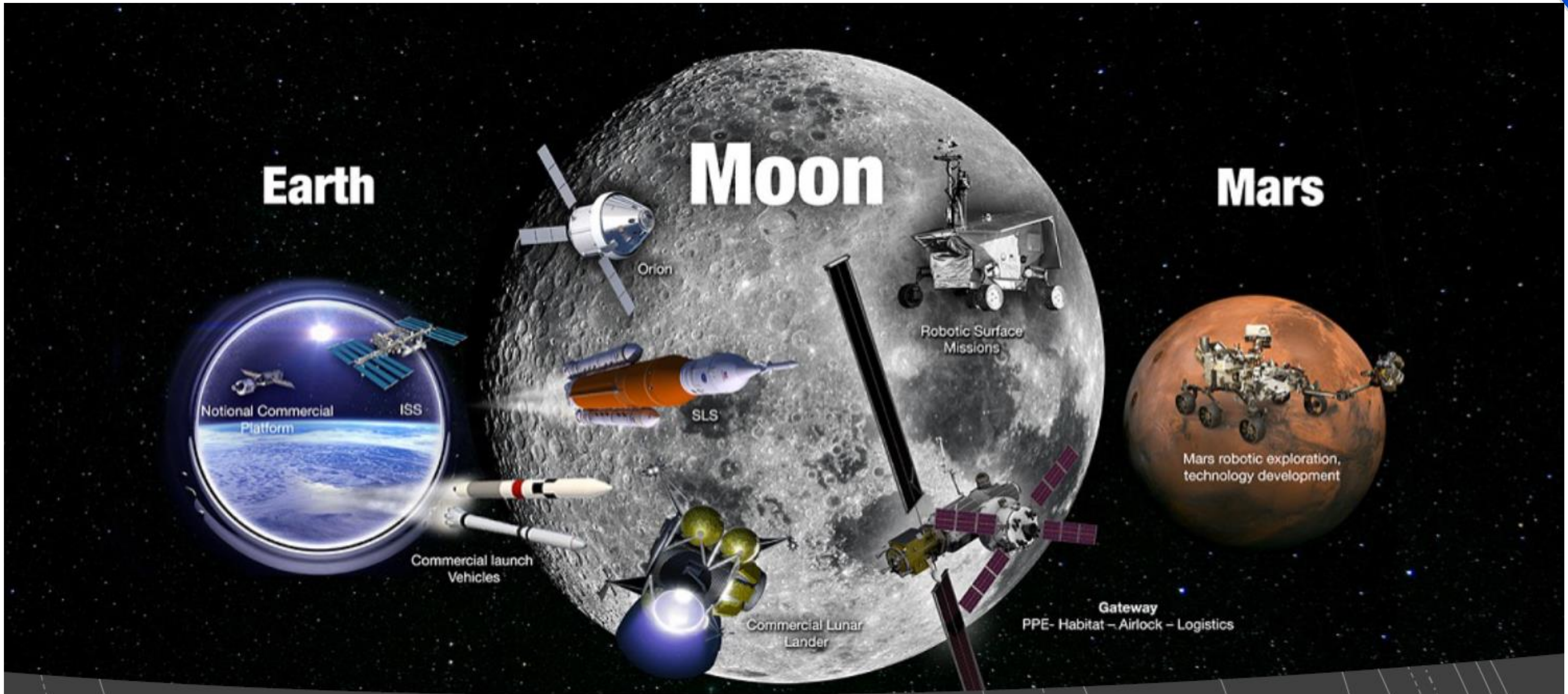
Additive Manufacturing Development, Certification, and Qualification Strategies for NASA Missions

Robert Carter[1]
NASA GRC - Deputy Chief Materials and Structures Division
NESC - Deputy Technical Fellow for Materials

Rick Russell[2], Alison Park[3], Douglas Wells[4], Brian West[4], Bryan McEnerney[3],
Andrew Glendening[5], and Timothy M. Smith[1]
[1]NASA Glenn Research Center, [2]NASA Retired, [3]NASA Langley Research Center, [4]NASA Marshall Space Flight Center, [5]NASA Goddard Research Center

SAE's Additive Manufacturing And Modeling For Mobility Production Workshop
September 11, 2023



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

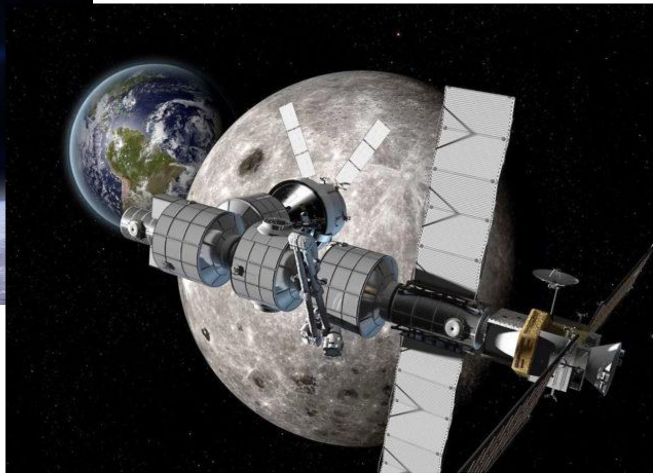
- Fully embraces advantages of AM
  - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
  - Especially in delivering high value, high performance AM hardware
- NASA has dual roles
  - Develop protocols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

NASA's motivation for AM Standard development

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

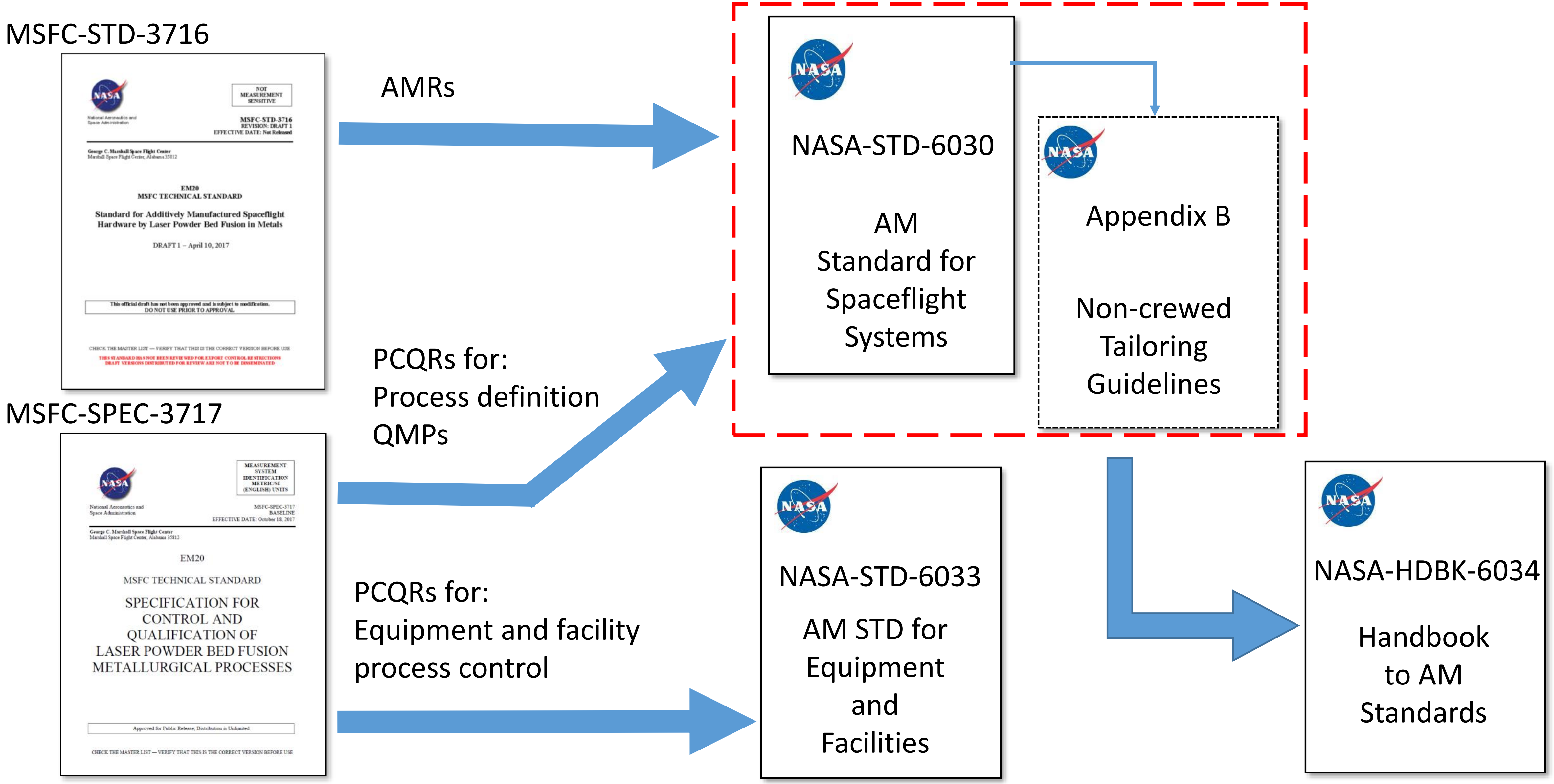
Low Earth Paradigm

Deep Space Paradigm

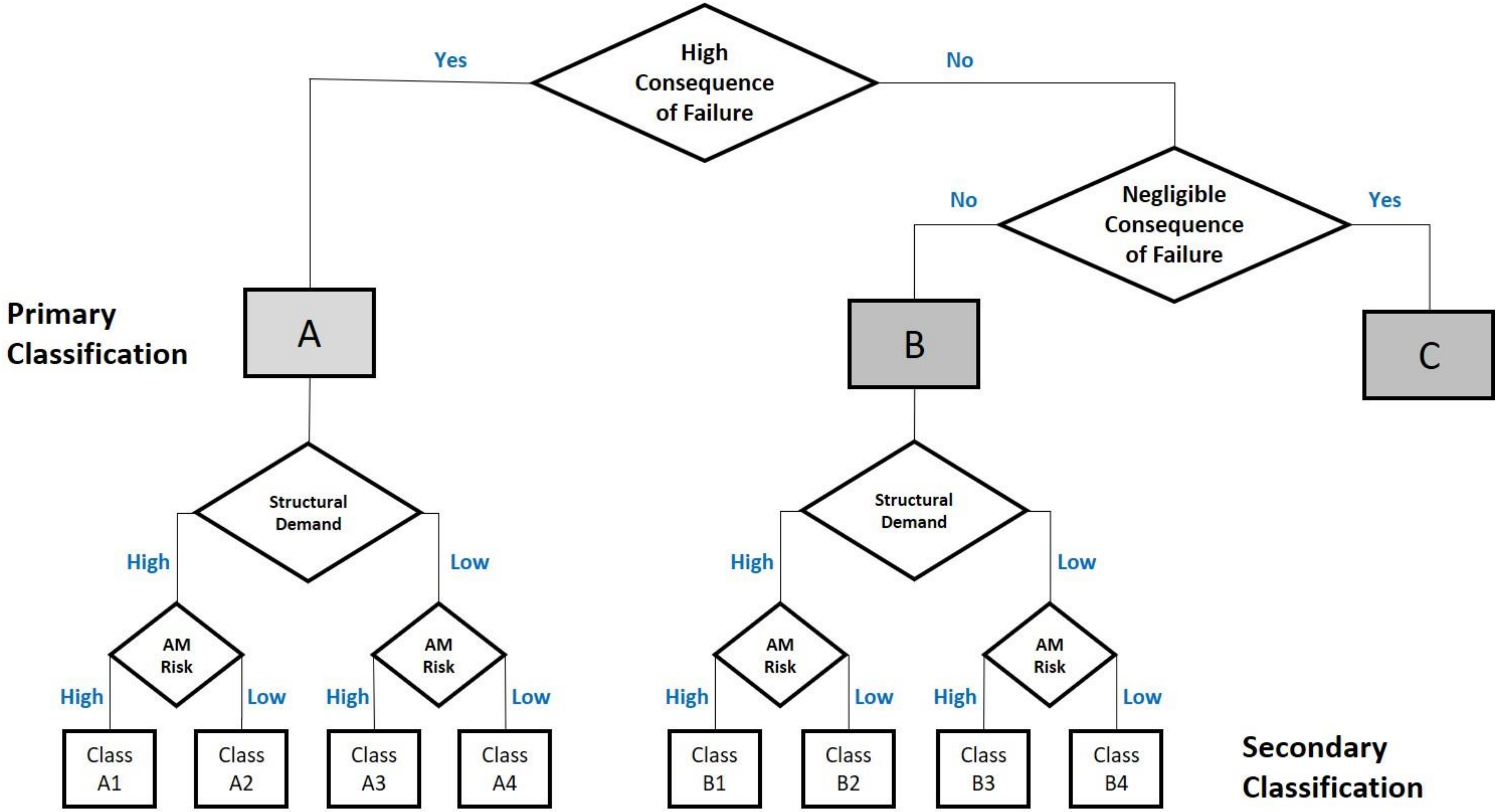


250 miles vs 83,000,000+ miles
15-30 year life vs 50 to 100+ years
Replacement parts vs Limited replacement parts
Safe haven of earth vs no safe haven

New Agency Document Structure



Classification



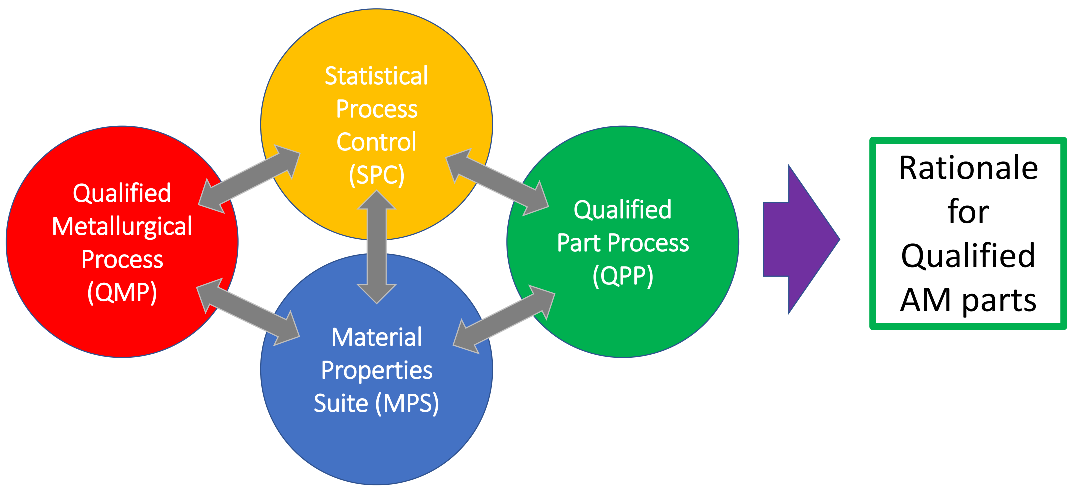
Applicability

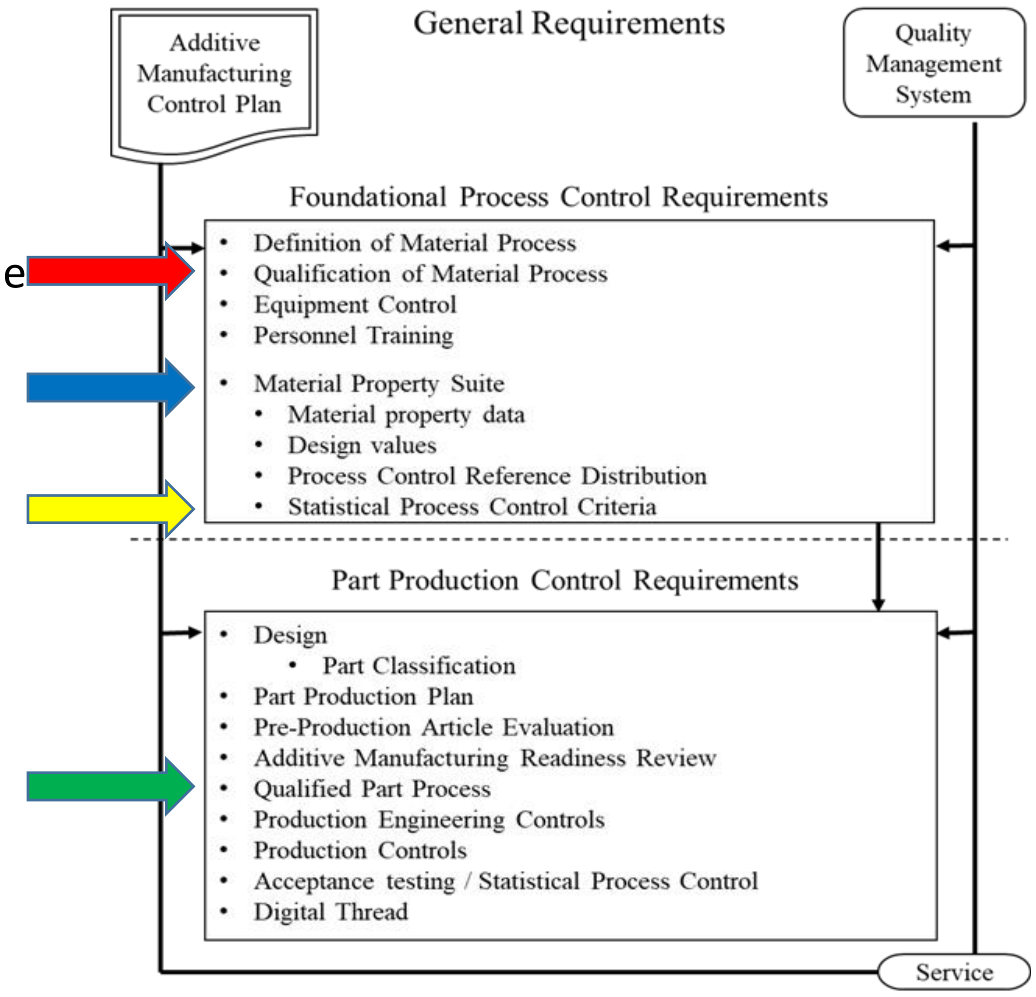
			Class		
Category	**Technology**	**Materials Form**	**A**	**B**	**C**
Metals	L-PBF	Metal Powder	X	X	X
	DED	Metal Wire	X	X	X
	DED	Metal Blown Powder	X	X	X
Polymers	L-PBF	Thermoplastic Powder		X	X
	Vat Photopolymerization	Photopolymeric Thermoset Resin			X
	Material Extrusion	Thermoplastic filament			X

- Adaptive technologies, where the heat input can change during the manufacturing process, are not allowed
  - e.g. Electron beam powder bed fusion (E-PBF)

Summary of Methodology

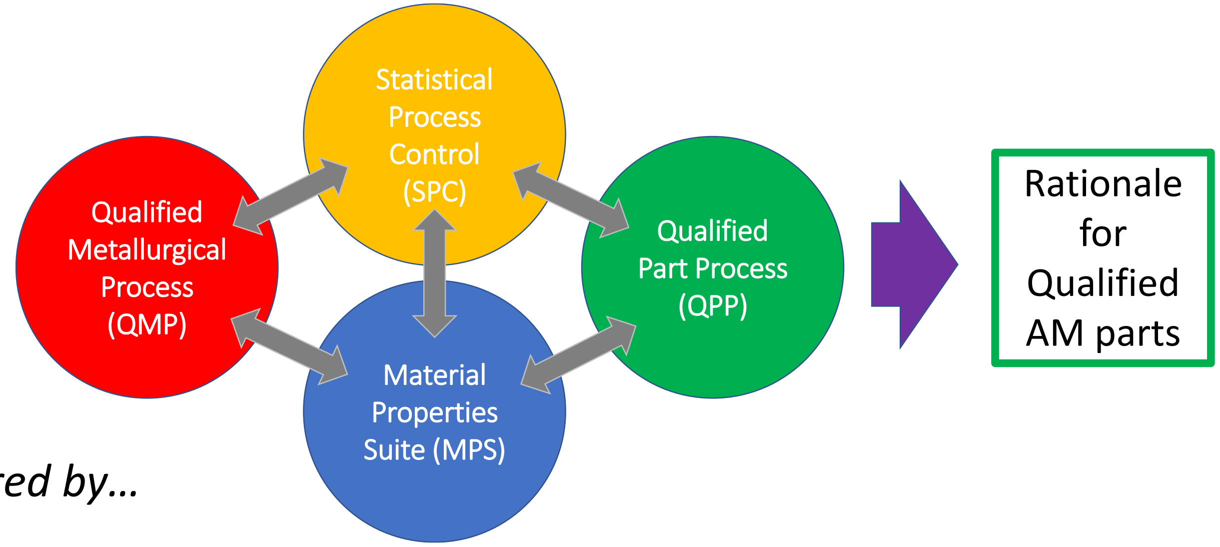
- General Requirements
  - Additive Manufacturing Control Plan (AMCP) and Quality Management System (QMS)
  - Backbone that defines and guides the engineering and production practices
- Foundational Process Control Requirements
  - Includes the requirements for AM processes that provide the basis for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





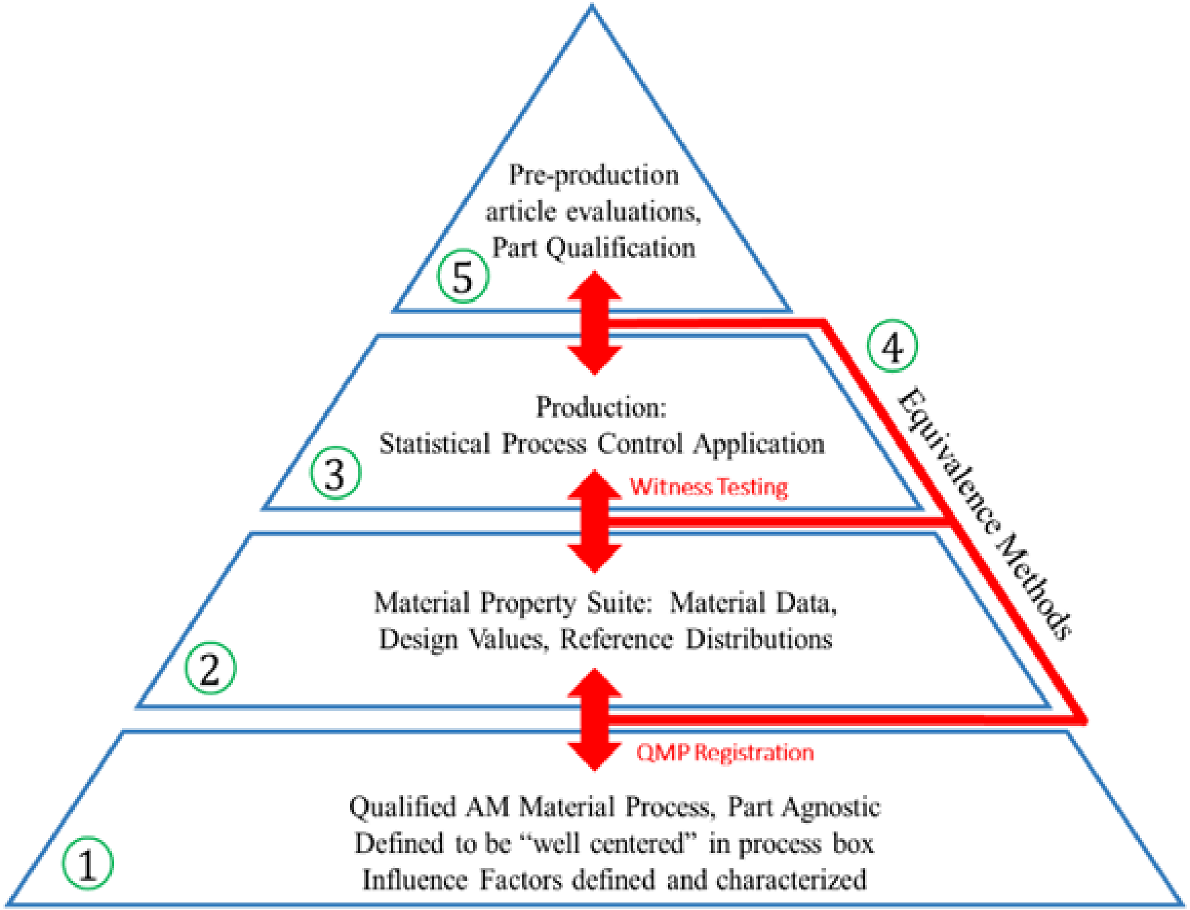
QMP: Qualified Material Process

- Begins as a Candidate QMP
- Defines aspects of the basic, *part agnostic*, fixed AM process:
  - Feedstock Controls
    - What you are building with
  - Fusion Process
    - How a machine operates
  - Thermal Process
    - Control what evolves your material state
- Qualification of the Candidate Material Process
  - Establishes a QMP: Qualified Material Process
  - Requirements vary based on classification
- Enabling Concept
  - Machine qualification and re-qualification, *monitored by…*
  - Process control metrics, SPC, *all feeding into…*
  - Design values



- AM machine and process are indelibly linked:
  - Step 1: Define a candidate process
  - Step 2: Qualify the candidate process to well-defined metrics

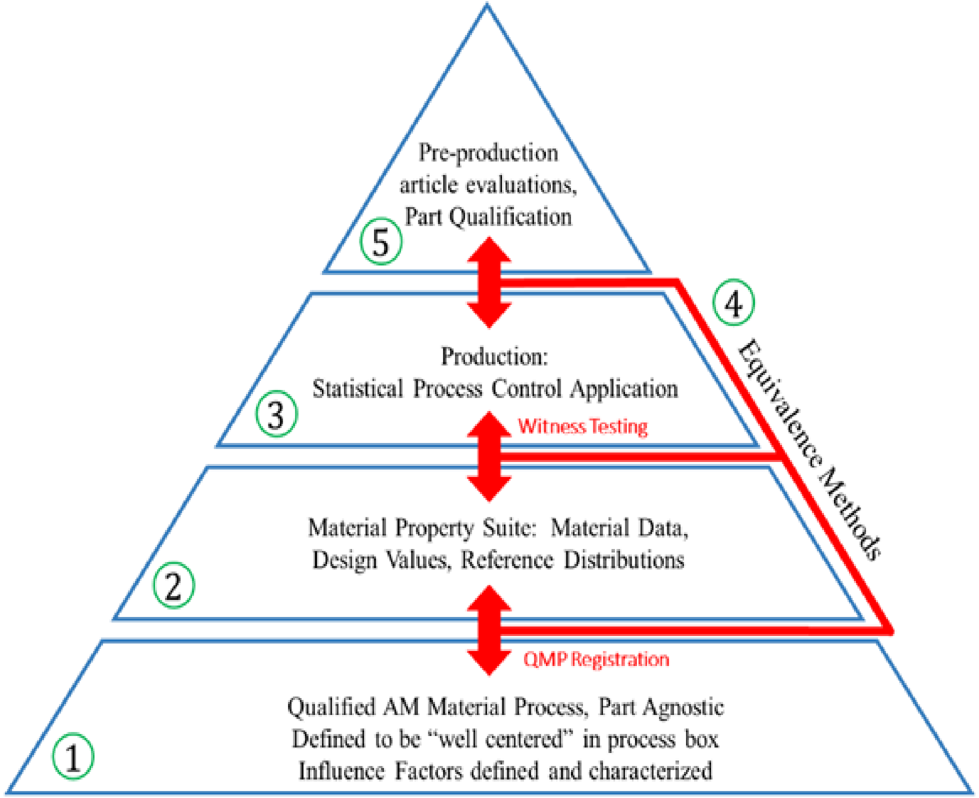
The QMP becomes the Foundation!



Material Properties

The Material Property Suite (MPS) consists of four inter-related entities:

1. Data Repository
2. Design Values
3. Process Control Reference Distribution (PCRD)
4. SPC acceptance criteria for witness testing

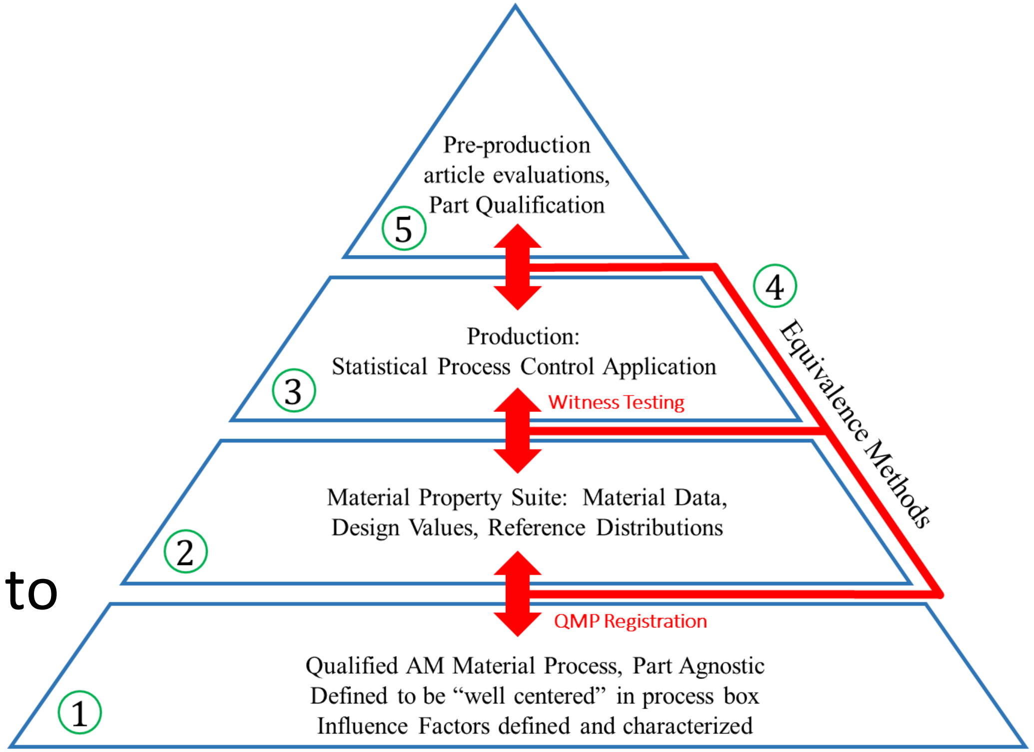


Publication of example Material Property Suite (MPS) expected in January 2024

Material Properties – Equivalency

Statistical process controls are important in sustaining certification rationale

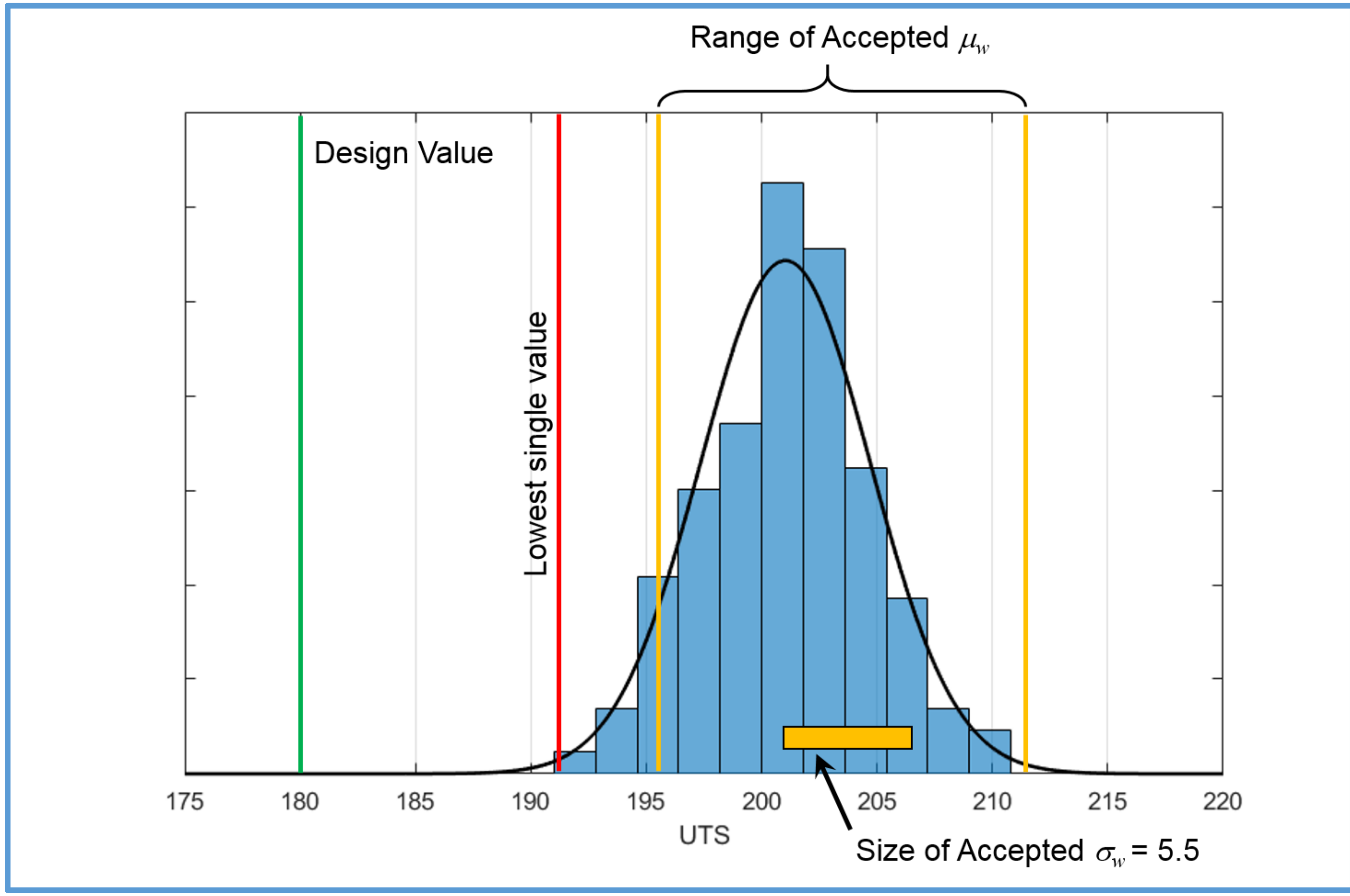
- *Statistical equivalency evaluations* substantiate design values and process stability build-to-build
  a) Process qualification
  b) Witness testing
  c) Integration to existing material data sets
  d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts



The dark and scary place most manufacturers are NOT used to operating….

Material Properties Suite – PCRD and SPC Criteria

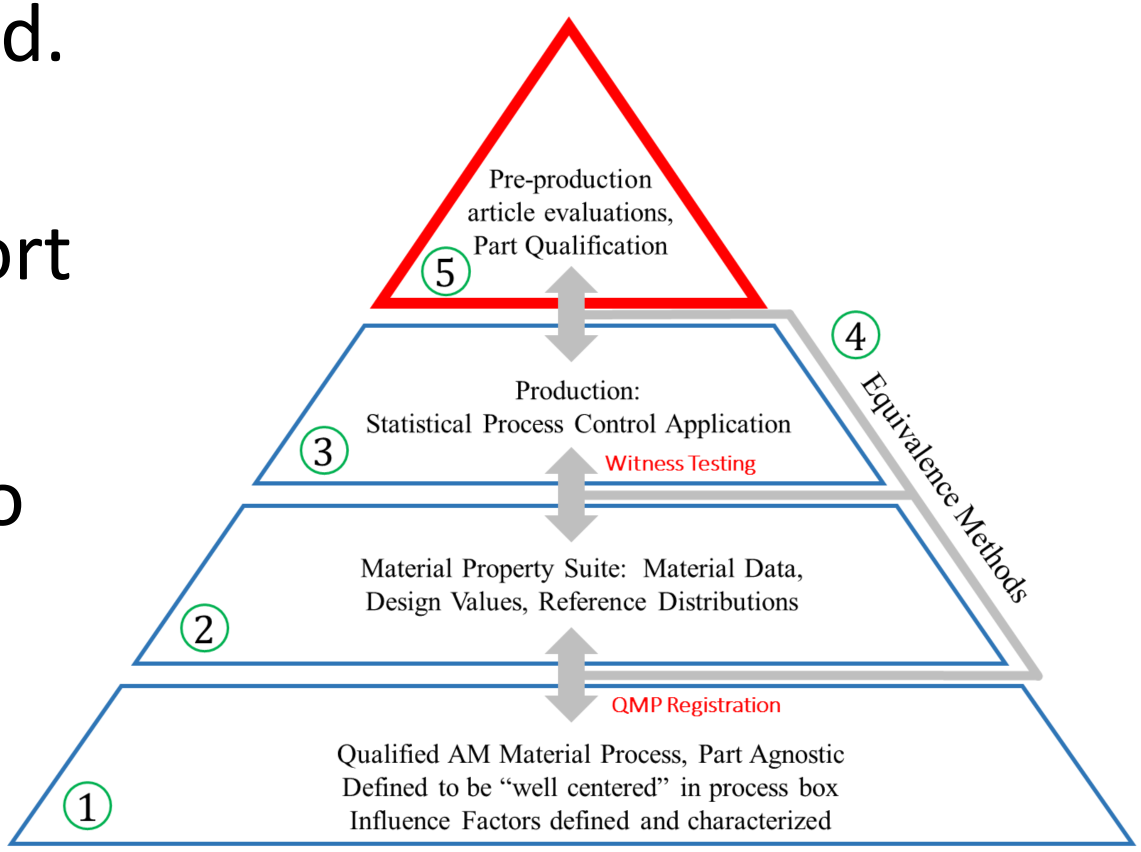
- Witness test acceptance is **not** intended to be based upon design values or "specification minimums"
- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values
- Suggested approach
  - Acceptance range on mean value
  - Acceptance range on variability (e.g., standard deviation)
  - Limit on lowest single value



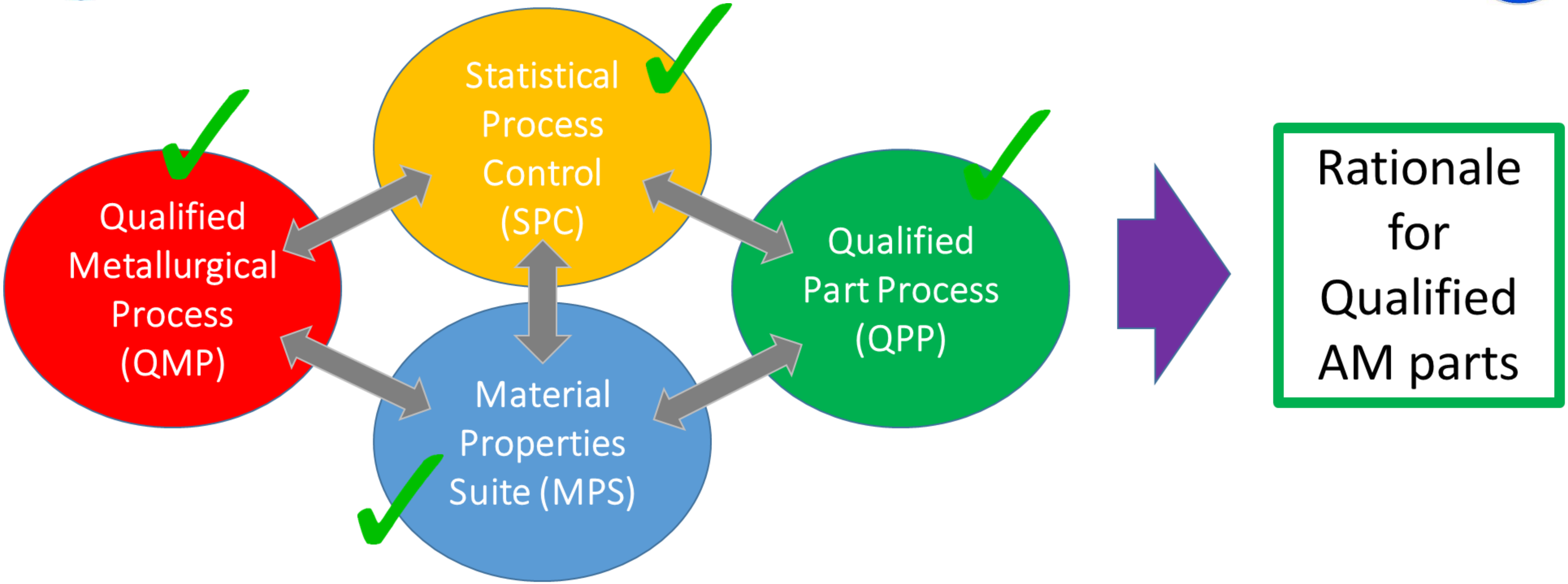
Foundation Complete!!

A basis to begin designing AM parts with certification intent is feasible once the foundation is laid.

Foundation is now ready to support AM part development in an environment with suitable rigor to establish certification.



Key AM Qualification Concepts



Part reliability rationale comes from the sum of both in-process and post-process controls, weakness in one must be compensated in the other

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

NASA's motivation for AM alloy development

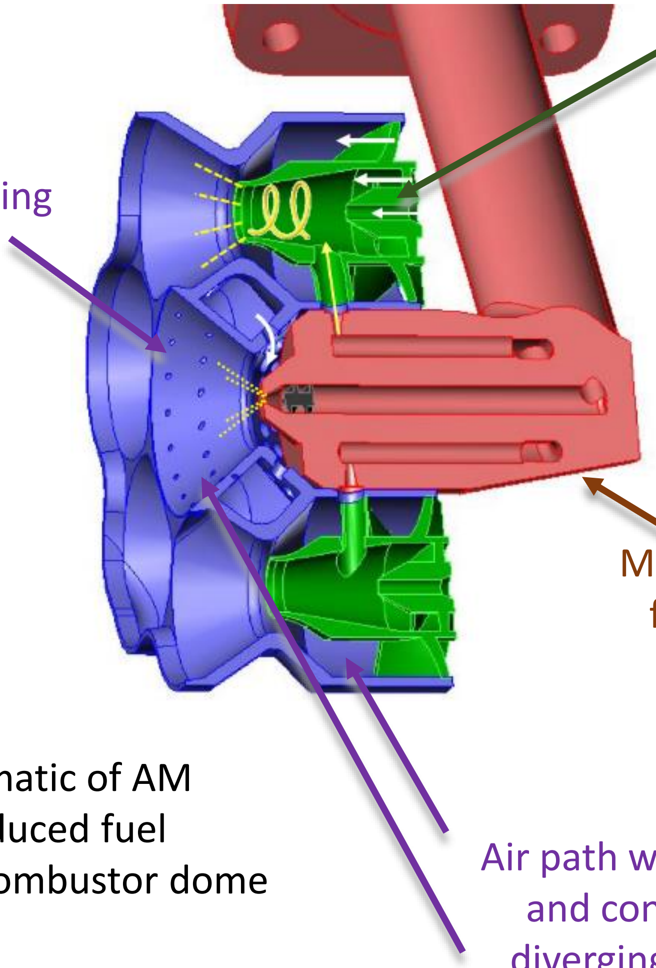
- NASA Missions typically require operation in extreme conditions
- Conventional materials and processing limit design and operation
- Success Case Study—GRX-810

Problem: Optimized Combustor Dome requires AM fabrication and higher than SOA temperatures

Proposed Solution: Develop a high ductility, high temperature material for an additively-manufactured (AM) combustor fuel nozzle and dome for supersonic aircraft (>1093°C (2000°F) operating temperature).

New Alloy and AM fabrication Enabled:

- Improvements to the turbine combustor design reducing NOx pollution and lowering weight
- Lean-front-end small-core combustors

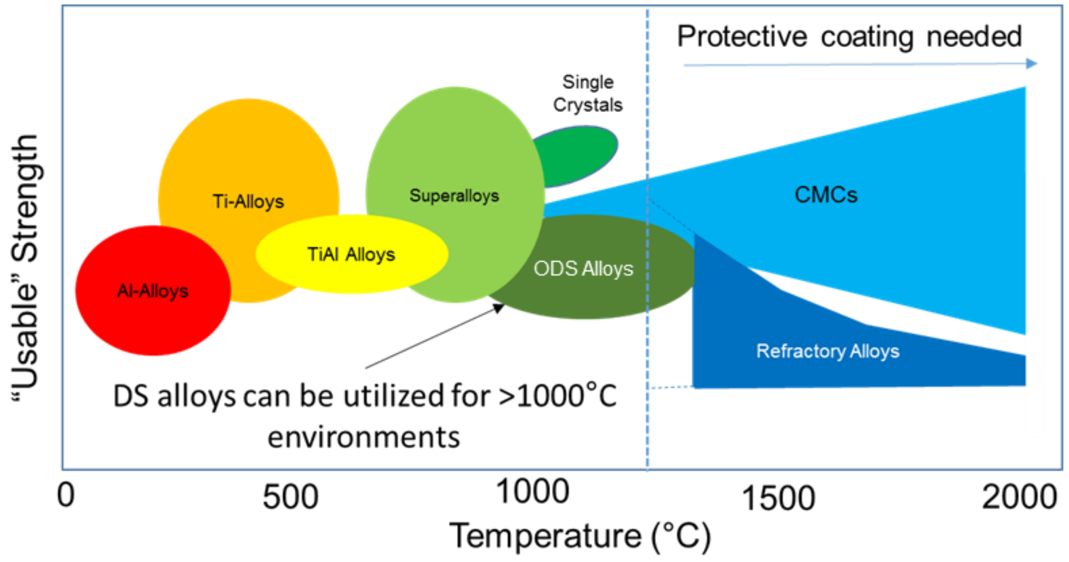


Schematic of AM produced fuel injector/combustor dome

High Temperature AM Compatible Materials

High Temperature Material Options:

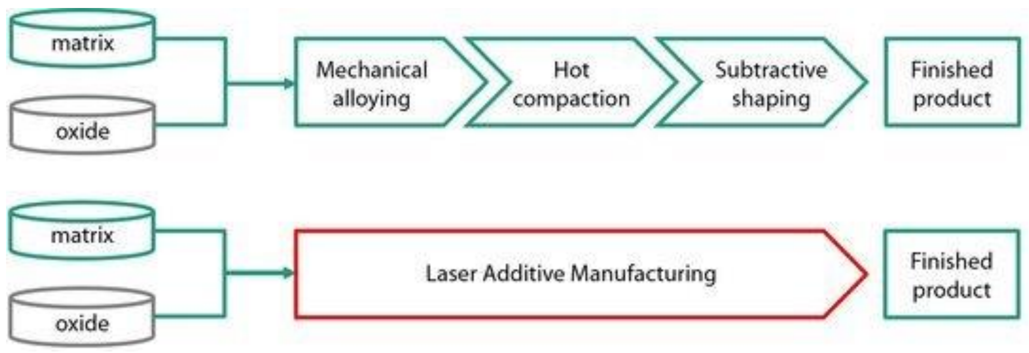
- Refractory metals
- Carbon-Carbon composites
- CMC's
- Ni-base superalloys
- Oxide Dispersion strengthened (ODS) alloys



Inspired by Andy Jones. ODS alloy Development

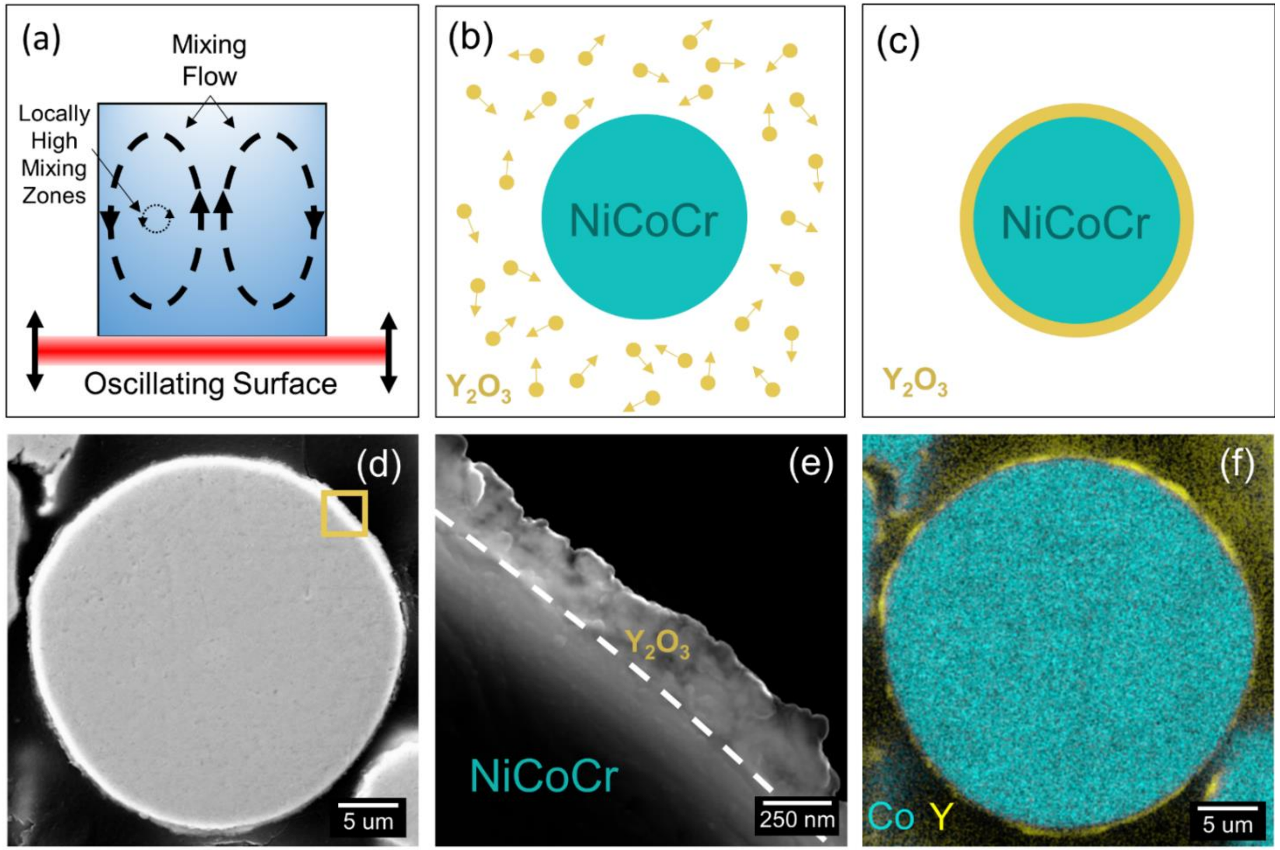
(ODS) alloys offer higher temperature capabilities compared to Ni-base superalloys. However, it has been a challenge to produce ODS alloys through conventional manufacturing methods.

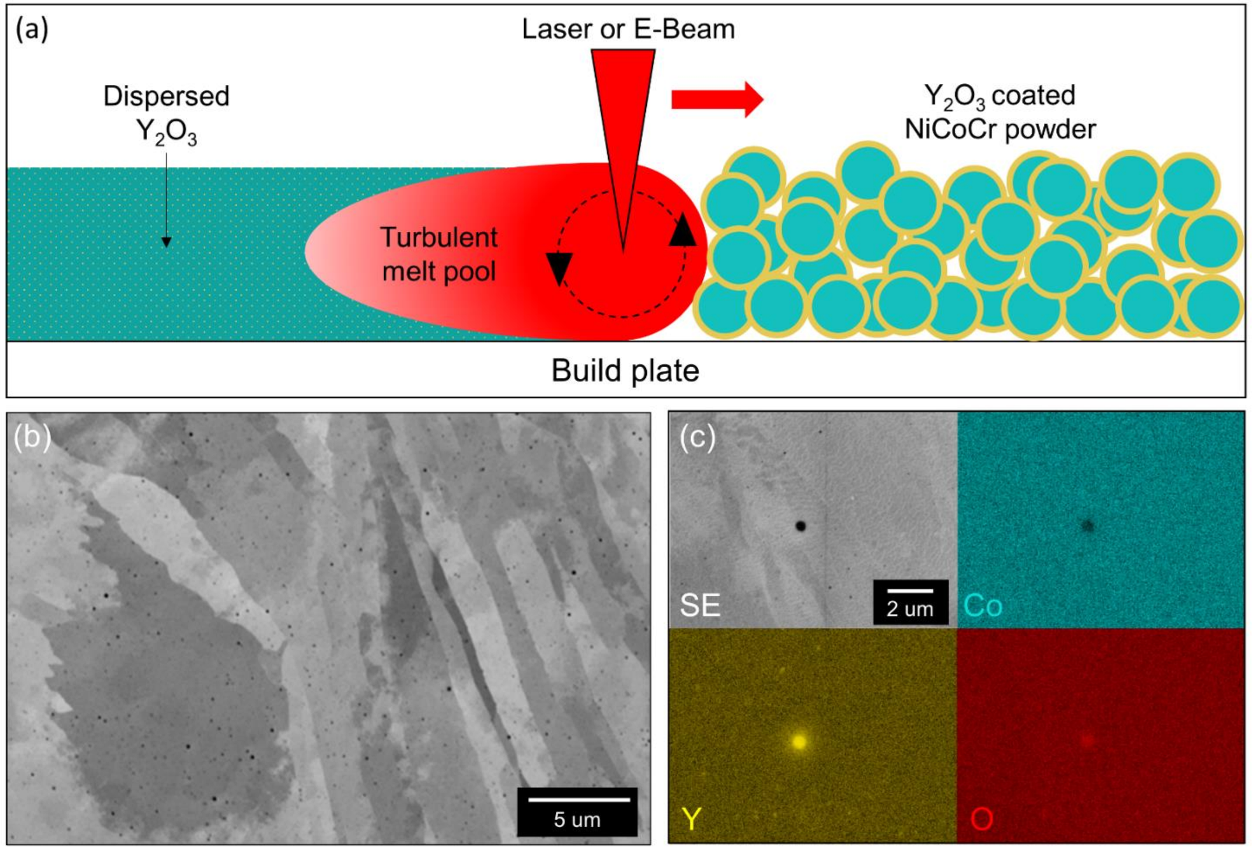
ODS Conventional Manufacturing vs AM



Radical New Approach Developed for ODS AM

Technique for coating metal powders with fine dispersoids was developed and demonstrated first for simple NiCoCr powders and then transitioned to ICME developed alloy Glenn Research Extreme-Temperature above 810°C (GRX-810)

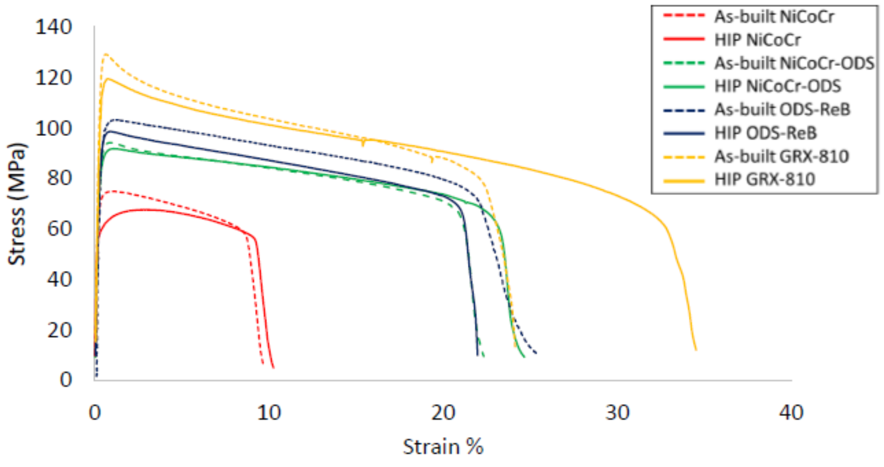




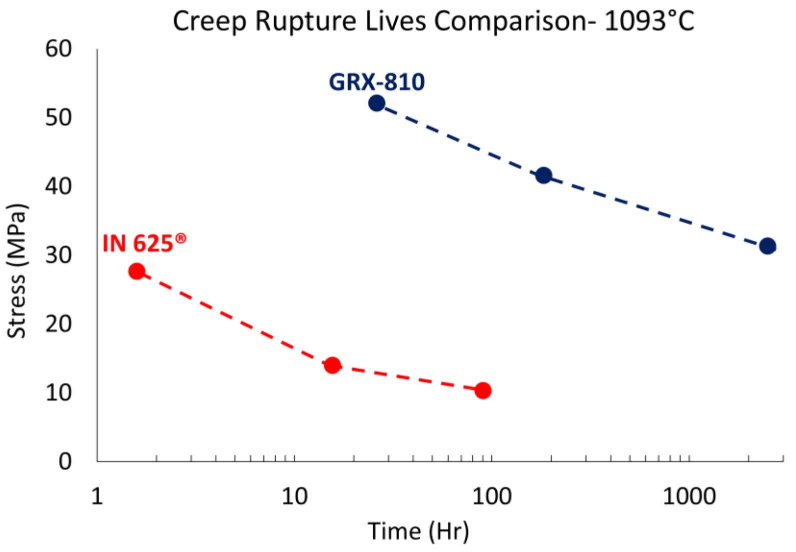
ODS and AM Provides Substantial Improvements

NASA alloy GRX-810 is an example of what can be achieved when a matrix is designed for optimum printing and solid solution strengthening then combined with dispersion strengthening for high temperature stability

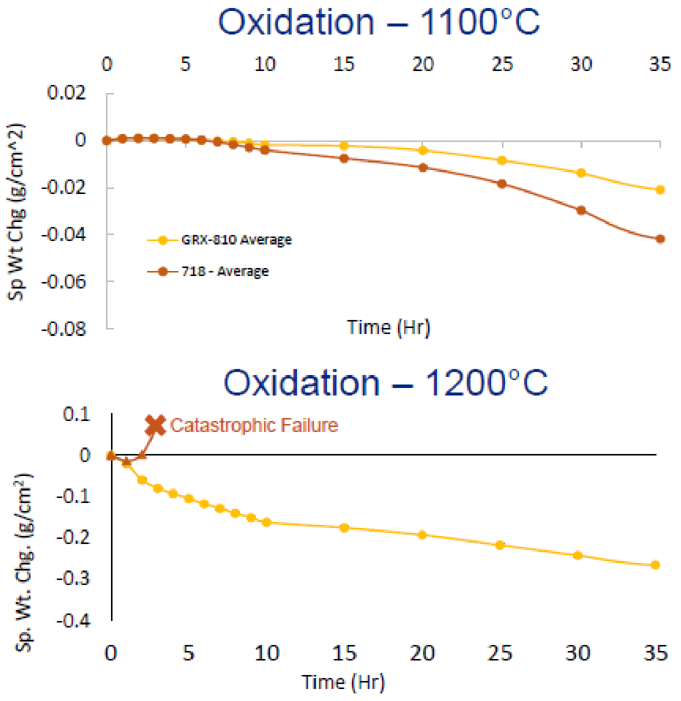
Better Specific Tensile Strength



1000x Better Creep Life
1093 C / 31 MPa

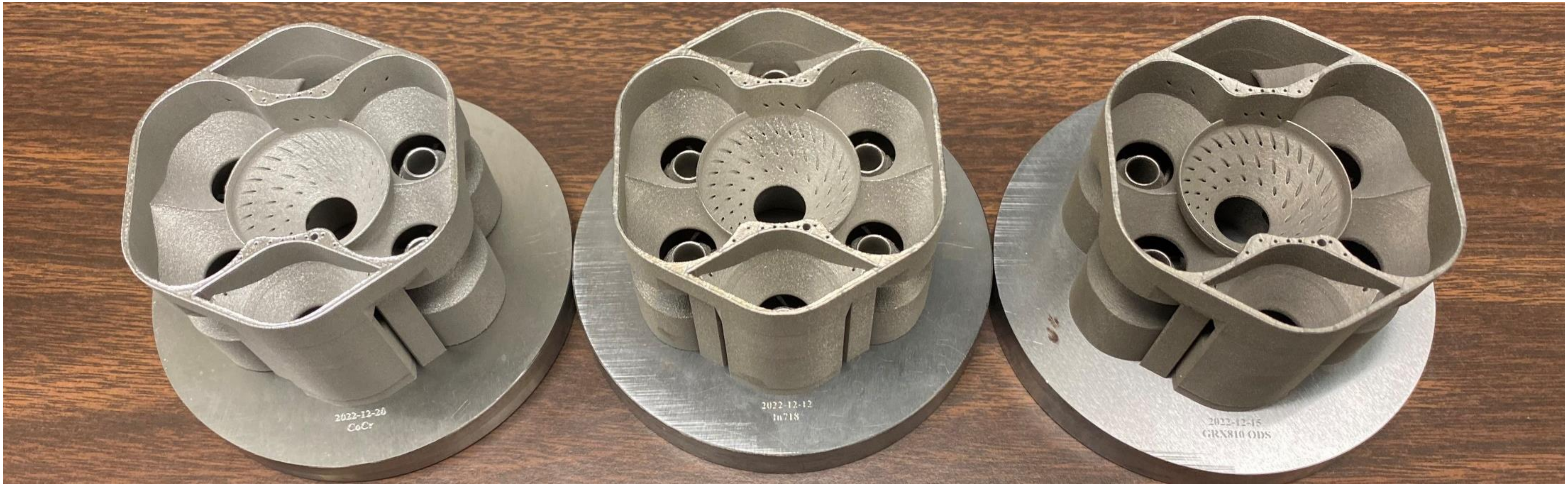


Better Oxidation Resistance



Component Demonstration: Combustor Dome

Three printed combustor domes were tested at NASA GRC combustor facility using relevant test conditions



CoCr | IN718 | GRX-810

Only GRX-810 dome survived without crack formation

Component Demonstration: Injector / Nozzle

GRX-810 LOX/CH4 injector and nozzle tested at MSFC Engine Test Stand

- Nozzle achieved 90 starts and 2,309 seconds of accumulated time
- Injector achieved 84 cycles and 2,228 seconds of accumulated time
- Injector provided at 5x improvement in erosion life compared to previously tested Alloy 718 and Alloy 625 injectors

- Separate design and testing of GRX-810 as a LOX/H2 injector also completed without erosion seen in conventional alloys

GRX-810 Honors

Article published in Nature:

Article

A 3D printable alloy designed for extreme environments

https://doi.org/10.1038/s41586-023-05893-0

Received: 7 October 2022

Accepted: 27 February 2023

Timothy M. Smith[1✉], Christopher A. Kantzos[1], Nikolai A. Zarkevich[2], Bryan J. Harder[1], Milan Heczko[3], Paul R. Gradl[4], Aaron C. Thompson[5], Michael J. Mills[3], Timothy P. Gabb[1] & John W. Lawson[2]

Conclusions

1. Certification rationale is heavily rooted in the foundational controls
2. Part Planning must confirm the foundation produces a good part consistently
3. Part production follows a fixed process with statistical process controls
4. Going forward NASA must develop a Fracture Control Framework for AM Parts which includes the adaptation of a Probabilistic Damage Tolerance Approach (PDTA)
5. Success of AM-specific alloys, for example GRX-810, provides solutions to the unique challenges of extreme aerospace requirements