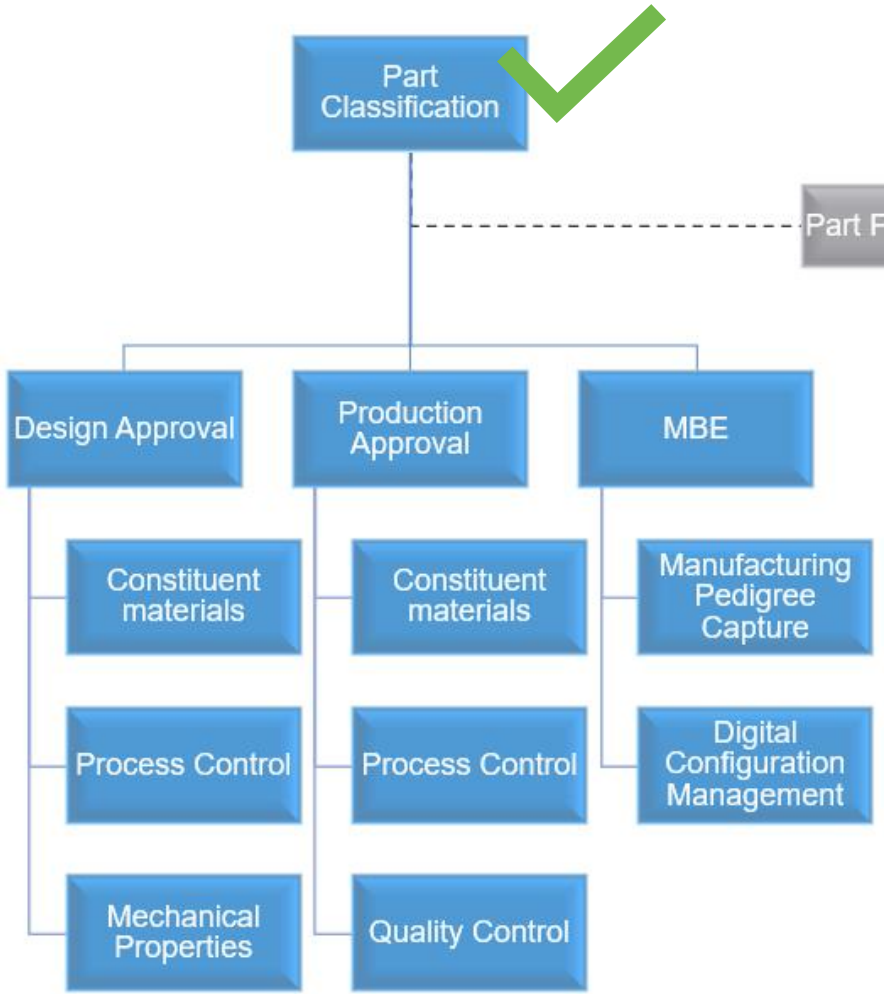
- ISO/ASTM 52910-18 Additive manufacturing — Design — Requirements, guidelines and recommendations

- F2971-13 Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
- ISO/ASTM 52902:2019 Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems
- NEWSTD(Z0669Z) WK74390 Practice for Additive Manufacturing of Metals—Data—File Structure for In-Process Monitoring of Powder Bed Fusion (PBF)

Design Engineer Training	Build Programmer Training	Machine Operator Training	Industrial/Manufacturing/Process Engineering Quality Engineer Training

Next Steps

ICAM2022



- Continue collaborating within Additive Manufacturing SDOs to further define downstream requirements
  - NDI acceptance level which uses part classification
  - IQ/OQ/PQ which uses part classification
- Collaborate with other ASTM committees to proliferate the standard and include F3572 document as a potential means of compliance
  - F37 – LIGHT SPORT AIRCRAFT
  - F38 – UNMANNED AIRCRAFT SYSTEMS
  - F39 – AIRCRAFT SYSTEMS
  - F44 – GENERAL AVIATION AIRCRAFT In-work
  - F46 – AEROSPACE PERSONNEL

Charles Park – ICAM 2022

Key Published Standards – ASTM F42/ISO TC261

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ASTM Qualification Program | Machine | Operators | Installation/ Operation/ Performance - **PRODUCTION**

ISO/ASTM 52901	ISO/ASTM 52904	ISO/ASTM 52941	ISO/ASTM 52942	ISO/ASTM 52930
Standard Guide for AM – General Principles – Requirements for Purchased AM Parts	**Practice for Metal Powder Bed Fusion Process to Meet Critical Applications**	**System Performance and Reliability – Acceptance Tests for Laser Metal PBF Machine for Metallic Materials for Aerospace**	**Qualifying Machine Operators of Laser Metal Powder Bed Machines and Equipment used in Aerospace Applications**	**Installation, Operation, and Performance Qualification for Production**
Provides requirements for purchased parts from AM. Includes part ordering information, part geometry, tolerances, repair methods allowed, and other requirements to be considered	Provides requirements applicable for *critical* components and mechanical test specimens using powder bed fusion (PBF) with both laser and electron beams	Specifies requirements & test methods for qual & re-qual of Laser PBF machines. Can be used to verify machine features during inspection, or after maintenance & repair	Specifies requirements for operators of Laser Metal Powder Bed Machine and equipment for AM in Aerospace applications. Qualification tests to include theory & practical tests, and evidence of visual acuity	This guide addresses IQ, OQ, and PQ issues directly related to the AM machine and connected equipment. Physical facility, personnel, process and material issues are included to the extent necessary to support machine qualification

AM Classification for Aerospace/Defense – ASTM F3572
Defining appropriate requirements

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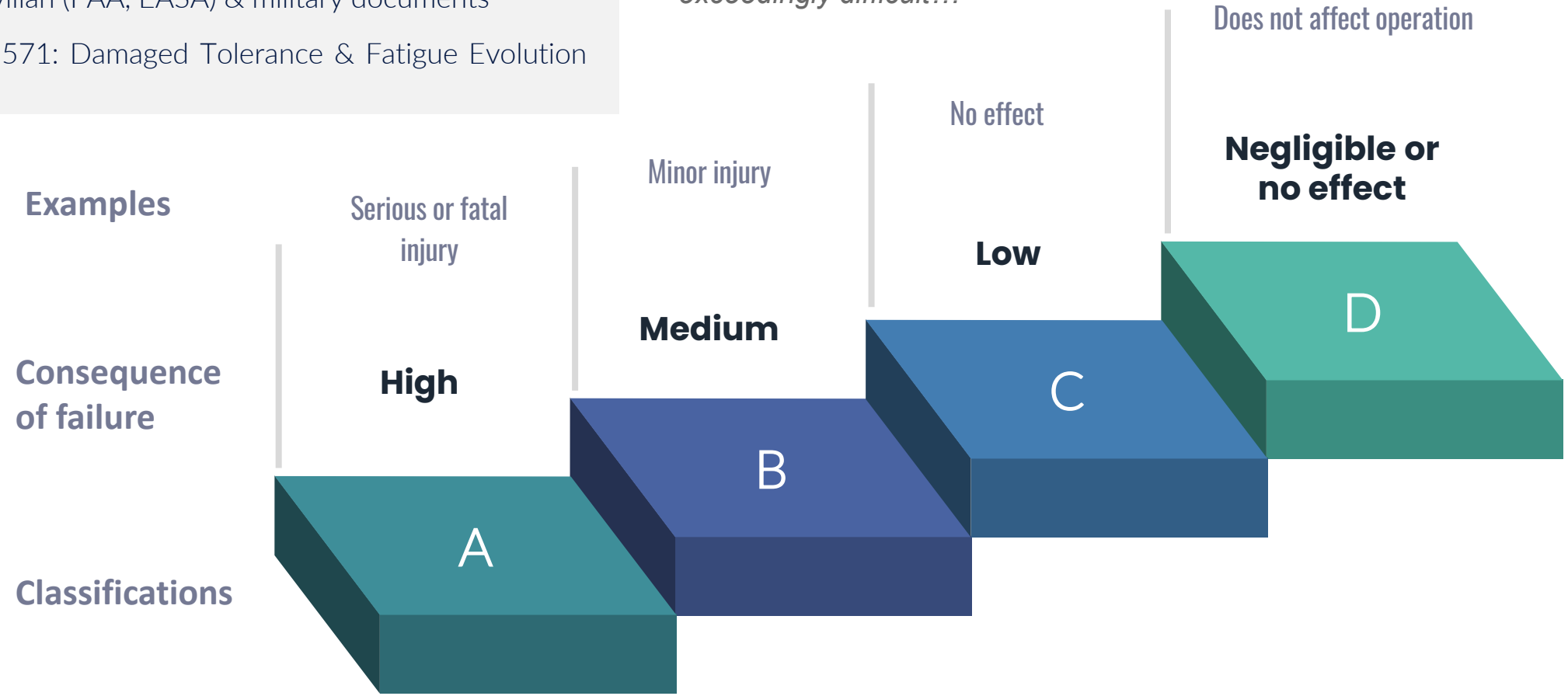
Published on Aug 5, 2022

- Alignment vs civilian (FAA, EASA) & military documents
- NAVAIR, AC25.571: Damaged Tolerance & Fatigue Evolution of Structure

*"Without carefully defined part classes, the ability to accurately **gauge the consequence of failure** associated with additively manufactured aviation parts within and across programs, projects, and suppliers becomes exceedingly difficult…"*



AM Materials Data – Increasing Maturing

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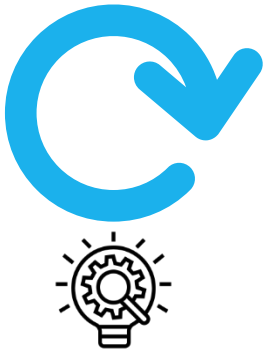
➢ Accelerate adoption of AM technologies through standardization by:

REQUIREMENTS & BEST PRACTICES

- Terminology, Pedigree, Specimen Geometry, Build & Test Plans
- Identify Process-Structure-Property Relationships
- Equivalency/Combinability of new or existing data



GENERATE HIGH-PEDIGREE DATA

- Consortia-funded R&D projects create *shared* high-pedigree “reference” material datasets to drive process-based material specifications

DATA MANAGEMENT SYSTEM

- Secure, Access-controlled Data Management System
- Establishing/Following standard data principles (e.g., CDD, CMD, CDEF, FAIR*)

STANDARDS DEVELOPMENT

- Transferring lessons learned and consortium approved materials data to standardization committees

Consortium for Materials Data & Standardization (CMDS)

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- CMDS enables collaboration on standardizing the requirements and best practices for generating high-pedigree materials data

- OEM/LSI End Users
- AM Equipment Manufacturer
- AM Contract Manufacturer/Supplier
- AM Materials/Feedstock Producer
- AM Post-processing and Testing Service Provider
- AM Software
- AM Process/Health Monitoring
- Industrial Equipment Producer (e.g., Furnace, Powder Handling Equipment,…)
- Government Agencies and Laboratories (DoD, DOE, NASA, NIST)

AM Certification Committee (AMCC)

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AM Certification Committee

- Created an AM certification committee including major OEMs
- Qualified AM supply chain with multiple industry approach
- Capture end-user requirements beyond standards
- The committee creates and oversee an audit program based on published international standards and industry best practices.

AM Certification Committee (24 members)

Medical

JABIL, BD, jri Orthopaedics, smith&nephew, Johnson&Johnson, Medtronic, stryker

Aerospace/Defense

NORTHROP GRUMMAN, LOCKHEED MARTIN, BOEING, GENERAL ATOMICS, AEROJET ROCKETDYNE, LEONARDO, Honeywell, Raytheon, BAE SYSTEMS, ST Engineering Aerospace, BELL, SAFRAN

Transportation

DAIMLER TRUCK, Ford, JOHN DEERE, gm, TESLA

Standards for AM Certification Audit Criteria

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Thank you for your attention!

Dr Martin White
mwhite@astm.org

See you there!