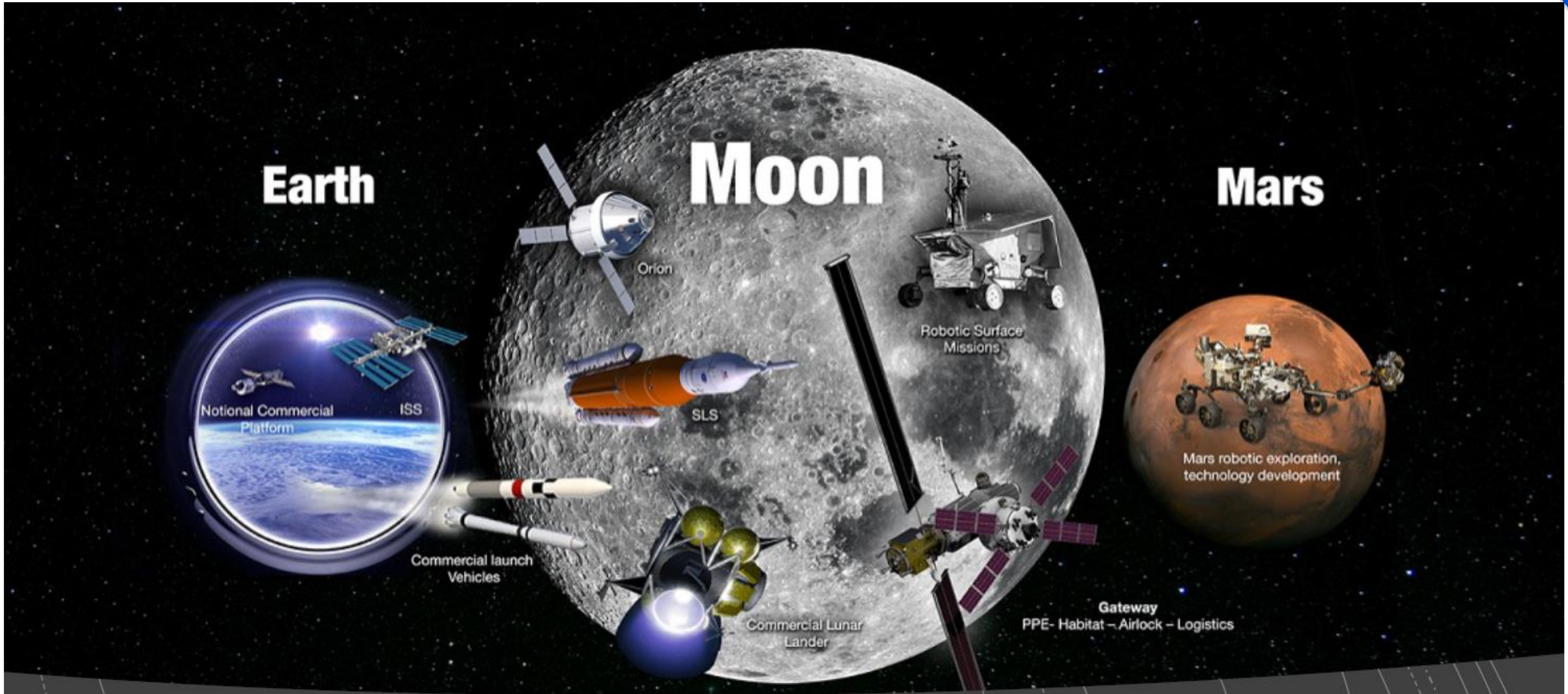
Additive Manufacturing for Space Applications

Rick Russell, NASA Technical Fellow for Materials

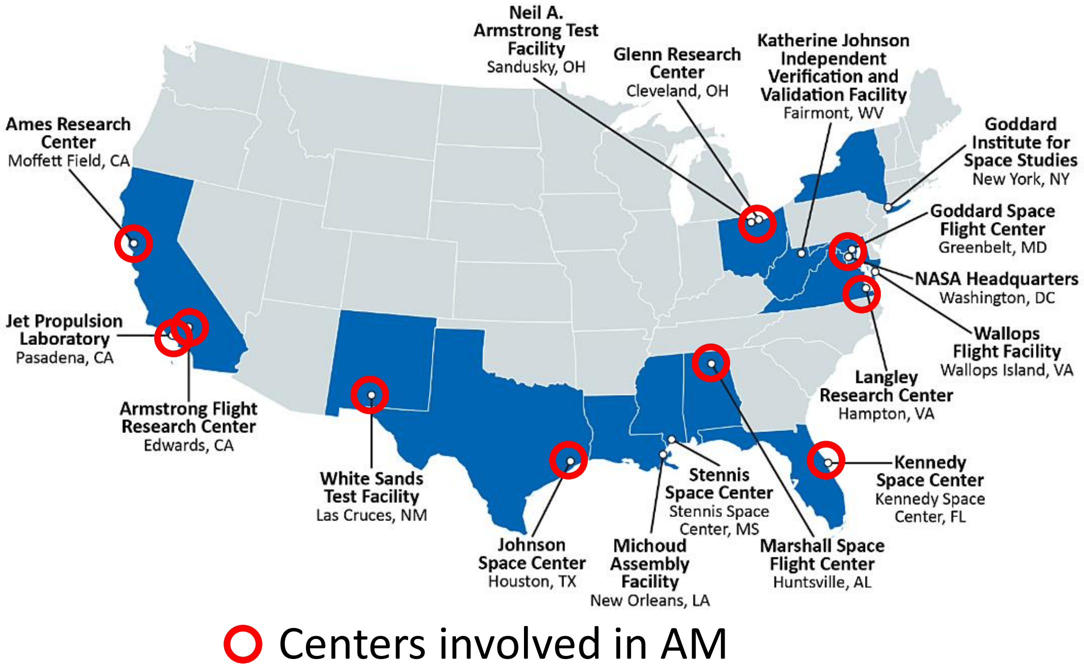
America Makes MMX
August 18, 2022



Exciting time at NASA with a lot of activities around Earth Orbit, getting ready to go to the Moon with eyes on Mars

Additive Manufacturing at NASA

- Fully embraces advantages of AM
  - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
  - Especially in delivering high value, high performance AM hardware
- NASA has dual roles
  - Drive and foster AM technology research and development in support of broad industry adoption and industrialization
  - Develop protocols for spaceflight hardware certification for access to space that can safely meet mission objectives



Additive Manufacturing at NASA

AM Technology Maturation

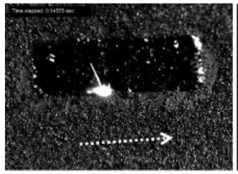
- AM Processes, Alloy, Part Development
- AM Process Selection – criteria, comparison, integrated evaluation
- New AM-able alloy development
- AIAA Book
- Material database metal AM properties to aid conceptual designs
- STRI Proposal call
- Tipping Point/ACOs/Commercial Partnerships
- Out of the world AM

Spaceflight AM Hardware Certification and Qualification

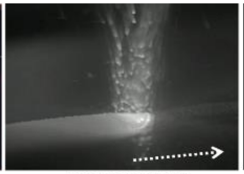
- NASA-STD-6030 and 6033
- Agency-wide AACT Team– AM Cert competency development + associated projects
- Active flight program insight activities
- Role of NDE and In Situ Process Monitoring
- Computational models for AM process validation
- Fracture control of un-inspectable AM parts

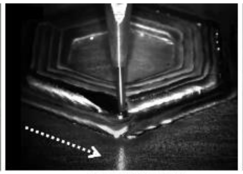
AM Technology Maturation and Process Selection

AM Processes for various applications

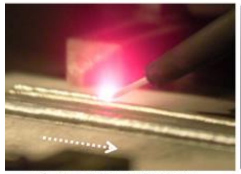

Laser Powder Bed Fusion

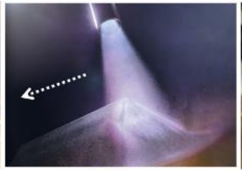

Electron Beam Powder Bed Fusion

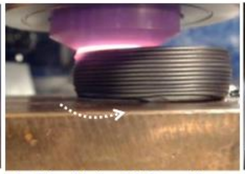

Laser Powder DED


Laser Wire DED


Arc Wire DED


Electron Beam Wire DED


Cold Spray


Additive Friction Stir Deposition

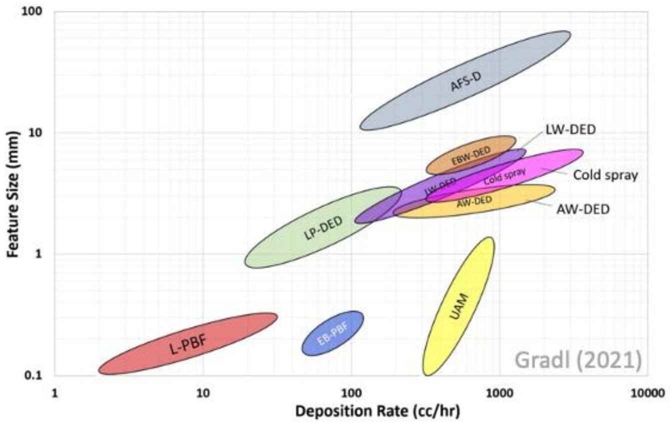

Ultrasonic Additive Manufacturing

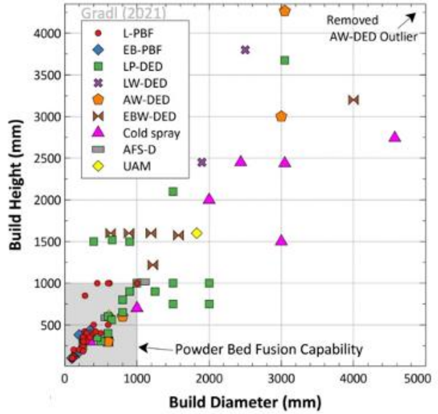
**Not inclusive of all metal AM processes*

A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden]*, C) Laser Powder DED *[Credit: Formalloy]*, D) Laser Wire DED *[Credit: Ramlab and Cavitar]*, E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar]*, F) Electron Beam DED *[NASA]*, G) Cold spray *[Credit: LLNL]*, H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic]*.

Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Release)

Various criteria for selecting AM techniques





Complexity of Features | Scale of Hardware | Material Physics | Cost | Material Efficiency

Speed of Process | Material Properties | Internal Geometry | Availability | Post Processing

Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Release)

Content credit : Paul Gradl (MSFC)

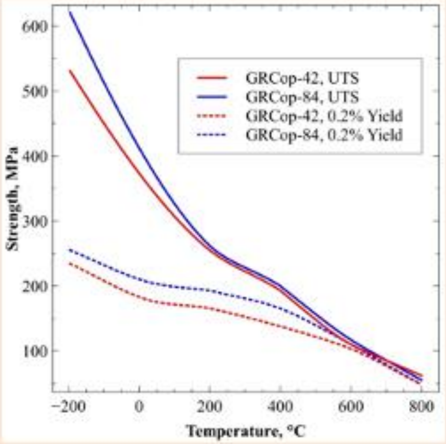
AM Technology Maturation
Rocket Engine Part Development and Hot Fire Testing

Content credit : Paul Gradl (MSFC)

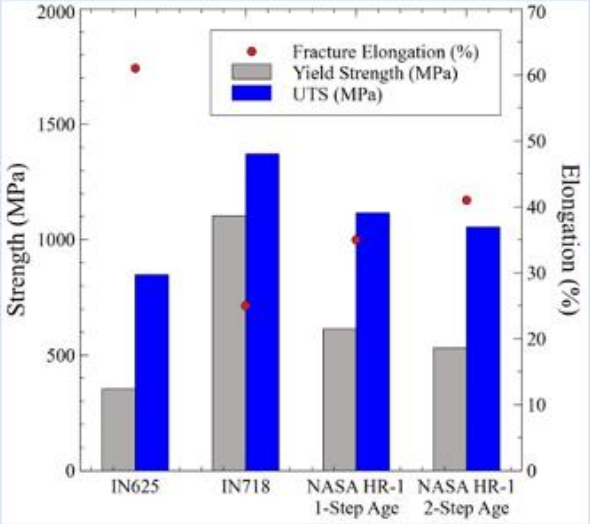
AM Technology Maturation - New Alloy Development

Enabling New Alloy Development using Additive Manufacturing

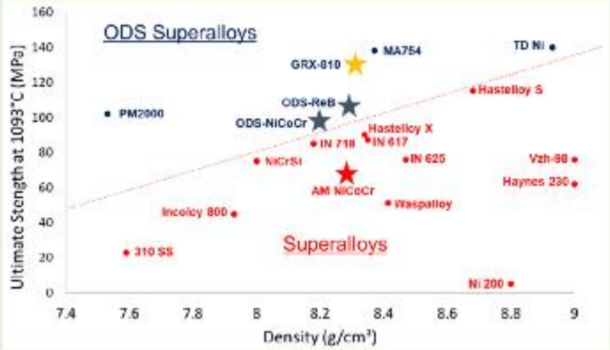
GRCop-42, High conductivity and strength for high heat flux applications

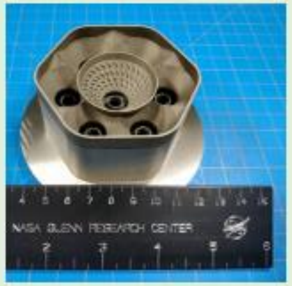


NASA HR-1, high strength superalloy for hydrogen environments



GRX-810, high strength, low creep rupture and oxidation at extreme temperatures





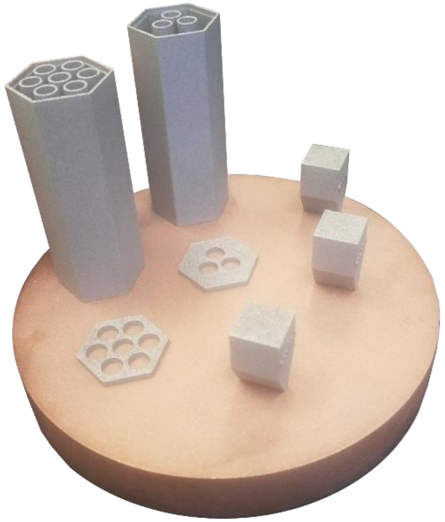
Ref: Tim Smith, Christopher Kantzos / NASA GRC 12

Content credit : Paul Gradl (MSFC)

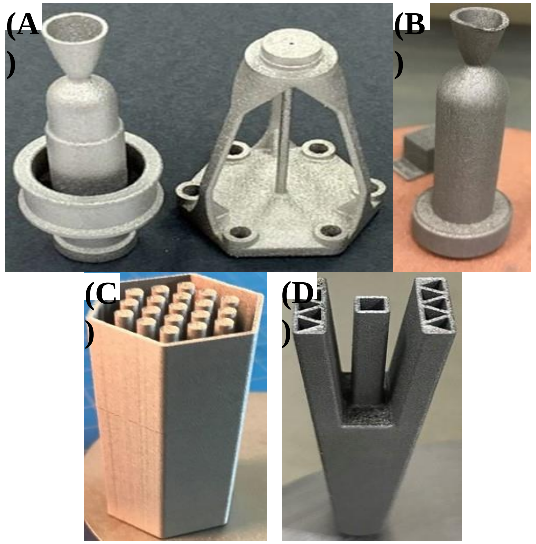
AM Technology Maturation - Refractory Alloy Development

- Refractory manufacture at MSFC
  - NTP fuel development (FY11-present)

- Refractory AM demonstrated using:
  - Laser powder bed fusion (L-PBF)
  - Electron beam PBF (EB-PBF)
  - Laser powder DED (LP-DED)
  - Electron beam wire DED (EW-DED)

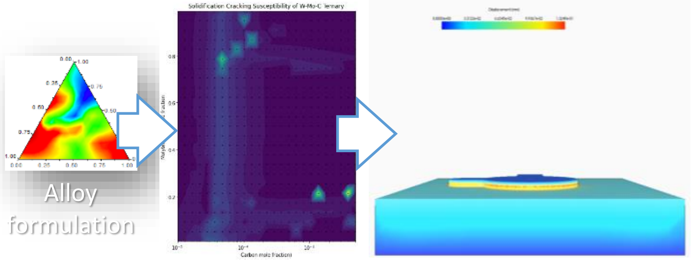


First NASA W AM build: NTP fuel clad with integrated coolant channels.



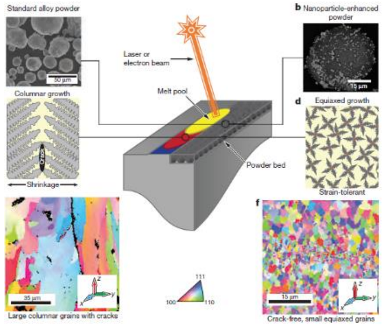
L-PBF AM (A) C103 1 N reaction chamber and thrust stand-off, (B) 1N AM W chamber, (C) AM W NTP fuel clad, (D) AM W hypersonic wing leading edge with integrated heat pipe channels.

- **Design AM-optimized refractory alloys**
  - Integrated Computational Materials Engineering (ICME).
  - Melt/solidification transformation and dynamics, crack susceptibility, AM build simulation, and property prediction.
  - NASA Ames Research Center & NASA MSFC lead.



Alloy formulation

Parameter prediction and simulation.



Nano-powder dispersoid stabilization and strengthening [1].

RHEA specimen characterization. Courtesy TAMU.

Content credit : Omar Mireles (MSFC)

AM Technology Maturation – Writing a book!

https://arc.aiaa.org/doi/book/10.2514/4.106279

Online version available now and hardcopy in mid-August

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022). *Metal Additive Manufacturing for Propulsion Applications*. AIAA Progress in Astronautics and Aeronautics Book Series. https://arc.aiaa.org/doi/book/10.2514/4.106279

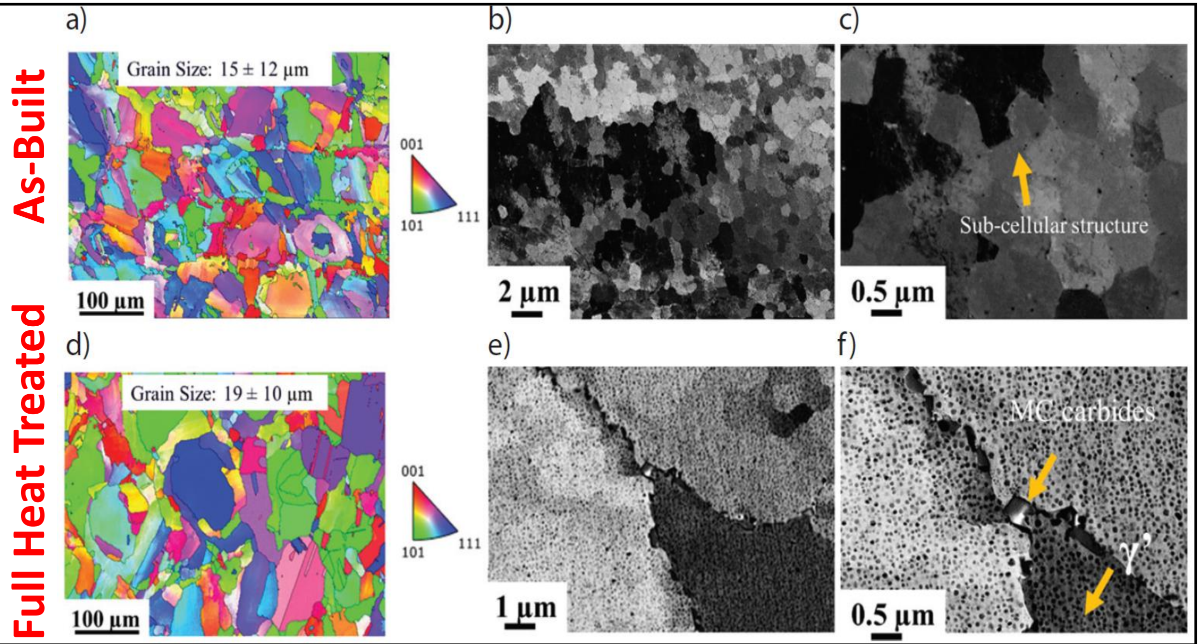
Additive manufacturing (AM) processes are proving to be a disruptive technology and are grabbing the attention of the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace. The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.

Content credit : Paul Gradl (MSFC)

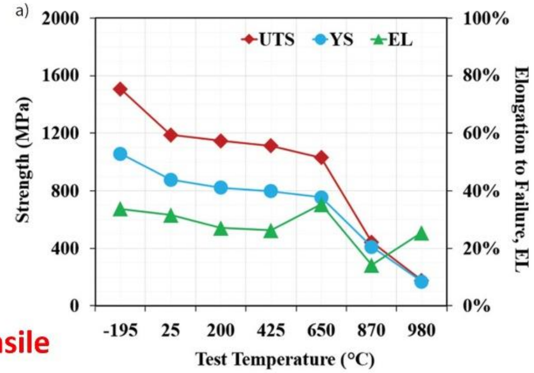
AM Technology Maturation – Property Database

Material	Power (W)	Layer Height (mm)	Scan Speed (mm/s)	Hatch Distance (mm)
Haynes 282	285	0.04	960	0.13

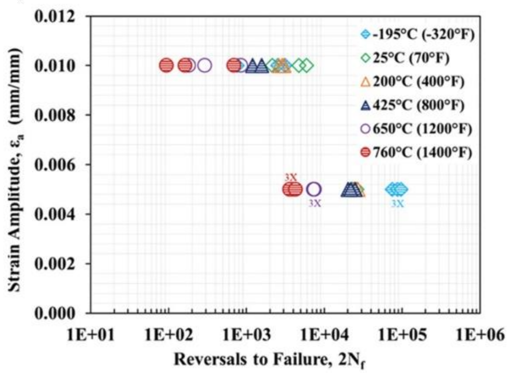
Procedure (Designation)	Temperature (°C)	Time (hrs)	Cooling
Stress Relief (SR)	1065	1.5	Furnace cool
HIP [2]	1162/103 MPa	3.5	Furnace cool
Solution Annealed (SOL)	1135	1	Argon quench
Double Step Aging (AGE)	1010	2	Furnace cool at 10°C/min
	788	8	2 bar Argon gas at 20°C/min



- Obtained material samples from L-PBF and LP-DED vendors with full traceability
- Characterization of as-built samples and evolution through heat treatments to select optimal heat treatment cycle (HIP baselined)
  - Partnership with Auburn NCAME
- After appropriate heat treatment cycle, complete temperature dependent tensile and fatigue testing
- Partial data set will be published as an appendix in upcoming AIAA book on AM
- All data will be published in a handbook and raw data uploaded to selected database (potentially MAPTIS)

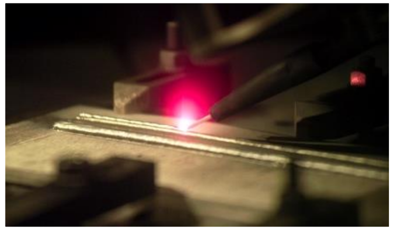


Tensile



LCF

AM Technology Maturation
Electron Beam Freeform Fabrication (EBF3)

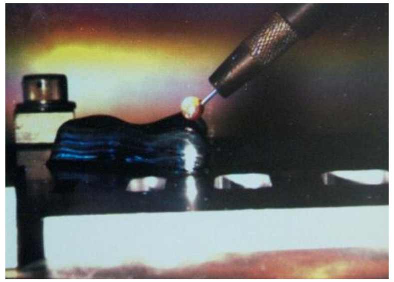


Ground-Based System for Large Structural Components

- Electron beam melts pool on substrate, metal wire added to build up parts in vacuum environment
- Large build volume (72” x 48” x 24”) and high deposition rates (3 to 30 lbs/hr) possible with lower resolution for parts that will be finish machined
- Dual wire-feed and free-standing, 6-axis part manipulation enables functional gradients and addition of details onto simplified preforms
- Alloys deposited include aluminum (2219, 2139, 2195), stainless steel (316), nickel (In625, In718), titanium (Ti-6-4, CP Ti), copper

Portable Systems for In-Space Simulation Experiments

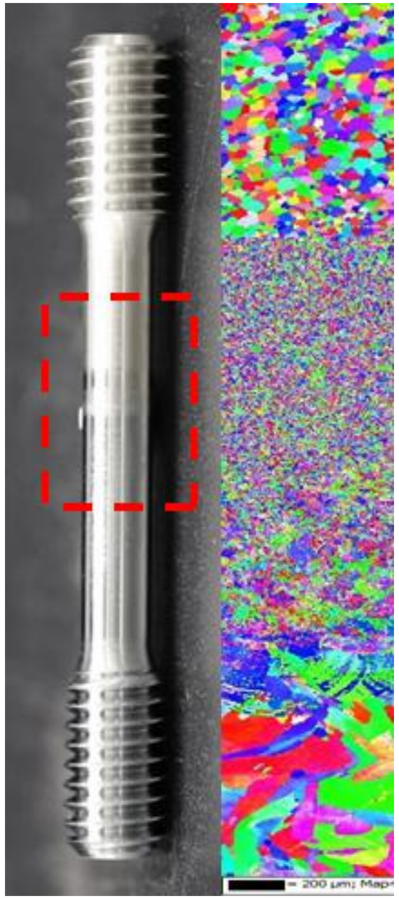
- First successful microgravity demos February 2006
- Microgravity tests support fabrication, assembly and repair of space structures and in-space manufacturing of spare parts
- Smaller build volume (12” x 12” x 12”) with finer wire for more precise deposits minimizing or eliminating finish machining
- Two systems designed and integrated in-house to assess different approaches for reducing power, volume and mass without impacting build volume



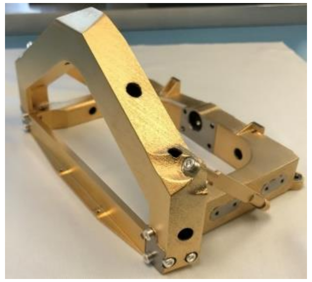
POC: Karen.M.Taminger@nasa.gov

AM Technology Maturation
Jet Propulsion Lab

- Additive hardware on Mars 2020 (Planetary Instrument for X-ray Lithochemistry)
  - Used tenets similar to NASA 6030
  - Structural components are EB-PBF Ti-6Al-4V
  - Non-structural components (covers) are L-PBF AlSi10Mg
- JPL qualifying L-PBF Al 6XRAM2 and Ti-6Al-4V to QMP-A per NASA-STD-6030 on EOS M290s
- Developing gradient alloy systems using Laser DED for potential inclusion on the Sample Return Lander

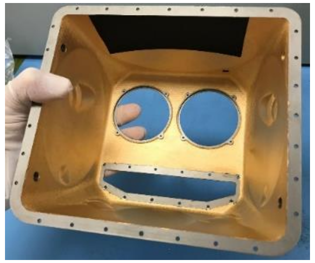


Gradient alloy sample, with EBSD plot of gradient region

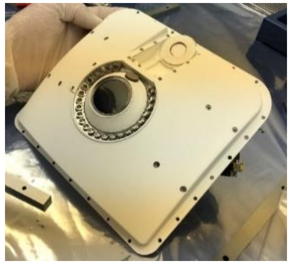


X-ray bench and support

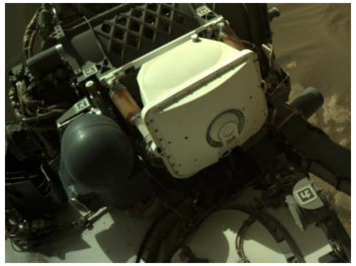
Mounting frame



Back cover



Front cover

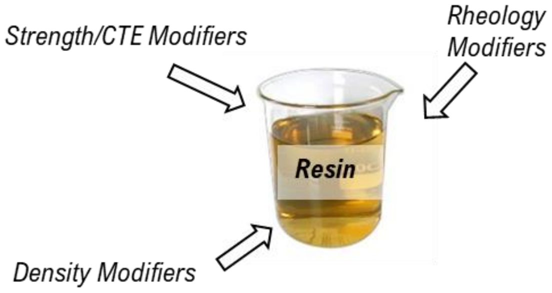


PIXL in service on Mars, image courtesy NASA/JPL-Caltech

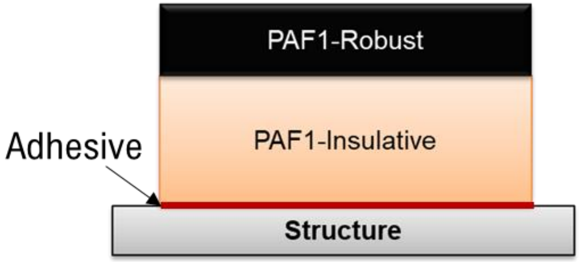
AM Technology Maturation
AM Thermal Protection System Development

Material development

Filled high temperature thermoset resins

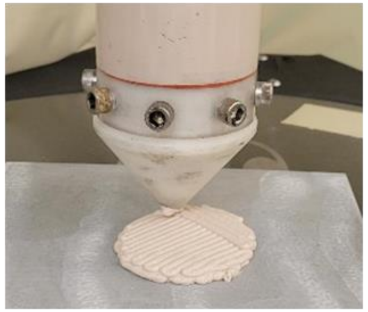


Multi-layer TPS construction

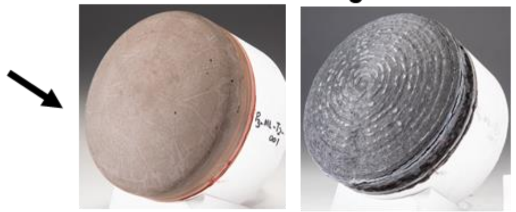


Material evaluations

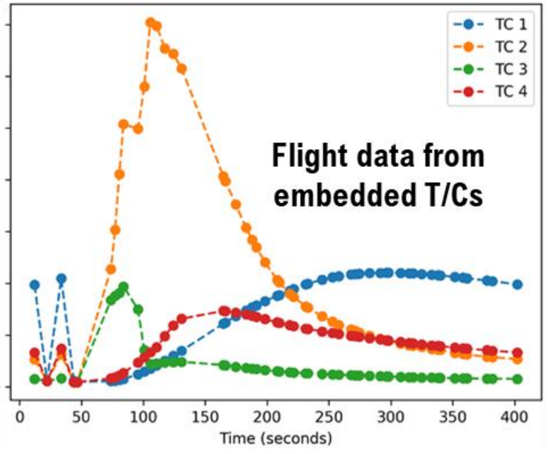
Print



Thermal Testing



Flight testing of an AMTPS heat shield

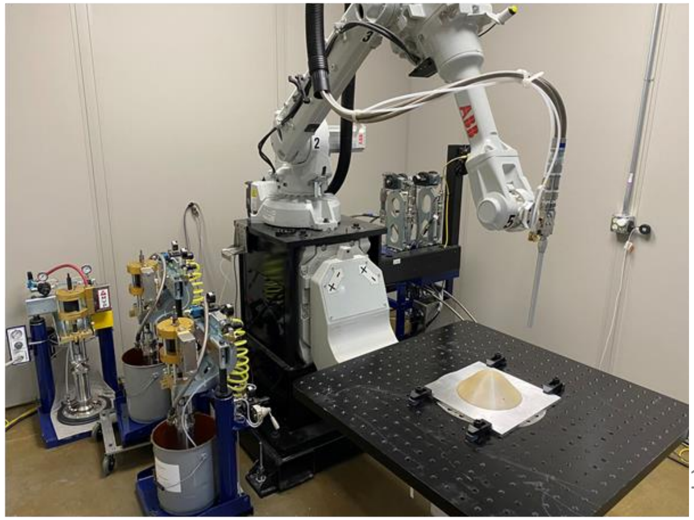


Build of AMTPS flight heat shield

University of Kentucky

Process scale-up

Large scale robotic AMTPS system under development at Oak Ridge National Lab



Oak Ridge National Laboratory

AM Technology Maturation
STRI Space Tech Research Grants Proposal Call

The goal of the institute is to conduct ground-breaking interdisciplinary research to exploit new advancements in computational tools in concert with experimentation to advance the use of model-based tools for accelerated certification of critical additively manufactured aerospace products.

1.Further the understanding of materials-processes-structure-property relationships for AM through integrated computational materials engineering (ICME), materials genome initiative (MGI), and other model-based approaches.

2.Demonstrate uncertainty quantified physics-based models and simulations to understand the factors that can affect the formation, distribution, and effects of process-induced defects and address other principal sources of variability.

3.Integrate and apply methodology, software tools, artificial intelligence and machine learning, and databases based on computational and experimental tools to a model-centric certification approach via digital twins.

4.Educate, Train, and Connect the Materials and Manufacturing R&D Workforce to promote US economic competitiveness and leadership in space and grow a world-class AM workforce.

Award Information - Preliminary Proposals Closed on 8.3.2022

- Expected duration: **5 years**
- Award amount up to **$3M per year** ($15M over 5 years)
- Award instrument: grants to U.S. universities
- Low to mid TRL
- Institutes expected (and *empowered*) to implement their own review internal processes
- NASA oversight – annual reviews and brief quarterly status reports

Content credit : Mallory James (MSFC)

AM Technology Maturation
Space Technology Research Grants Early Innovation Awards

ESI20 – Year 2 to Year 3 Continuation Advancement of Additive Manufacturing Techniques for High Temperature Materials	**INSTITUTION**
Efficient Alloy and Process Design for Additive Manufacturable Refractory Alloys	Texas A&M University
Design of Refractory Alloys for Processing by Additive Manufacturing and Service at Extremely High Temperatures	Carnegie Mellon University
Conventional and Flash Sintering of Tungsten and Tungsten Alloys Prepared by Robocasting of ALD-doped Precursors	University of Colorado, Boulder

AM Technology Maturation
In-Space Manufacturing (ISM)

On-Demand Manufacturing & Recycling of Plastics

- 3D printing and recycling system designed to repeatedly recycle plastic materials into feedstock for additive manufacturing in the microgravity environment of the ISS.

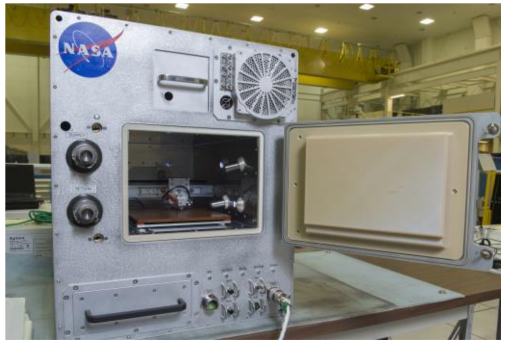
On-Demand Manufacturing of Metal

- Additive and subtractive manufacturing systems for creating metal parts on demand.

On-Demand Manufacturing of Electronics

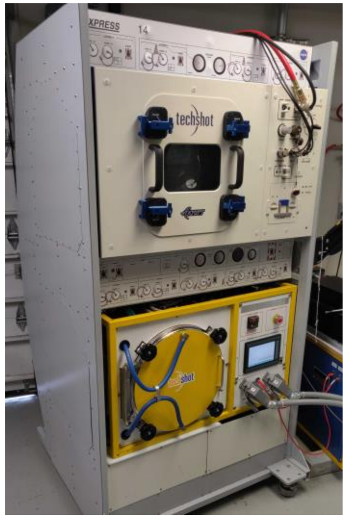
- Ability to fabricate electronics during missions, such as crew and structural monitoring systems and sensors.

First 3D printer in space, 2014 ISS Demonstration



Refabricator ISS Demonstration

Redwire Commercial ISS Additive Manufacturing Facility (AMF)

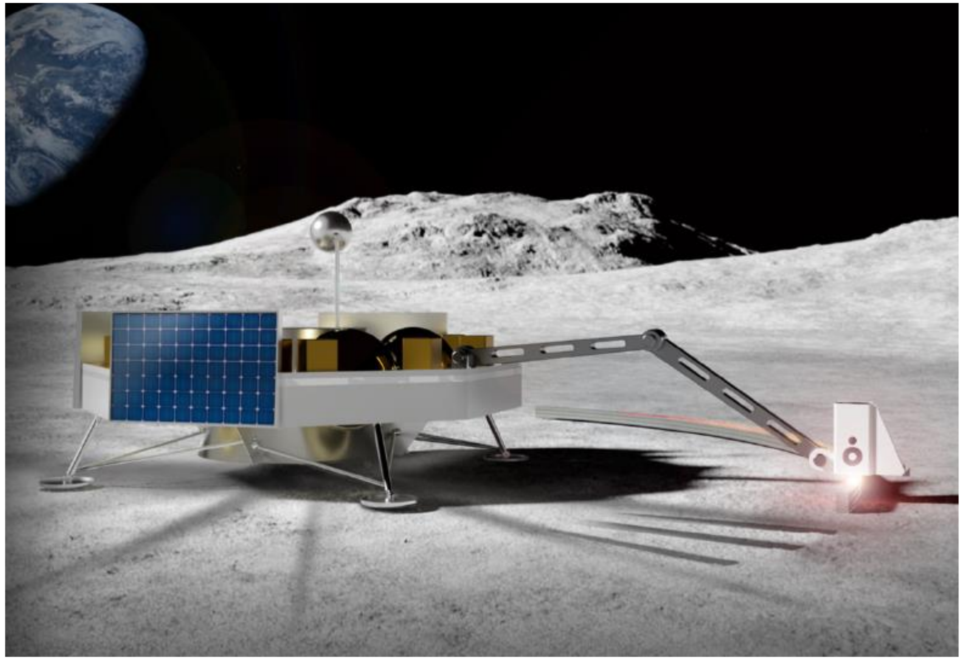


Techshot Fabrication Laboratory

POC: Karen.M.Taminger@nasa.gov

AM Technology Maturation
Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT)

- **Develop, deliver, and demonstrate capabilities to:**
  - Protect crew and hardware
  - Build infrastructure
  - Construct landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials
  - Candidate methods include both cementitious and straight regolith (melting) methods



Demonstration Mission, DM-1 (~2026)

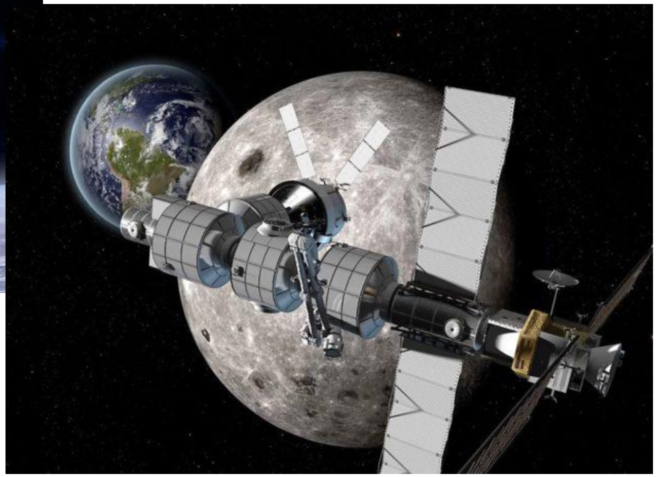
Partners: ICON, SEArch+, USAF, Defense Innovation Unit, Texas Air National Guard

Spaceflight AM Certification
Motivation for Standard Development

- AM parts are being use for NASA programs in critical applications
- Human exploration of space, especially deep space, requires <u>extreme</u> reliability

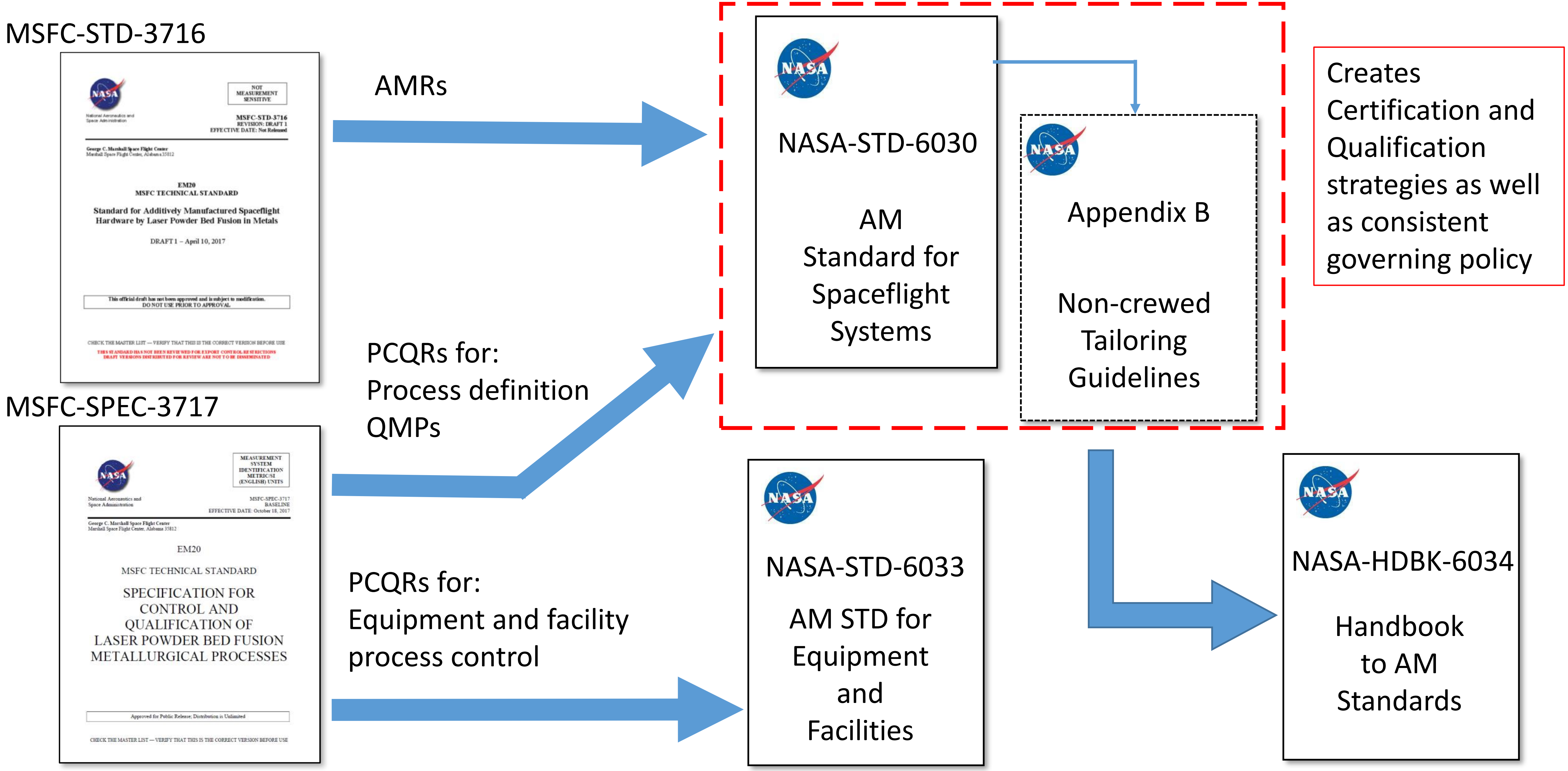
Low Earth Paradigm

Deep Space Paradigm



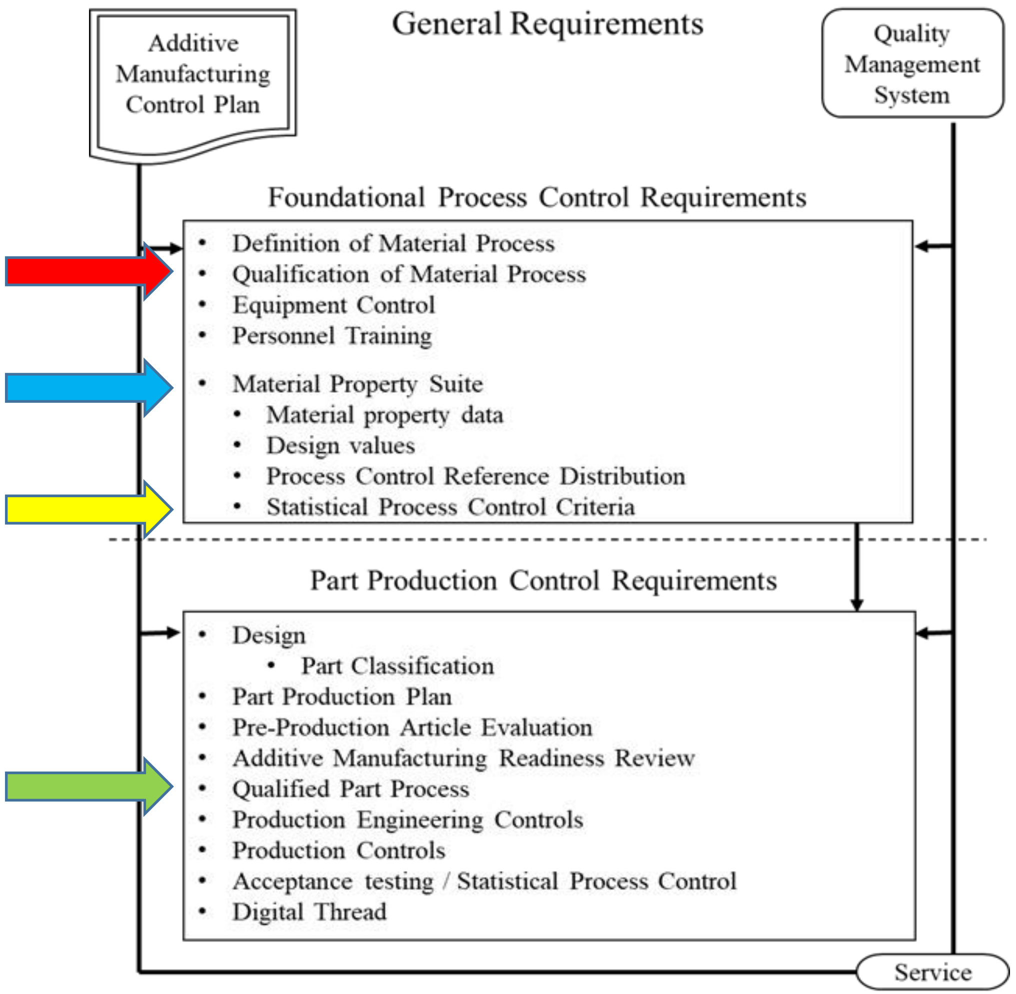
250 miles vs 83,000,000+ miles
15-30 year life vs 50 to 100+ years
Replacement parts vs Limited replacement parts
Safe haven of earth vs no safe haven

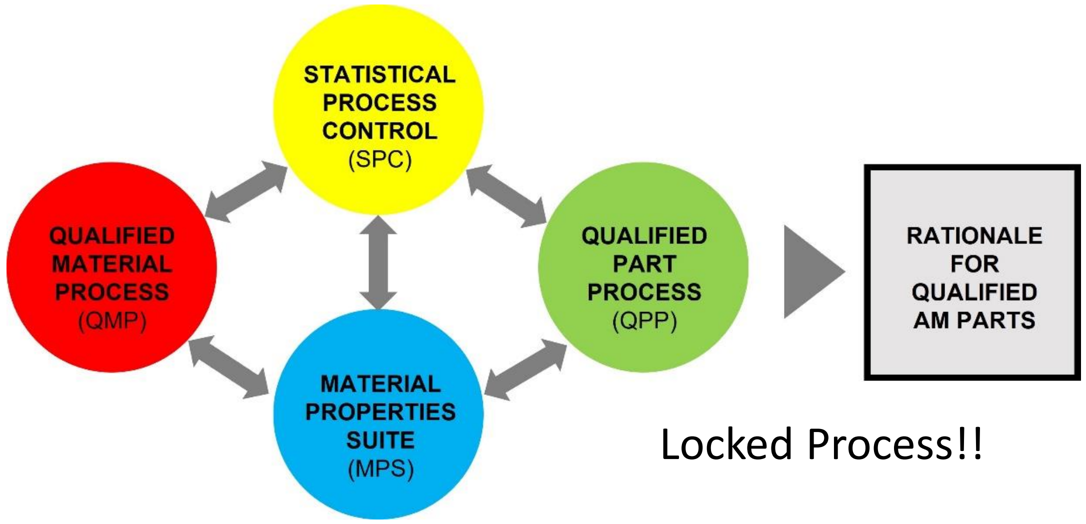
Spaceflight AM Certification Standard Development



NASA-STD-6030: Summary of Methodology

- General Requirements
  - Additive Manufacturing Control Plan (AMCP) and Quality Management System (QMS)
  - Backbone that defines and guides the engineering and production practices
- Foundational Process Control Requirements
  - Includes the requirements for AM processes that provide the basis for reliable part design and production
- Part Production Control Requirements
  - Includes design, assessment controls, plans (PPP), preproduction articles and AM production controls





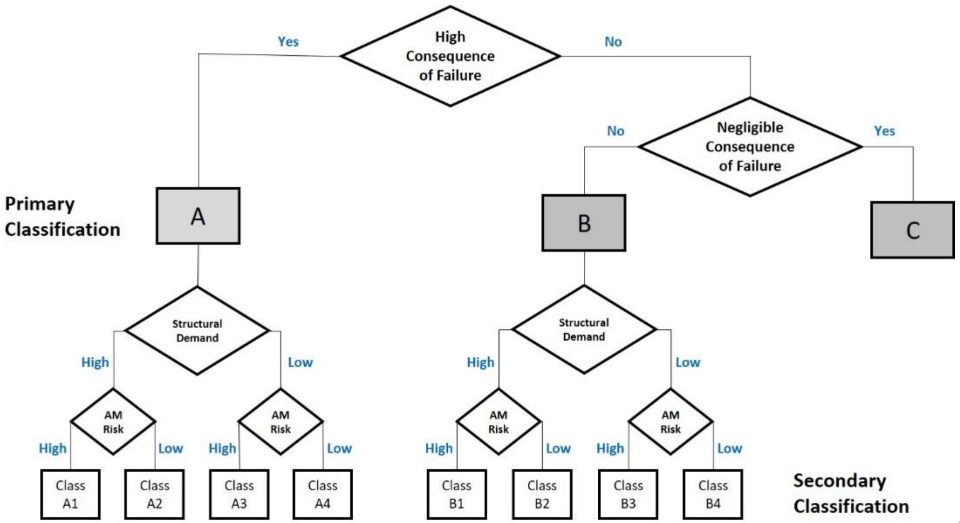
Locked Process!!

NASA-STD-6030: Key Elements

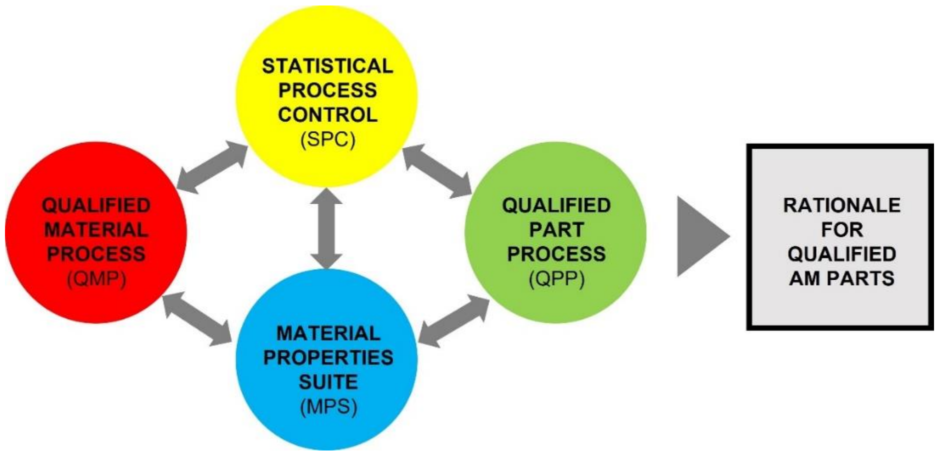
Applicable Technologies

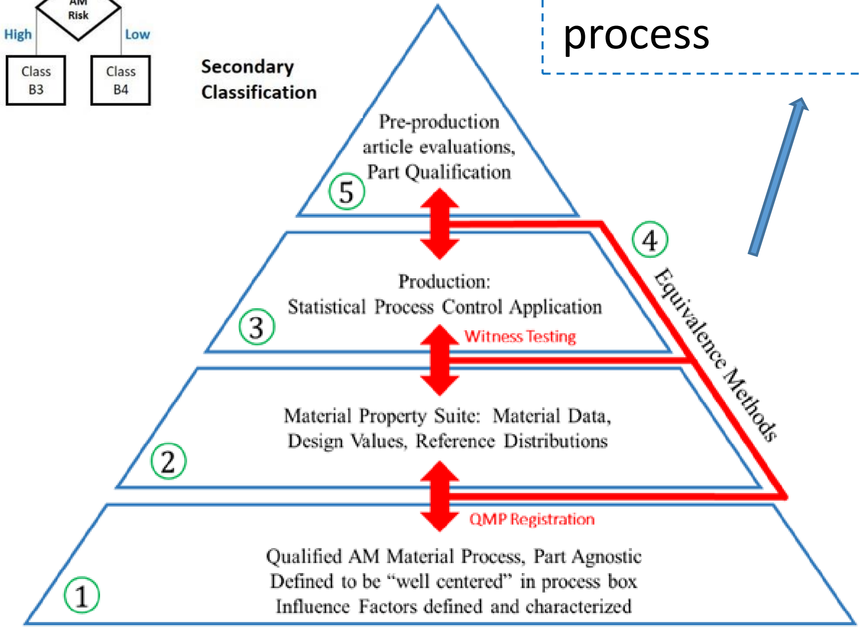
Category	Technology	Materials Form
Metals	Laser Powder Bed Fusion (L-PBF)	Metal Powder
	Directed Energy Deposition (DED), Any Energy Source	Metal Wire
	DED, Any Energy Source	Metal Blown Powder
Polymers	L-PBF	Thermoplastic Powder
	Vat Photopolymerization	Photopolymeric Thermoset Resin
	Material Extrusion	Thermoplastic Filament

Classification System



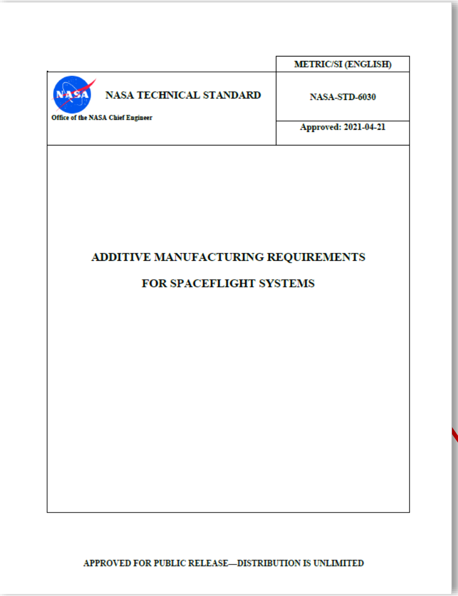
Approach is heavily rooted in metallurgical understanding and respecting the evolving and meticulous metallic AM process





NASA-STD-6030: Training Class

- Class on NASA Approach to AM Q&C Methodology at ***The Aircraft Airworthiness & Sustainment Conference***
  - Class: August 29, 2022
  - Full Conference: Aug 29 – Sept 2
  - The Sawgrass Marriott Resort, Ponte Vedra, FL
- Course Objectives:
  - Reinforce a basic understanding of AM processes
  - Become familiar with NASA-STD-6030 and NASA-STD-6033 requirements
  - Appreciate integrated path to Qualification and Certification
  - Understand products necessary to get you to Qualification and Certification



METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6030

Approved: 2021-04-21

ADDITIVE MANUFACTURING REQUIREMENTS

FOR SPACEFLIGHT SYSTEMS

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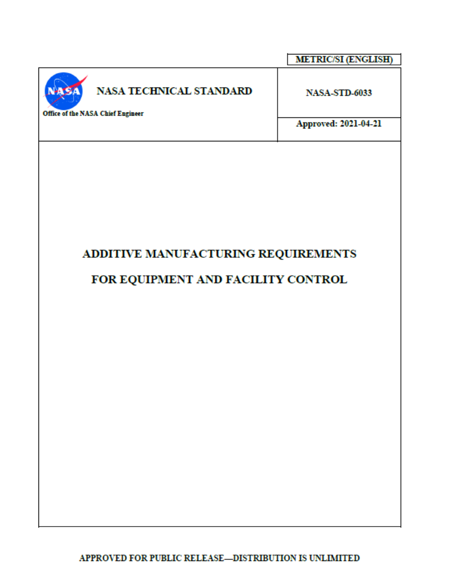

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NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6033

Approved: 2021-04-21

ADDITIVE MANUFACTURING REQUIREMENTS

FOR EQUIPMENT AND FACILITY CONTROL

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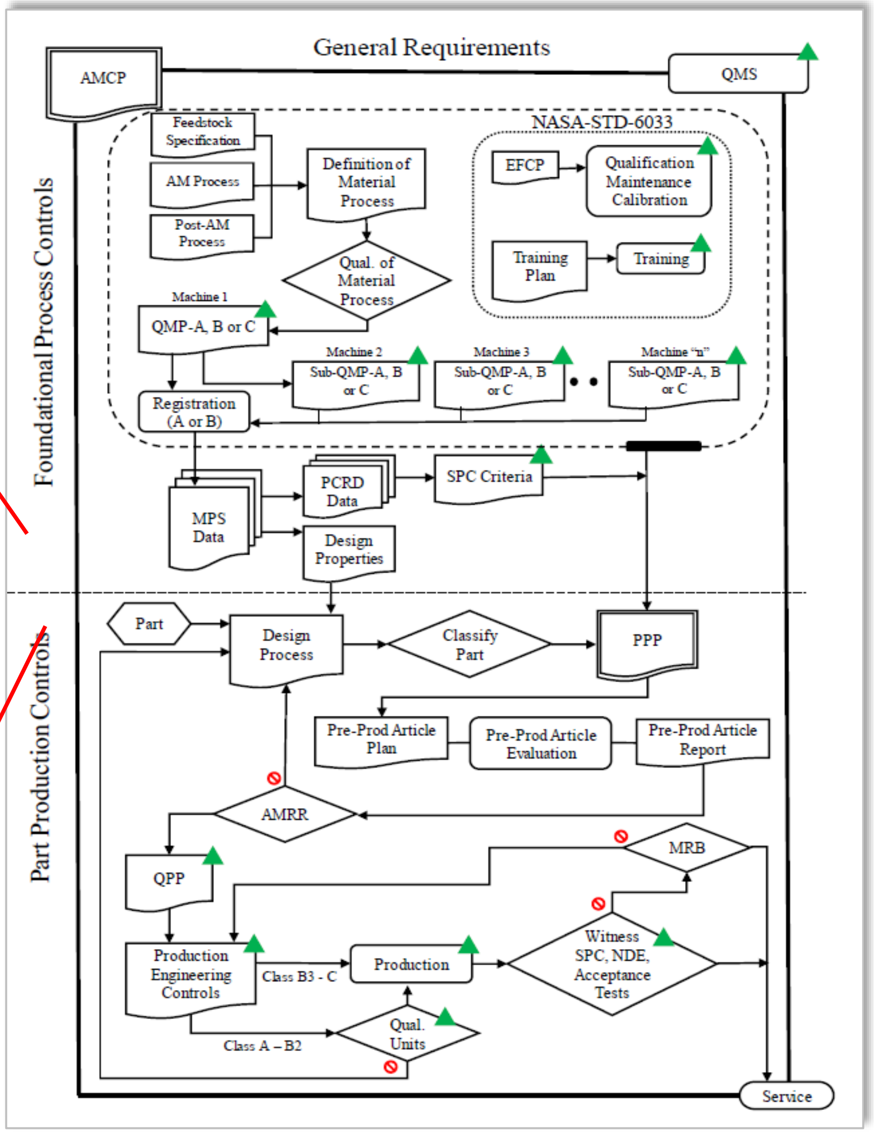
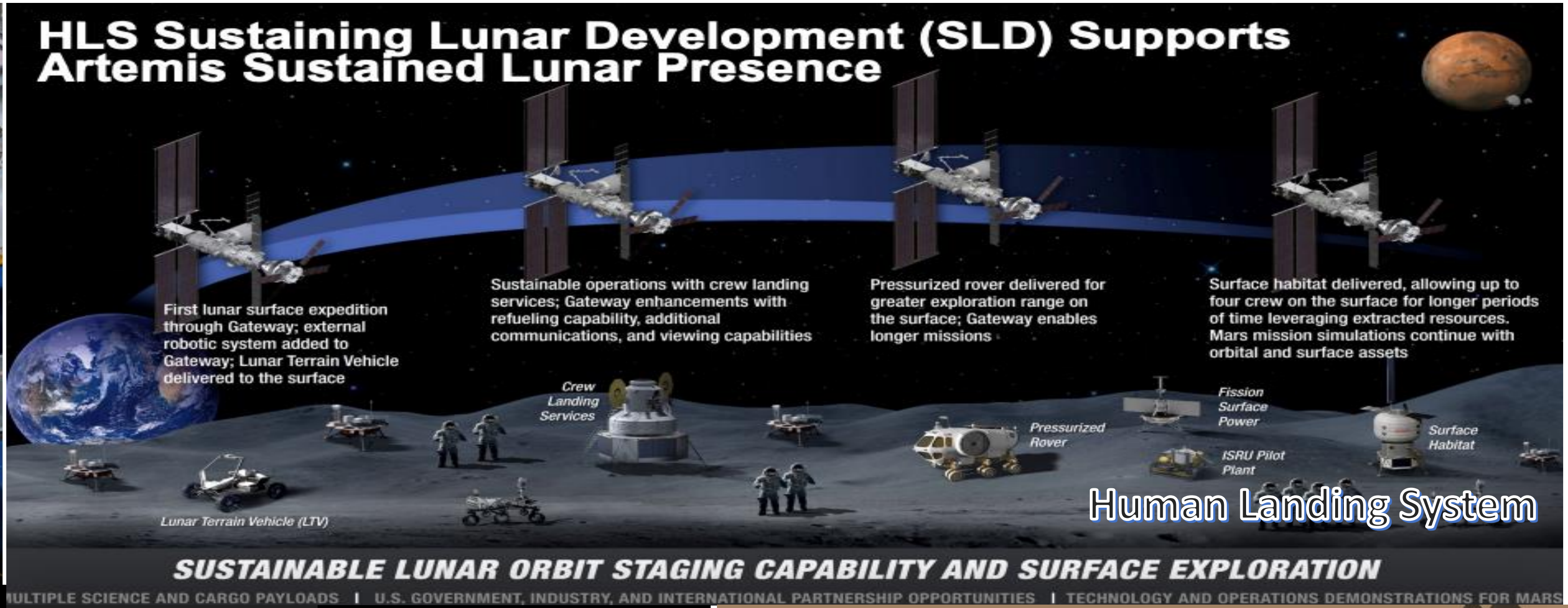


From NASA-STD-6030

Spaceflight AM Certification
Active Flight Program Support



Spaceflight AM Certification Collaborations

Carnegie Mellon University

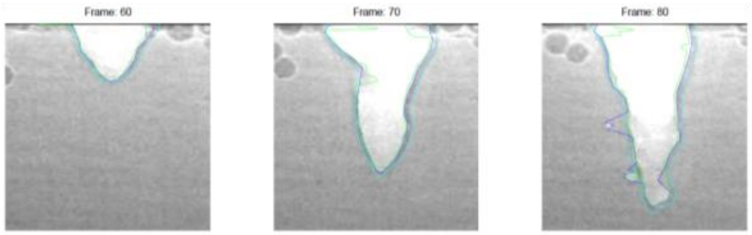
NASA University Leadership Initiative at Carnegie Mellon University on *Development of an Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation*
(6 universities, 2 small businesses)
Focused on development of defect-based process maps that guide AM production machine settings to minimize or eliminate those manufacturing defects.
→ Process Windows to Guide AM Machine Settings

Transformation Tools and Technologies Project's effort on *Qualification and Certification of Advanced Manufacturing-Based Materials and Structures*
Focused on understanding the effect of processing on evolution of material microstructure and defects and the resulting effects of microstructure and defects on lifecycle performance
→ Microstructurally-Informed Durability and Damage Tolerance

Content credit : Ed Glaessgen (LaRC)

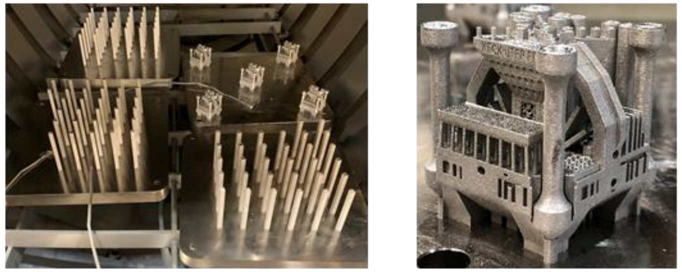
Spaceflight AM Certification
Transformational Tools and Technologies Project

Data Science



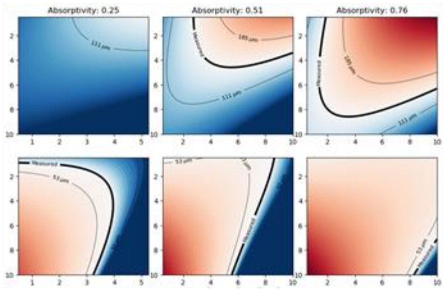
Automated vapor depression boundary identification using machine vision

PSP Round Robin



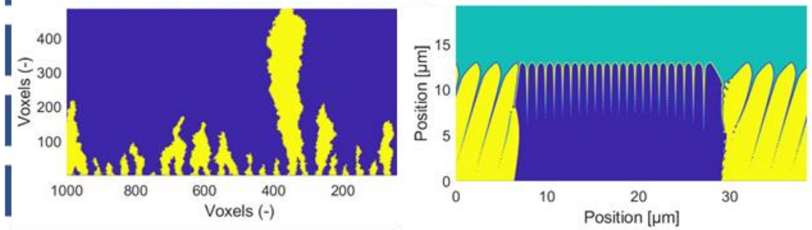
Process structure property (PSP) round robin for laser powder bed fusion machine variability

Thermal Simulation



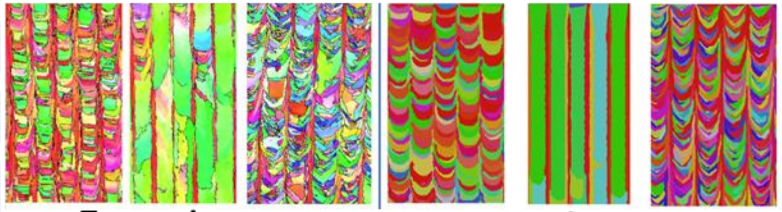
Efficient and flexible probabilistic calibration of finite element (FEM) process models using measured data

Multi-Fidelity Microstructure Simulation



Crystallographic texture evolution modeling through joint Monte Carlo & Phase Field simulations

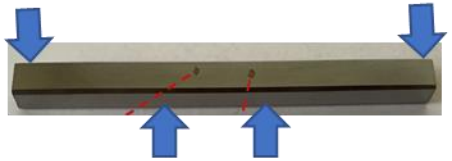
Microstructure Simulation and Validation



Experiment Simulation

Simulated grain shapes and textures compared with experiment

Mechanical Testing



4 Point Bend Specimen

Compact Tension Specimen

Understanding the effects of processing defects on fatigue crack initiation and propagation

Content credit : Ed Glaessgen (LaRC)

Approved for Public Release on 08/19/2021
Document ID: 20210020659

Spaceflight AM Certification
Agency-wide AM Cert support Team (AACT)

- **Need for AACT:** There is no formal and "institutionalized" group, no formal authority for technical integration across agency, scattered and sporadic support to high-risk programs.
  - Missed opportunity for knowledge advancement and gap closure, everyone needs it but no one program could fund it.
  - Education of NASA workforce and SMEs; hinderance to being a smart buyer.
  - Technical hurdles for AM certification remain significant

- **Goal:** Enabling AM adoption as safely as possible without additional barriers
  - *Develop* Smart Buyer NASA workforce to ensure sustainable agency-wide AM Certification
  - Advocate for critical AM tech advancement and capabilities across the agency, cross agency risk reduction
  - Provide centralized leadership for AM technical integration across agency

- **Near-Term Objective:**
  - Work risk mitigation/capability enhancing projects to close gaps in current certification knowledge
  - Form AM SME competency development program (OJT training, mentoring, external engagement)
    - Train them to be, and be recognized as, the go-to experts
  - Continue supporting programs with critical AM qual/cert activities

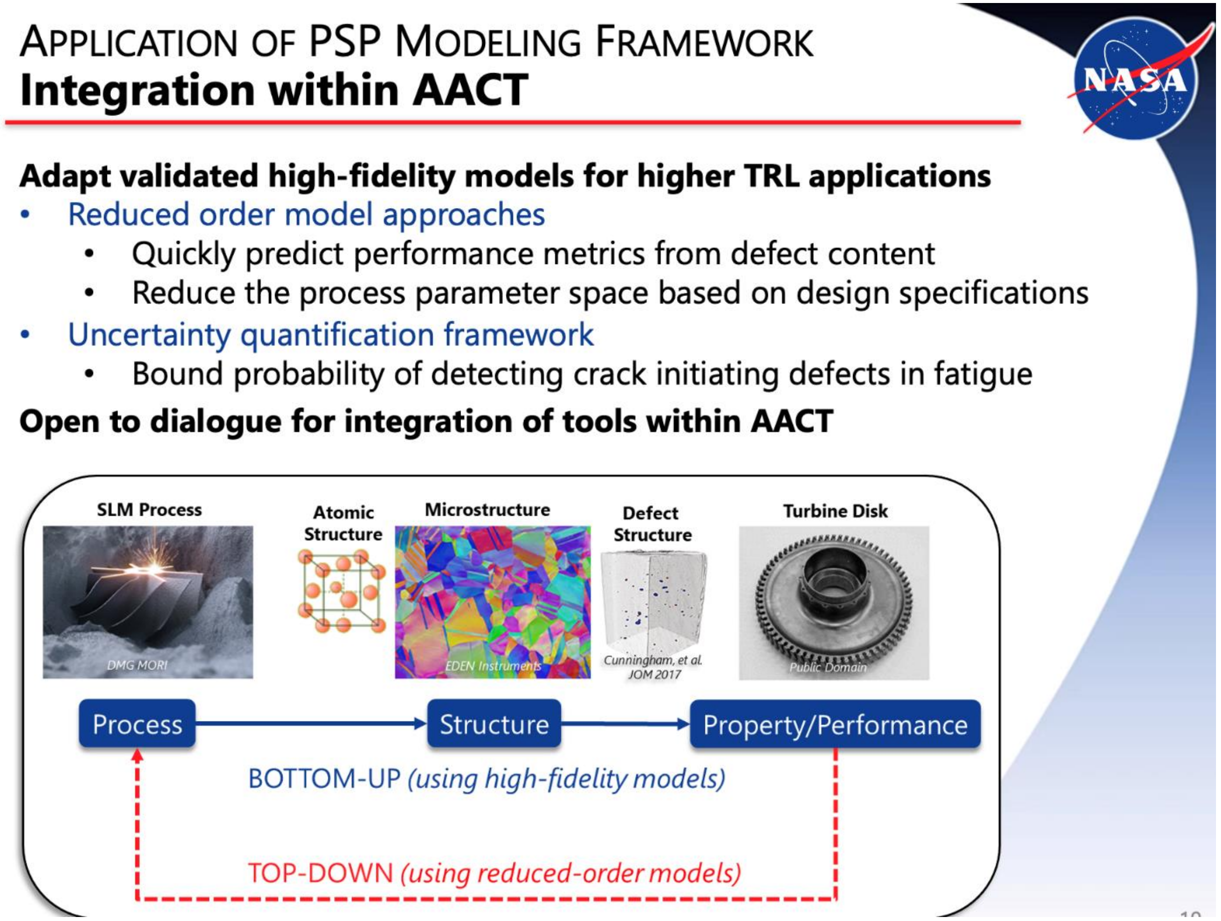
Spaceflight AM Certification
Fracture Control Framework for AM Parts

- Fracture control is reliant on understanding the design, analysis, testing, inspection and tracking of hardware.
  - The adaptation of state-of-the-art AM technologies introduces new and unique challenges
    - e.g. Multiple lasers and adaptive technologies
  - For AM applications the application of conventional NDE techniques is questionable
  - There is a need to produce alternate approaches through the adaptation of a Probabilistic Damage Tolerance Approach (PDTA)
    - Computational modeling for AM
    - Understanding the "Effects of defects"
    - In-situ monitoring and inspection

These items MUST Work together not separate

Spaceflight AM Certification Computational Modeling of AM

- Two aspects of qualification and certification to consider:
  1. Design Certification
     - Demonstration that design meets all the requirements of the defined mission
  2. Hardware Certification
     - Demonstration that the hardware meets all the requirements of the certified design

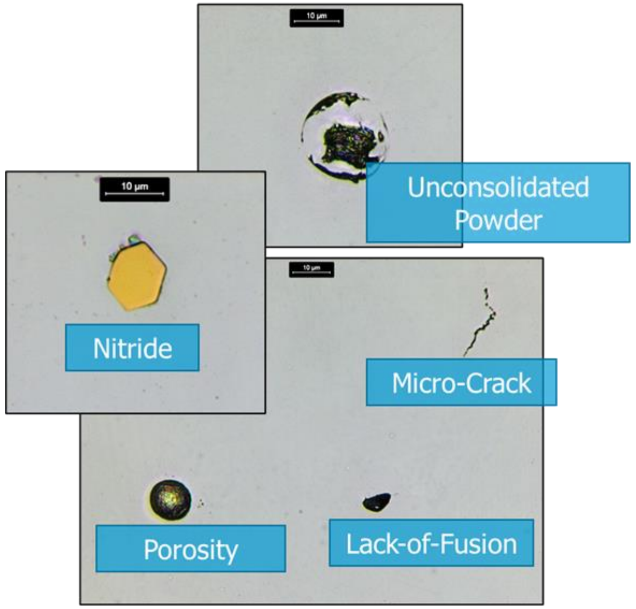


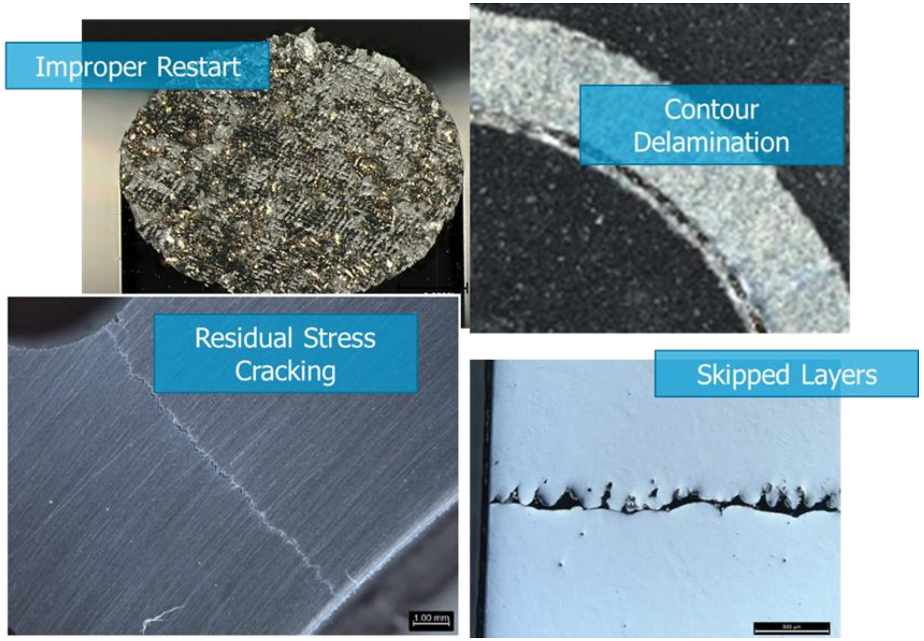
Spaceflight AM Certification
Effects of Defects

<u>Flaws in AM fall into two categories</u>

1. **<u>Inherent flaws</u>** – Flaws that are representative of the characterized nominal operation of a qualified AM process.
2. **<u>Process Escape flaws</u>** – Flaws that are not representative of the characterized nominal operation of a qualified AM process.

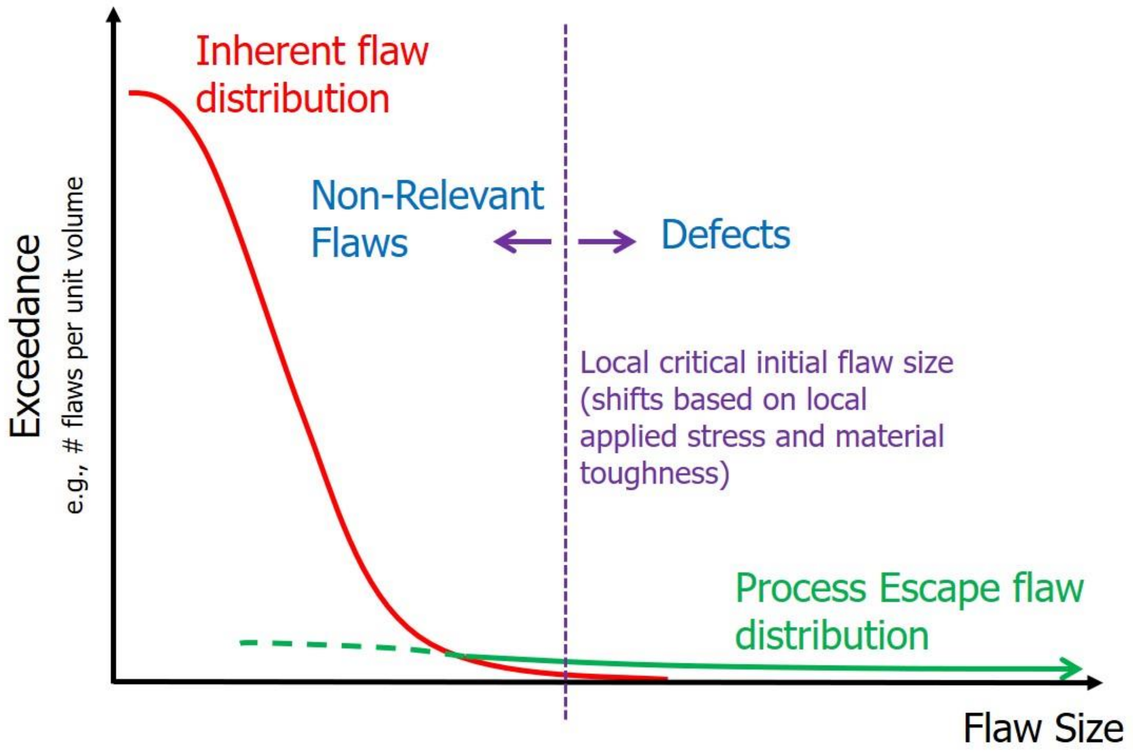
- **<u>Flaw</u>** – an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.
- **<u>Defects</u>** – one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.





Spaceflight AM Certification
Effects of Defects

- Phase 1: Understanding inherent defects
- Phase 2: Using process controls to control inherent defect populations
- Phase 3: Understanding Rogue (process escape) defects



Spaceflight AM Certification In-Situ Monitoring

- NASA-STD-6030 requires
  - Quantitative NDE for class A parts
  - NDE for process control for class B parts
  - In-situ monitoring must be qualified in manner analogous to other NDE techniques

Must meet requirements of NASA-STD-5009

- Two main functions of in-situ process monitoring:

- <u>Process Control</u>
  - Real-time warnings of build problems
  - Check for process drift
  - Monitor effects of parameter changes
- <u>Part Quality</u>
  - Quantitative analysis
  - Requires correlations between indications, physics of the process and actual defects
  - Need to know probability of detection

Spaceflight AM Certification In-Situ Monitoring

- Challenges to using in-situ monitoring:
  - Indirect defect observations will require an understanding of the physics
  - Current certification approach requires a locked process
    - For real-time changes a new approach is needed
  - Current certification approach does not accommodate the use of adaptive systems
    - Creates two issues for verification
      1. Verify the senor performance, algorithm and machine response (control system)
      2. Verify the physics – does controlling this parameter result in a good part?

Spaceflight AM Certification
In-Situ Monitoring NASA/ASTM Workshop

- NASA sponsored a workshop focused on in-situ technology readiness for application in AM qualification and certification June 28-29, 2022.
- The workshop was run by the ASTM AM CoE
- Objectives
  - Middle-to-high technology readiness level (TRL) in situ technologies that show promise for near-term use
  - Approaches to qualification of in situ methods for use as a quality assurance tool in critical applications
  - Methods for integrating in situ data in AM production including real-time detection and closed-loop control
  - Standardization gaps, key challenges, and research & development needs

- Day 1 included 9 technical talks and a panel discussion
- Day 2 included breakout sessions
  - Topic 1: Technical Development/Maturation
  - Topic 2: Types of Detectable Defect States
  - Topic 3: Data/Defect Correlation
  - Topic 4: Real-Time Detection & Closed-Loop Control
  - Topic 5: Standards

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

Event outcome = Public Roadmap

Questions?