National Aeronautics and Space Administration

Methodologies for Qualification of Additively Manufactured Aerospace Hardware

Swedish Royal Academy of Engineering Sciences
Stockholm, Sweden
June 26, 2018

Douglas N. Wells
Brian M. West
NASA Marshall Space Flight Center
Huntsville AL, USA

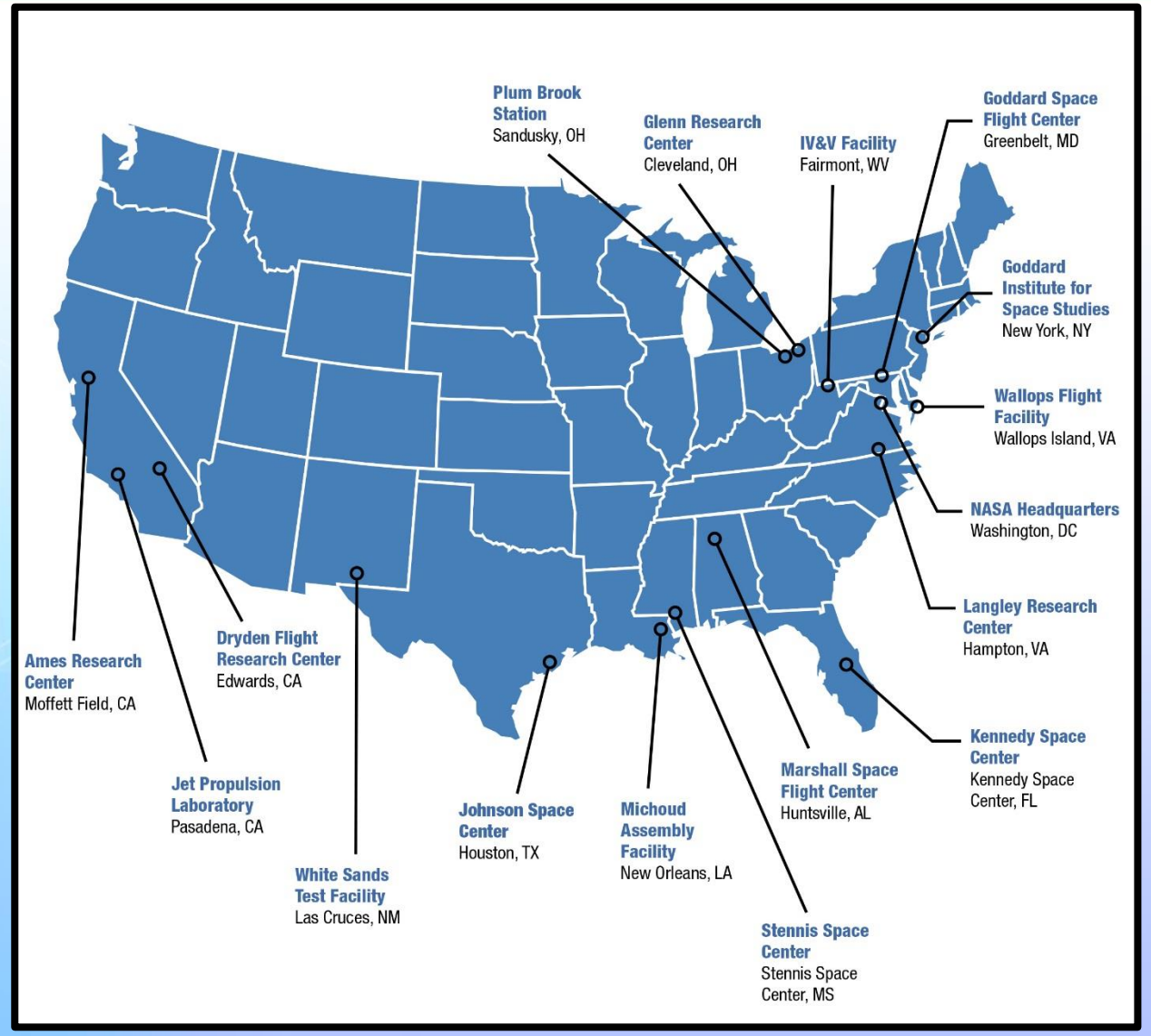
Overview of Discussions

- Additive Manufacturing at NASA
- NASA MSFC AM technical standards
- Key AM Qualification Concepts
- Foundational Controls
  - Qualified Metallurgical Process
  - Material properties
- Part production process
  - Qualified Part Process
- Observations, Challenges, and Closing

Overview of NASA

NASA is not homogeneous

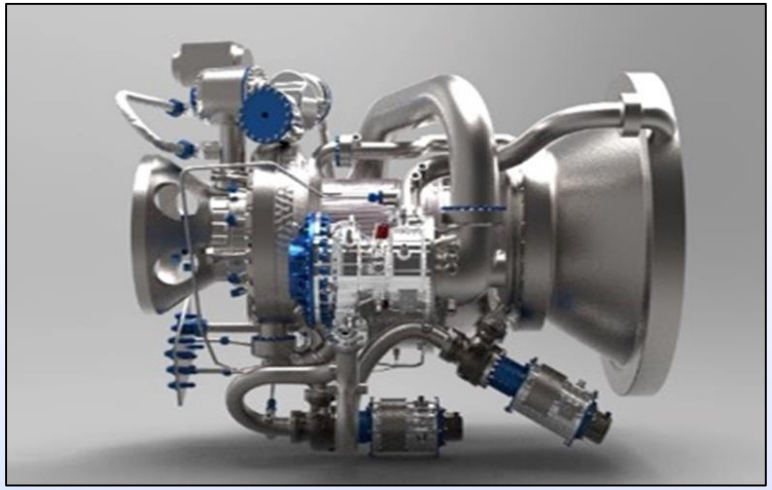
- Technical and risk cultures vary by facility and mission as shaped by its history
- Human-rated spaceflight
  - JSC, KSC, MSFC
- Space Science
  - GSFC, JPL
- Aeronautics
  - LaRC, GRC, ARC



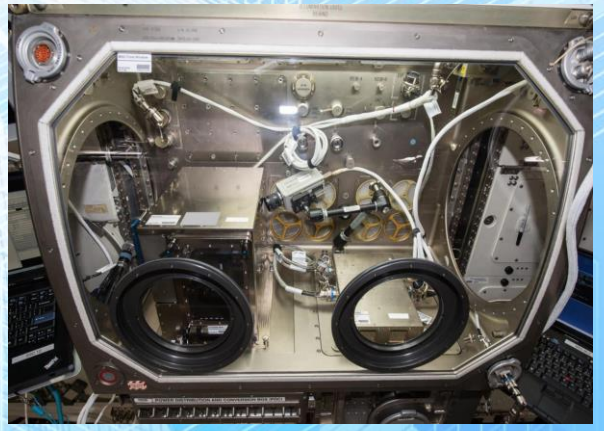
Additive Manufacturing at NASA

AM in space-related NASA missions:

For-space:

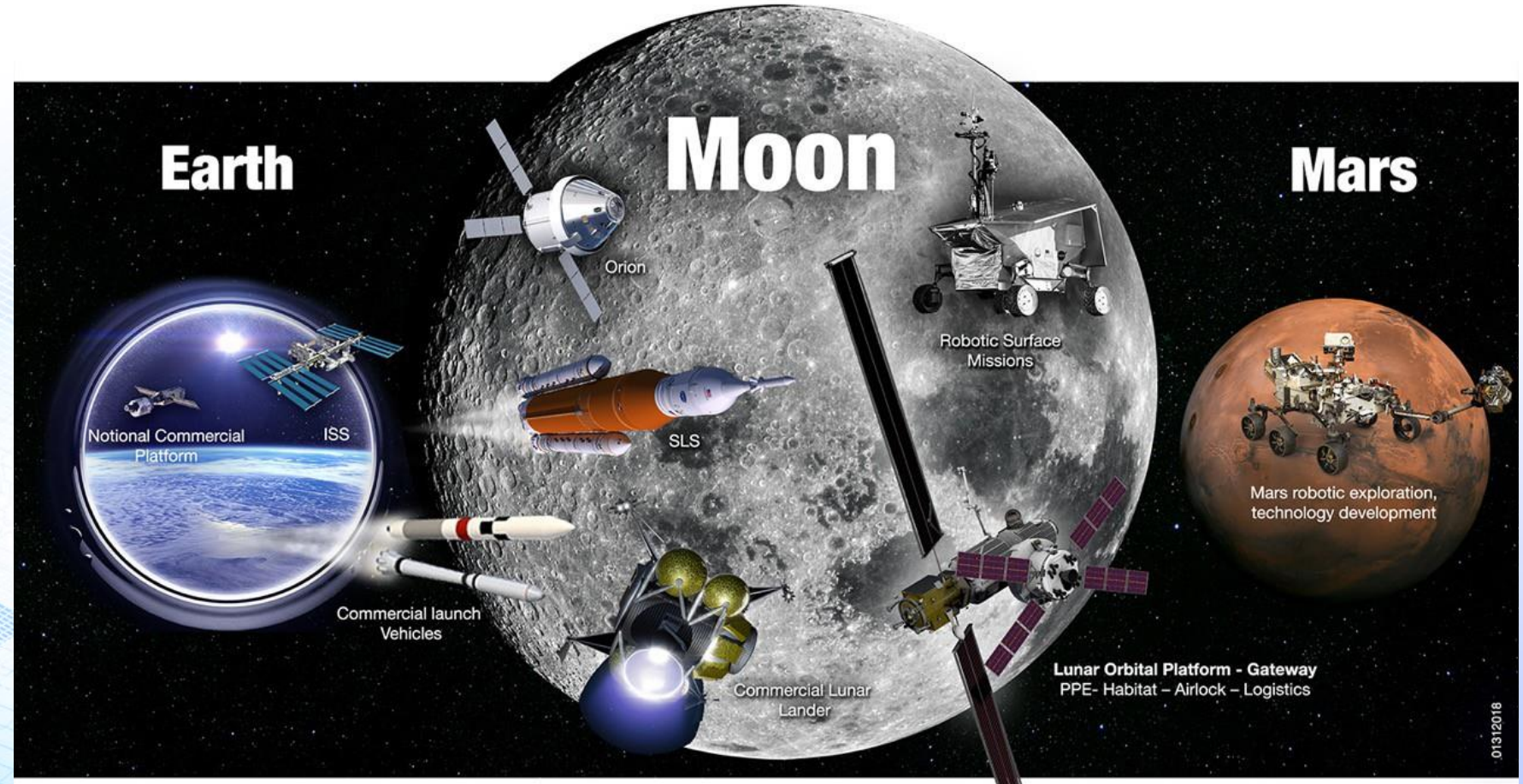


In-space:



MADE IN SPACE

Supporting the Mission



In LEO
Commercial & International partnerships

In Cislunar Space
A return to the moon for long-term exploration

On Mars
Research to inform future crewed missions

Additive Manufacturing (at MSFC)

- Extensive experience in Additive Manufacturing (AM) technologies, and have been involved in about 30 different AM systems in the past 26 years.
- Over $10M capital investments in metallic powder bed systems in the past 5 years, and have committed significant engineering manpower resources
- NASA AM Objectives
  - Decrease production lead time & costs
  - Develop Flight Certification Standards
  - Process development and characterization
  - Share knowledge and data in pursuit of smart vendor base
  - Design optimized components & test at relevant conditions
  - Appropriate Application
    - High complexity & difficult to manufacture
    - Low production rate
    - Long lead time & high cost

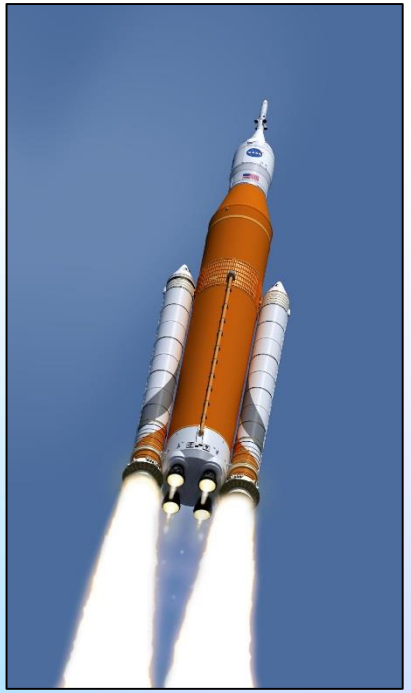
NASA MSFC AM Standards

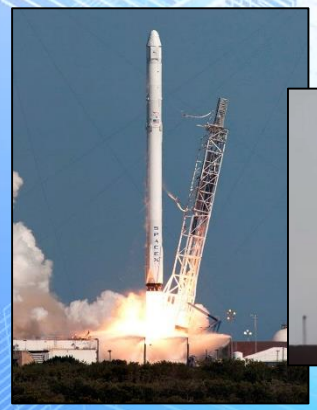
Motivation: Laser Powder Bed Fusion in near term, human-rated flight projects:

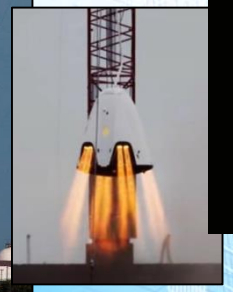
- Space Launch System
- Orion Spacecraft
- Commercial Crew Program

Document content is determined by

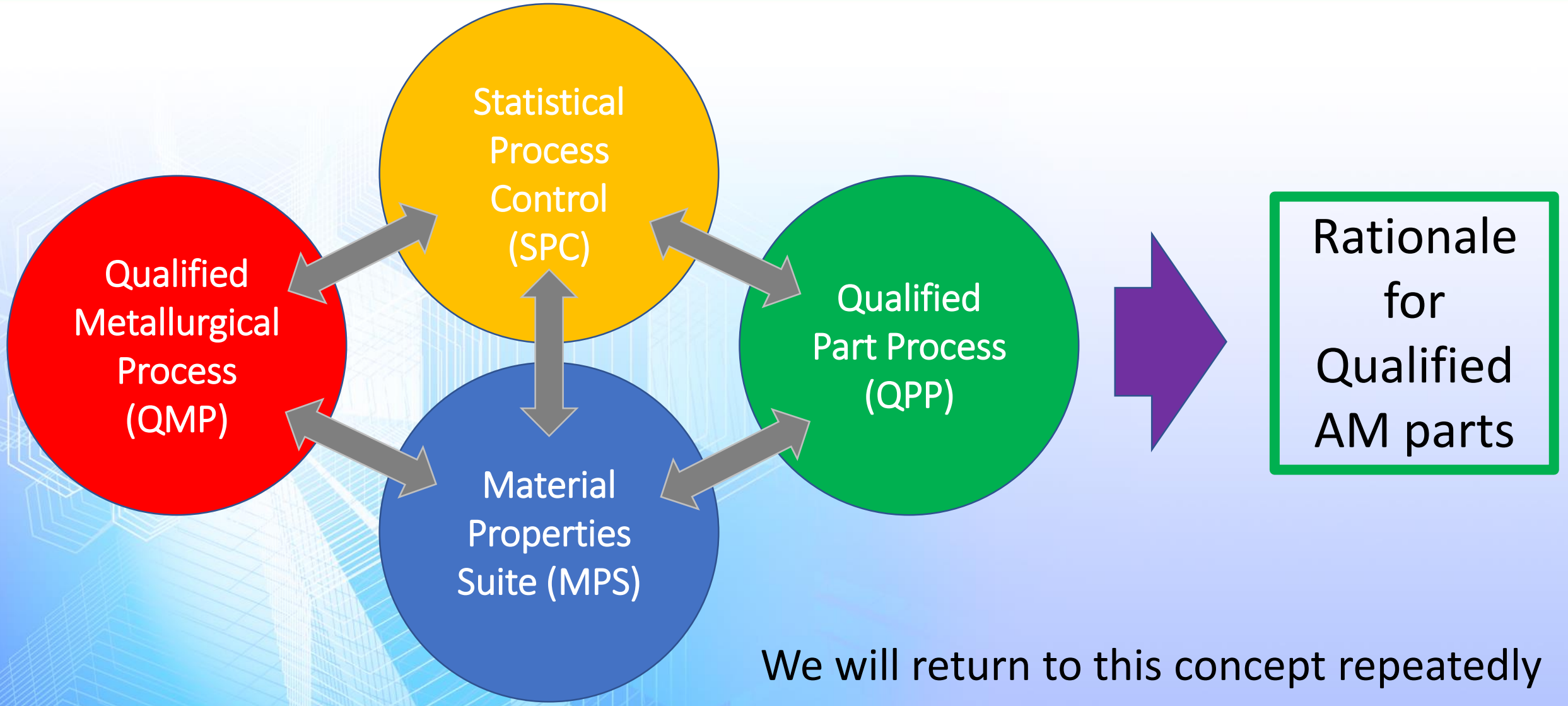
- *Policy*: MSFC-STD-3716 and
- *Procedure:* MSFC-SPEC-3717





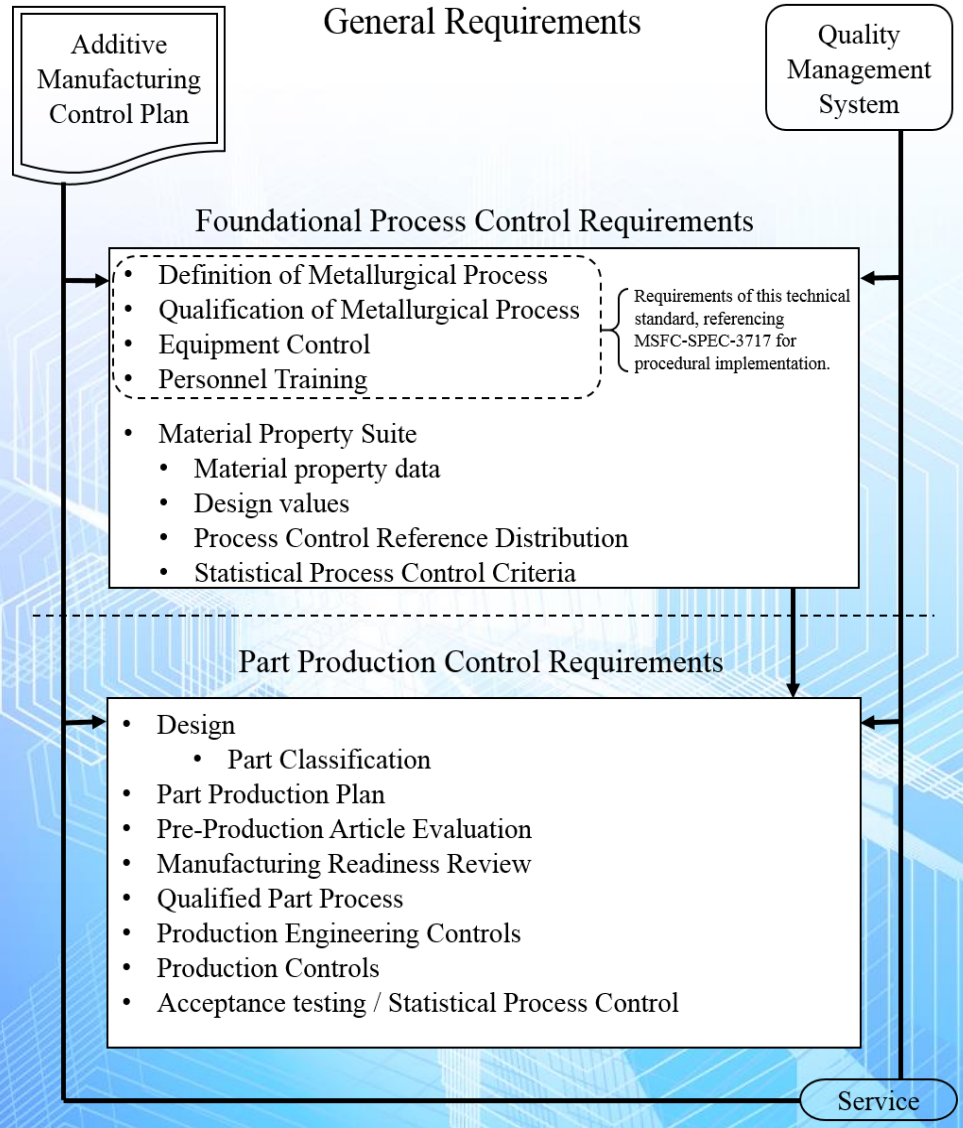


Key AM Qualification Concepts

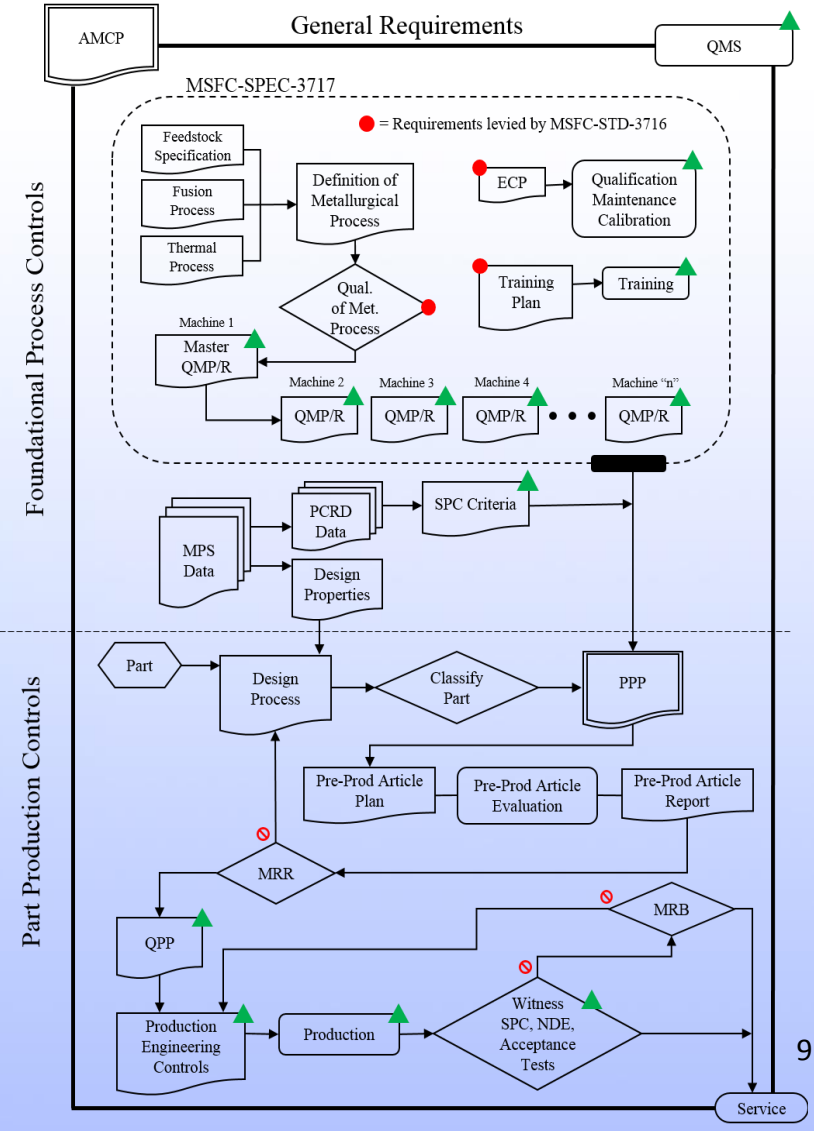


We will return to this concept repeatedly

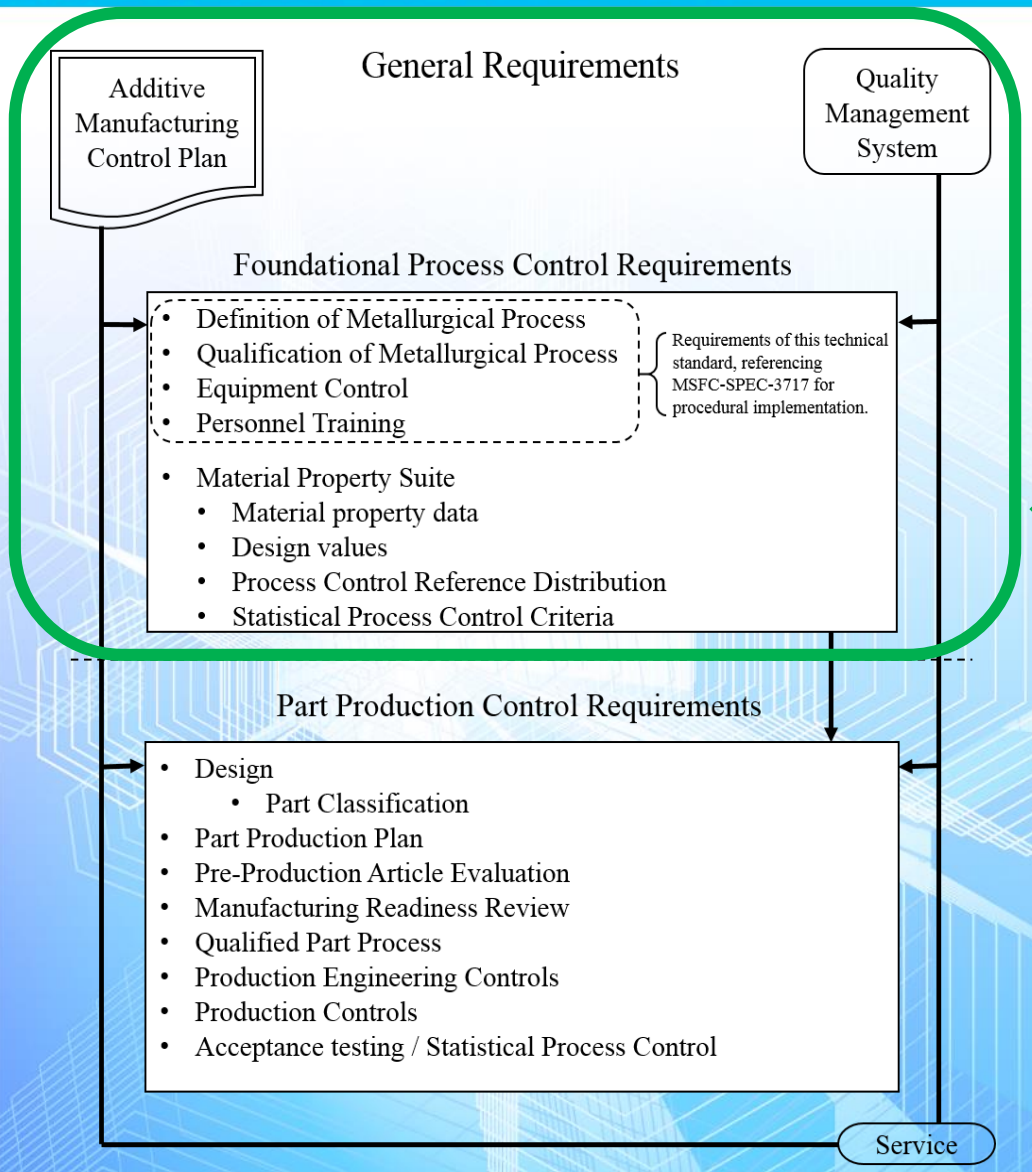
Overview of Current Requirements



Flowcharts from MSFC-STD-3716



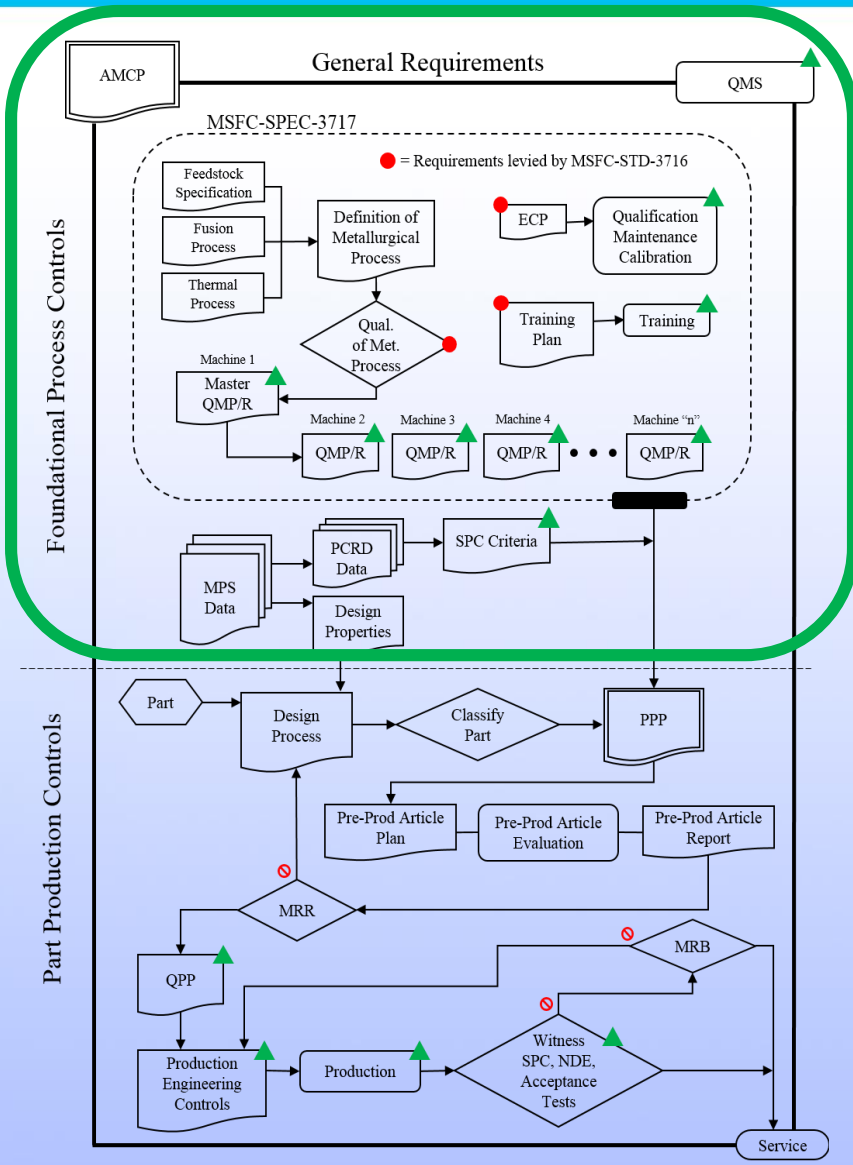
Overview of Current Requirements



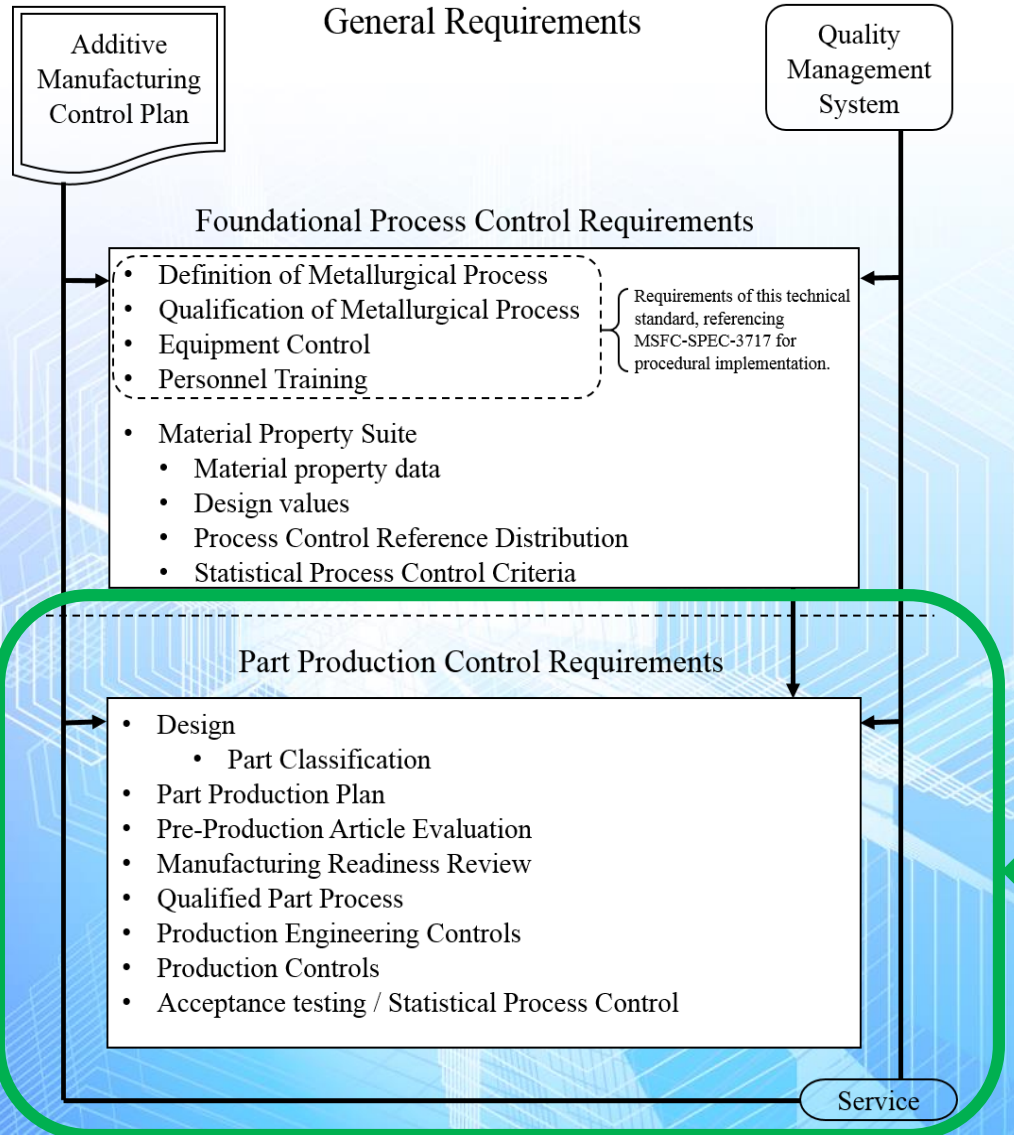
Flowcharts from MSFC-STD-3716

First Part of Lecture:

General Requirements and Foundational Process Controls



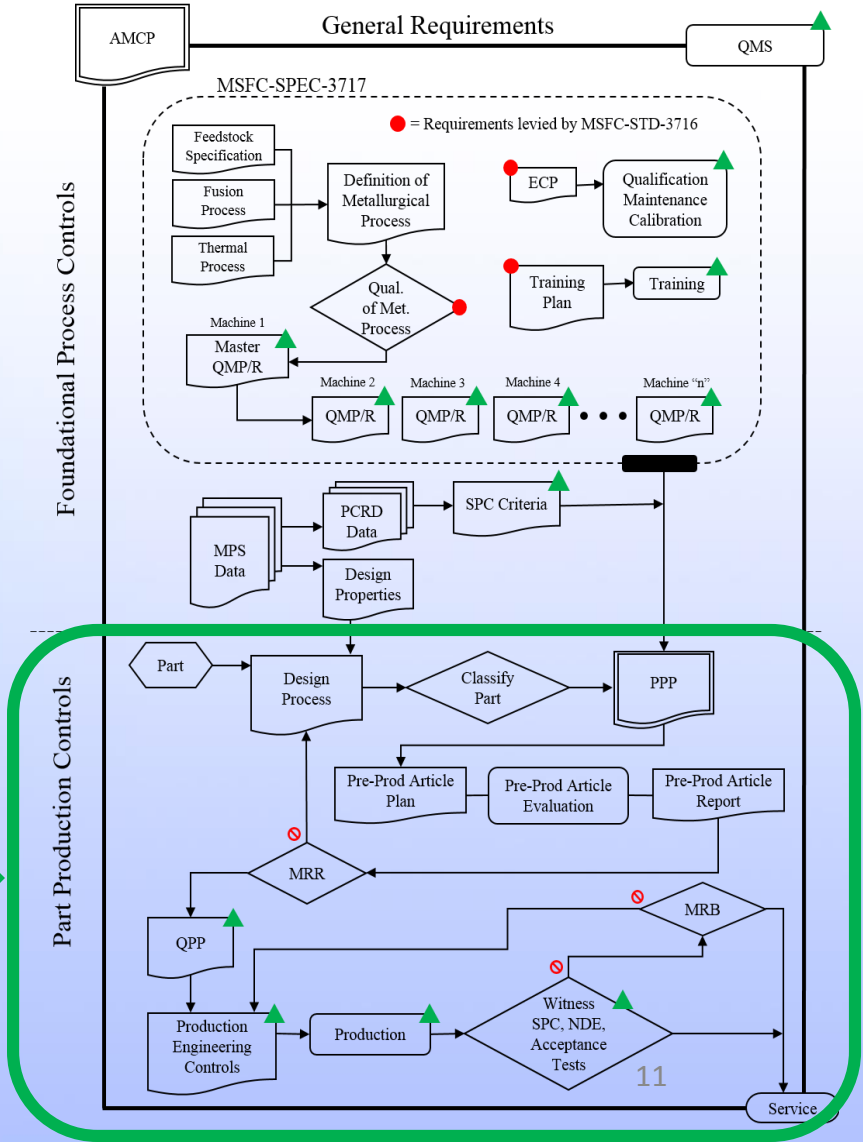
Overview of Current Requirements



Flowcharts from MSFC-STD-3716

Second Part of Lecture:

Part Production Controls

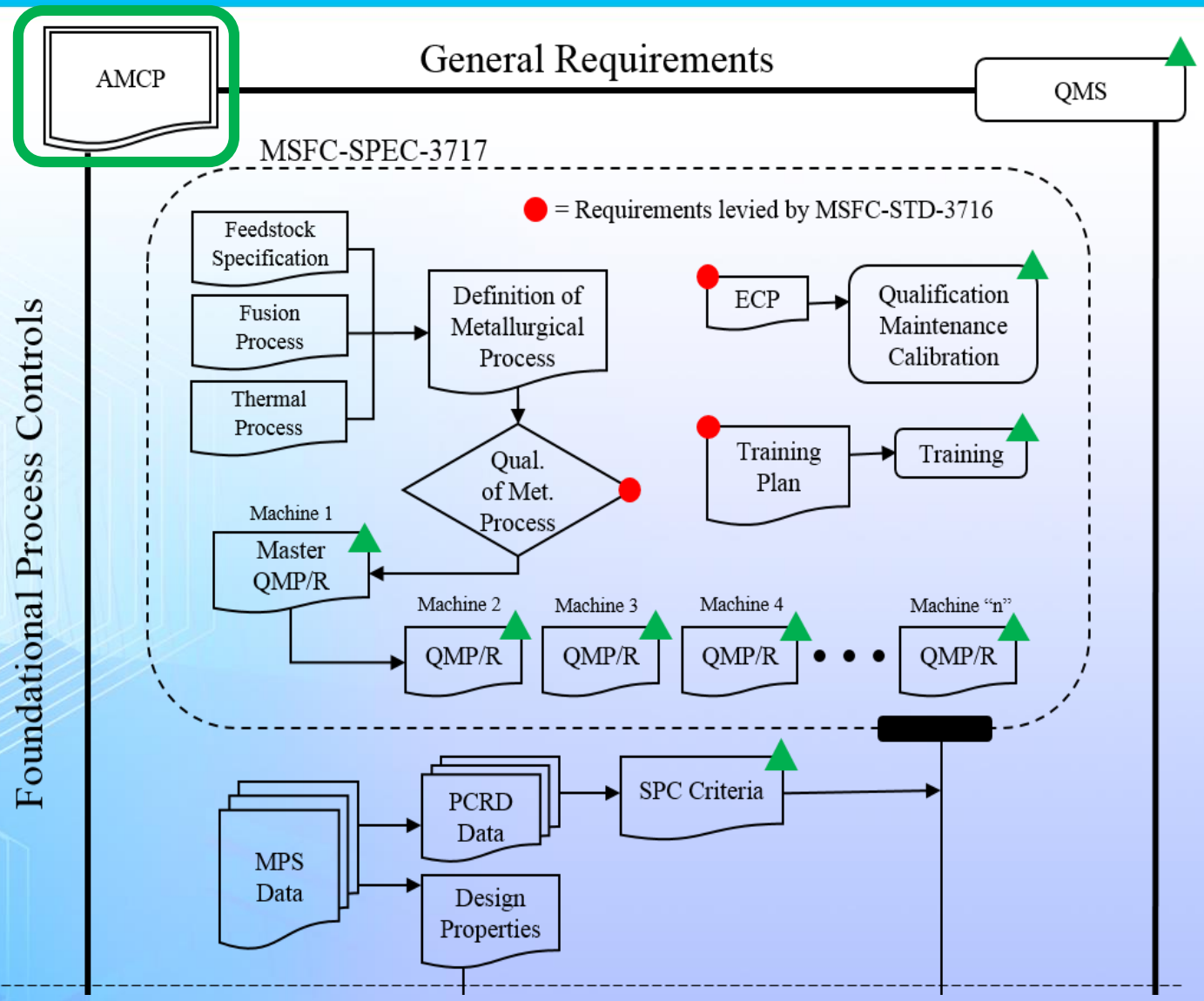


General Requirements and Foundational Process Controls

Overarching and Foundational Controls

Additive Manufacturing Control Plan

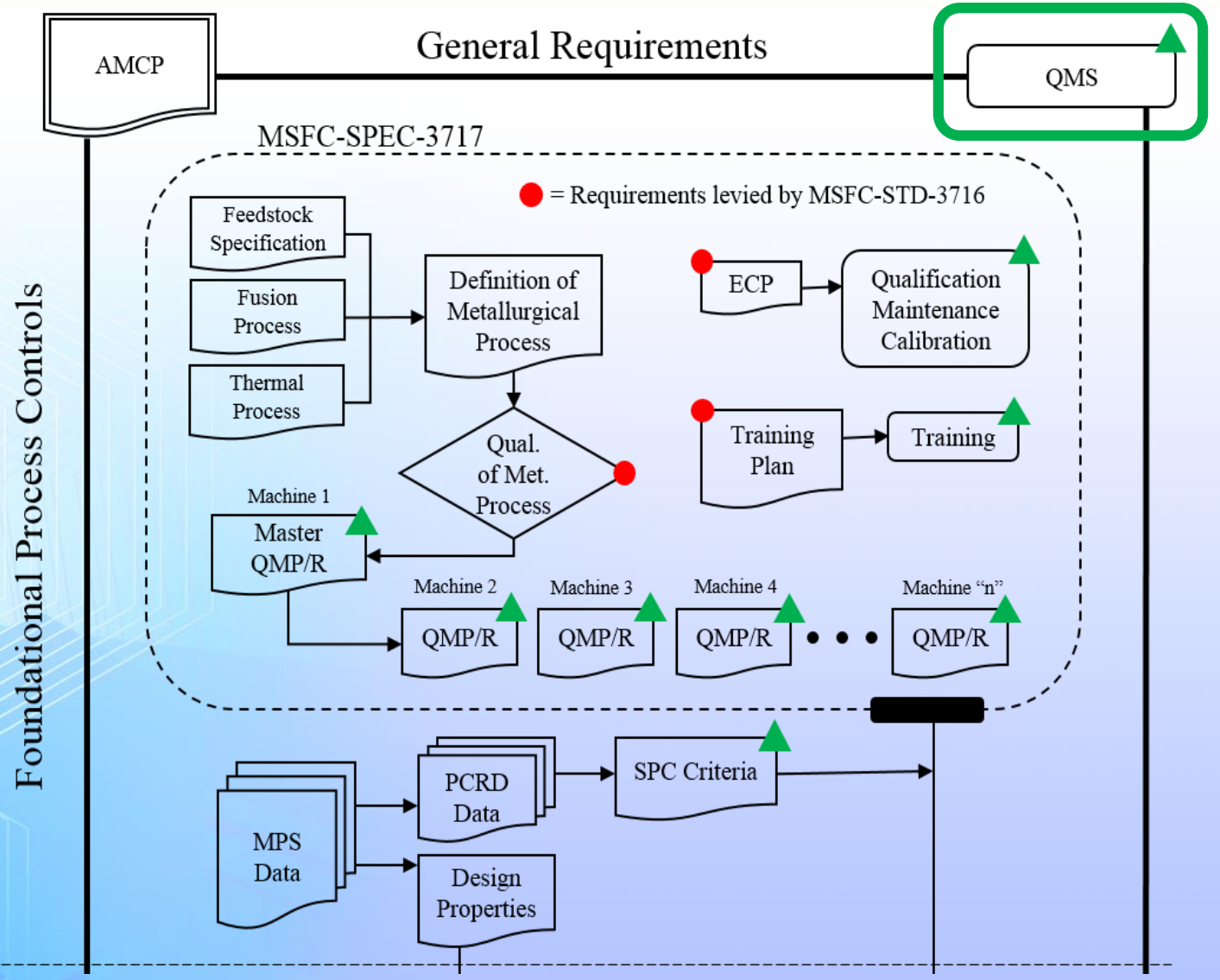
- Critical to define implementation policies for program or project
- Describes implementation of all requirements
  - Includes tailoring of requirements
- Becomes governing document in place of standards



Overarching and Foundational Controls

Quality Management System

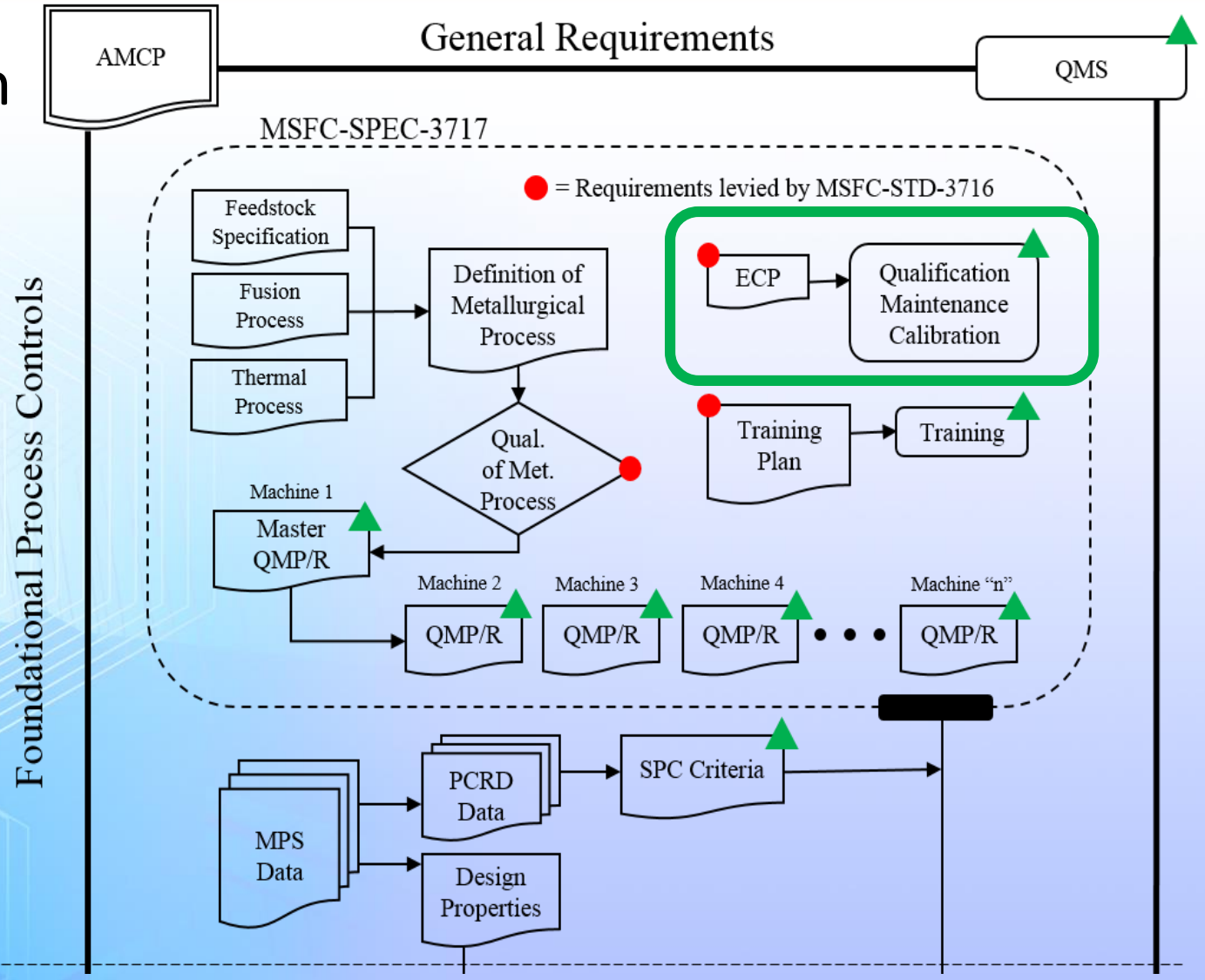
- Critical to define implementation policy
- Describes implementation of all requirements
- Becomes governing document in place of standards



Overarching and Foundational Controls

Equipment and Facility Control Plan

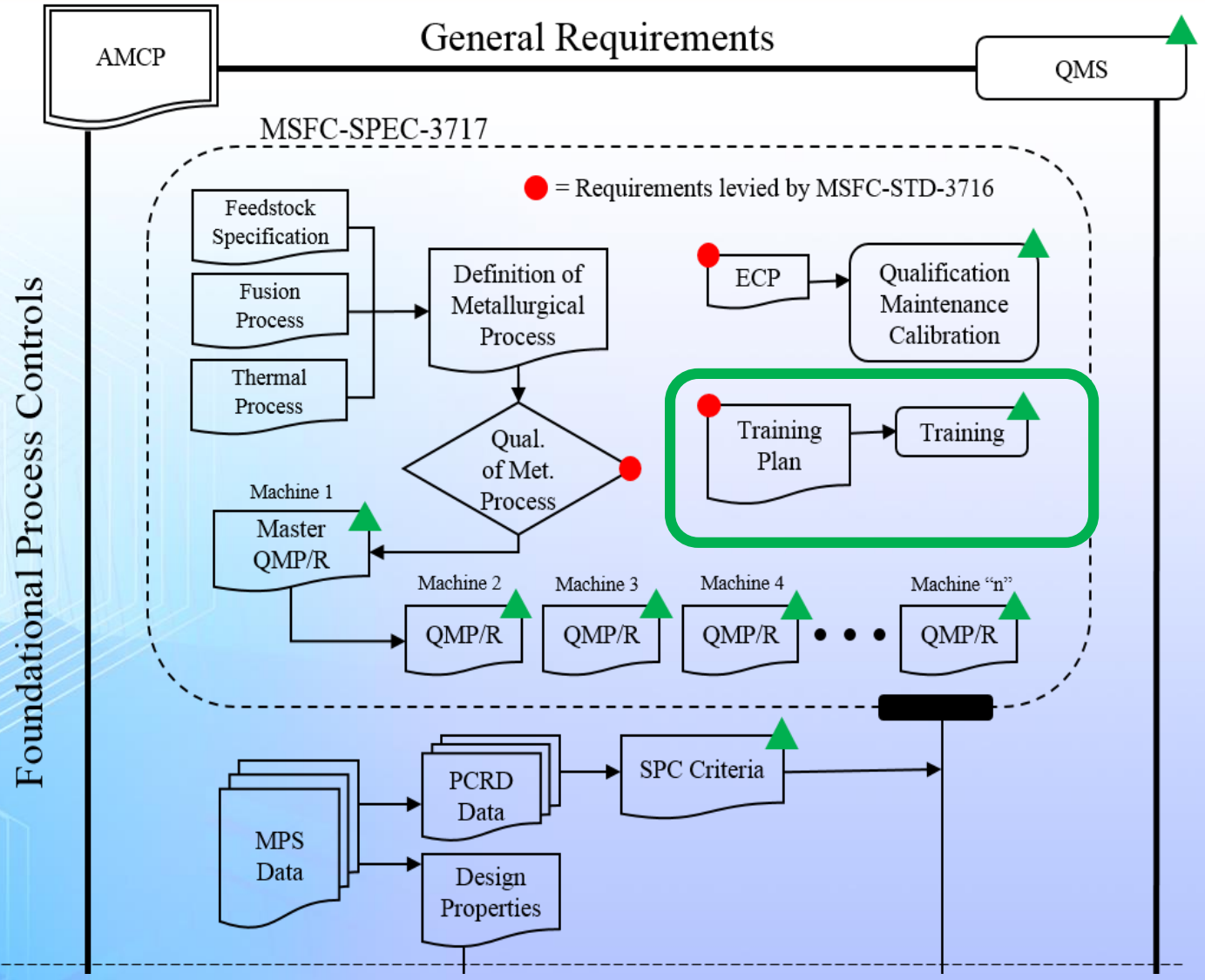
- Plan required by Standard
  - Procedures in Specification
- Flexibility in implementation
- Governs AM equipment and facility
  - Qualification
  - Maintenance
  - Calibration



Overarching and Foundational Controls

Personnel Training

- Training Plan required by Standard
  - Expectations in Specification
- Flexibility in implementation
- Covers all personnel involved in AM
  - Consistent framework for training and certification of abilities
  - Clear delineations of abilities and responsibilities associated with granted certifications
  - Evaluations demonstrating adequacy
  - QMS awareness



Qualified Metallurgical Process

Qualified Metallurgical Process

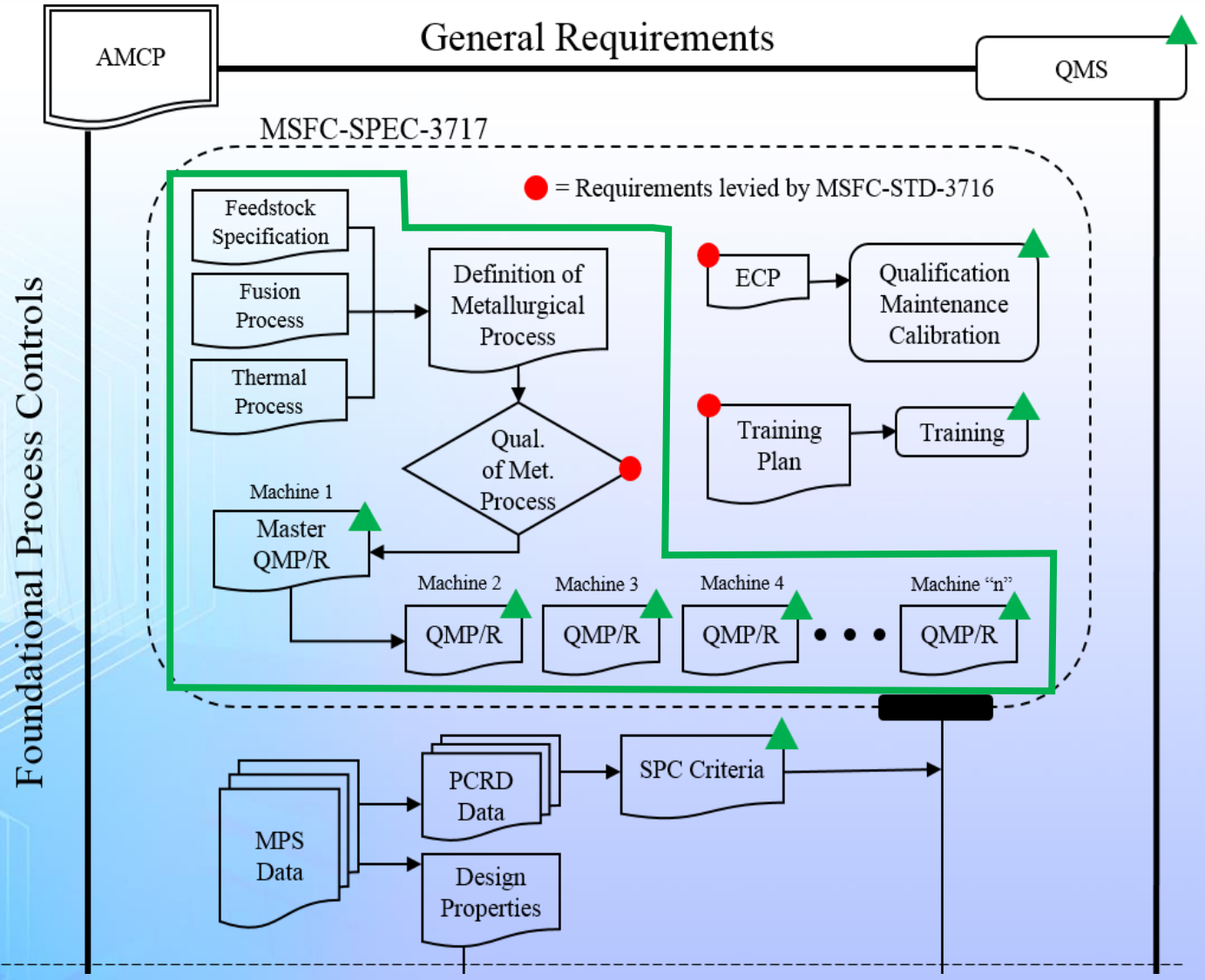
Begins as a ***Candidate*** Met. Process

Defines aspects of the basic, ***part agnostic***, fixed AM (L-PBF) process:

- Feedstock
- Fusion Process
- Thermal Process

Enabling concept

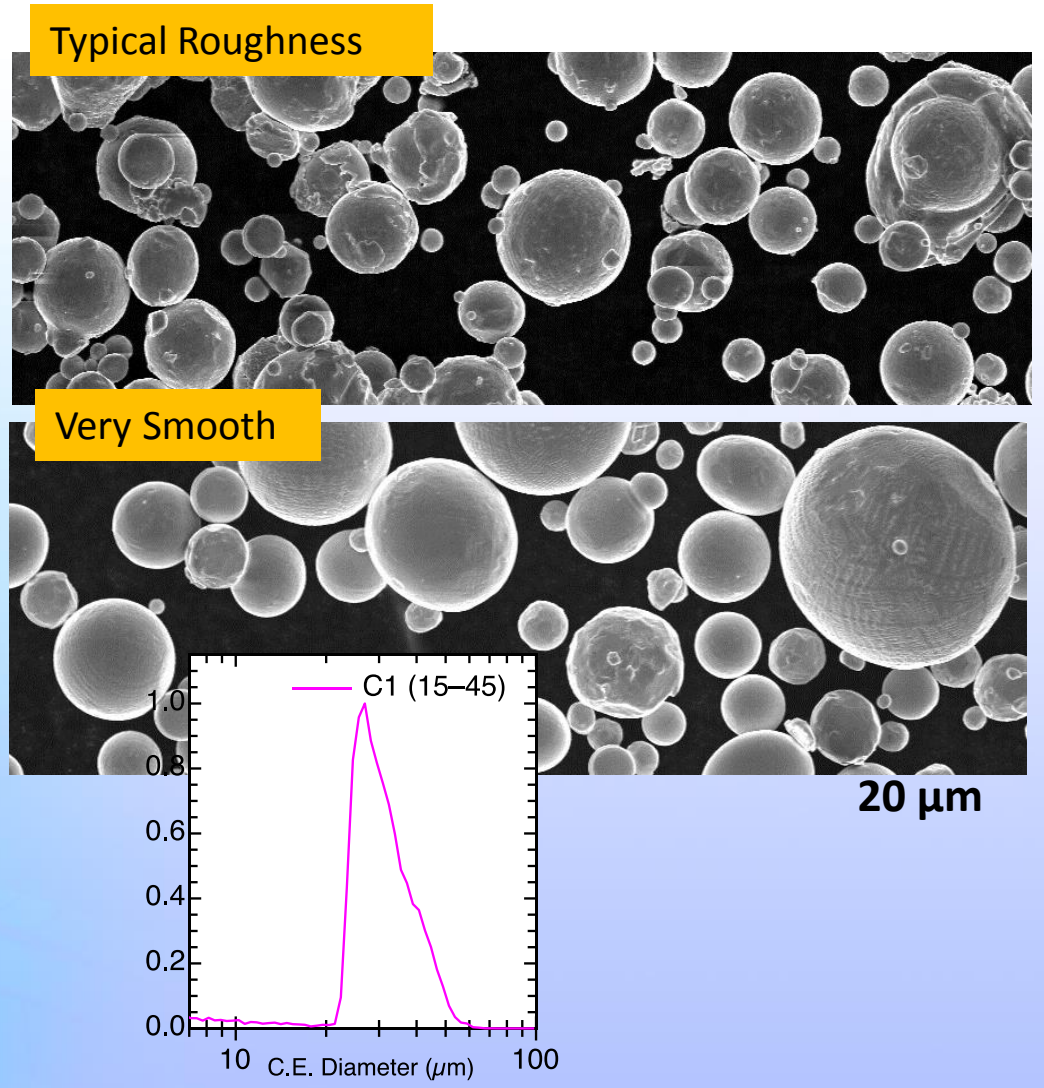
- Machine qualification and re-qualification
- Process control metrics, SPC
- Design values



Candidate Metallurgical Process

Feedstock Controls

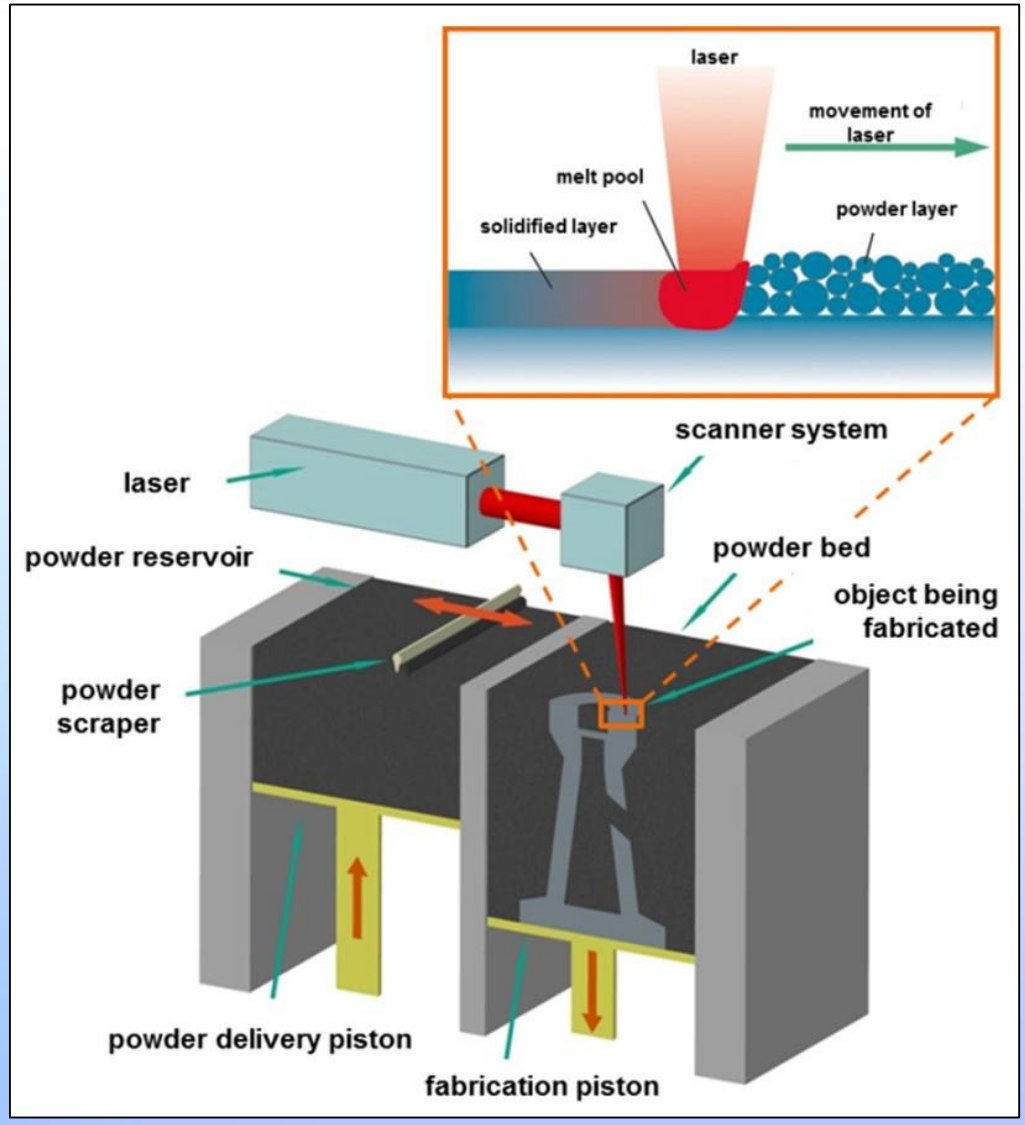
- Method of manufacture
- Chemistry
- Particle Size Distribution
- Particle morphology
- Blending and doping controls
- Cleanliness and contamination
- Packaging, labeling, environmental controls
- Reuse controls



Candidate Metallurgical Process

Fusion Controls

- Equipment:
  - Make, Model, *Serial Number*
  - Software/Firmware versions
  - Settings (dosing, recoater speed)
- Atmosphere Controls
  - Oxygen limits
  - Ventilation flow rate
  - Gas quality (purity, dew point)
- Fusion Parameters
  - Layer thickness
  - Power, speed, hatch, contours…



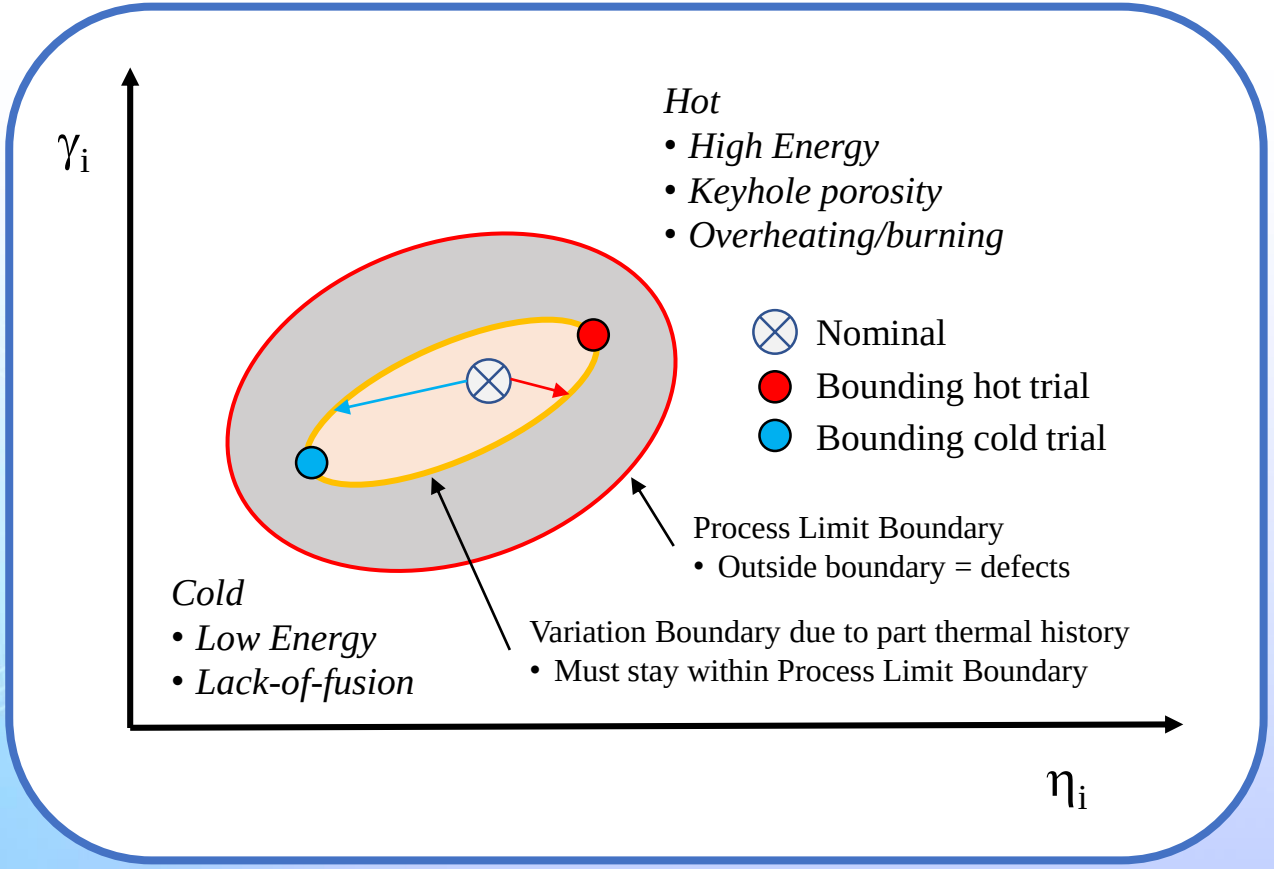
Source: Fraunhofer IWU

Candidate Metallurgical Process

Fusion Controls

Tolerance to variation

- Part build scenarios create variation in process conditions
  - Thermal history effects
  - Scan patterns
- "Process Box" evaluation for qualification
- QMP needs to be "centered" in the process box to allow robust part build capability



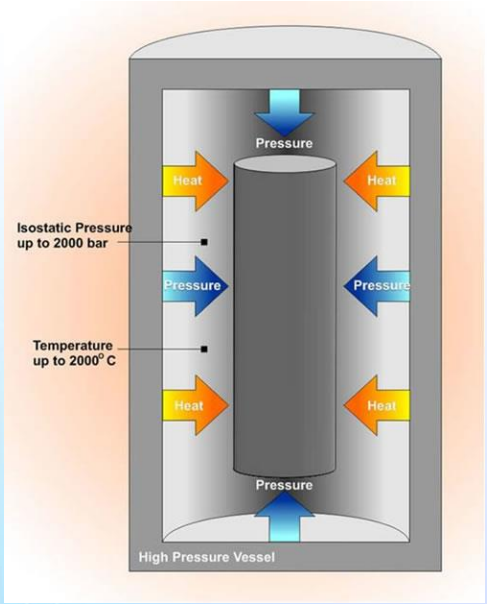
Process Box: Resulting variations in nominal commanded process due to part geometry, scan pattern and thermal history

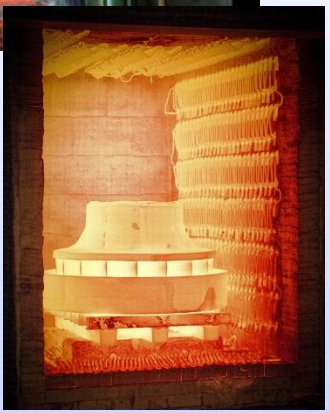
Candidate Metallurgical Process

Thermal Process

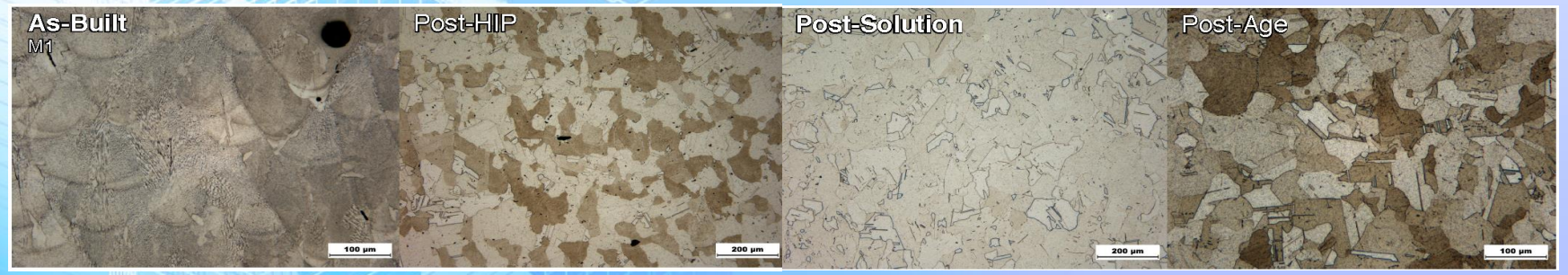
Post-build Thermal Processing

- Includes definition of all thermal process steps
- *Evolution of microstructure*
- Stress Relief, Hot Isostatic Pressing, Solution Treating, Aging, etc.





IN718 Microstructural Evolution



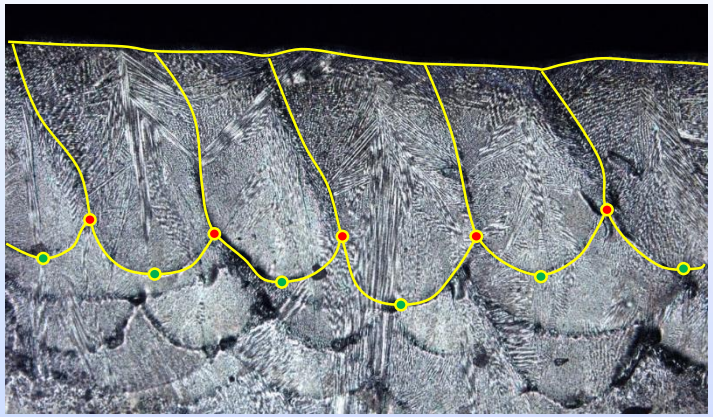
Qualified Metallurgical Process

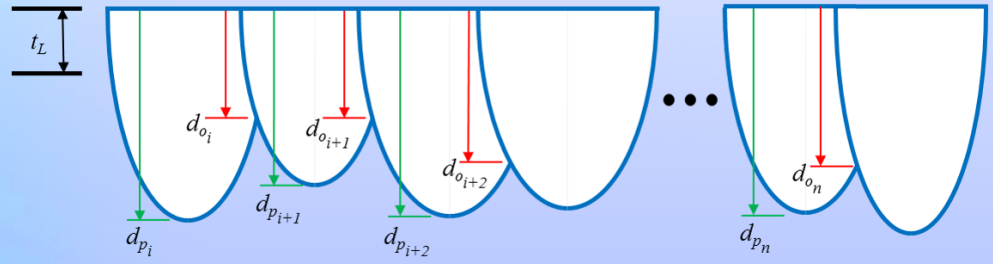
Qualification the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

Step 1: Metallurgical Qualification

- Consistency throughout build area
- Tolerance to variation
- Interface quality (restart, contour passes, striping, islands, multi-laser zones)
- Top layer melt pools
- Microstructural evolution
  - Final state free of strong texture





Melt Pool Evaluation

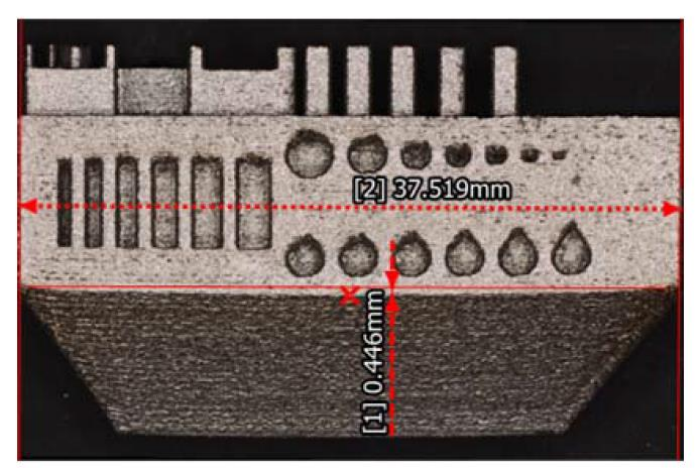
Qualified Metallurgical Process

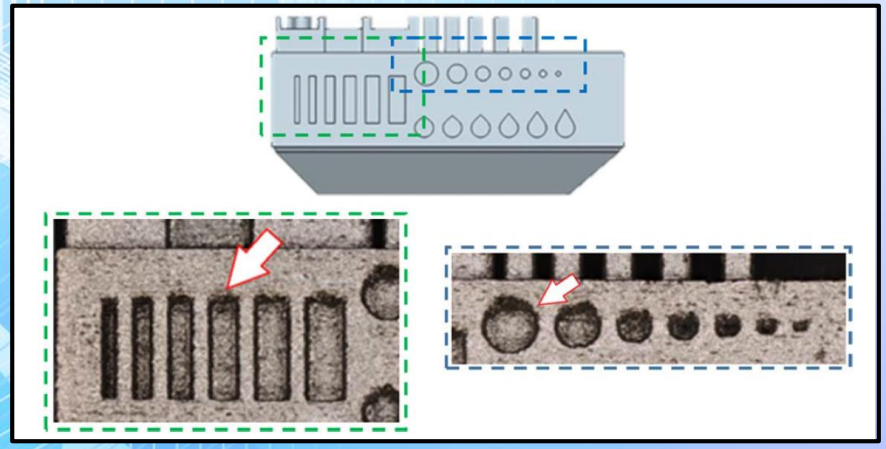
Qualification the Candidate Metallurgical Process

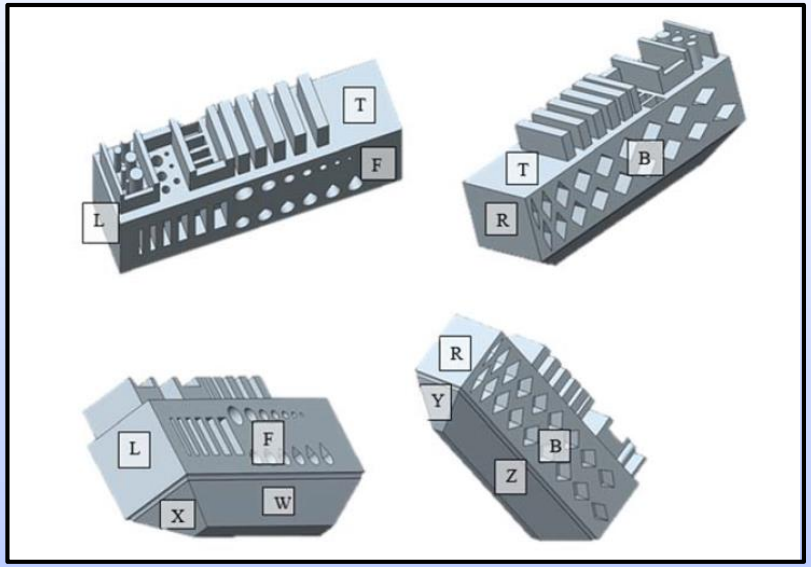
Establishes a QMP: Qualified Metallurgical Process

Step 2: Surface texture and detail resolution

- Reference Parts
- Mix of qualitative and quantitative measures







Qualified Metallurgical Process

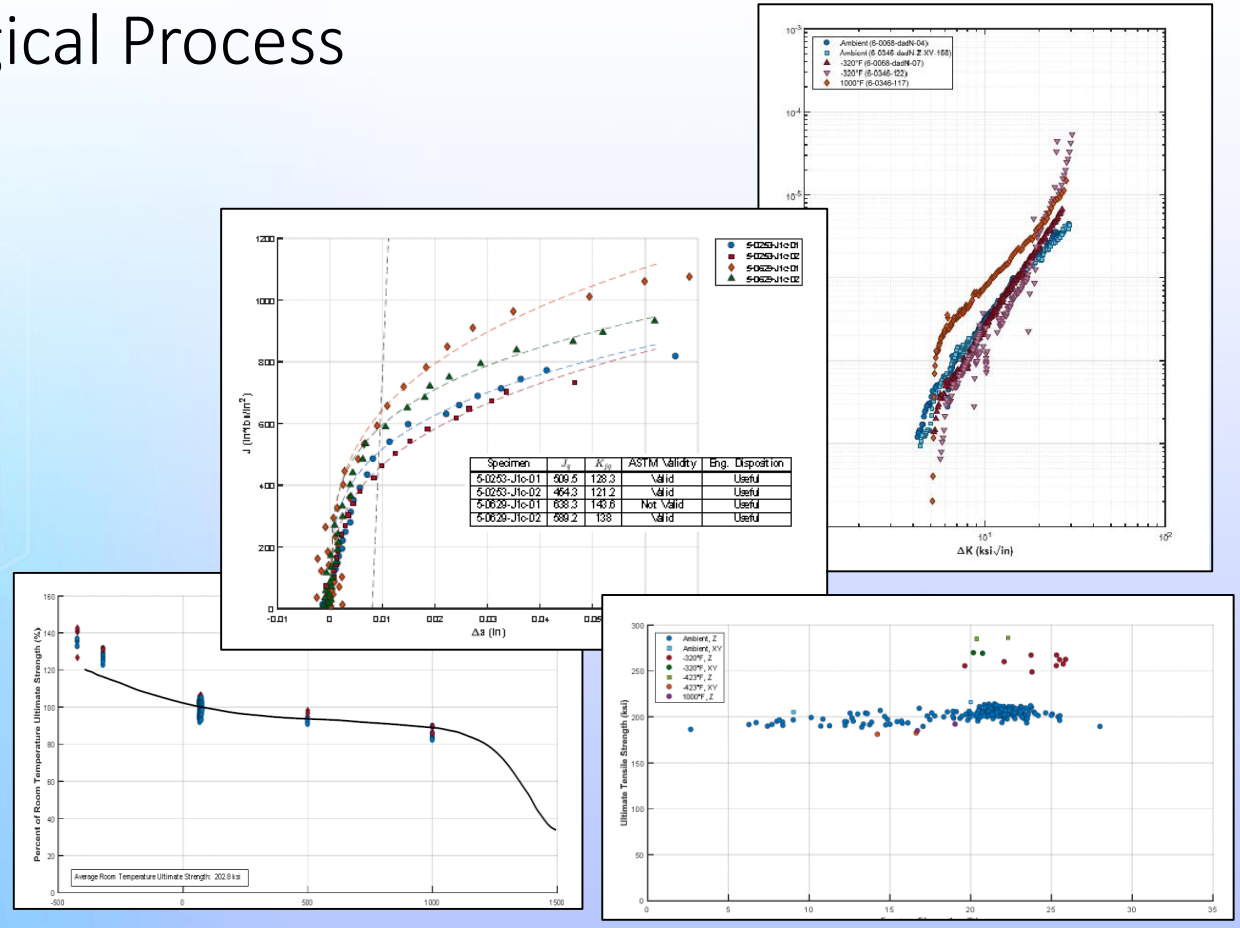
Qualification the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

Step 3: Mechanical properties

- Tensile, fatigue, toughness…
- Registration through Equivalence
  - Material Property Suite
  - “In-family” performance

QMP “Registration” is the process of demonstrating properties of the qualified process are equivalent to those in the applicable MPS - the next topic.

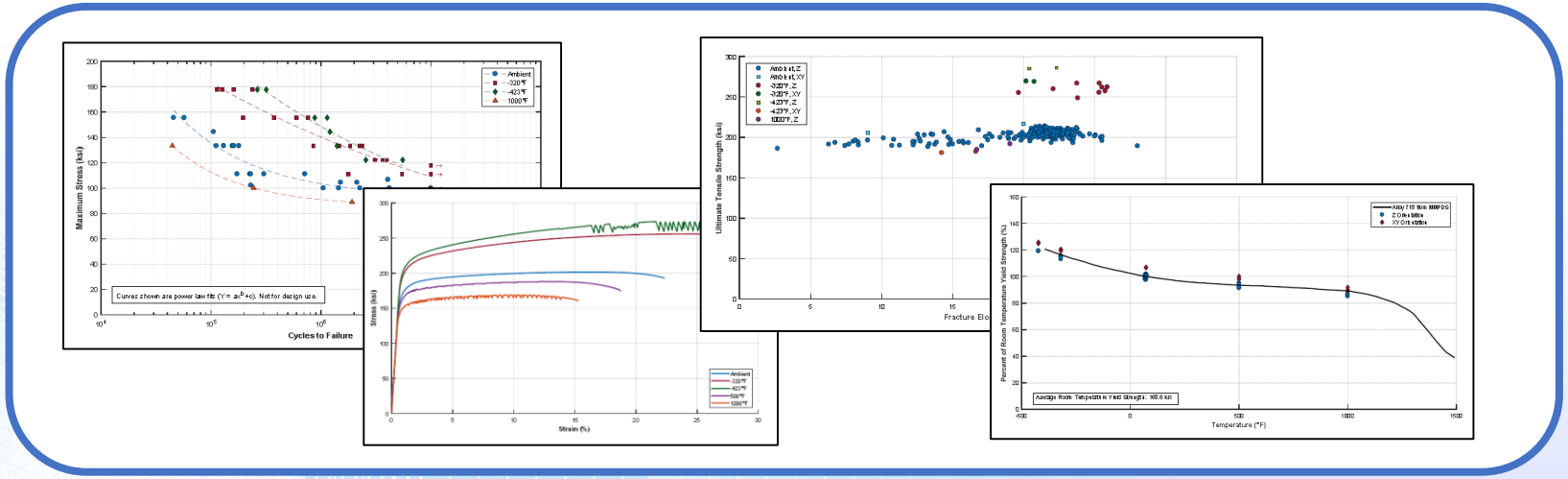


Material Property Suite

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

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

Material Property Suite



Data Repository

Includes data from

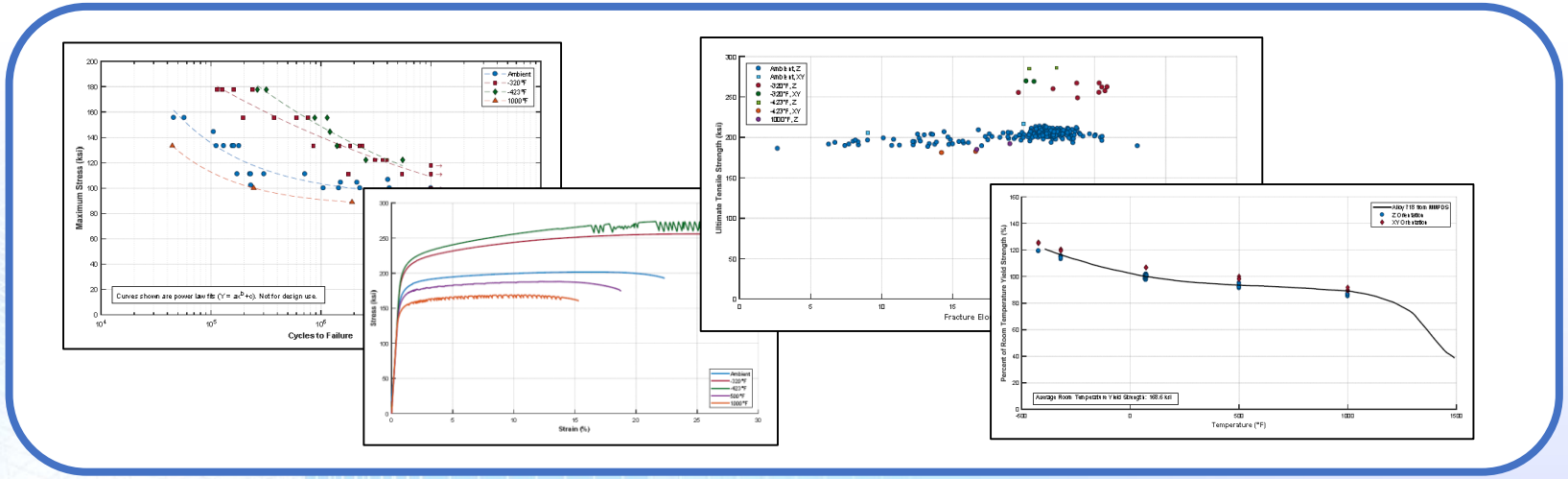
- Qualification testing
- Material Characterization
- Pre-production Article Evaluations

Grouping of data

Group data by

- QMP = Material/process/heat treat
- “Combinable” conditions for design

Material Property Suite

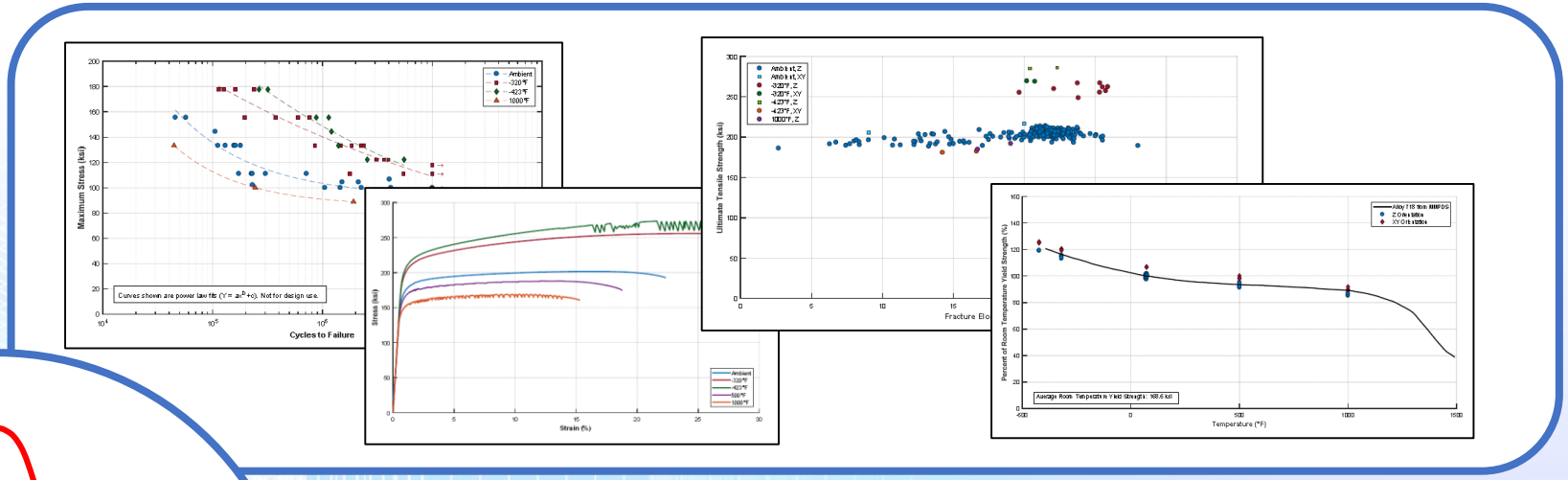


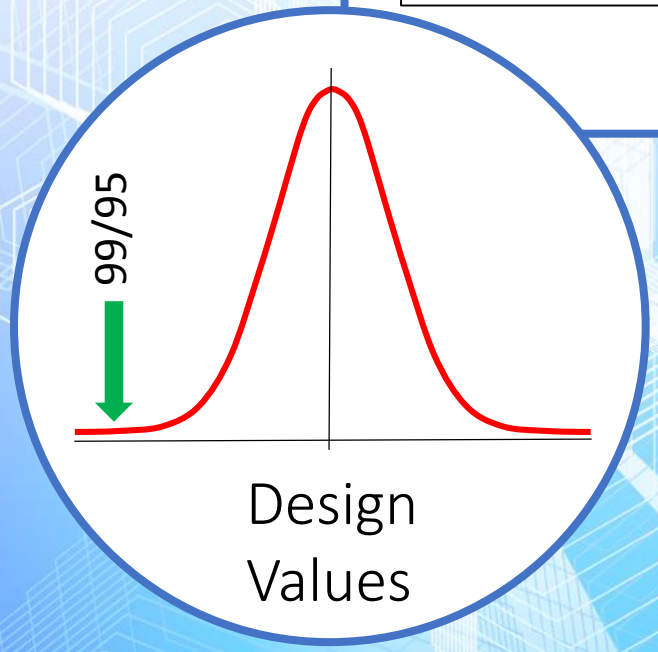
Data Repository, continued

Contains all data needed for

- Setting Design Values
- Property equivalence evaluations and QMP Registration
- Setting the Process Control Reference Distribution

Material Property Suite

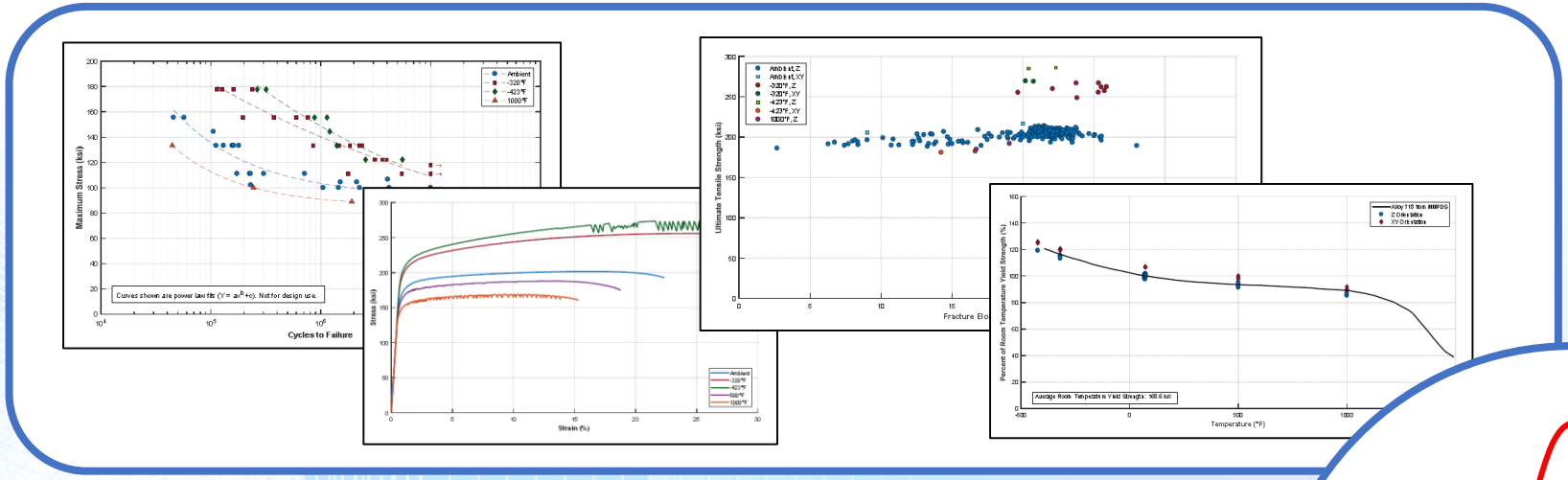




Design Values

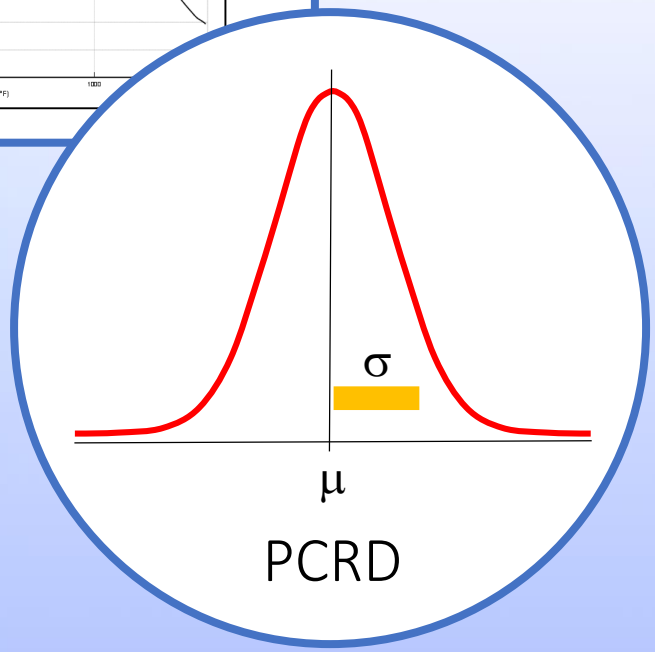
- Statistically substantiated
- Applicable sources of variability included
- Utilizes all appropriate data sources in Repository
- May include additional margin for safety

Material Property Suite

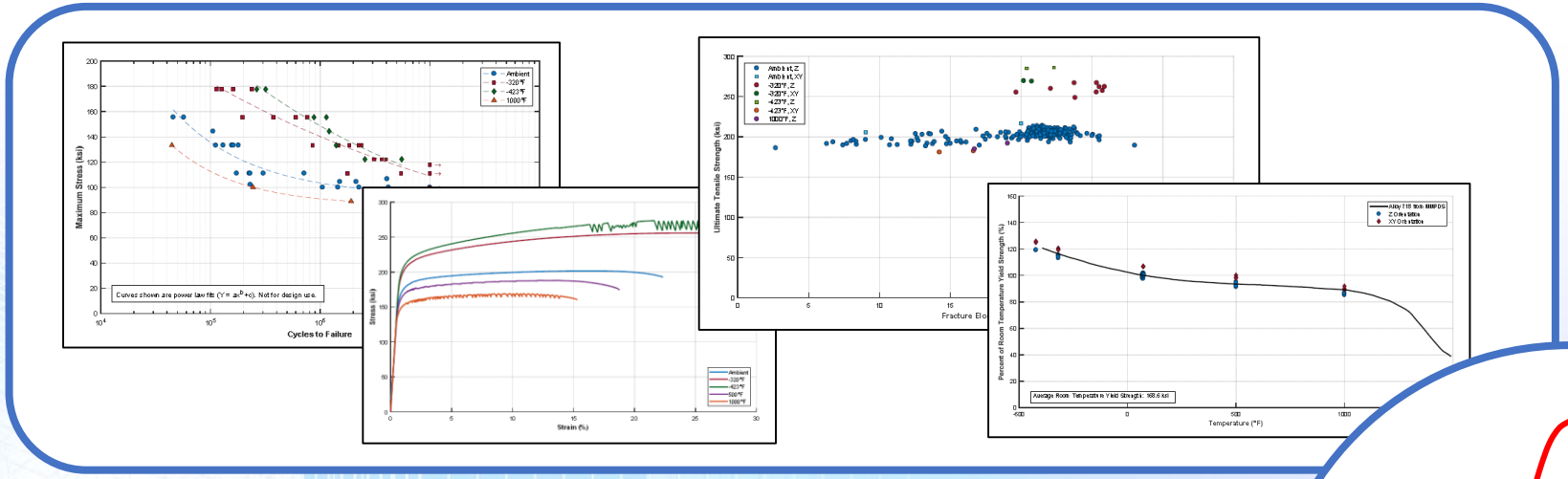


Process Control Reference Distribution

- Statistically describes nominal witness behavior
- Utilizes all appropriate sources of *witness coupon data* in Repository
- Used to set acceptance criteria for witness tests



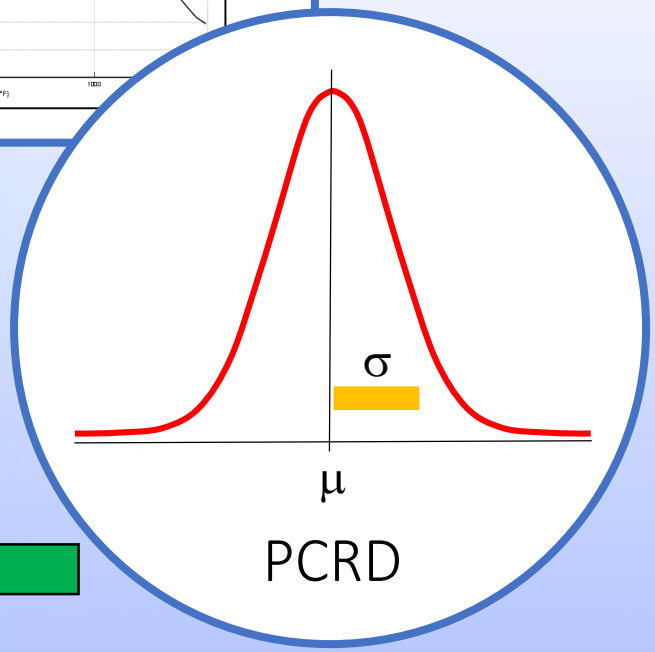
Material Property Suite



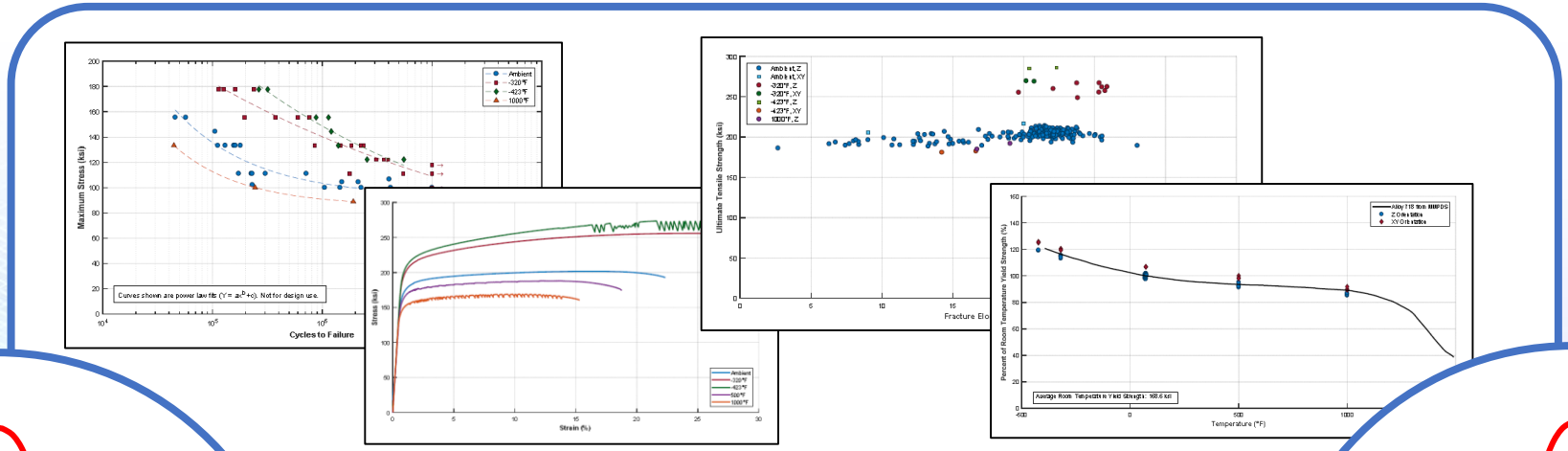
Statistical Process Control Acceptance Criteria

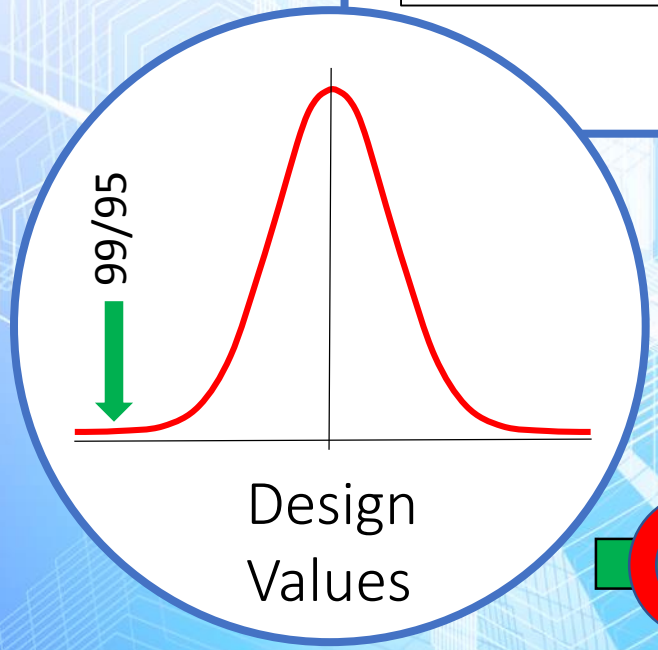
- Derived from PCRD
- Acceptance criteria for witness tests

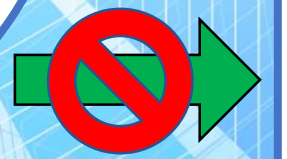
SPC Acceptance Criteria for Witness Testing



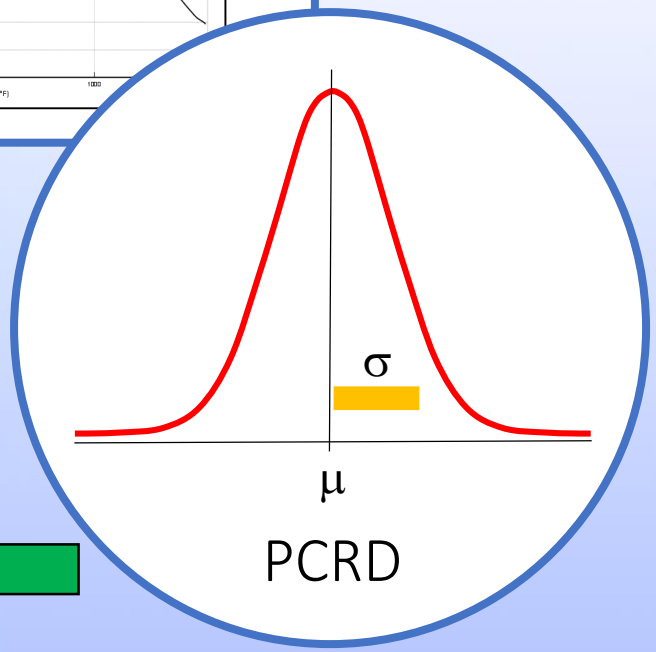
Material Property Suite







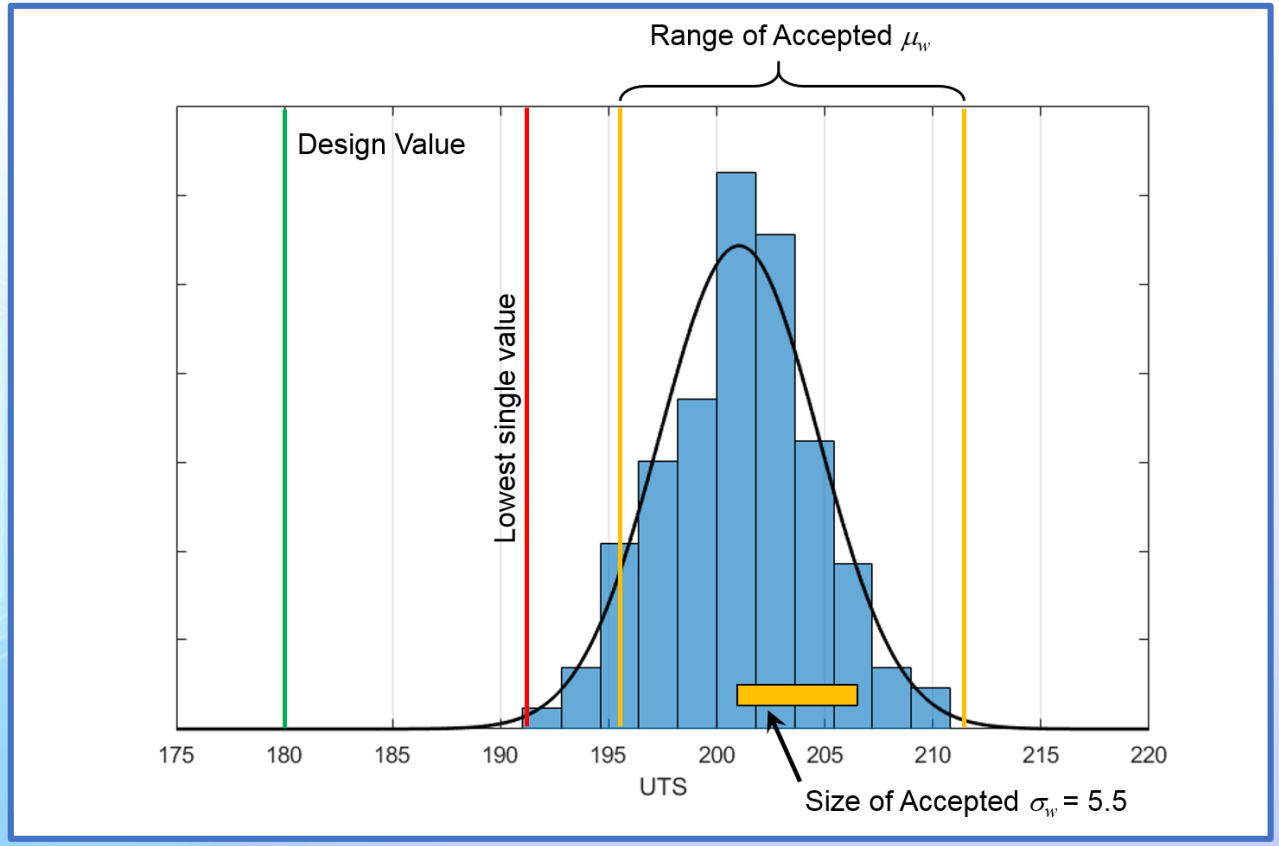
SPC Acceptance Criteria for Witness Testing



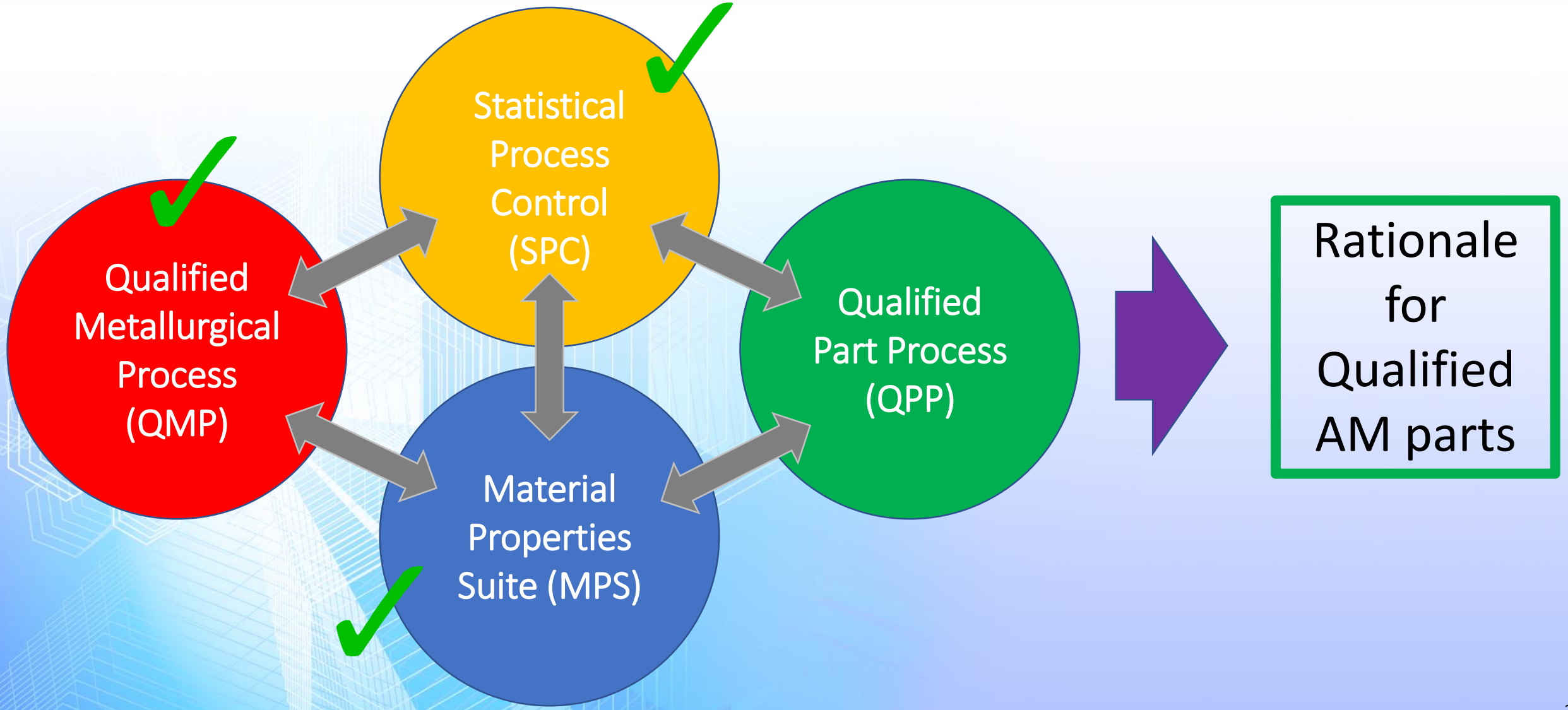
Material Property Suite

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

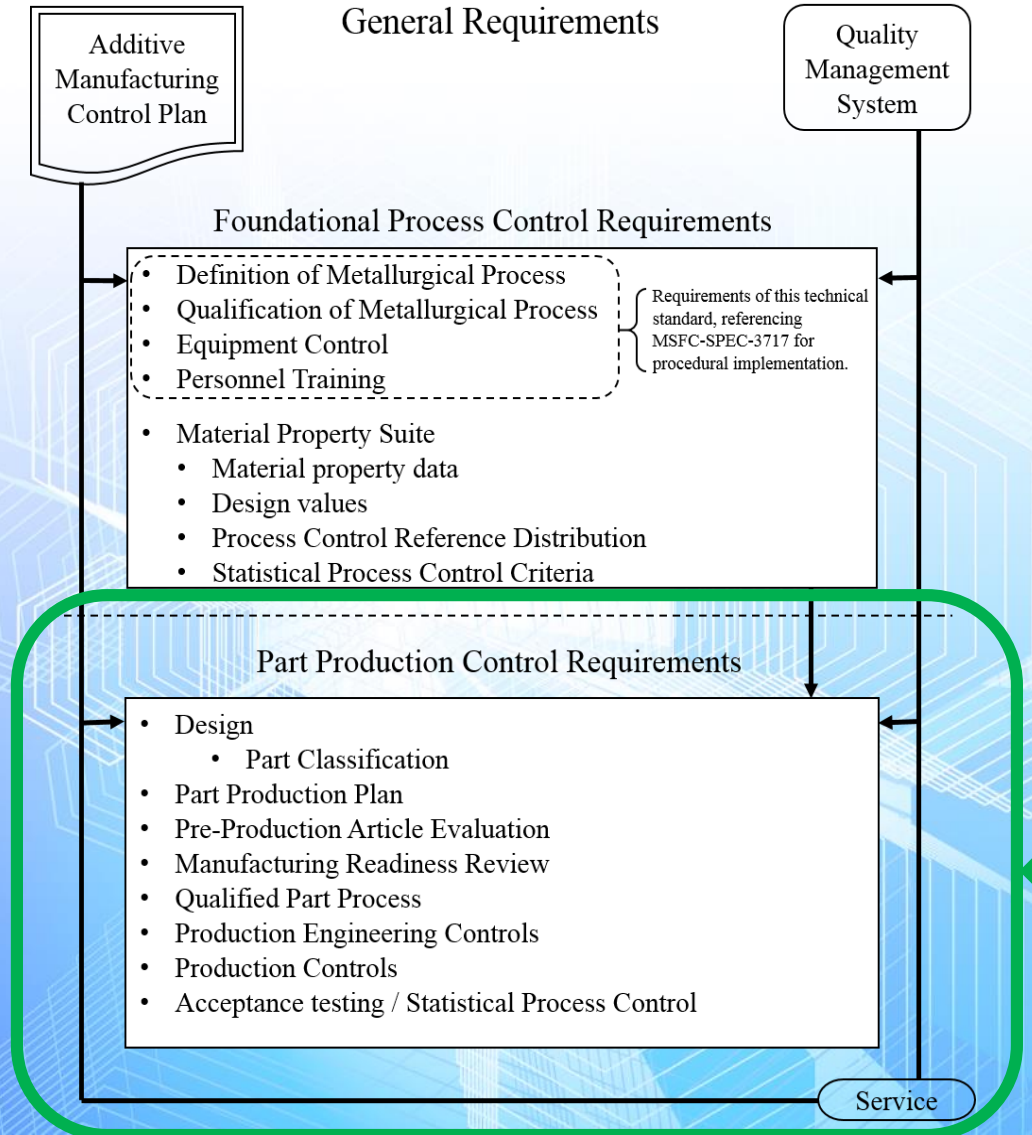


Checkpoint: Key AM Qualification Concepts



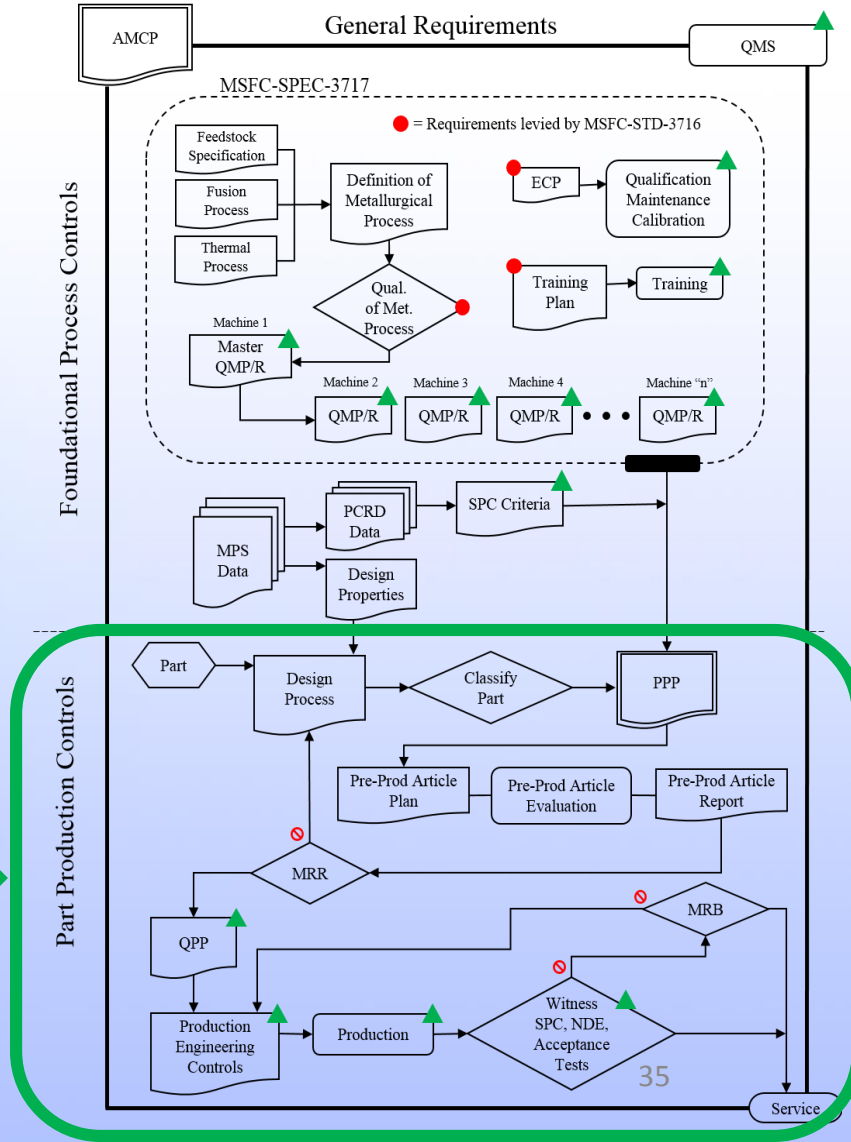
Part Production Controls

Overview of Current Requirements



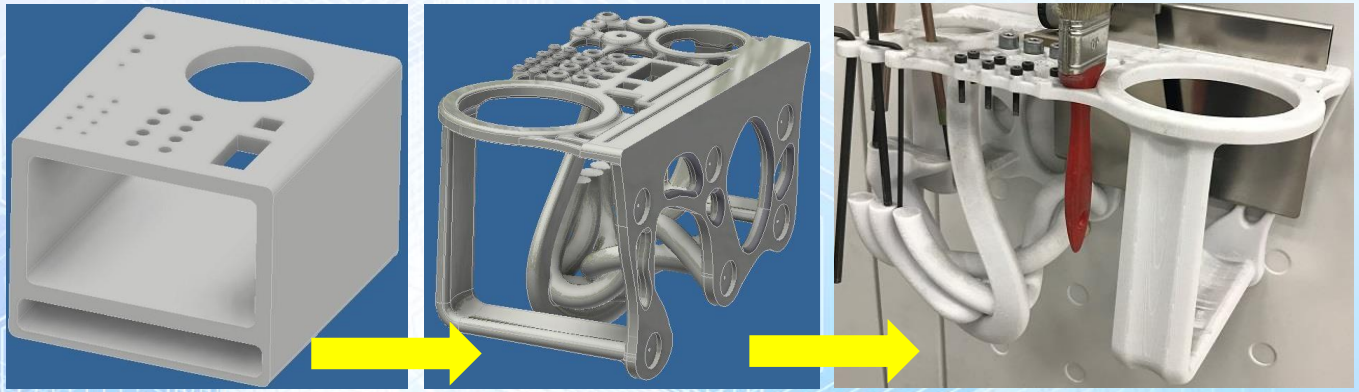
Candidate Part

Part Production Controls

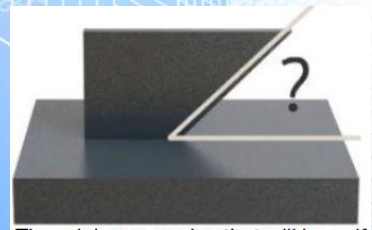


Design Process

- Design For Additive Manufacturing Paradigm Shift
  - New benefits bring new constraints
  - Must decide manufacturing method as early as possible

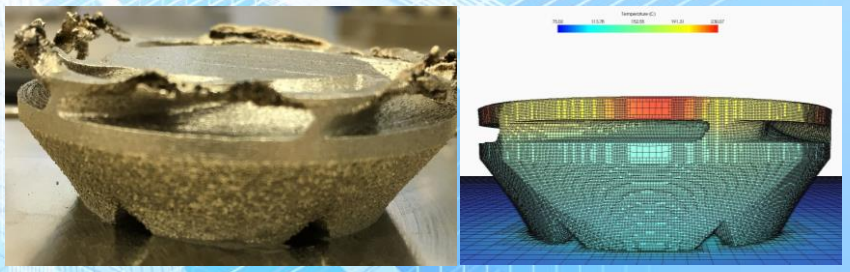


Topology Optimization FDM Tool Rac.

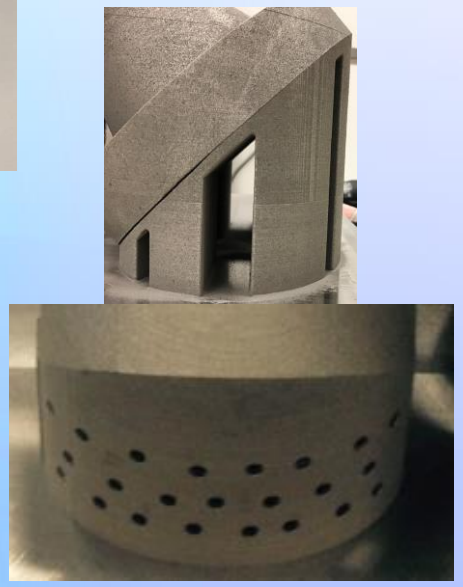


The minimum angles that will be self supporting are approximately:
- Stainless steels: 30 degrees
- Inconels: 45 degrees
- Titanium: 20-30 degrees
- Aluminium: 45 degrees
- Cobalt Chrome: 30 degrees

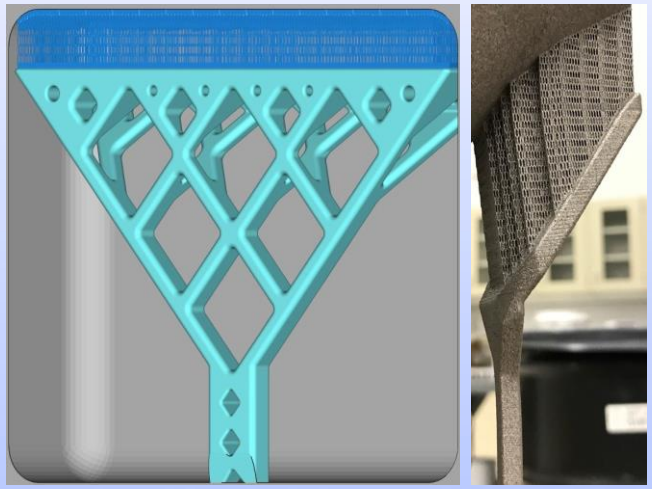
Self-Supporting Angles



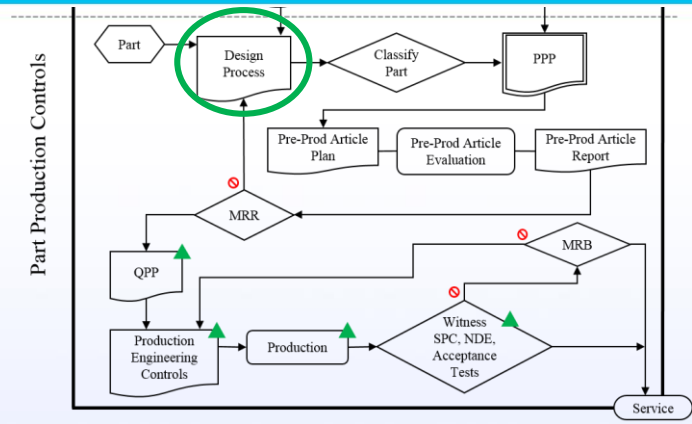
Build Simulation



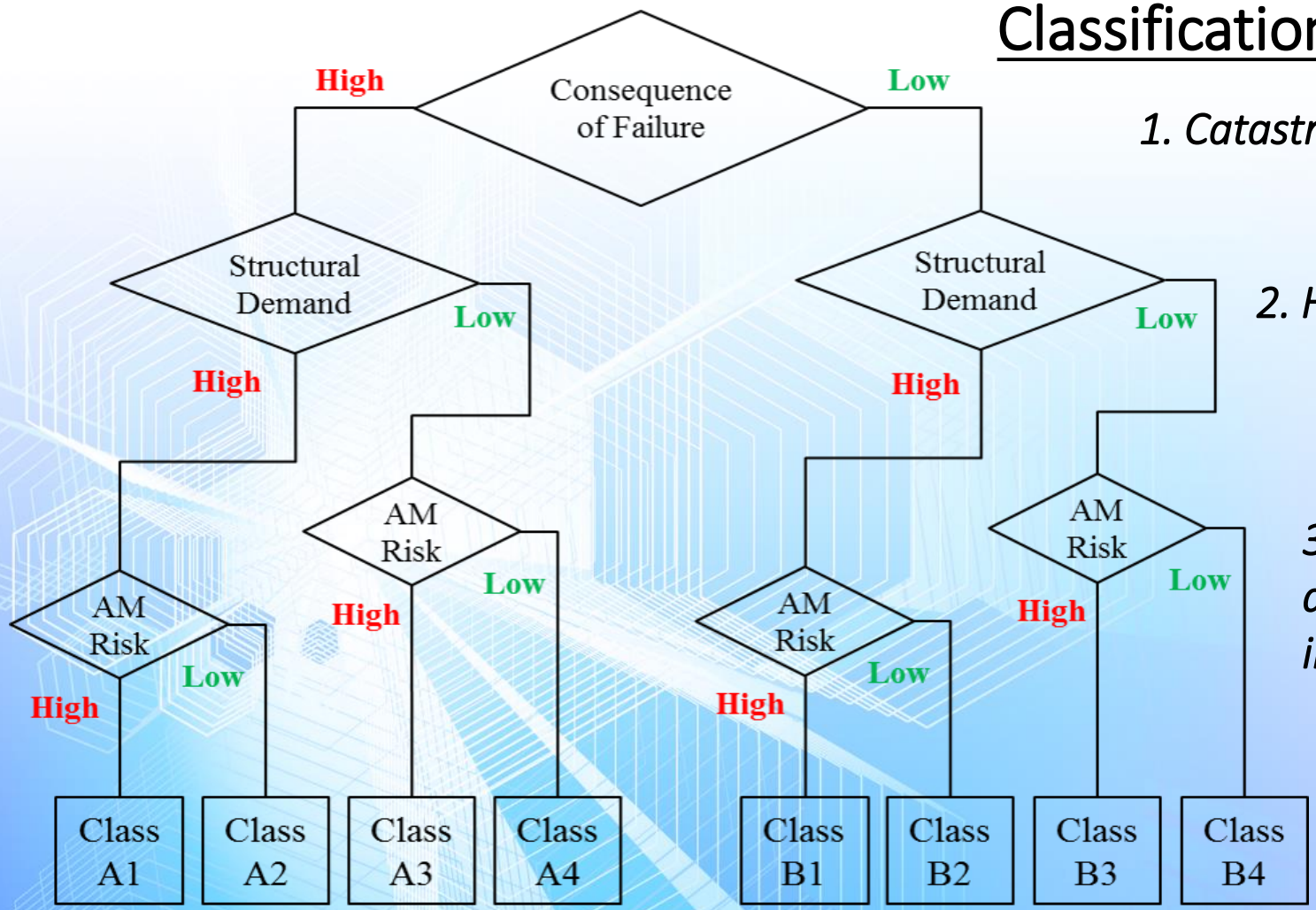
Powder Removal Features



Hybrid crown & perforated block support



Part Classification



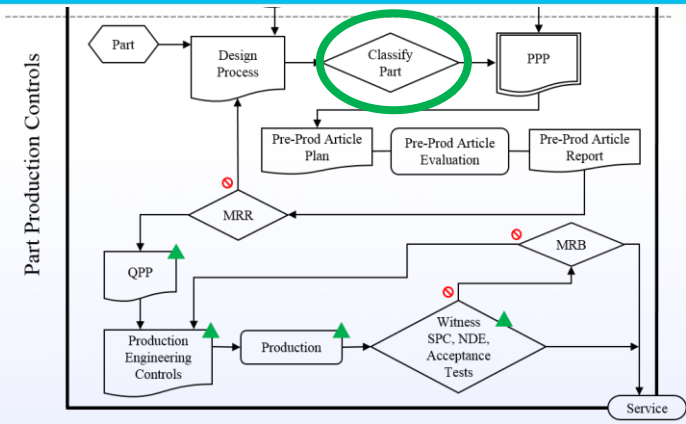
Classification System

Classification Questions

1. Catastrophic Failure?

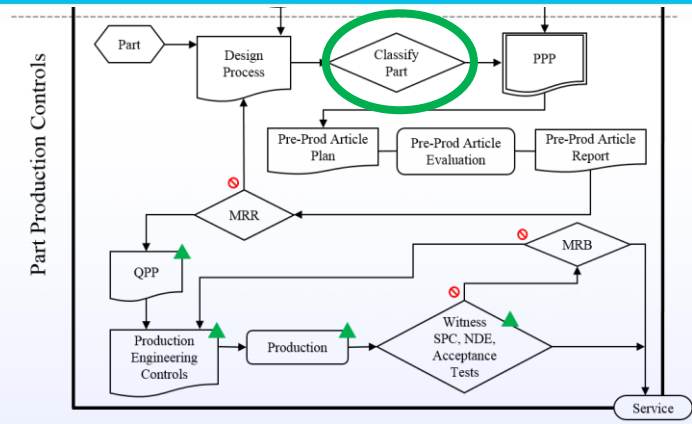
2. Heavily Loaded?

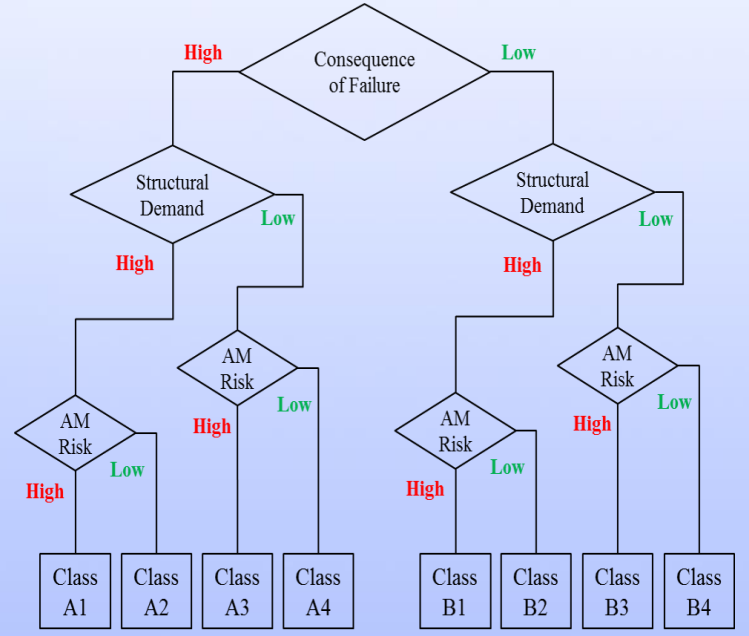
3. Does the build have challenging aspects or areas that cannot be inspected?



Part Classification

- Part Classification system is a ***risk communication*** tool
  - What happens if the part fails?
  - How severe is the stress in the part?
  - How challenging is the part to design, build, and ***inspect***?
- Established criteria at each step for consistency
- The higher a part's classification, the more stringent the downstream requirements become
  - B4 parts should need less scrutiny than an A1 part
  - Non-destructive evaluation needs also likely to differ
- Part-specific tailoring starts with classification

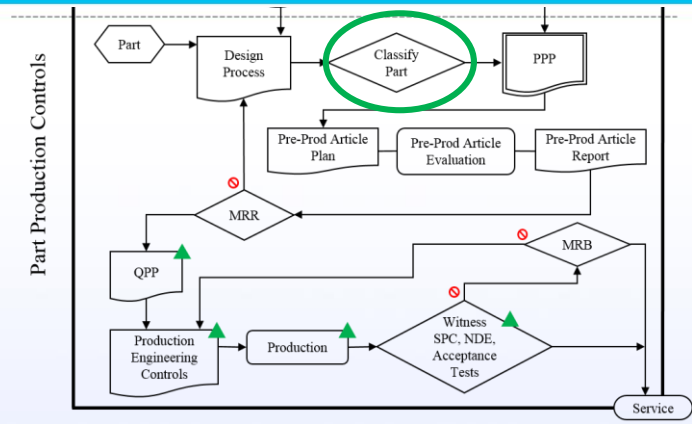


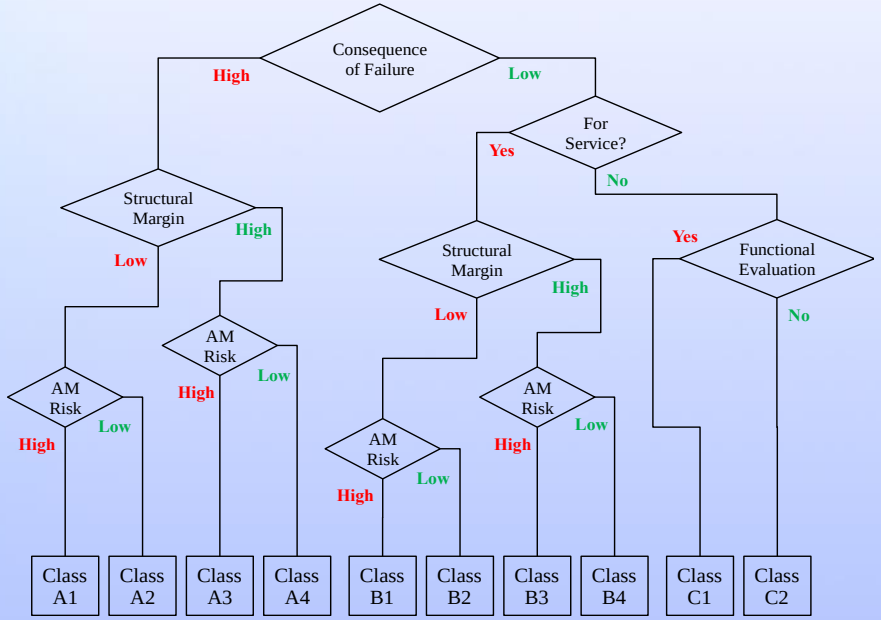


Part Classification

Challenges to the classification system encountered early

- Draft version contained a Class C for non-service components
  - Intent: fit check parts, demonstrations, visual/design aids
  - Revision now considering a “non-structural” for-service Class C
- Did not account for Science Mission Classes (biased to human-rating perspective)
  - Mission classes A-D are defined per NASA NPR 8705.0004
  - Hubble Telescope is a Class A and a Cubesat would be a Class D
- Part Class and Mission Class together influence the requirement set to maintain appropriate levels of mission assurance commensurate with the scenario.
- Future Agency-Level documents will be written for each of the following areas
  - Manned Space Flight
  - Non-Manned Space Flight, with Mission Classes A-D
  - Aeronautics



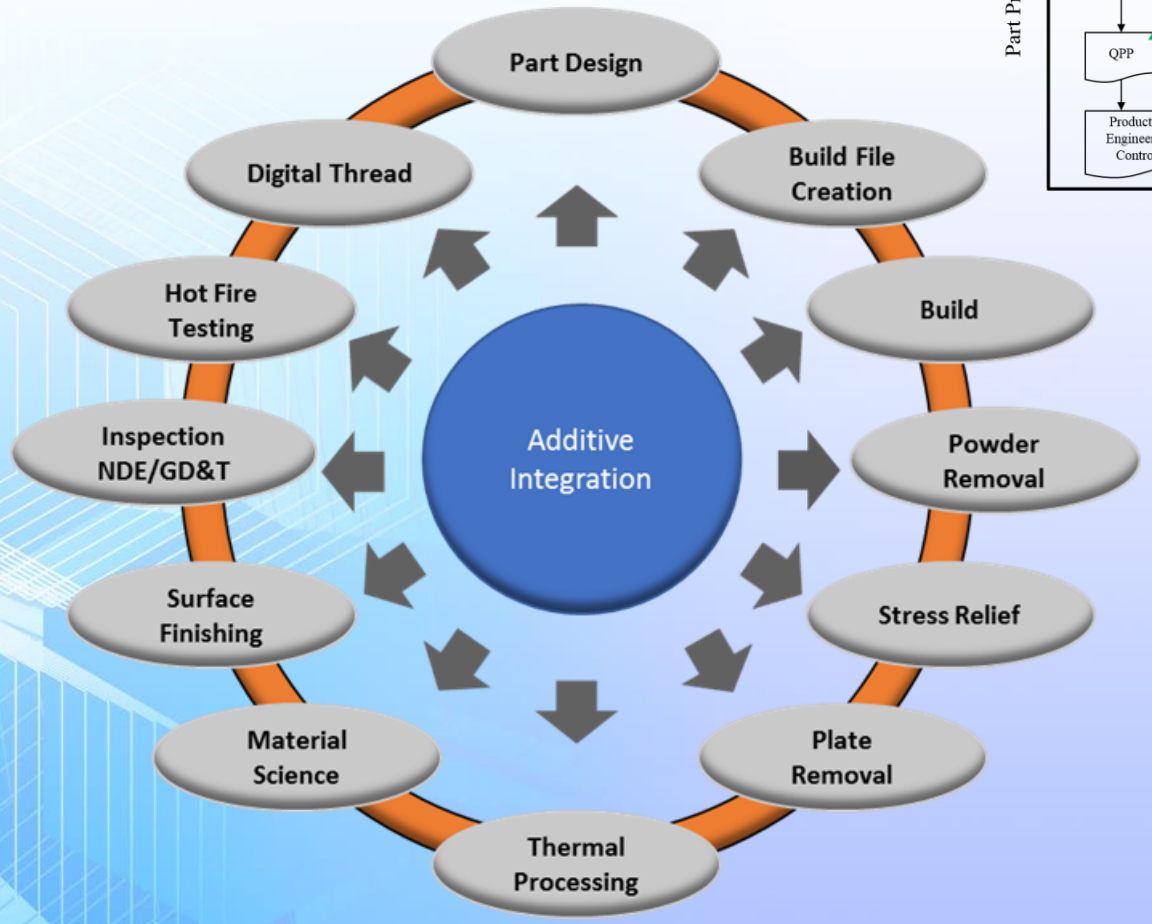


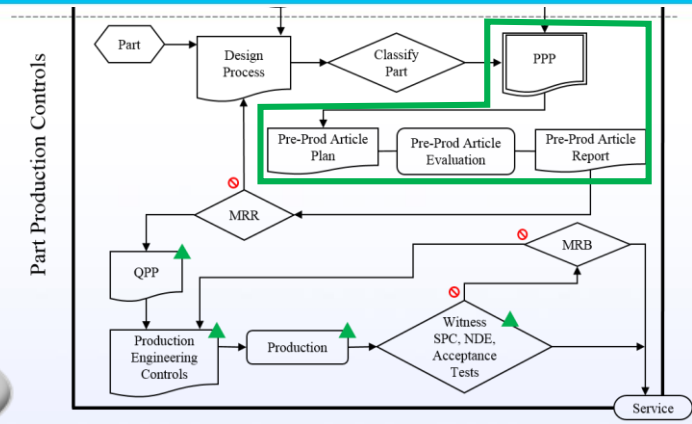
Draft Classification System

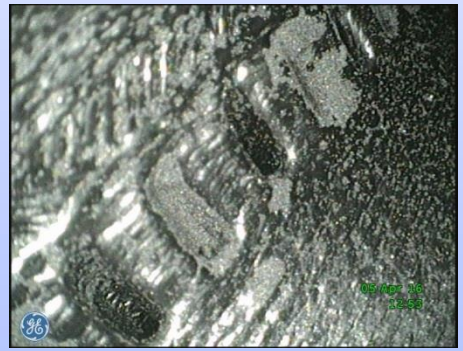
Part Production Plan

Part Production Plans force integration of part processing

- Interdependence of layout and downstream requirements
  - Surface finishing
  - Inspection
  - Powder removal
- Common Challenges:
  - Integrated Structural Integrity Rational
    - Required statement of how part integrity is assured (NDE, proof test, process controls)

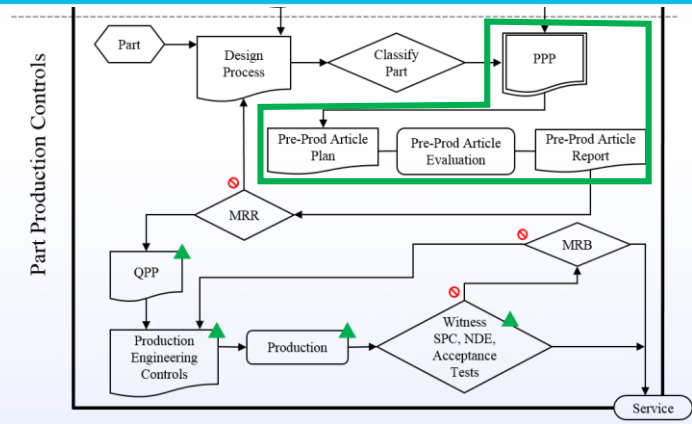




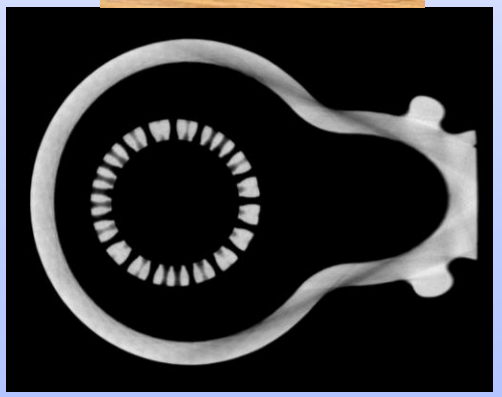


Part Production Plan

- PPP, Common Challenges (Continued)
  - Locked build files
  - Understanding cryptographic hash
  - Description of controlled post processes
  - NDE Plan
  - Pre-Production Article Plan
    - Critical Areas
    - Thin Sections
    - Thick Sections



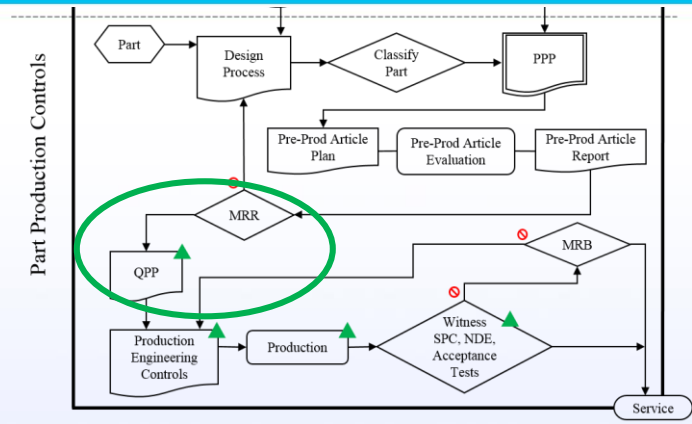
Stray vectors



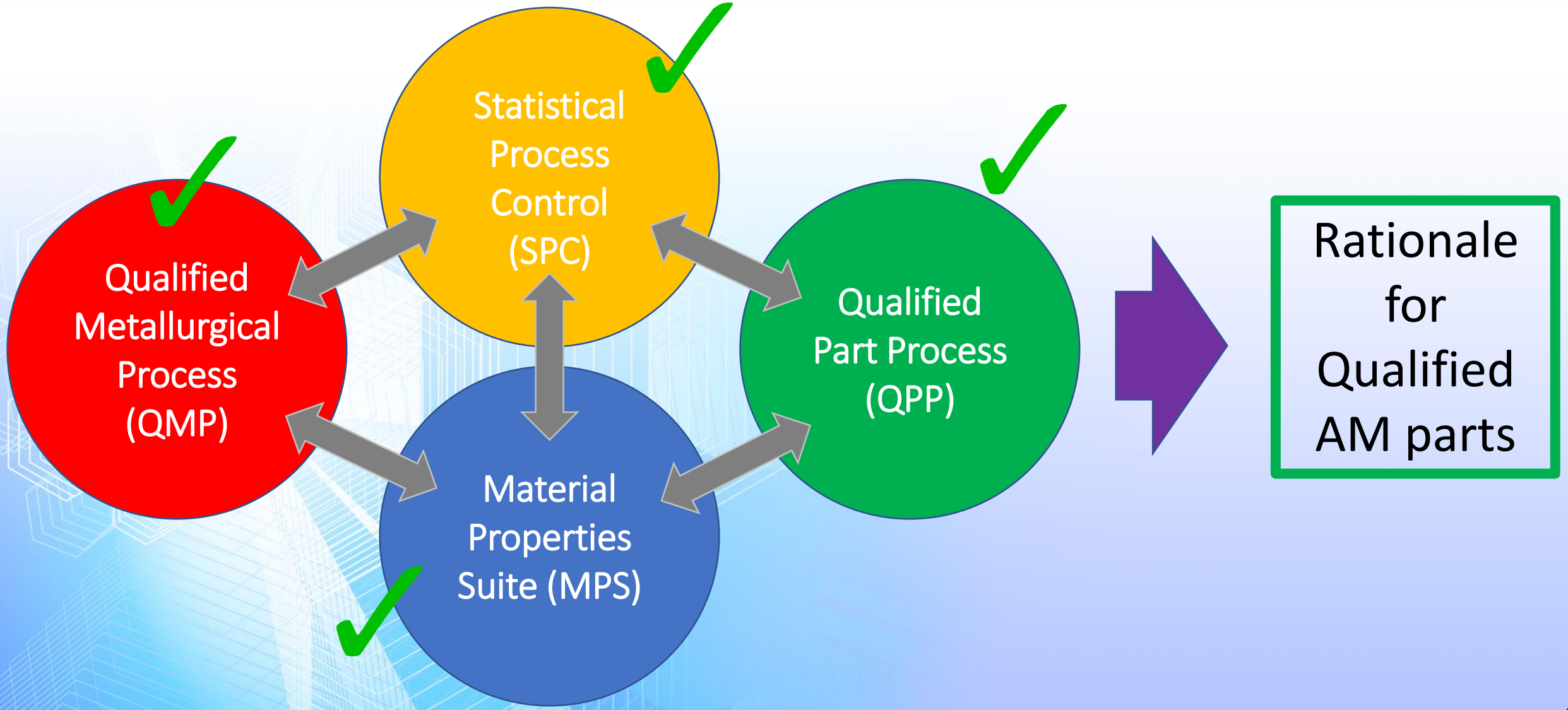
Qualified Part Process

Establishing a Qualified Part Process

- Pre-Production Article Evaluation
  - Powder removal, dimensions, surface quality, mechanical properties, internal quality, microstructure, high risk areas…
- Additive Manufacturing Readiness Review
  - Stakeholder review of production engineering record, part drawing, approved PPP, Pre-Production Article Report…
  - If successful, ***AMRR demarcates when part process is qualified***
- Complete part manufacturing process is locked for production
  - No changes without re-qualification or proper disposition
  - QPP state is documented in the Quality Management System



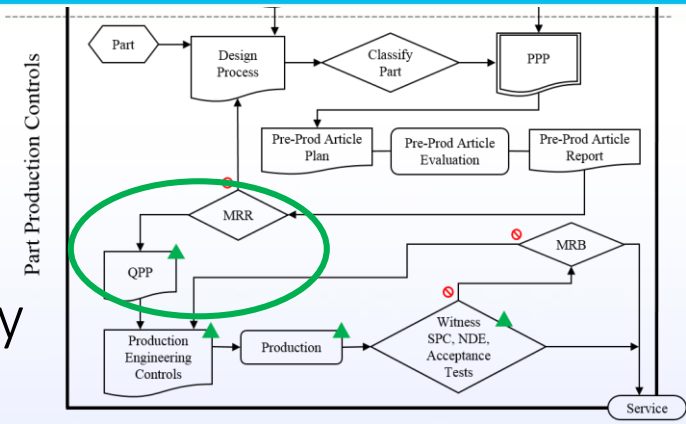
Key AM Qualification Concepts

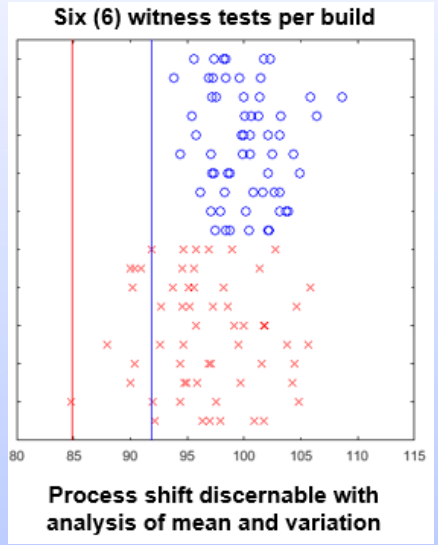


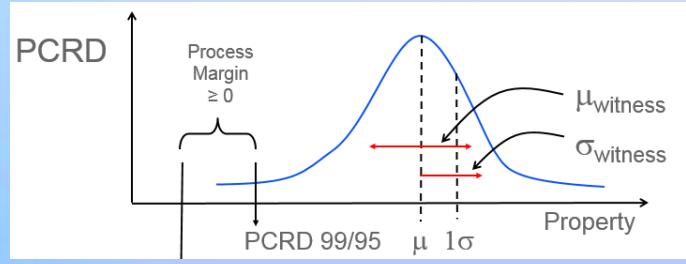
Preparing For Production

Part Production – Follow-through on controls

- Statistical Process Control (SPC)
  - Stand Alone acceptance, just making one part
    - A1: 6 tensile, 2 HCF, 2 Met, 1 Chemistry, 1 Full height Contingency
    - Compare to PCRD
  - Continuous Production
    - A1: 4 tensile, 1 Met, 1 Chemistry, 1 Full height Contingency
    - Compare to continuous Control Chart
    - Intermittent SPC evolution builds during production
    - SPC Challenges:
      - Do the samples stay with the parts?
      - How to flag a part without the samples tested?
      - Setting limits that identify drift







Common Challenges

- Turn around of samples used to monitor builds
  - Often three or more months from build to fully heat treated test data
  - Delay is a risk!
- Conventional manufacturing facilities and vendors are not used to the required level of process control
  - Much more difficult when working with vendors
  - Switching Alloys
  - Powder Reuse
- Cleaning of AM parts for contamination-sensitive applications
- Understanding “Influence Factors” in mechanical properties
- Implementing fracture control
- Maintaining the Digital Thread

Coming Reliance on In-Situ Monitoring

How to approach in-situ monitoring of AM processes?

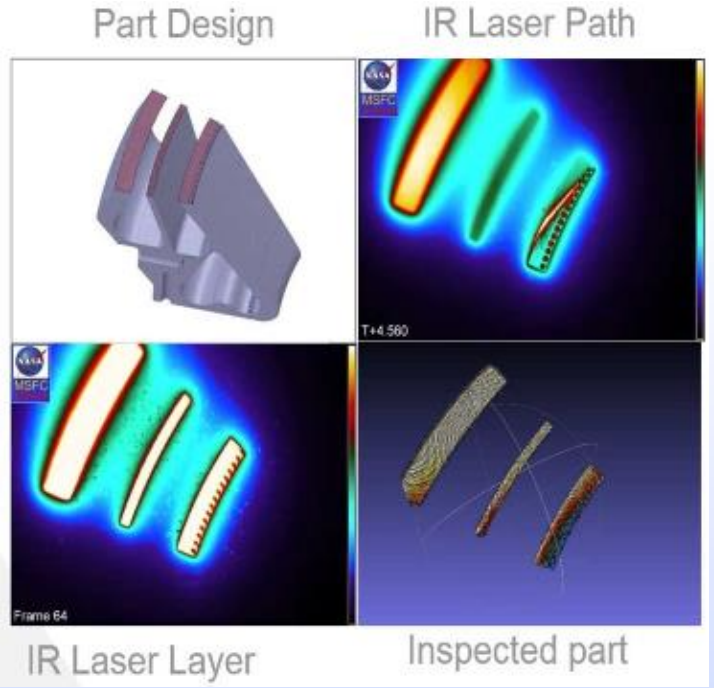
- Harnessing the technology is only half the battle
  - Detectors, data stream, data storage, computations
- Second half of the battle is quantifying in-situ process monitoring ***reliability***

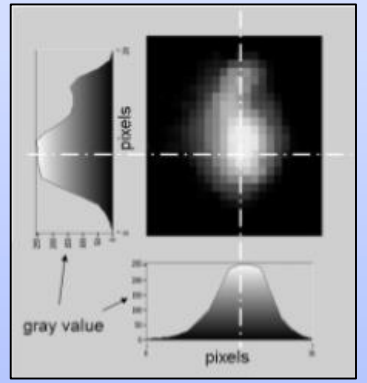
Community must realize that passive in-situ monitoring is an NDE technique

1. Understand physical basis for measured phenomena
2. Proven causal correlation from measured phenomena to a well-defined defect state
3. Proven level of reliability for detection of the defective process state
   - False negatives and false positives → understanding and balance is needed

Closed loop in-situ monitoring adds significantly to the reliability challenge

- No longer a NDE technique – *may not be non-destructive*
- Establishing the ***reliability of the algorithm*** used to interact and intervene in the AM process adds considerable complexity over passive systems

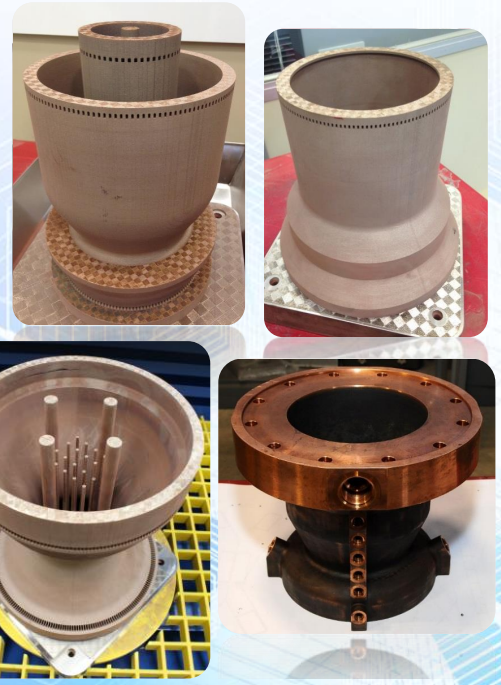




Concept Laser QM Meltpool

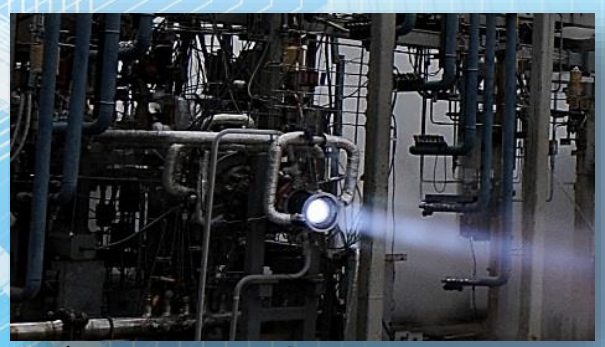
Application

- Final Box: Service!

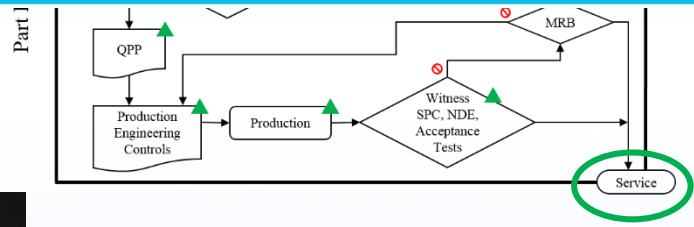


GRCop-84 3D printing process developed at NASA and infused into industry

Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate



LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power



Injector

- Decreased cost by 30%
- Reduced part count: 252 to 6

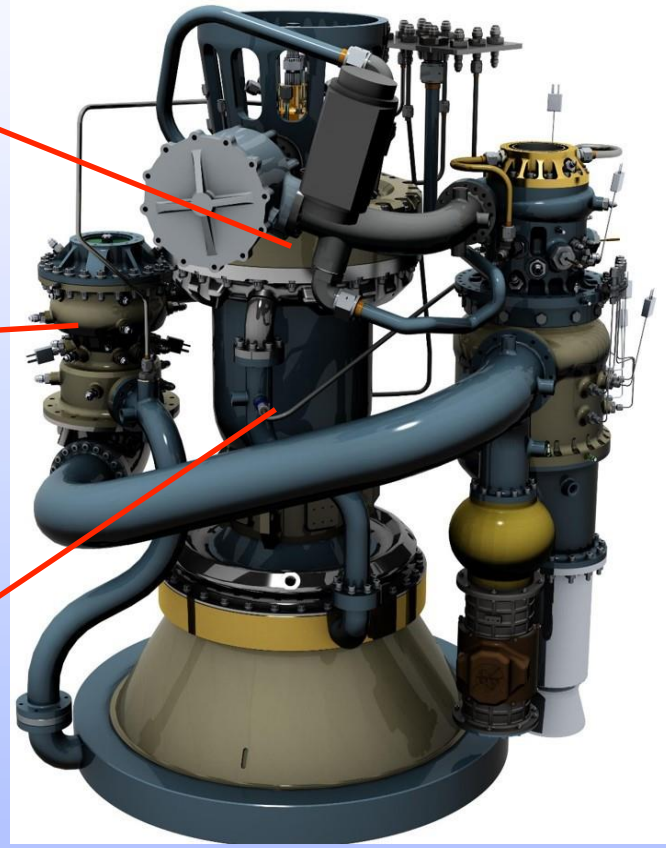
FTP

- Schedule reduced by 45%
- Reduced part count: 40 to 22
- Successful tests in both Methane and Hydrogen

MCC

- Schedule reduction > 50%
- SLM with GRCop-84
- Methane test successful

AM Demonstrator Engine



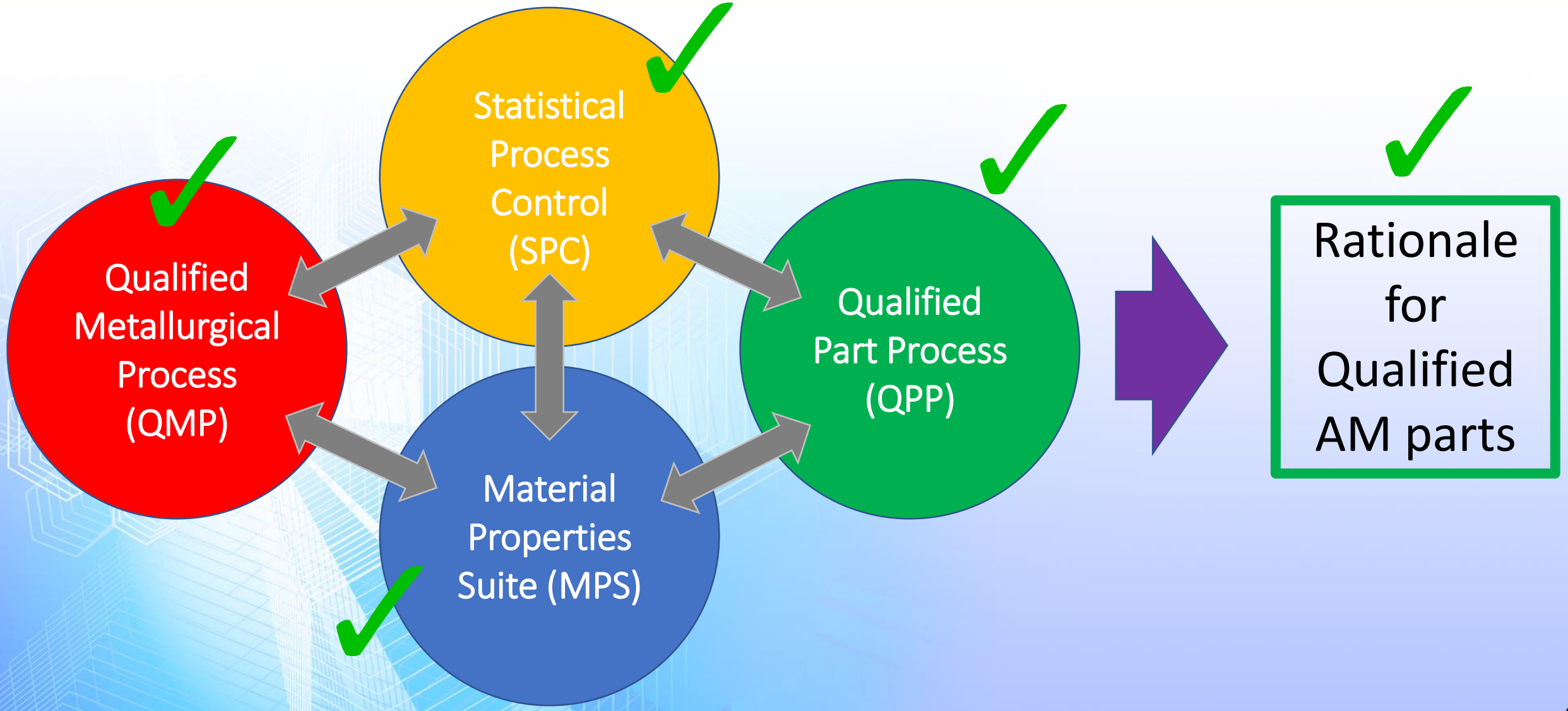
Summary

Currently, there are two primary opportunities to ensure AM reliability

1. In-Process Controls (Control what you do)
   - Qualify the AM Process (QMP) and Part Process (QPP)
   - Understanding fundamentals, and knowing the process failure modes (pFMEA)
   - Identifying observable metrics and witness capabilities
   - Meticulous process scrutiny through SPC
2. Post-Process Evaluation (Evaluate what you get)
   - Non-destructive Evaluation, Proof testing
   - Post-build process monitoring data evidence

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

Key AM Qualification Concepts



Thank you!

Back Up

Mission Class Breakdown

- Missions Classes based on risk:
  - Class A (per NPR 8705.0004)
  - Class B (per NPR 8705.0004)
  - Class C (per NPR 8705.0004)
  - Class D (per NPR 8705.0004)
  - Associated GSE and test hardware

NPR 8705.4 – Appendix B

Characterization	Class A	Class B	Class C	Class D
Priority (Criticality to Agency Strategic Plan)	High priority	High priority	Medium priority	Low priority
National significance	Very high	High	Medium	Low to medium
Complexity	Very high to high	High to medium	Medium to low	Medium to low
Mission Lifetime (Primary Baseline Mission)	Long, > 5 years	Medium, 2-5 years	Short, < 2 years	Short, < 2 years
Cost	High	High to medium	Medium to low	Low
Launch Constraints	Critical	Medium	Few	Few to none
In-Flight Maintenance	N/A	Not feasible or difficult	Maybe feasible	May be feasible and planned
Alternative Research Opportunities or Re-flight Opportunities	No alternative or re-flight opportunities	Few or no alternative or re-flight opportunities	Some or few alternative or re-flight opportunities	Significant alternative or re-flight opportunities
Examples	HST, Cassini, JIMO, JWST	MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads	ESSP, Explorer Payloads, MIDEX, ISS complex subrack payloads	SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads, SMEX

Part Production Plan Content

MSFC Technical Standard EM20		
Title: Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals	Document No.: MSFC-STD-3716	Revision: Baseline
	Effective Date: October 18, 2017	Page: 59 of 93

APPENDIX A. PART PRODUCTION PLAN CONTENT

This Appendix is not a mandatory part of the standard. The information contained herein is intended for guidance only.

The L-PBF PPP is expected to address the following content. Items in this list that are fully controlled by the AMCP need not be repeated in the PPP. The combined requirements of the AMCP, part drawing, and PPP are to be sufficient to produce the production engineering record.

- Drawing number and part name
- Part synopsis, providing a brief summary of
  - The purpose of the part in context to the system,
  - The operational environments (temperatures, fluids),
  - CAD model views to illustrate the part and key features
- Material
  - Identification of the QMP specified for production.
  - Identification of MPS used for assessment
- Part classification with summary rationale for consequence of failure, structural demand, and AM risk
- Integrated Structural Integrity Rationale for the part
  - Describe limiting factors in strength and fracture analyses
  - Highlight areas of high structural demand and high AM risk per classification
  - Describe all non-destructive testing and the degree of coverage or any limitations
  - Describe all proof test operations, including role in integrity rationale, method of analysis, and coverage or limitations
- List of required witness tests, witness articles, and associated acceptance requirements
- Illustration of the complete build with part orientation, location, and witness specimens
- Summary list or table with all production steps in sequence as governed by the Production Engineering Record
  - Include all key operations such as build, powder removal, as-built inspection, support removal, platform removal, heat treating, cleaning, welding, machining, surface treatments, NDE steps, proof test.
- Description of any specific controls required for post-build part processing operations that are process-sensitive, i.e., outcome of the operation is difficult to verify but critical to the part
- Pre-production article requirements, or reference to a separate plan
- List of references supporting the PPP (analysis reports, fracture control reports, etc.)
- Complete list of all required part acceptance certificate-of-compliance information
  - Dimensional inspection report, NDE reports, powder lot, build logs, etc.