Considerations for the Expanding Use of Computational Materials Capabilities in Additive Manufacturing

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Virtual

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Outline

- ICME / CM – background and motivation
- Regulatory landscape
- Industry trends
- Metal AM as a use case
- V&V framework as a key enabler
- Overview of CM*4*QC Steering Group
- Summary

Note: *in the context of this presentation*, the terms **CM** (Computational Materials) and **ICME** (Integrated Computational Materials Engineering) are used *interchangeably*

ICME as ~~Emerging~~ *Evolving* Technology

AIM Program Overview

DARPA AIM

DARPA

The AIM program initiative created a new materials development methodology that accelerates the insertion of new materials in order to achieve parity with the engine/platform development/design cycles. Accomplishments of the AIM program include:

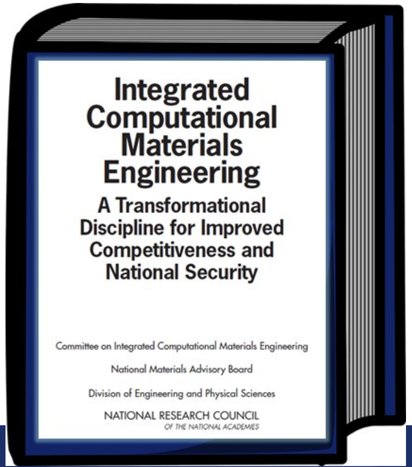
- Establish design-driven material requirements by tightly coupling design and materials activities and tools.
- Providing earlier information (with confidence bounds) to designers throughout the development cycle.
- Controlling the performance, producibility, and cost of materials.
- Reducing risks of new material insertion risk while also decreasing costly, time-consuming data generation.
- Creating a knowledge base and tool kit for designers that links with computational design tools.

Commonly identified benefits:

- **Cost savings**
- **Novel fit-for-purposes materials**
- **Integrated design, *certification*, and flexible manufacturing**
- **Risk reduction (*program risk vs. product safety risk*)**

Keeping pace with industry needs

Requires significant maturation to realize this benefit



Materials Genome Initiative
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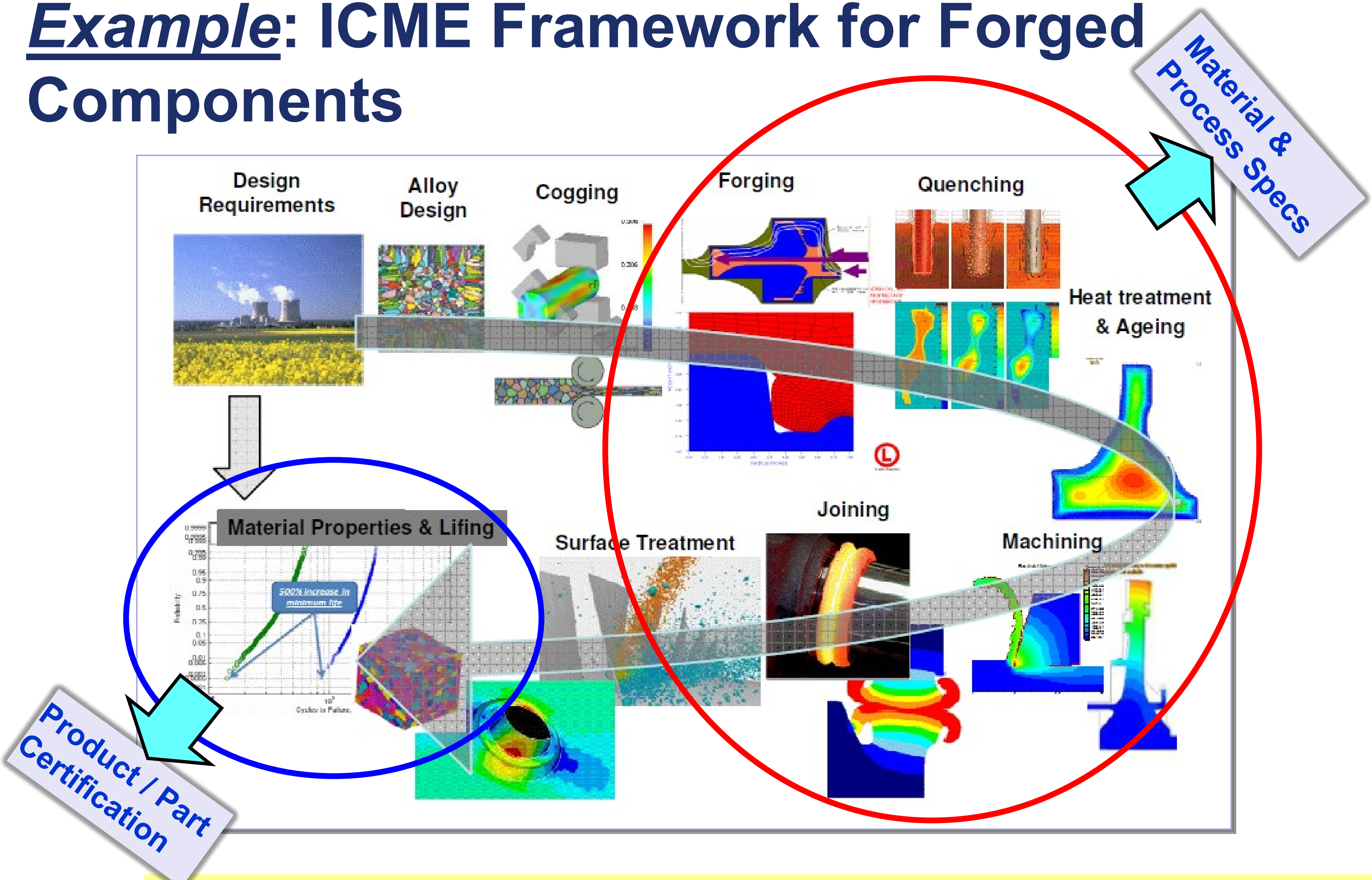
About the Materials Genome Initiative

The **Materials Genome Initiative** is a federal multi-agency initiative for discovering, manufacturing, and deploying advanced materials twice as fast and at a fraction of the cost compared to traditional methods. The initiative creates policy, resources, and infrastructure to support U.S. institutions in the adoption of methods for accelerating materials development.

Example: ICME Framework for Forged Components



Reference: *M. Glavicic et al., "Application of ICME to Turbine Engine Component Design Optimization", AIAA 2011-1738*

14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.603 Materials

- The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must —
  a) ***Be established on the basis of experience or tests;***
  b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
  c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

§ 25.605 Fabrication Methods

a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification.

b) Each new aircraft fabrication method ***must be substantiated by a test program.***

14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.613 Material Strength Properties and Design Values

a) Material strength properties must be ***based on enough tests*** of material meeting approved specifications ***to establish design values on a statistical basis***.

b) Design values must be chosen to minimize the probability of structural failures due to material variability.

d) The strength, detail design, and fabrication of the structure ***must minimize the probability of disastrous fatigue failure***, particularly at points of stress concentration.

e) Greater design values may be used if a "premium selection" of the material is made in which a ***specimen of each individual item*** is ***tested before use***.

No Allowance for Modeling or Analysis

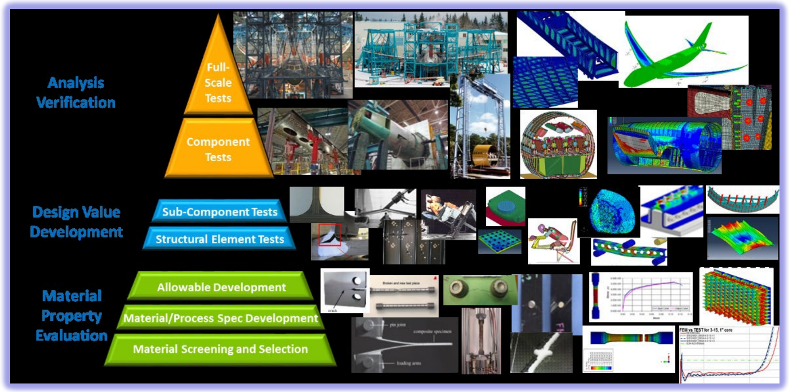
Examples of "Model-Friendly" Domains

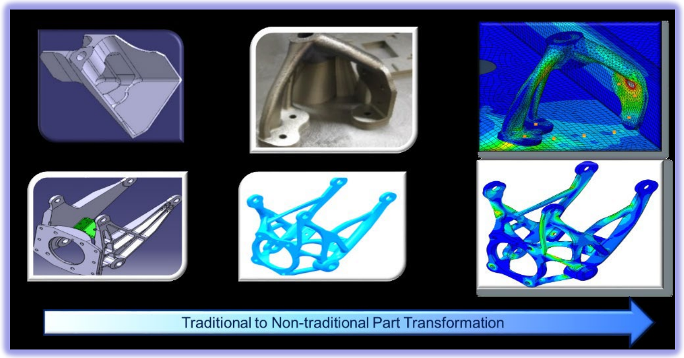
- **Proof of Structure → <u>Part 25</u> (14 CFR 25.307)**
  - **Structural analysis may be used *only if the structure conforms to that for which experience has shown this method to be reliable***
- **Damage Tolerance → <u>Part 25</u> (AC 25.571-1D)**
  - **In general, "analysis supported by test evidence" is accepted**
- **Damage Tolerance → <u>Part 33</u> (AC 33.70-1)**
  - **Analysis is accepted (e.g. stress, heat transfer, crack growth, …)**
    - **However, "…*the analysis approach should be validated against relevant test data*"**
- **<u>AC 20-146</u> "*Methodology for Dynamic Seat Certification by Analysis*" → *Parts 23, 25, 27, 29***
  - **Needs to be validated by test**
  - **One of the few examples of "certification by analysis" (CbA)**
  - ***Rational Analysis* - an analysis based on good engineering principles, judgment, and/or *accepted methodology* (AC 25.562-1b)**

Industry Trends

Example - "Smarter Testing"

"*Use of advanced analysis techniques* using fundamental (coupon-derived) inputs can lead to reduced quantities of program-led mid-level structural tests, reducing airplane development costs and risks".





"…AM presents new challenges for certification in that there are no traditional validated analysis methods suited to the arbitrary and organic nature of many AM parts…"

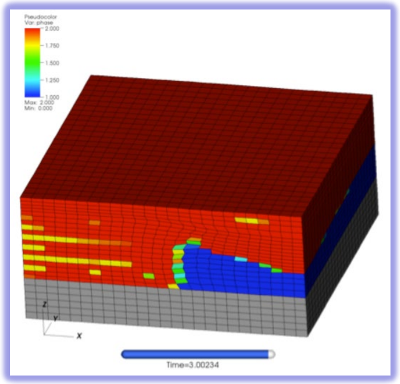
Reference: S. Chisholm et al, "*Smarter Testing Through Simulation for Efficient Design and Attainment of Regulatory Compliance*", Boeing, Presented at 30th ICAF Symposium – Kraków, 5 – 7 June 2019.

AM as a Use Case for Developing Model-based Qualification Framework

- **Relevance to other material systems' attributes** (*casting, welding, powder metallurgy, …)*
- **Highly complex "eco system" (process → microstructure → properties)**
- **Pathway to future technologies (e.g. UAS/UAM) and applications:**
  - Topologically optimized structures
  - Location specific / gradient microstructures
  - Multi-material systems
  - Multi-functional systems (e.g. embedded electronics)

Modeling as an Enabler for Q&C of AM

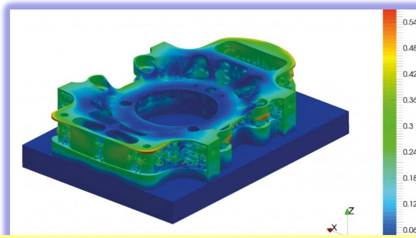
Physics-based process models have been identified as being foundational to qualification of additively manufactured metal parts.



Ref: W. King, "Accelerated Certification for Additively Manufactured Metals", LLNL, 2015.

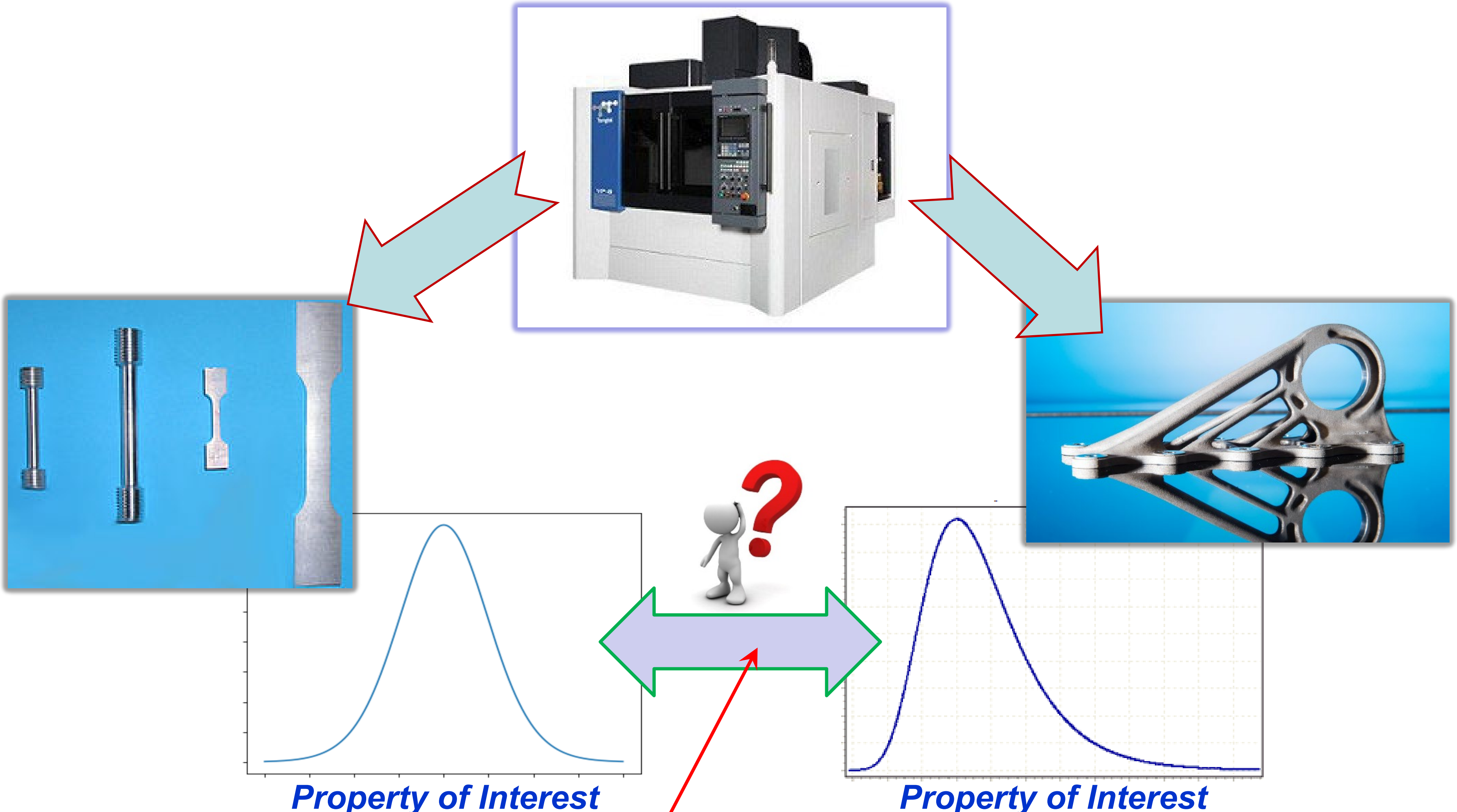
Examples of CM application areas for AM:

- **Process parameters optimization**
- **In-situ monitoring algorithms**
- **Prediction of distortion**
- **Effect of defects on part's durability**
- **Correlation between coupon-level and part-level properties** → *see next slide*



Source: https://www.metal-am.com/articles/distortion-in-metal-3d-printing-modelling-and-mitigation/

Example: Part vs. Coupon Properties



This understanding can be enabled by physics-based CM models

Multi-Scale Framework Considerations

Process → Microstructure → Properties

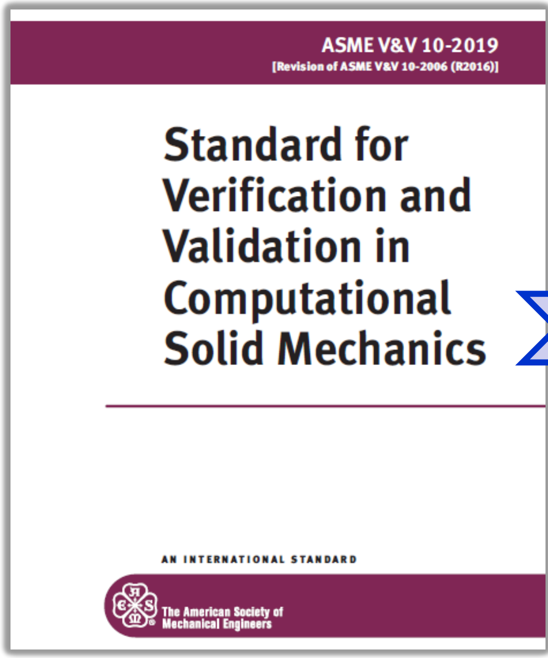
- Not everything has to be (*or can be…*) derived from the first principles
  - A meaningful combination of physics-based and *empirical* models can be used as a maturation path
  - ➢ "Big Data" / ML may provide a complementary approach
- Models validation is key → V&V and UQ
  - But the level of effort can sometimes overshadow the conventional characterization approach…

See next slide

- "Meso" attributes can be used to streamline process control. *Examples*:
  - Use of microstructure attributes to control part's properties
  - Controlling melt pool in AM process

V&V Framework for ICME

General V&V Framework
(for Computational Solid Mechanics)



V&V Framework Tailored to ICME

"The application of verification and validation will accelerate the maturation of ICME by sharpening focus on the critical needs of its customers and associated decision-makers."

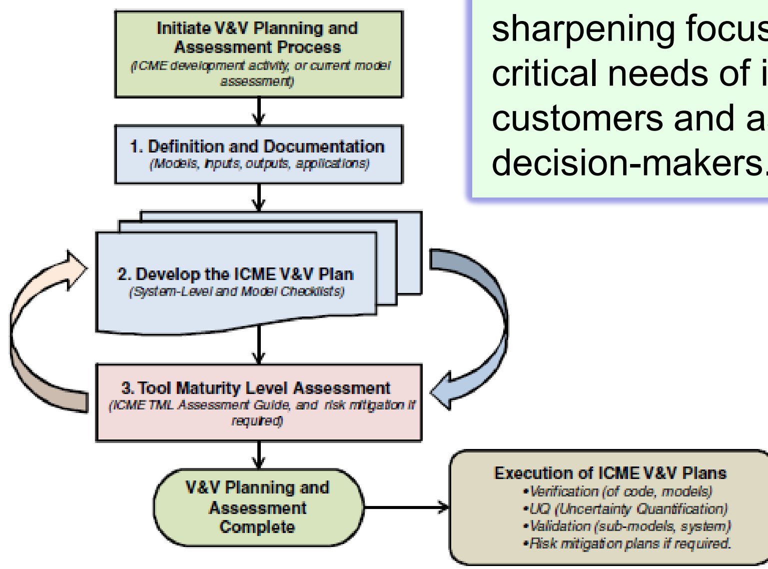


Figure 1 Flow chart of simplified ICME V&V planning and assessment process.

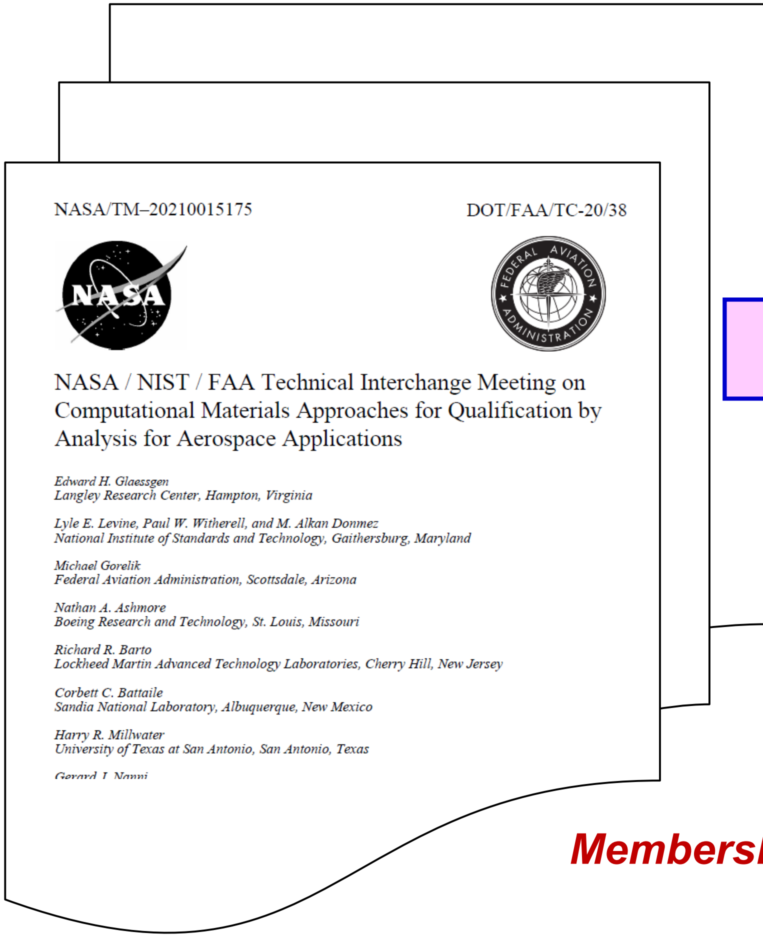
Ref: B. Cowles et al, "*Verification and validation of ICME methods and models for aerospace applications*", Integrating Materials and Manufacturing Innovation 2012 (http://www.immijournal.com/content/1/1/2)

sponsored by AFRL / USAF

NASA / NIST / FAA Technical Interchange Meeting (TIM) on Computational Materials Approaches for Qualification by Analysis for Aerospace Applications

- **Held at NASA Langley Research Center on January 15-16, 2020.**
- **Motivated by three related factors:**
  - The aerospace industry's increasing interest in expanding the use of computational materials for Q&C of process-intensive metallic materials.
  - The rapid maturation of computational materials capabilities across a range of applications.
  - A general lack of coordination of development and investment in these capabilities by funding organizations.
- **Included 60 subject matter experts (SMEs) representing 8 aerospace manufacturers, 7 government organizations and 2 universities.**
- **Key *objectives* were to:**
  - Understand existing gaps in model-based, e.g., computational materials, capabilities for processing and performance prediction for aerospace materials and components.
  - Forecast how capabilities can be matured to support material, process and part-level Q&C.

Development of Computational Materials (CM) Capabilities for Metal AM



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NASA / NIST / FAA Technical Interchange Meeting on Computational Materials Approaches for Qualification by Analysis for Aerospace Applications

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Co-organizers: NASA and FAA

Membership

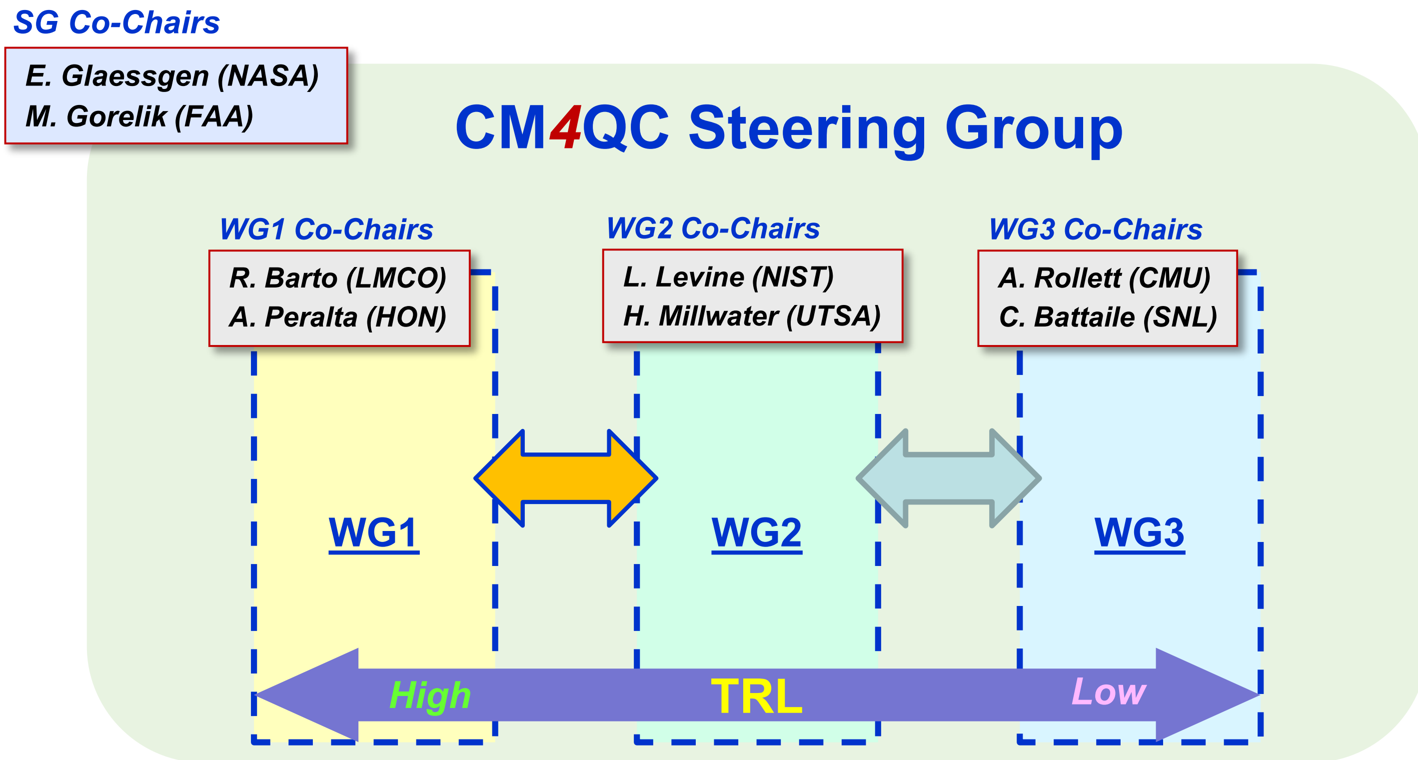
Government	Industry	Academia
NIST	Boeing	Carnegie Mellon
AFRL	Lockheed-Martin / Sikorsky	UTSA
Sandia NL	Raytheon / P&W	Vanderbilt
NAVAIR	GE Aviation	Penn State
ORNL	Spirit Aerosystems	Northwestern
Army Aviation	Honeywell Aerospace	
NASA	Howmet Aerospace	
FAA	SwRI	
	Northrup-Grumman	
	Textron Aviation / Bell	

CM4QC SG formed per recommendations of the Jan. 2020 TIM

Goals of the CM4QC Steering Group

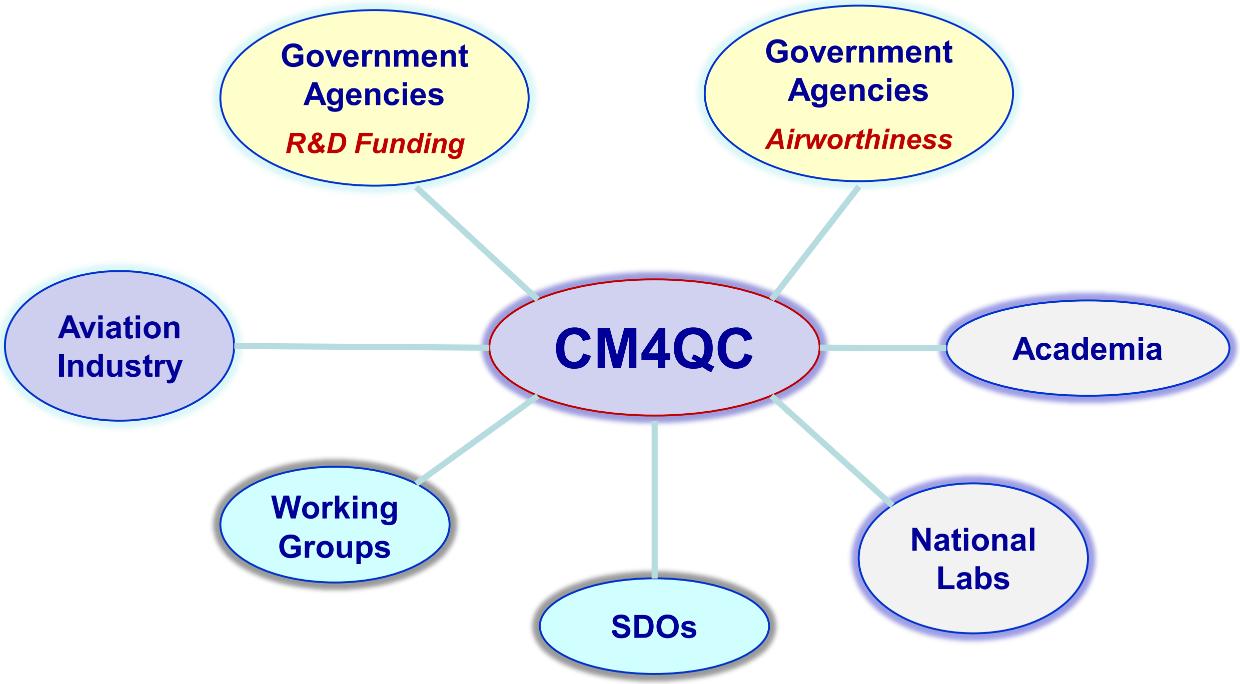
- To inform U.S. industry and the U.S. government regarding the R&D investment opportunities toward development of CM-based approaches for qualification and certification (Q&C) of process intensive metallic materials (PIM)
  - Initial focus is on powder bed fusion (PBF)
  - Subsequent consideration of wire directed energy deposition (DED) and powder DED.
- To identify key considerations and enablers required to increase airworthiness / certifying authorities' acceptance of computational methods use for Q&C of structural or flight-critical PIM parts
- To increase dialogue among the stakeholder organizations, develop a common understanding of the state-of-the-art of CM in the Q&C domain including related gaps and challenges.
- To seek opportunities for sharing capabilities, methods, tools, codes, best practices and discussion of regulatory considerations.

CM4QC Org Chart



- **WG 1**: Understanding industry priorities / timeline and key regulatory considerations
- **WG 2**: Strategies for maturation and transition of Research to Engineering
- **WG 3**: Development of required computational materials and measurement capabilities

Key Stakeholders for CM4QC SG



Development of CM Roadmap

- **Key output of the current phase of CM*4*QC activities**
- **Target completion date – mid-2022** *(estimate)*
- ***Examples* of the Roadmap topics:** ***- preliminary -***
  - *Industry's vision for CM adoption*
  - *Identification of key CM and enabling technologies*
  - *Key elements and associated methods for CM V&V framework*
  - *Technology maturation path*
  - *"State of industry" assessment of CM tools*
  - *Considerations for acceptable levels of V&V (regulatory perspective)*
  - *Key elements of the CM Eco System's*

Summary

- Gradual maturation of ICME / CM is a good path forward
  - Strong interest from industry, supported by a technical and business case
  - Demonstrated early successes *outside of regulatory domain* (e.g. material & process development and optimization, preliminary design)
  - Longer-term – increasing use in Q&C domain
- Key requirements for maturation of CM: UQ and V&V
  - A heavily data-driven process
- Metal AM as a "use case" for CM
- Complex multi-disciplinary problem → *importance of inter-agency and industry-government-academia collaboration, and engagement with SDOs*

Discussion

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