NASA's Certification and Qualification Strategies for Additively Manufactured Hardware

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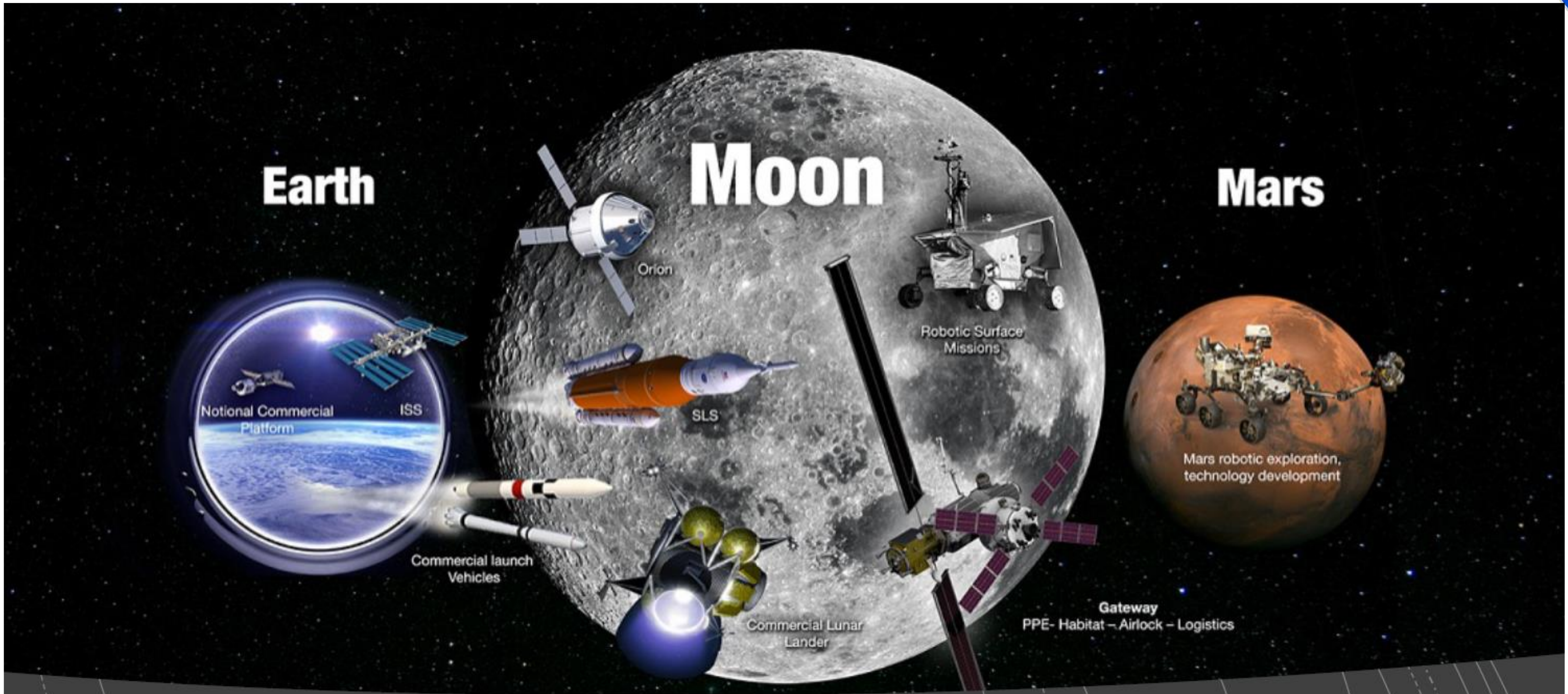
Advanced Manufacturing Workshop
4th International Conference on Generation IV and Small Reactors (G4SR-4)
Toronto, Canada
October 3, 2022



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

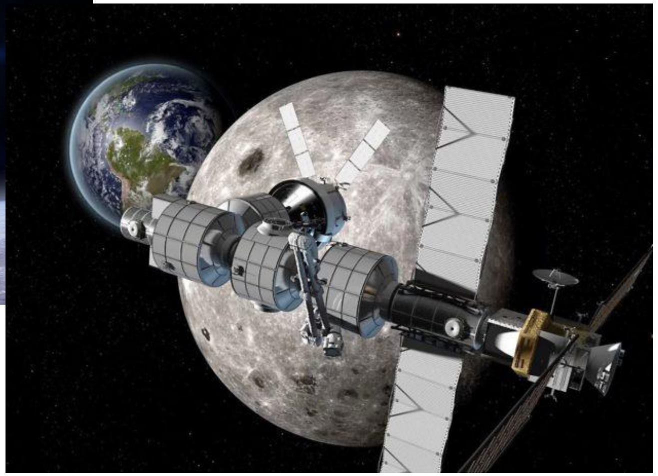
- Fully embraces advantages of AM
  - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
  - Especially in delivering high value, high performance AM hardware
- NASA has dual roles
  - Drive and foster 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 ⟵ Today's focus

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 <u>extreme</u> reliability

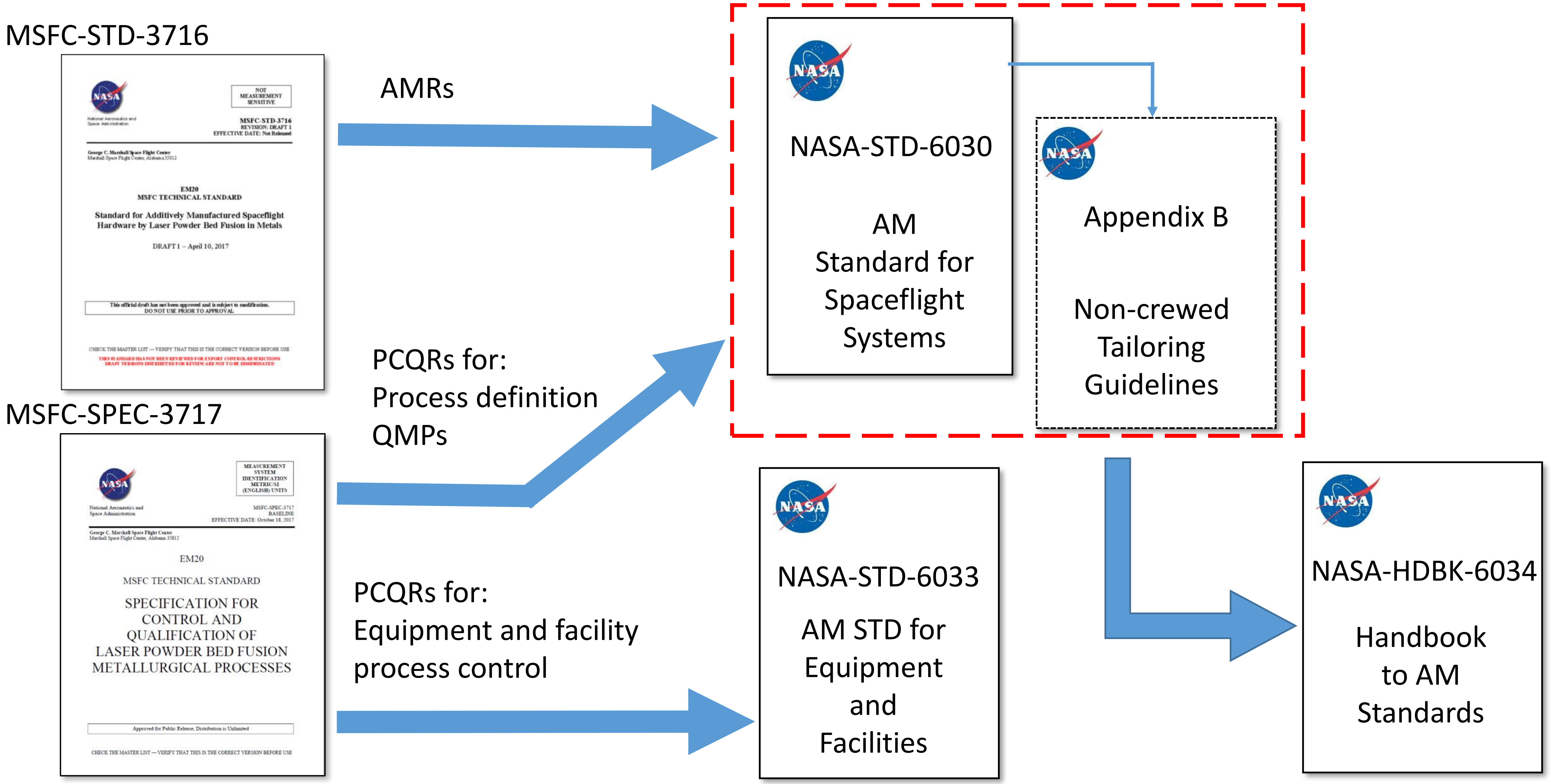
Low Earth Paradigm

Deep Space Paradigm

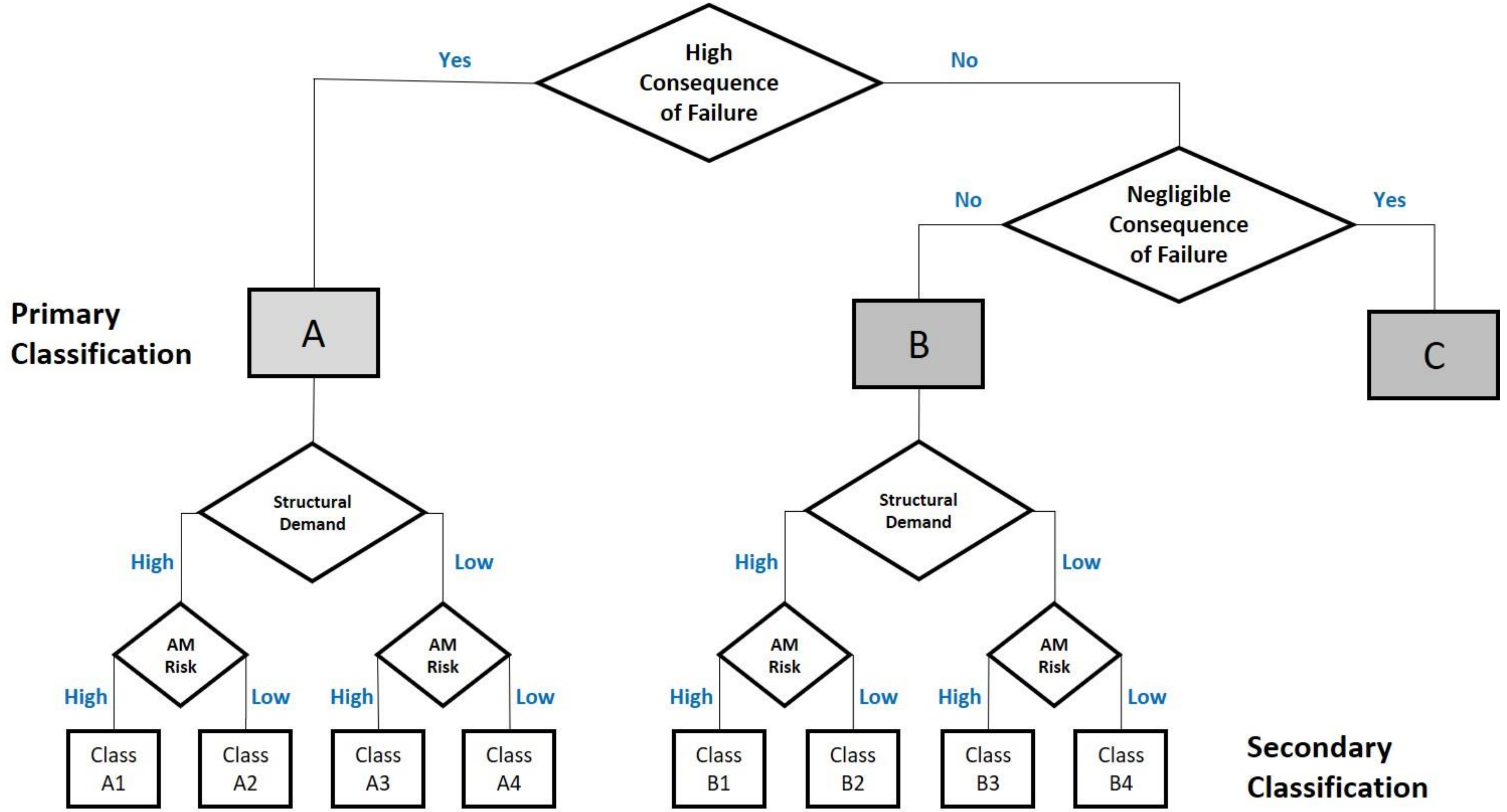


250 miles vs 83,000,000+ miles
15-30 year life vs 50 to 100+ years
Replacement parts vs Limited replacement parts
Safe haven of earth vs no safe haven

New Agency Document Structure



Classification



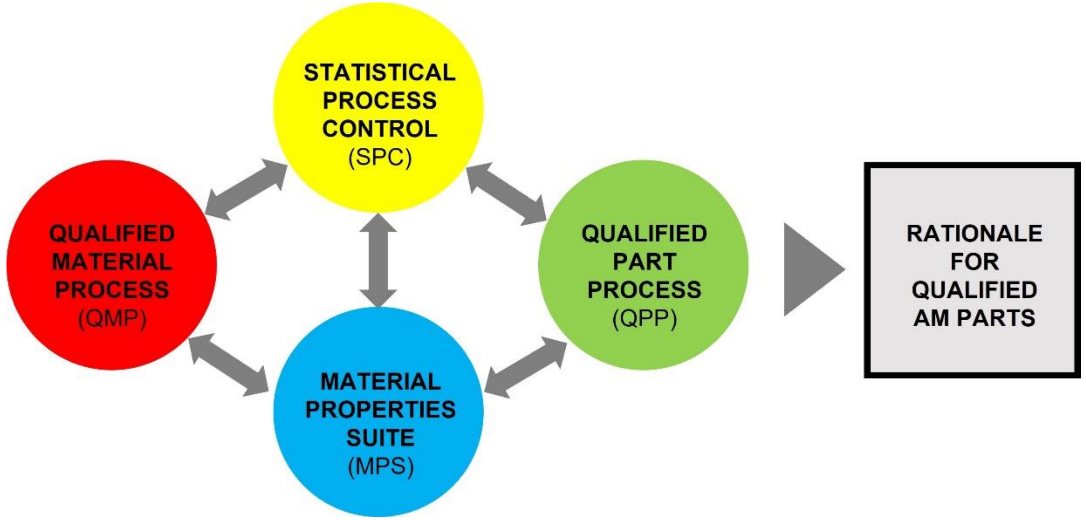
Applicability

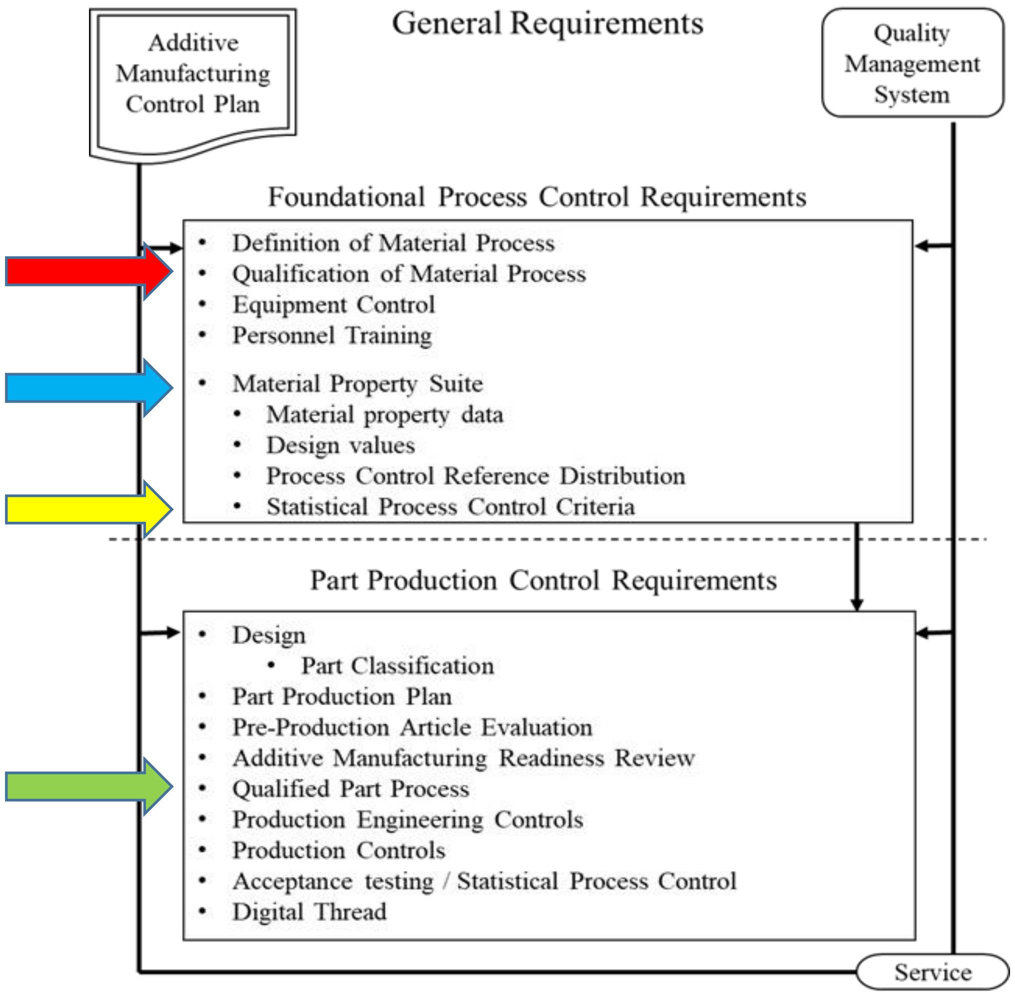
			Class		
Category	**Technology**	**Materials Form**	**A**	**B**	**C**
Metals	L-PBF	Metal Powder	X	X	X
	DED	Metal Wire	X	X	X
	DED	Metal Blown Powder	X	X	X
Polymers	L-PBF	Thermoplastic Powder		X	X
	Vat Photopolymerization	Photopolymeric Thermoset Resin			X
	Material Extrusion	Thermoplastic filament			X

- 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

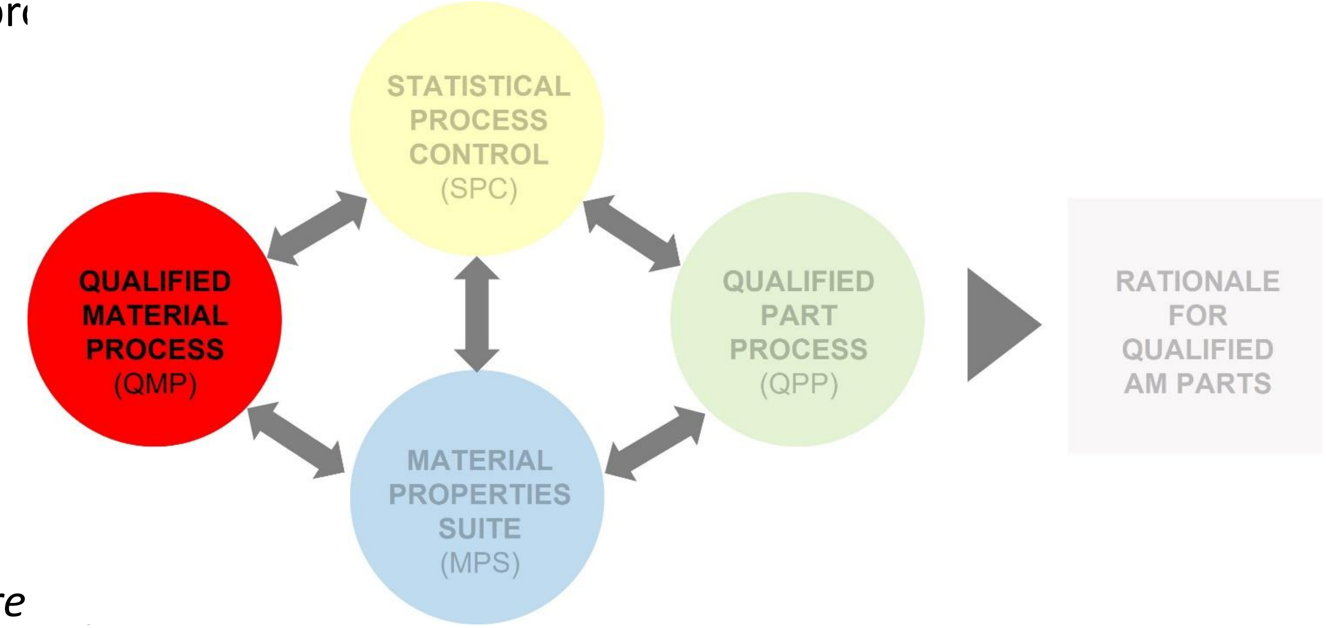
- General Requirements
  - Additive Manufacturing Control Plan (AMCP) and Quality Management System (QMS)
  - Backbone that defines and guides the engineering and production practices
- Foundational Process Control Requirements
  - Includes the requirements for AM processes that provide the basis for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





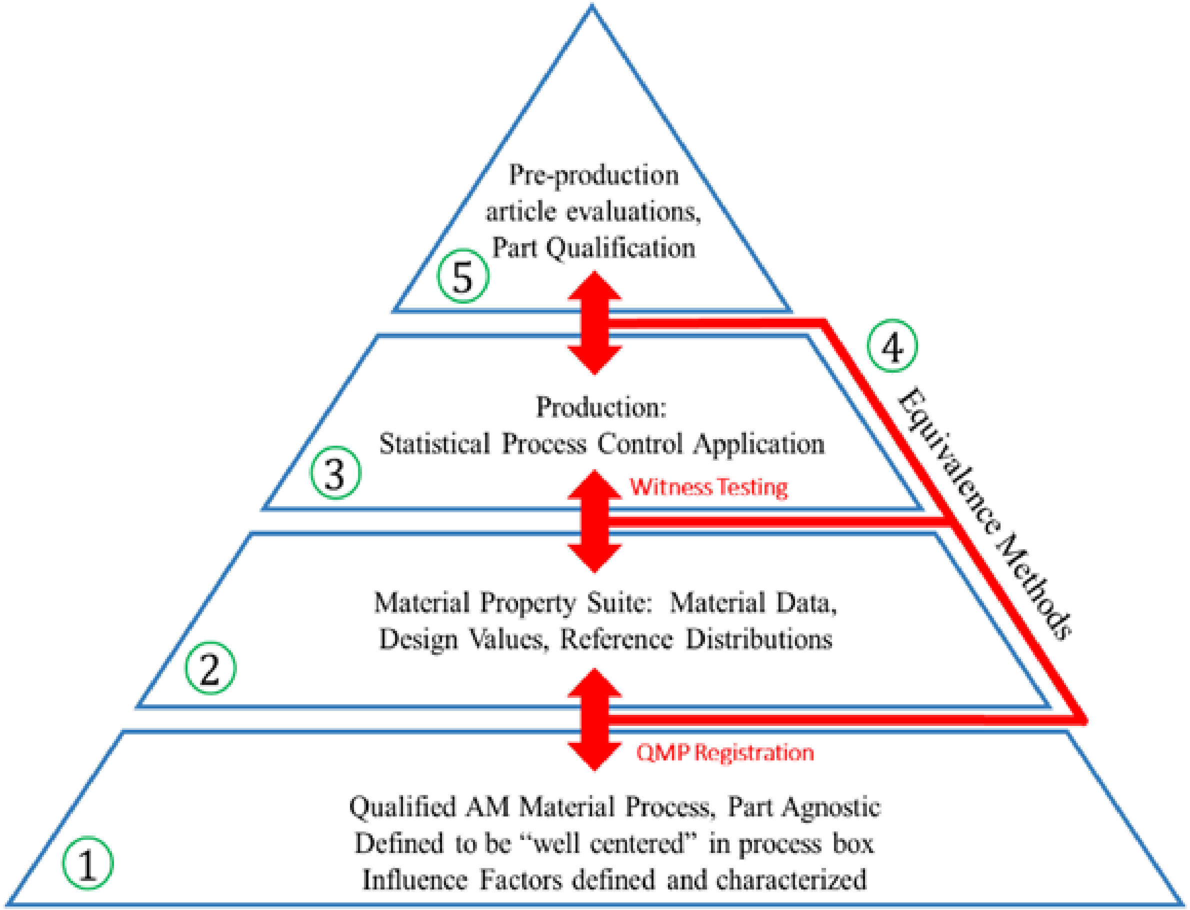
QMP: Qualified Material Process

- Begins as a C<u>andidate</u> QMP
- Defines aspects of the basic, *<u>part agnostic</u>*, fixed AM pr
  - 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, *monitore*
  - 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

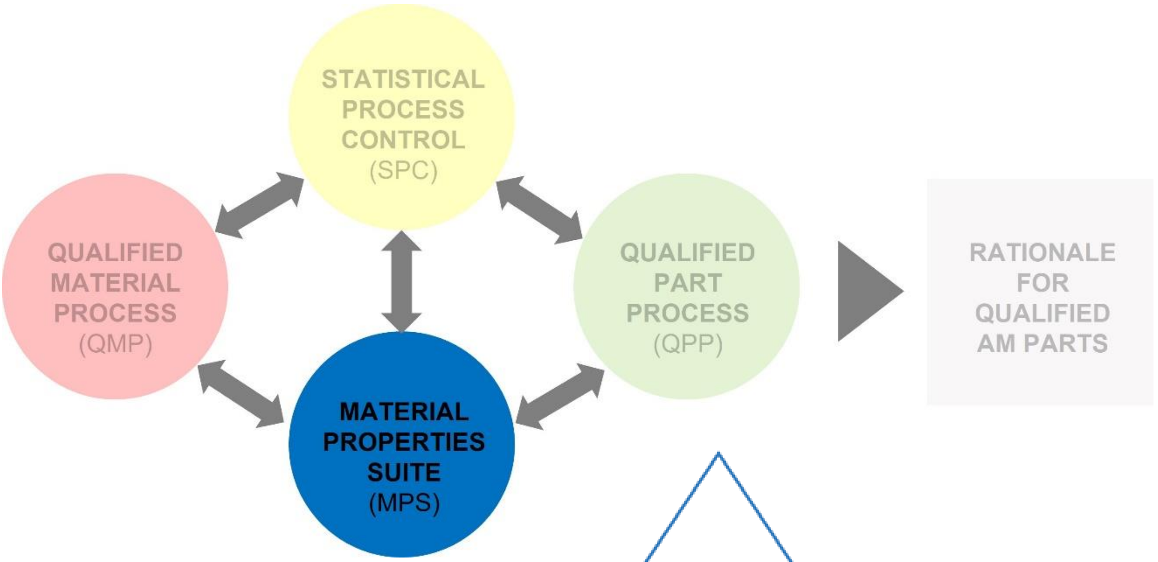
The QMP becomes the Foundation!

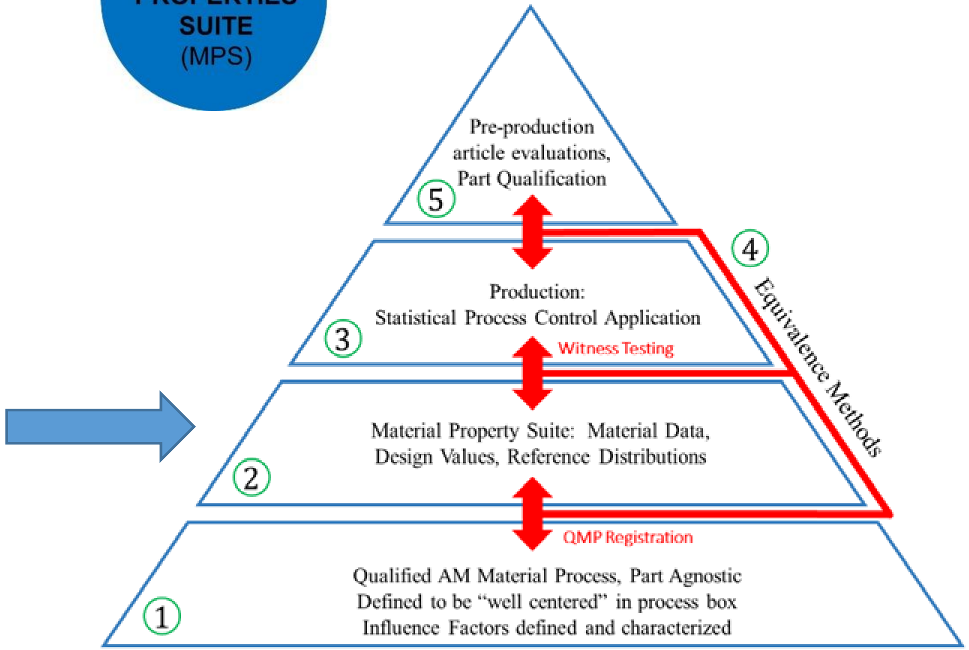


Material Property Suite

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

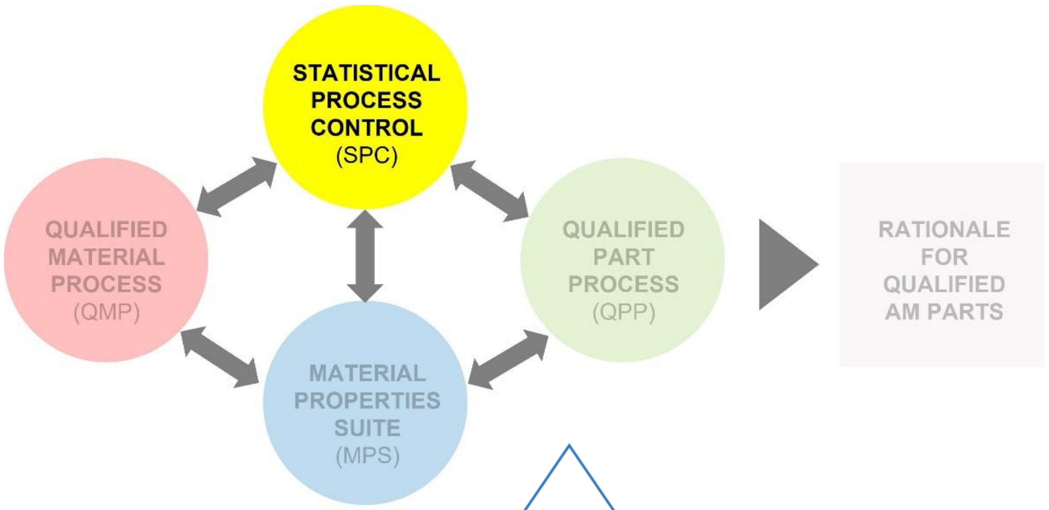


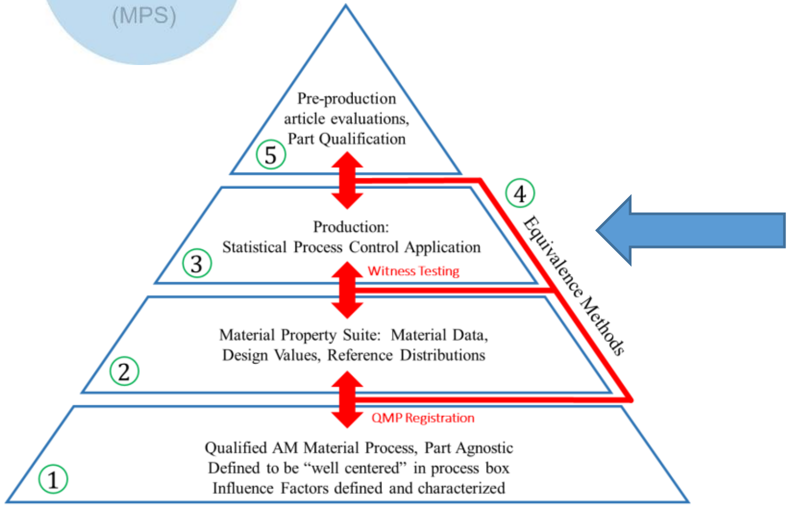


Statistical Process Control (SPC)

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

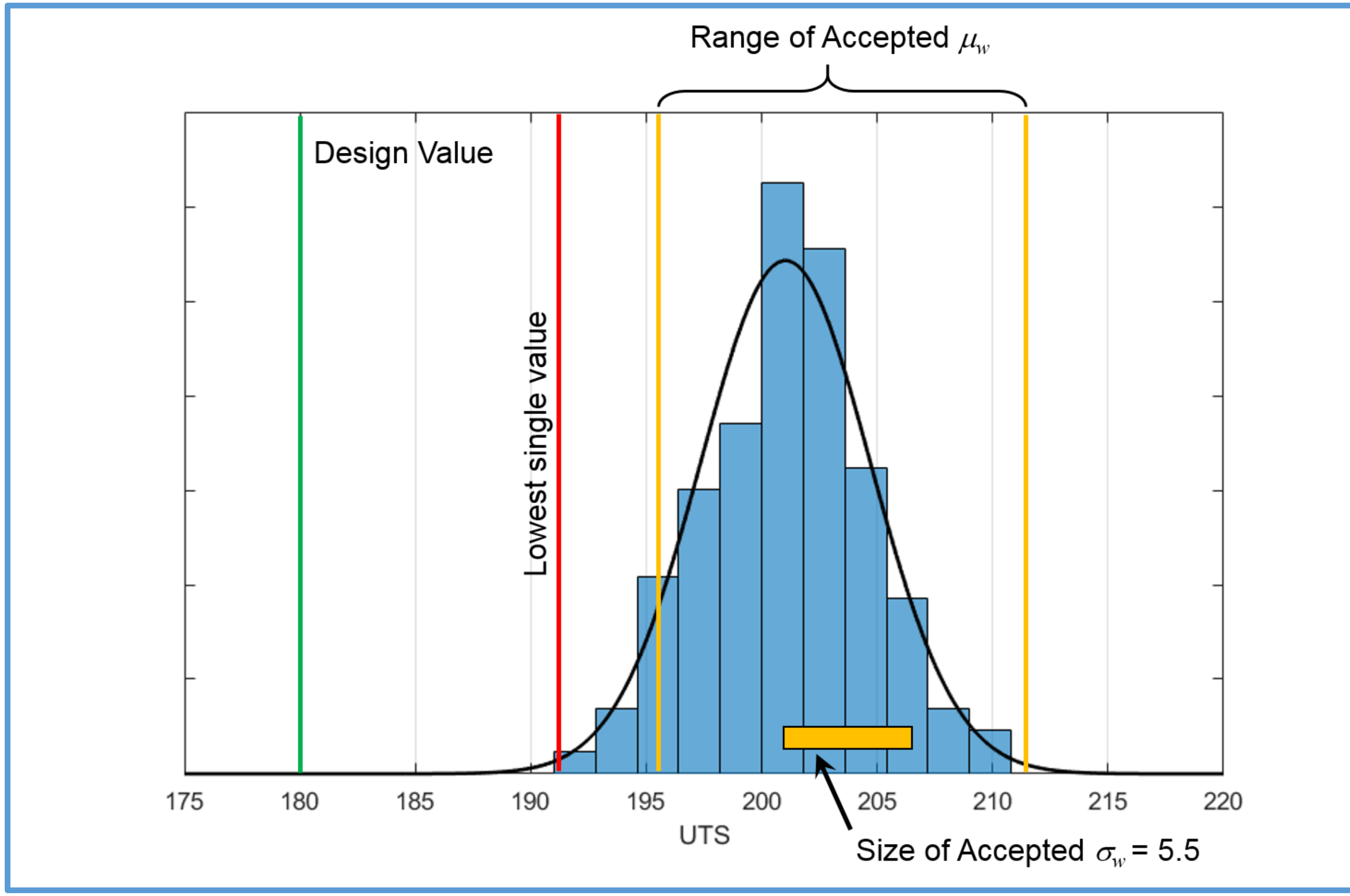




The dark and scary place most manufacturers are NOT used to operating….

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



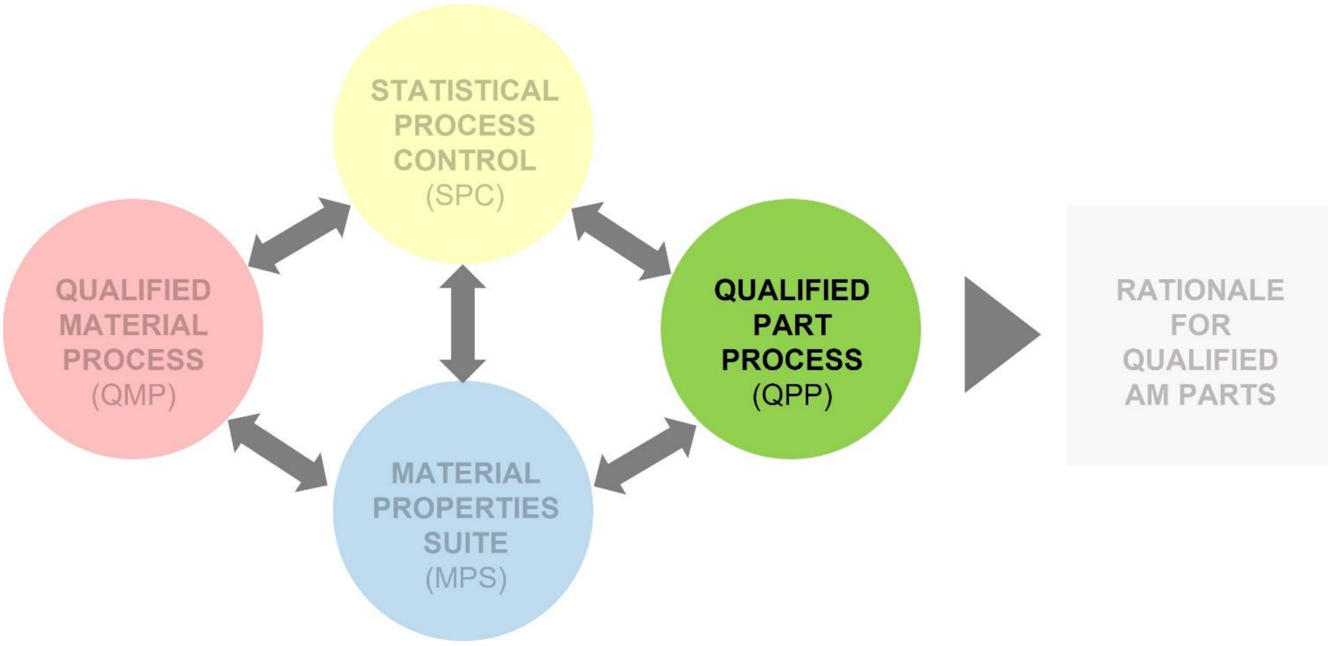
Equivalency

- One of this standards key strengths is its reliance on material engineering equivalence
  - Methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet all of its expectations.
  - The enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
  - Requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

$\boxed{\text{Process} \rightarrow \text{Structure} \rightarrow \text{Property} \rightarrow \text{Performance}}$

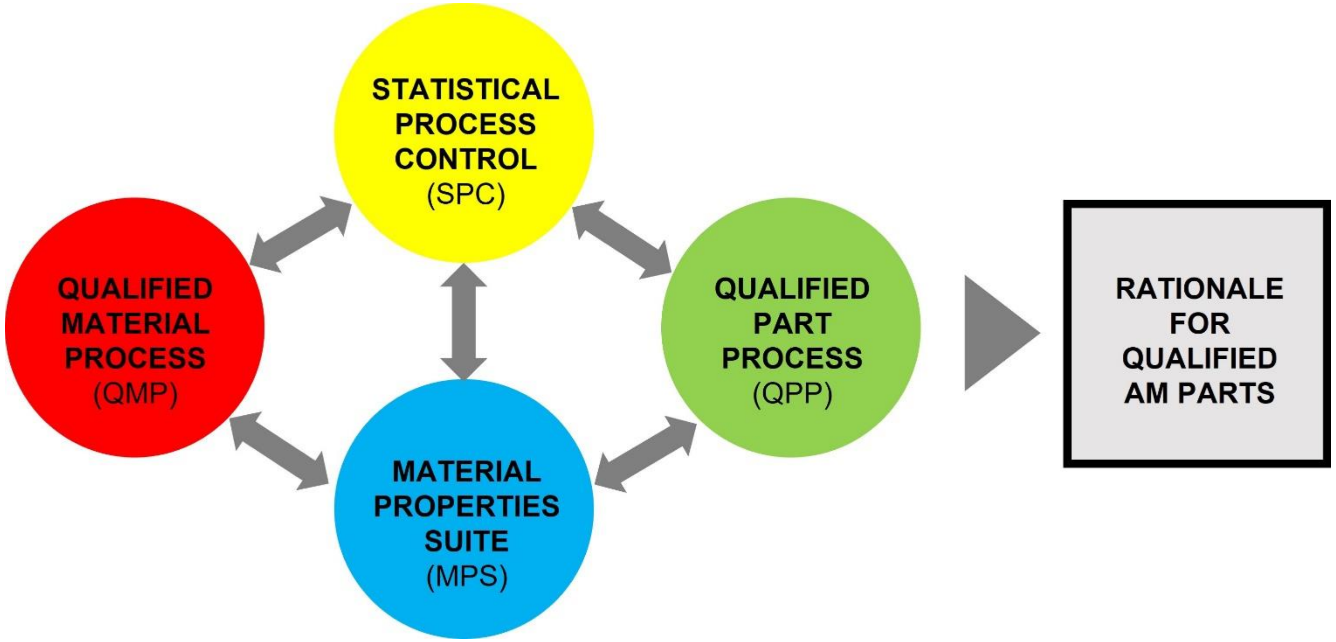
Qualified Part Process (QPP)

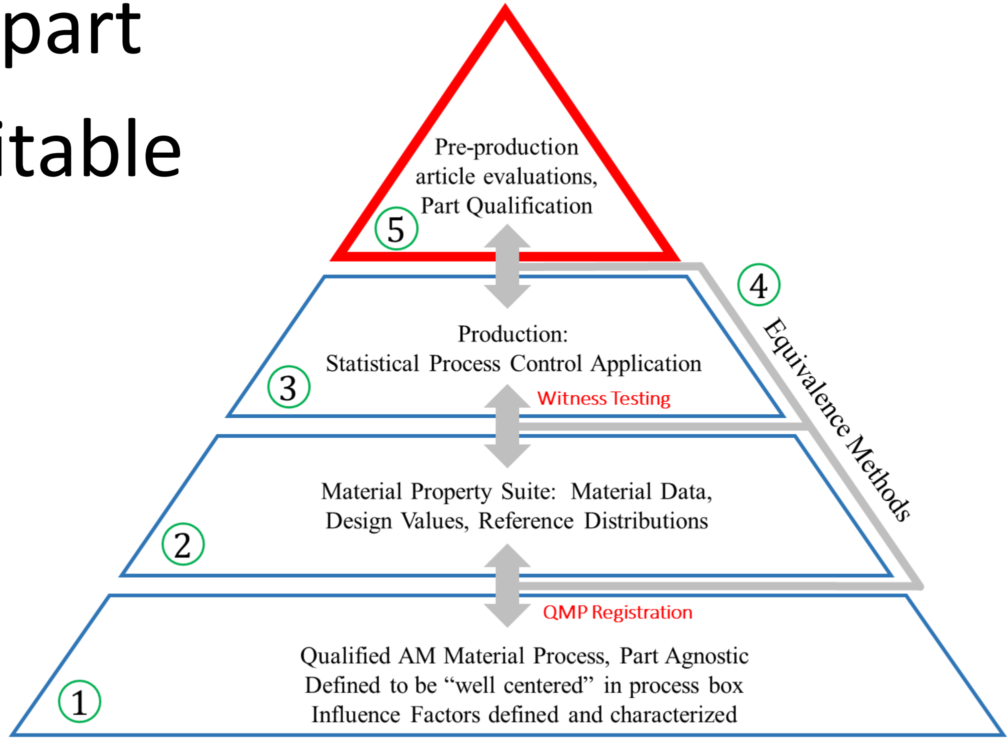
- Agreed upon and approved AM Part Production Plan
- Pre-production article evaluation plan
- AM Manufacturing Readiness Review (Do we have our ducks in a row?..)
    - All stakeholders agree AM part development is successful and complete for qualification or production articles to be produced
    - Demarcates the point in time when changes to AM part definition (digital files, engineering instructions, etc) are locked. NO MORE CHANGES
    - Qualified Part Process (QPP) state is documented in the Quality Management System
- Produce to the Plan and STICK TO THE PLAN



Foundation Complete!!

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

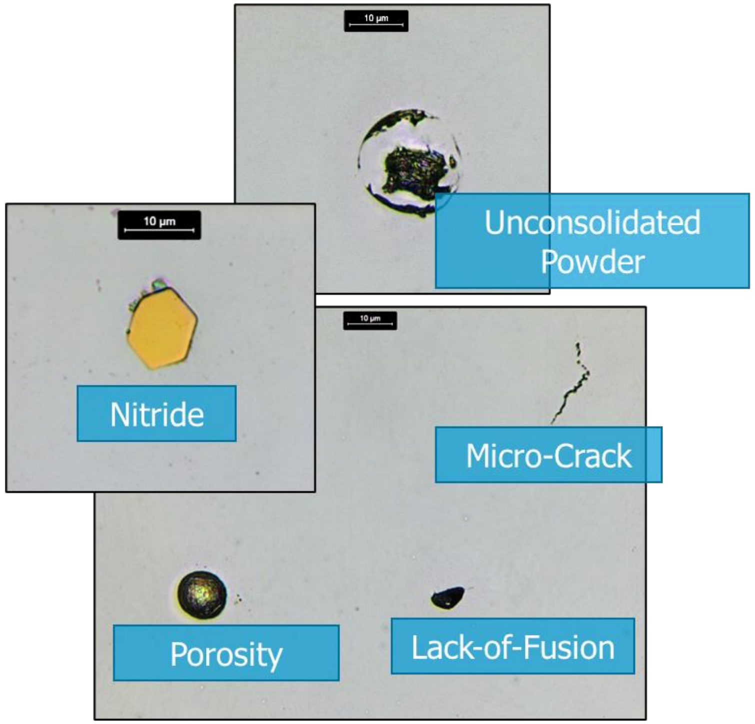
These items MUST Work together not separate

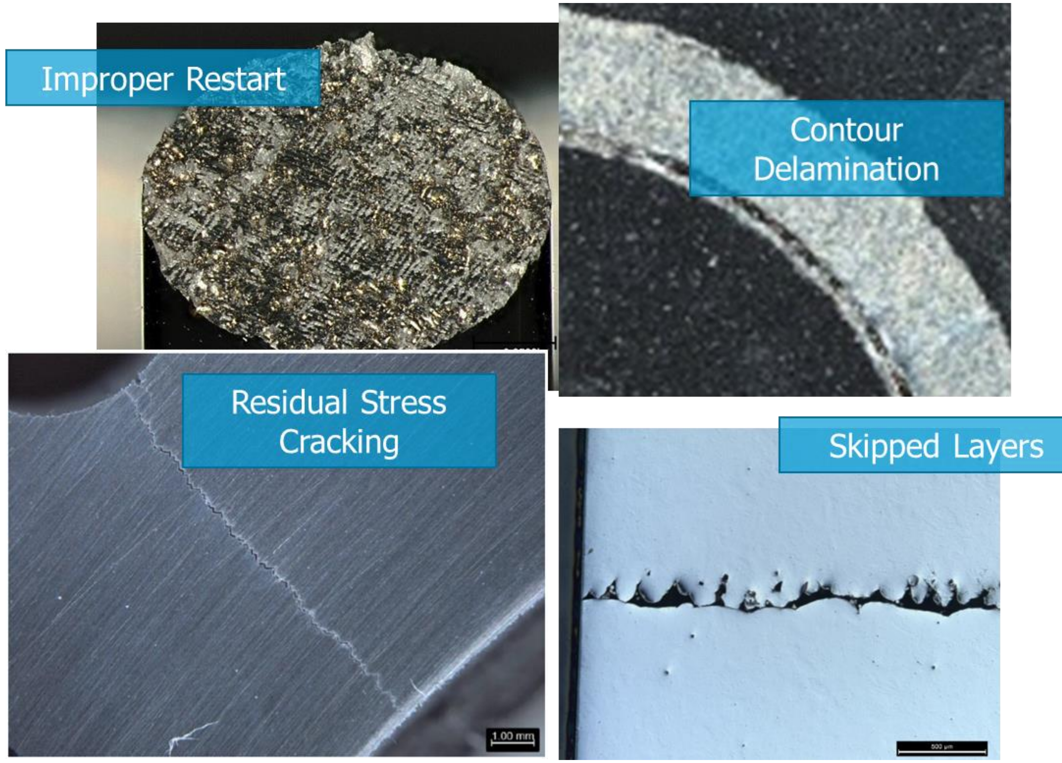
Computational Modeling of AM

- 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
- Opportunities for computationally-assisted qualification and certification
  - Focus primarily on augmenting the existing qualification and certification processes, NOT replacing them
  - Such methods fit into current NASA AM requirements
  - Such tools will require verification and validation
  - Leverage government-industry partnerships

Effects of Defects

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



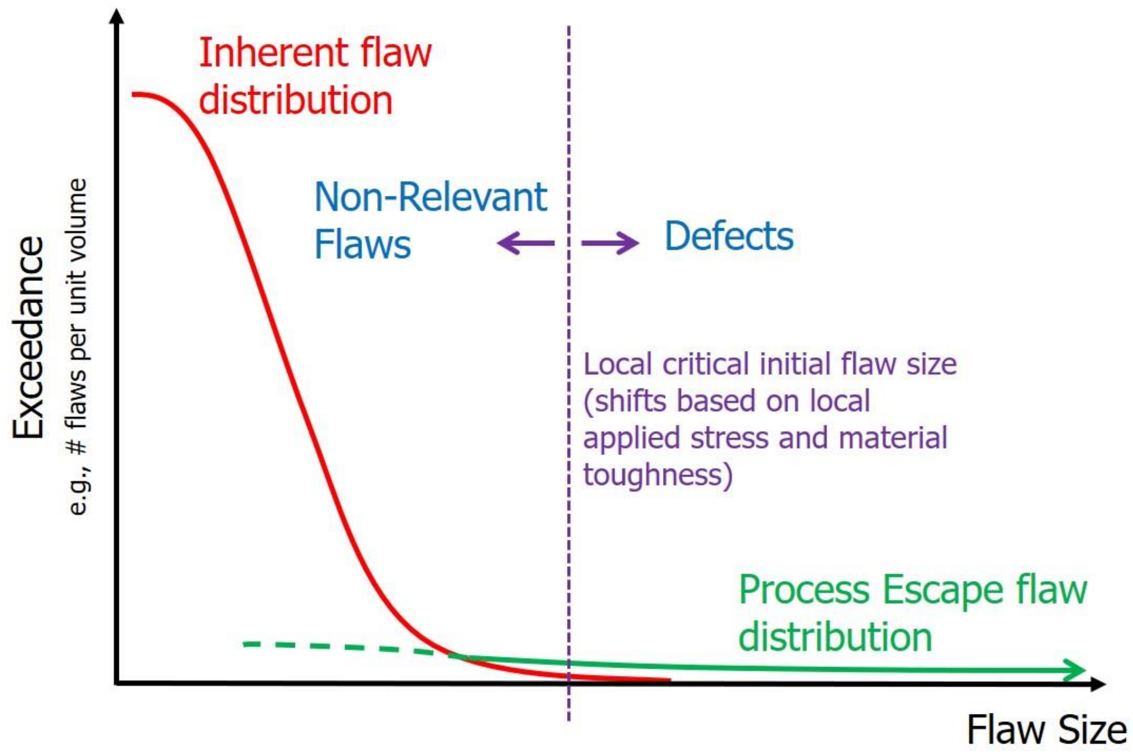


Flaws in AM fall into two categories

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

Effects of Defects

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



In-situ Monitoring

- NASA-STD-6030 requires
  - Quantitative NDE for class A parts
  - NDE for process control for class B parts

Must meet requirements of NASA-STD-5009

  - In-situ monitoring must be qualified in manner analogous to other NDE techniques
- 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

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?

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?