NASA's Standards and Qualification for Additive Manufacturing

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TRISMAC2021 - 6th Trilateral Safety and Mission Assurance Conference

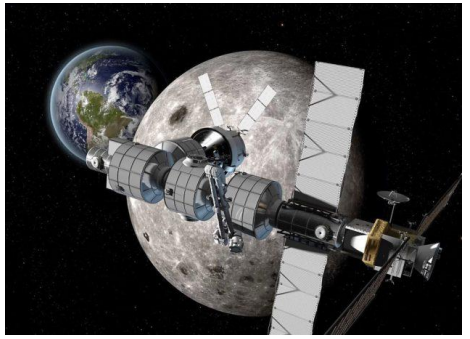
20 May 2021

Additive Manufacturing: The Future is Now!!

NASA's motivation for AM Standards

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

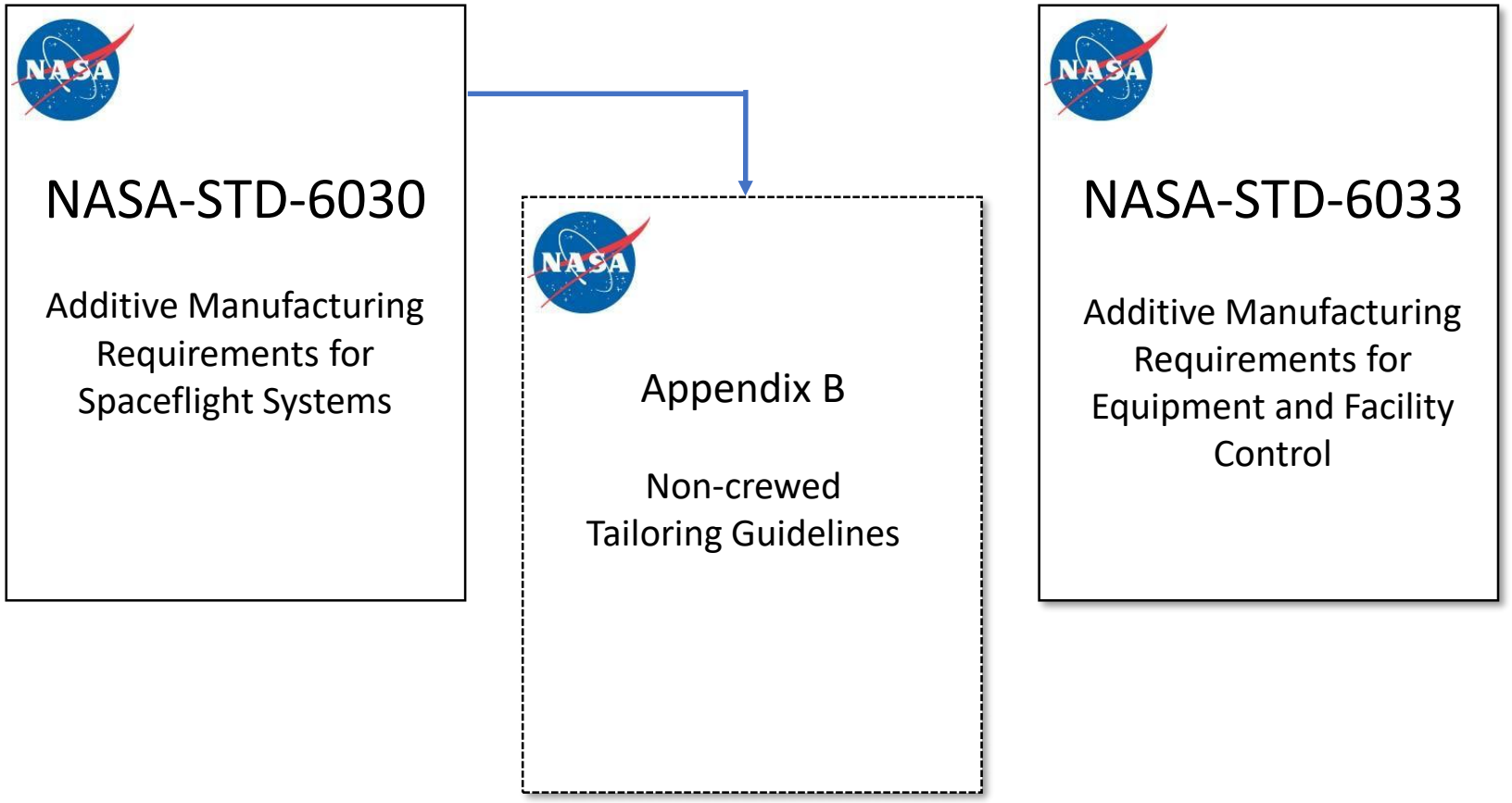
Low Earth		Deep Space
400 km	vs	400,000 - 400,000,000+ km
15-30 year life	vs	50 to 100+ years
Replacement Parts	vs	Limited Replacement
Nearby Safe Haven	vs	Largely on your own



Certification and Qualification

- There is NO centralized Certification or Qualification body at NASA.
- Each individual Program/Project will be responsible for “Qualifying*” AM Processes and “Certifying” AM Flight Hardware.
  - *or accepting another projects “qualification”
- NASA’s Engineering and Safety Center (NESC) is standing up an Intra-Agency team representing all major centers to coordinate these efforts.
- The hope is that by maintaining a single “NASA AM Ecosystem”, the non-recurring engineering costs associated with each new using program or project will be dramatically reduced.

The New Standards – April 2021

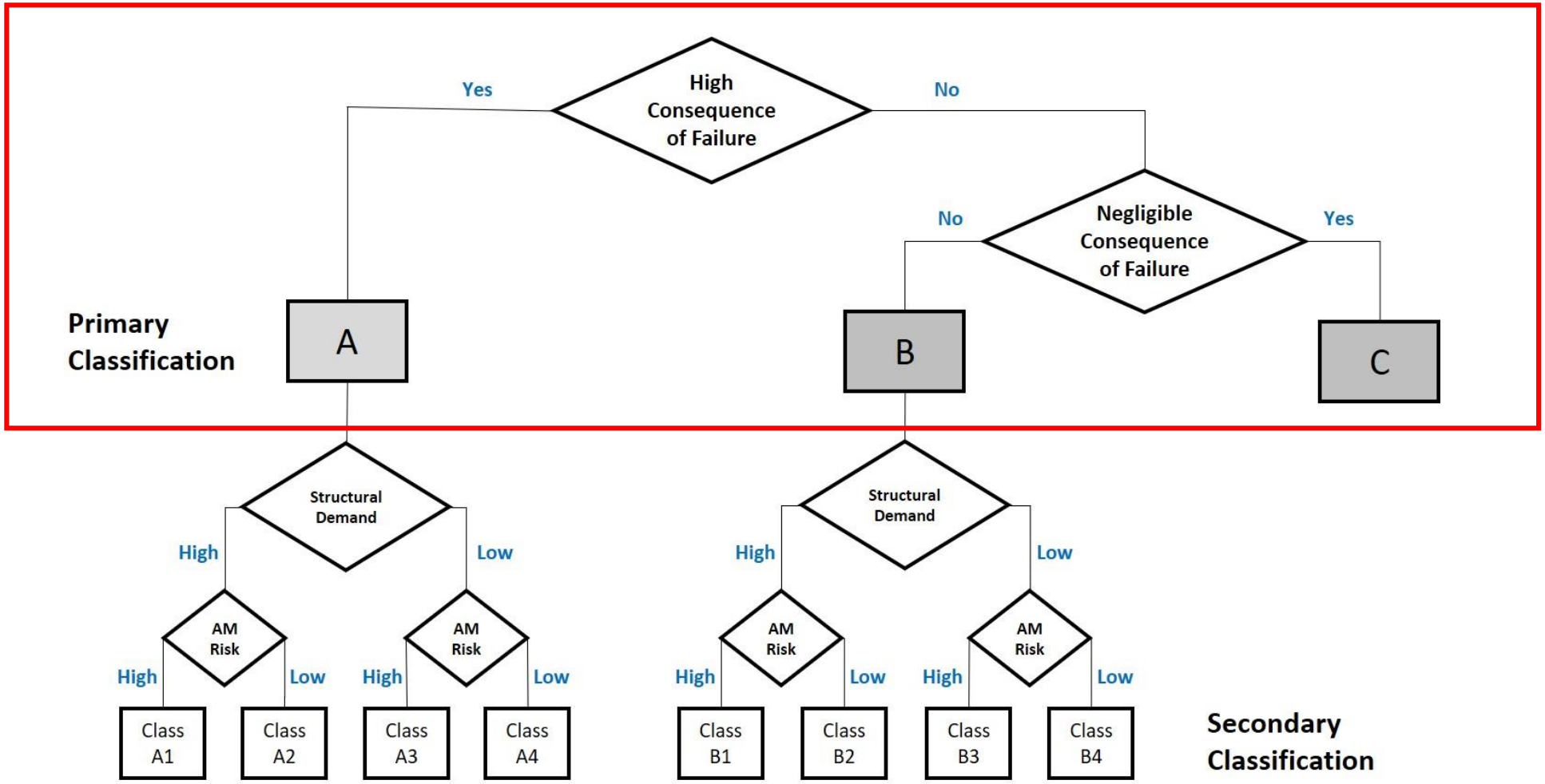


Applicability

			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 covered by NASA-STD-6030
  - e.g., Electron beam powder bed fusion (E-PBF)

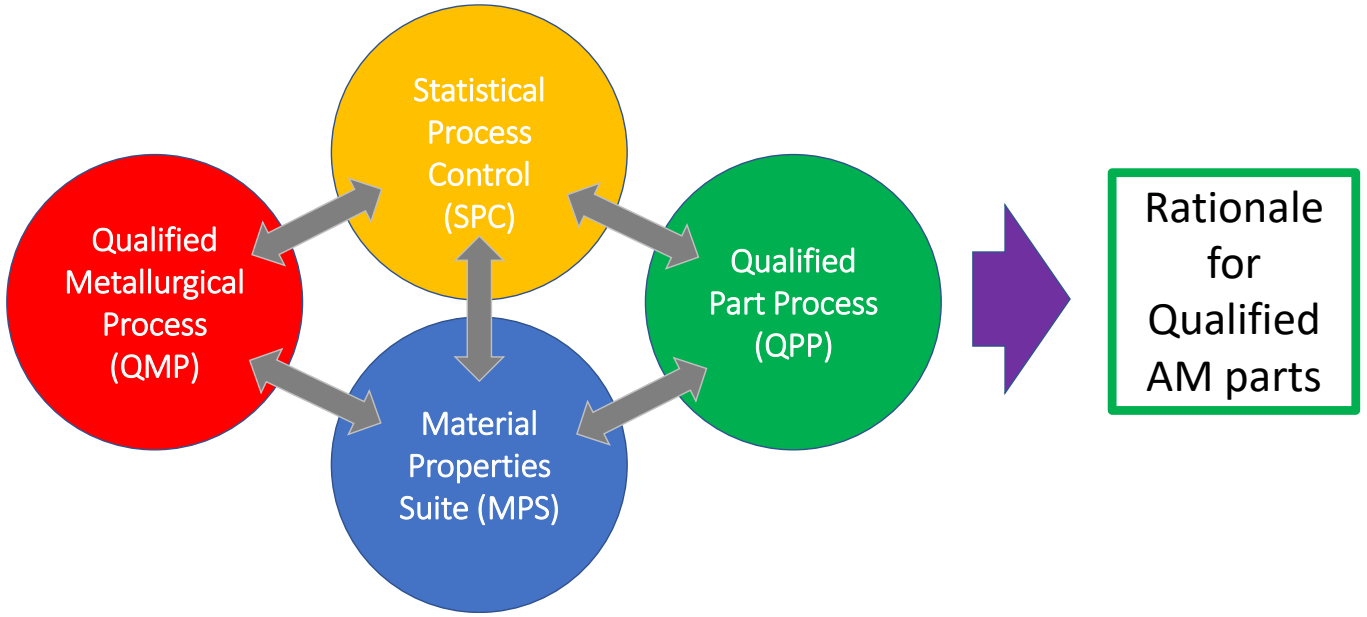
Classification



AM Qualification: Governing Principles

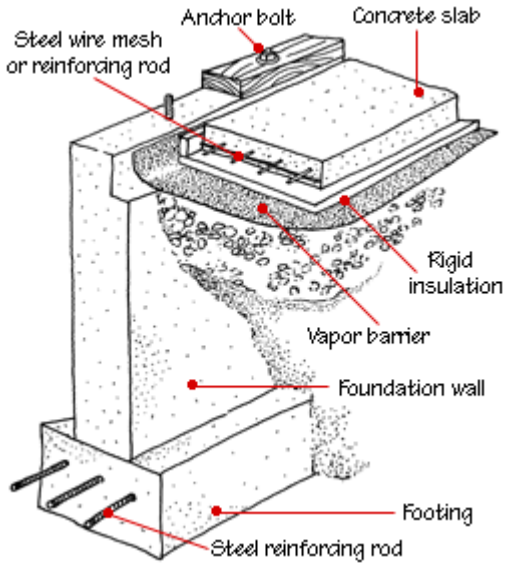
- *Understanding* and *Appreciation* of the AM process
- *Integration* across technical disciplines and throughout the process
- *Discipline* to define and follow the plan

- Have a plan
- Integrate a Quality Management System
- Build a foundation
  - Equipment and Facility
  - Training
  - Process and machine qualification
  - Material Properties / SPC
- Plan each Part
  - Design, classification, Pre-production articles
  - Qualify and lock the part production process
- Produce to the plan – **Stick to the plan**



Building a Foundation

- **Planning for AM certification does NOT start with a part**
- AM Control Plan should define how the foundation for certification is structured and how it operates
  - Equipment and Facility Controls
  - Personnel Training
  - Process/Machine Qualification
  - Material Properties
  - Statistical Process Controls
- Building this foundation can take <u>years</u>
- For most programs, flying a Class A or B part will require a pre-existing foundation, the schedule won't let you start from scratch



General Requirements

Additive Manufacturing Control Plan (4.2)

Quality Management System (4.4)

Foundational Process Control Requirements

- Equipment Control
- Personnel Training

See NASA-STD-6033 for procedural implementation.

- Definition of Material Process (5)
- Qualification of Material Process (5)
- Material Property Suite (6)
  - Statistical Process Control Criteria (4.11, 6.4)
  - Material Property Data (5, 6, 6.4)
  - Process Control Reference Distribution (6.9)
  - Design Values (6.11)

Part Production Control Requirements

- Design
  - Part Classification (4.3)
- Production Engineering Controls (4)
  - Statistical Process Controls (4.11, 6.4, 6.9)
- Acceptance Testing / Statistical Process Control (4, 4.11, 6.4)
- Digital Thread (4.13)
- Part Production Plan (7)
- Pre-Production Article Evaluation (7.5)
- Additive Manufacturing Readiness Review (8.1)
- Qualified Part Process (8.3, 8.4)

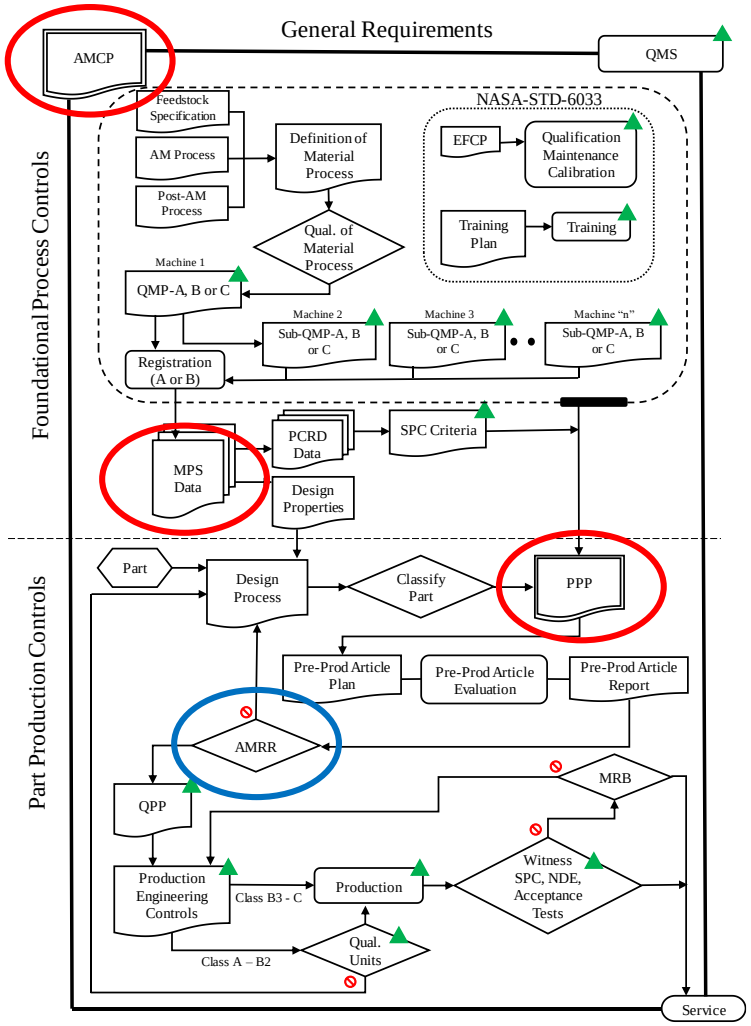
Service

Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

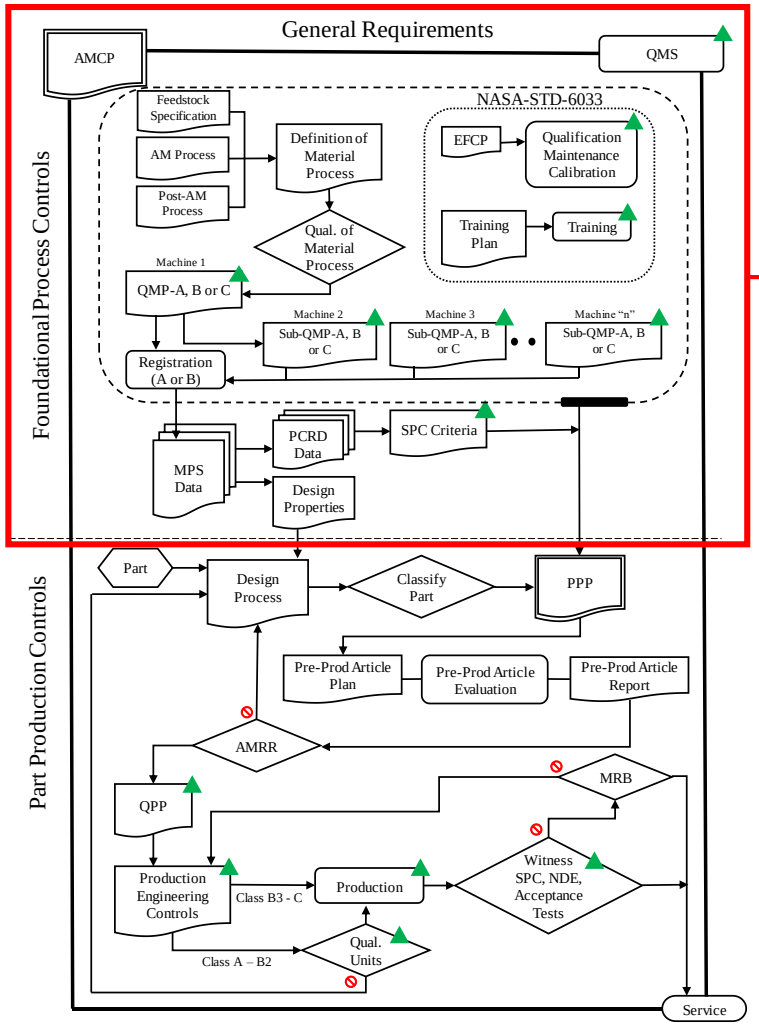
Deliverables

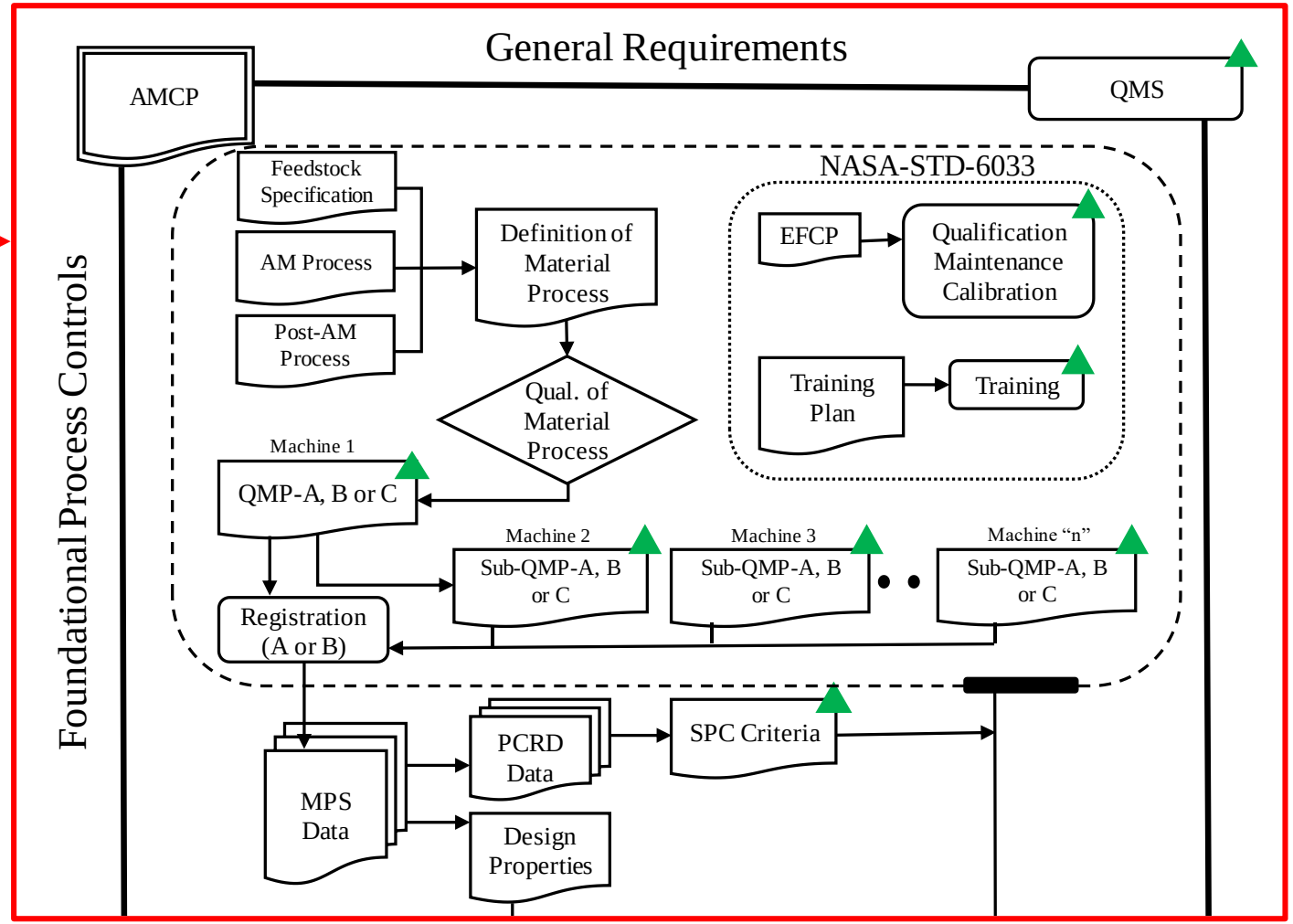
- There are only three deliverables:
  - Additive Manufacturing Control Plan (AMCP)
  - Material Property Suite (MPS) via an MUA
  - Part Production Plan (PPP)

- In many/most cases NASA is expected to be invited to the Additive Manufacturing Readiness Review (AMRR)
  - NASA's attendance is only required for Class A1 or A2 Parts
  - NASA's approval is not required (unless a using project says it is)



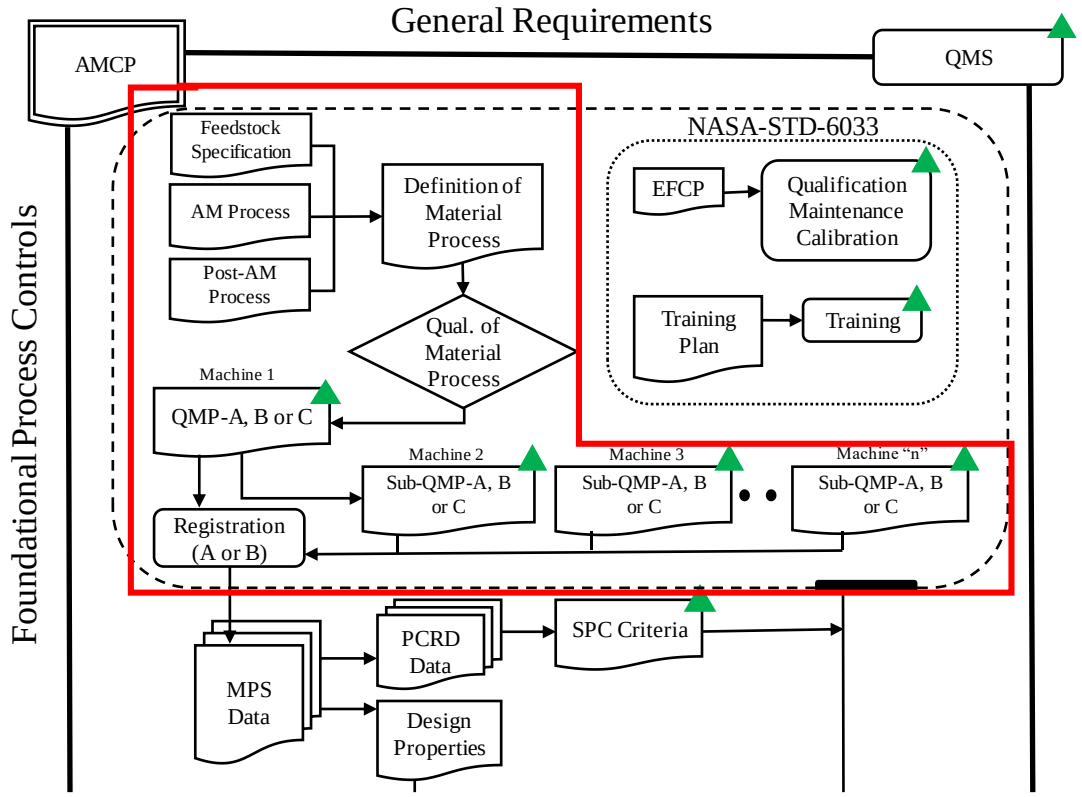
Summary of Methodology





Qualified Material Process (QMP)

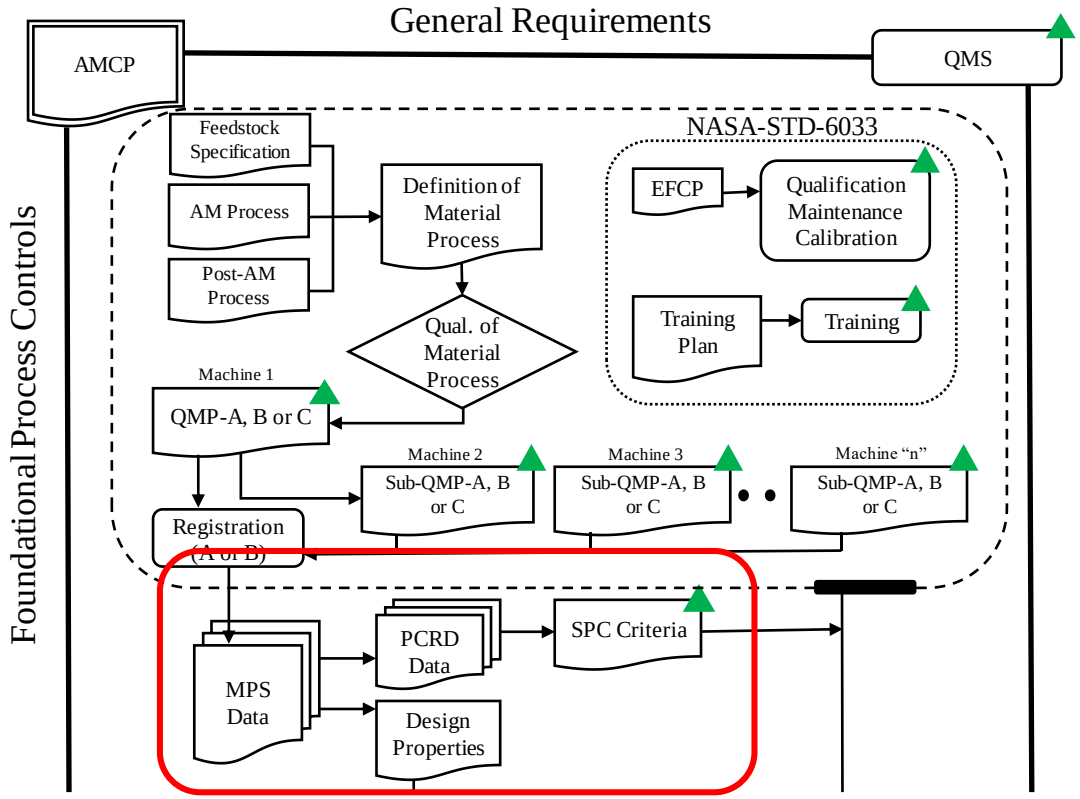
- Begins as a Candidate QMP
- Defines aspects of the basic, part agnostic, fixed AM process:
  - Feedstock
  - Fusion Process
  - Thermal Process
- Enabling Concept
  - Machine qualification and re-qualification, monitored by…
  - Process control metrics, SPC, all feeding into…
  - Design values



Material Property Suite (MPS)

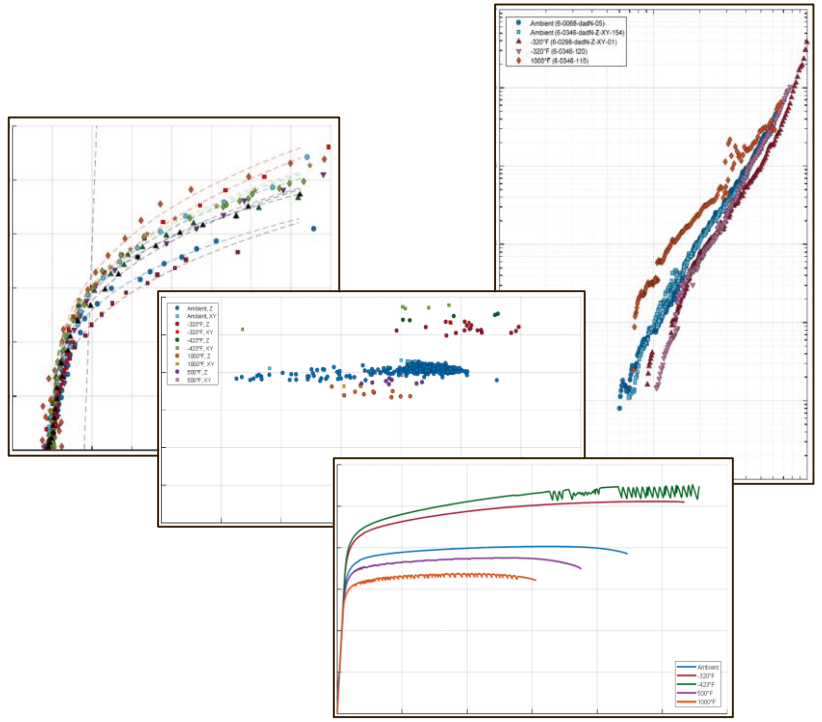
The Material Property Suite (MPS) consists of four interrelated entities:

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



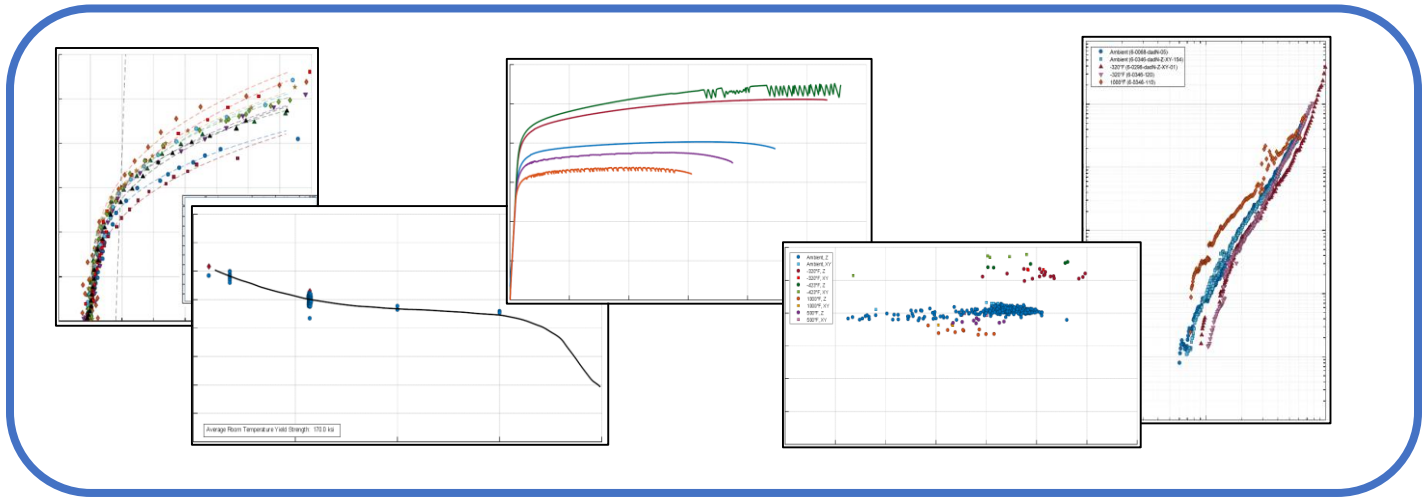
Material Property Suite (MPS)

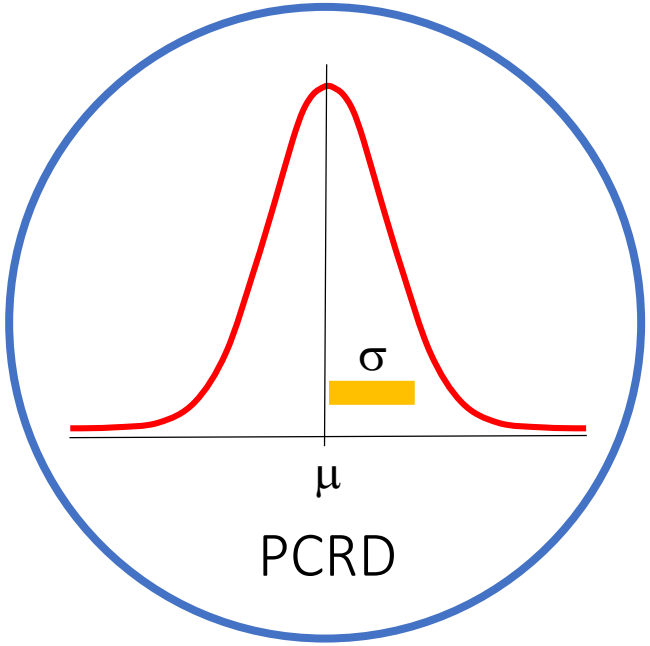
- Material properties and design values in additive manufacturing require modifications to the approach typical of traditional metallic materials
- Requirements are more similar to those used in composites (see CMH-17)
- Important distinctions arise due to the sensitive nature of the process and individualistic aspect of AM machines.
- Each machine is a foundry!
- Traditional supplier roles and responsibilities shift with the AM machine making the final material product form and part. (think castings)
- **AM Vendor is responsible for material integrity**



Process Control Reference Distribution (PCRD)

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



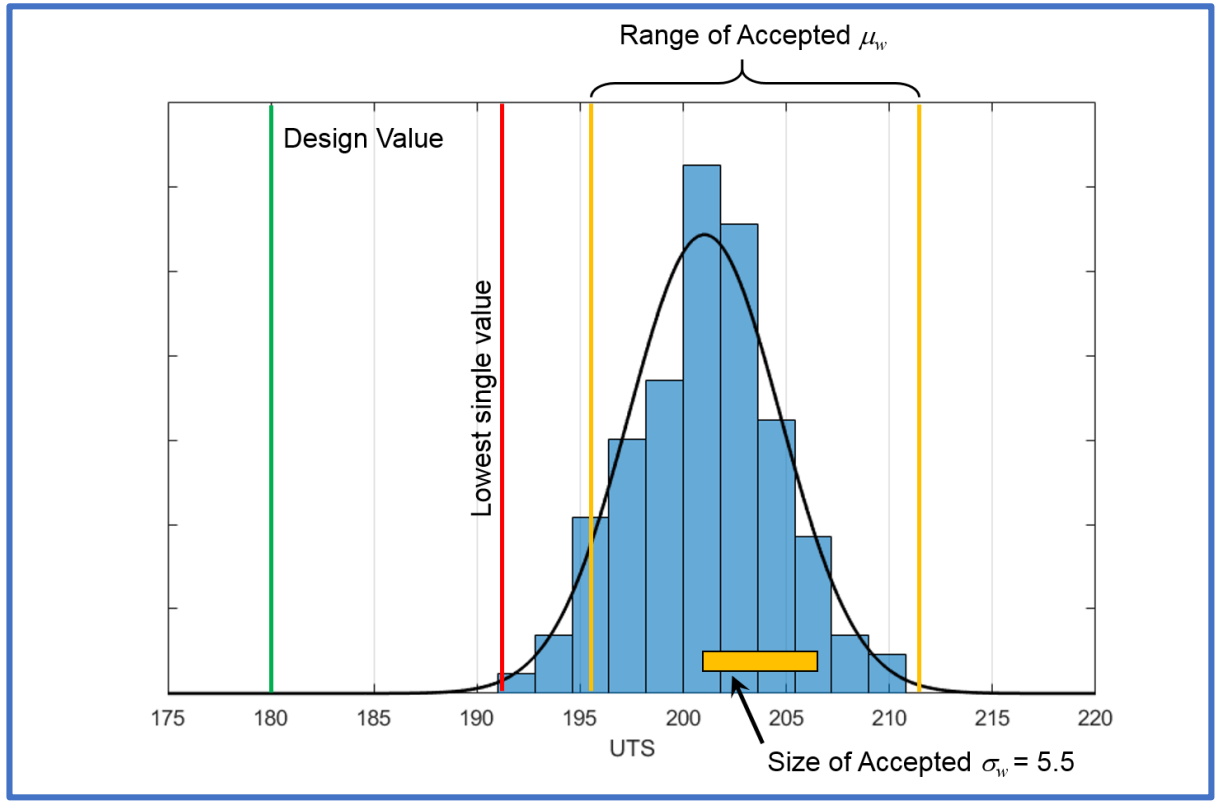


Statistical Process Control

- Derived from PCRD
- Acceptance criteria for witness tests

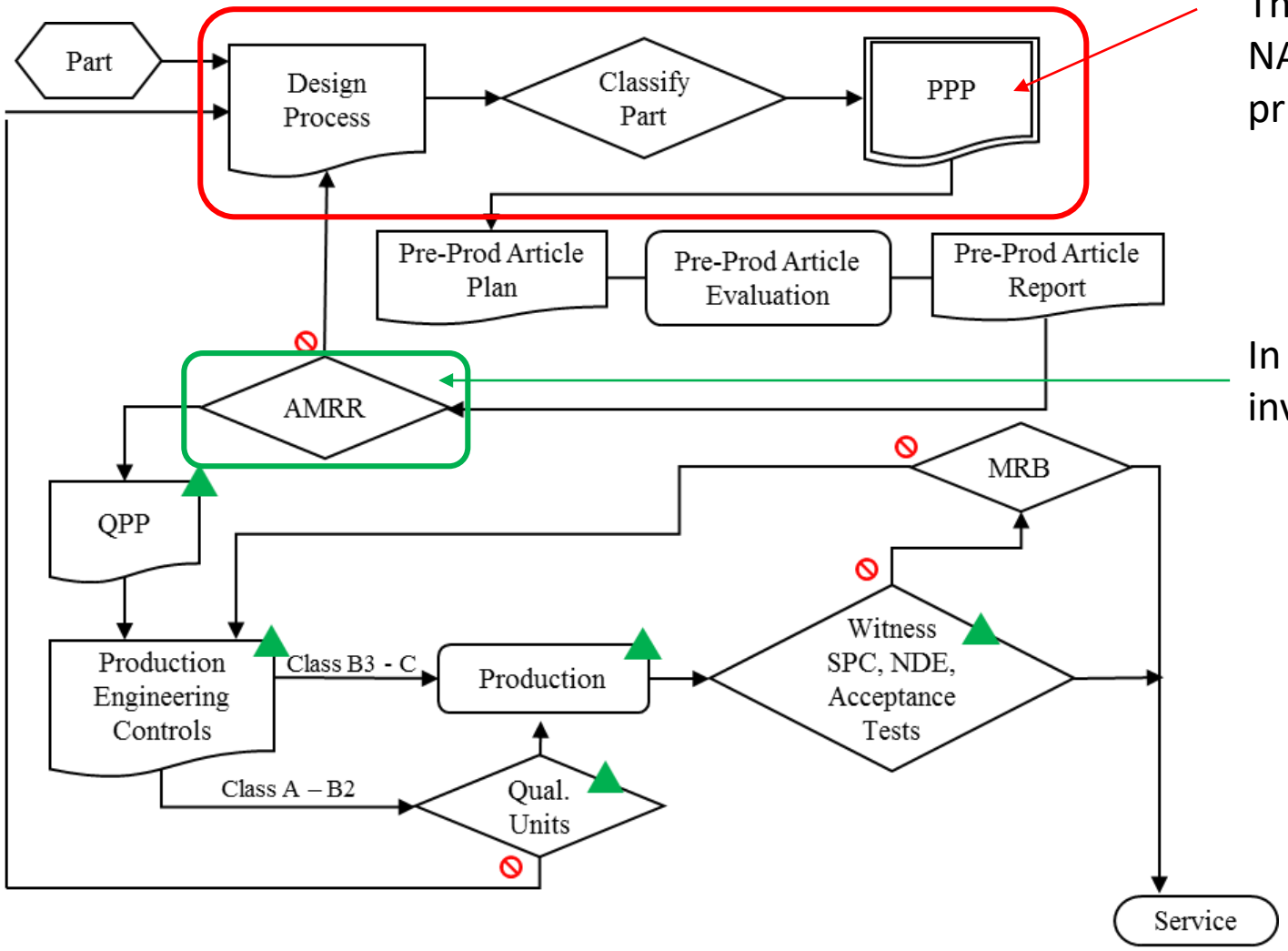
PCRD and SPC Criteria

- 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



Design Process

Part Production Controls

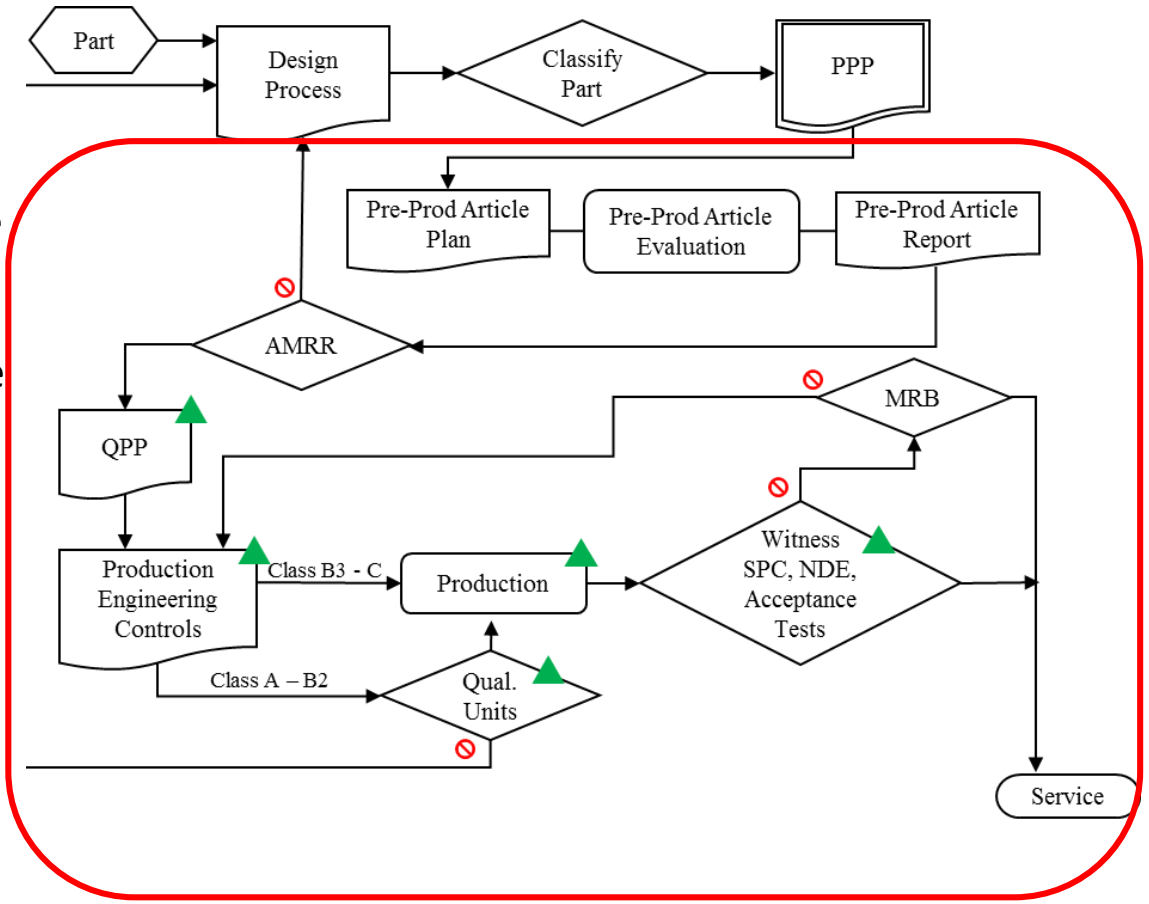


This is the last point where a NASA approval is required prior to the delivery of a part

In most cases, we do want to be invited to the readiness review

AM Part Production

- **Follow the plan, always, with no short-cuts**
- Do not change a Qualified Part Process without re-qualification
- Efficiency in process monitoring is critical to minimize the inevitable disruption
  - Witness tests can take considerable time to complete
  - Track the performance of each machine using all available metrics by control chart
  - In-process monitoring may provide early warning of changes in machine performance
- Emphasize the importance of inspection for every part
  - Not just NDE, but visual inspection of as-built conditions
  - Watch for changes in part appearance – colors, support structure issues, witness lines/shifts
- Consider systemic implications for all non-conformances



Quality Assurance's Role

You don't have to be a Materials Engineer…

Quality Assurance's Role

- Foundational Process Controls are only as good as the Quality Program(s) in which they reside
  - Fully involved Quality Management Systems
  - Equipment and Facility Controls
  - Training
  - Process/machine qualifications
  - Machine Maintenance
  - Statistical Process Control
  - Product and Performance Verification/Validation
  - etc…
- Part planning must confirm the foundation produces a good part consistently
- Part production follows a fixed process with statistical process controls

Control what you do :: Evaluate what you get

Quality Management Systems

4.4.1 Quality Management Systems *– A QMS compliant to SAE AS9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations, or an alternate QMS approved by the CEO and NASA, documented or referenced in the AMCP,* ***shall*** *be in place for all entities involved in the design, production, and post-processing of AM hardware*

- Quality Management System/QMS is mentioned ~100 times in NASA-STD-6030
- Having a well defined and executed QMS is *critical* for the production of high reliability spaceflight hardware.
- Almost every work product mentioned in NASA-STD-6030 must be maintained under configuration/revision control

Equipment and Facilities Control

- NASA-STD-6033
- Feedstock Management
  - Similar to weld wire/powder
- Digital Thread

  The virtual medium in which data are stored and subsequently referenced through a part's life cycle. This configuration-managed infrastructure contains and fingerprints the digital references for a part from foundational process controls through part production controls.
- (Machine) Installation Controls

Equipment and Facilities Control, cont.

- (Machine) Operational Controls
  - Operational Procedures and Checklists
  - In-Situ Monitoring
  - Configuration Management of AM Machines
    - Maintenance, calibration, and qualification events.
    - Machine manufacturer service calls.
    - Repairs or other changes to machine.
    - Changes to associated computers used in production of files for printing (e.g., changes in computer-aided design and slicing software).
    - Updates to software and firmware versions.
  - Maintenance
  - Associated Equipment
  - Calibration

Equipment and Facilities Control, cont.

- AM Machine Qualification
  - AM Machine Qualification Status for Production
  - Establishing Initial Qualification
  - Reestablishing Qualification
- Operator Certification
  - Training Program

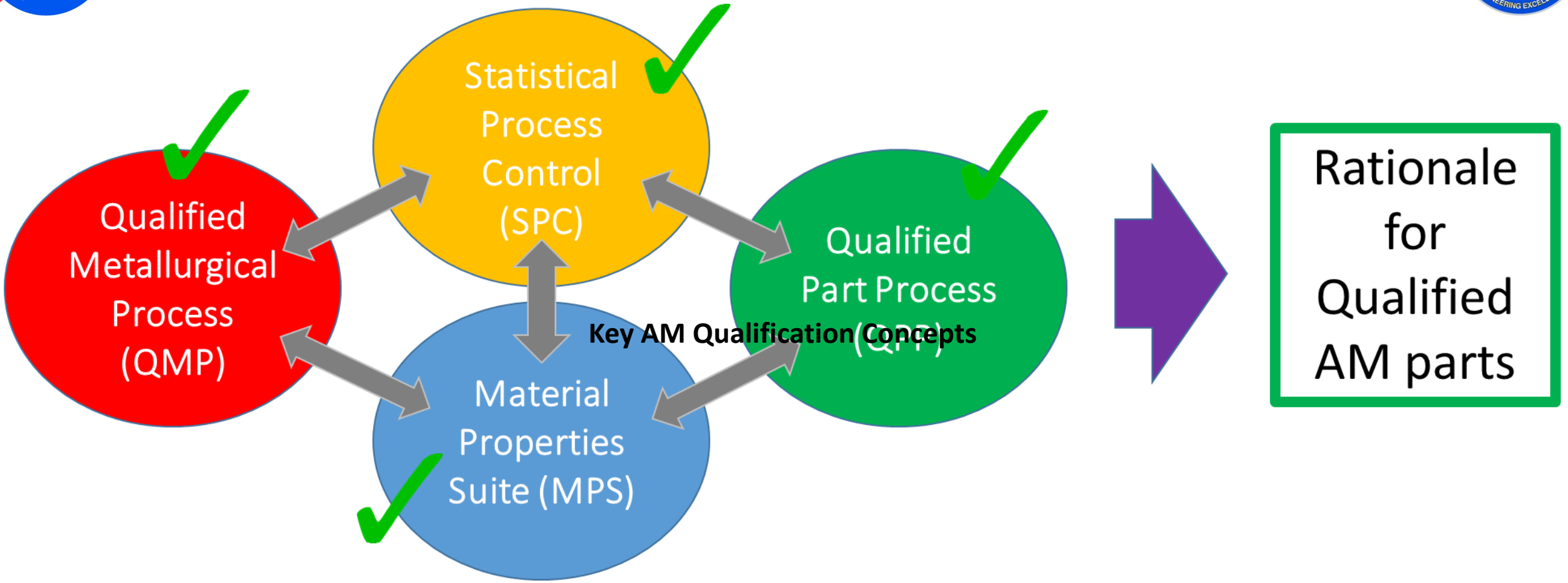
Post Production

- NASA-STD-6033 has requirements pertaining to the maintenance of *“Any associated equipment whose performance can impact the ability of the AM parts produced to meet the specified requirements”*
- However, there will likely be equipment, operations, and processes that fall outside of NASA-STD-6030 and NASA-STD-6033 that still require attention and scrutiny, e.g.,:
  - Nadcap™ accreditations (suggested, but not required)
  - Pyrometry (AMS 2750 for heat treatment, HIP, etc.)
  - Subtractive Machining
  - Surface Finishing (plating, painting, etc.)

Testing

- The only production tests that NASA-STD-6030 defines in detail are witness tests
  - Tensile
  - Microstructural Evolution
  - Chemistry
  - Fatigue
- But there are other tests and evaluations that, while NOT defined in detail, still require formal documentation and implementation
  - Statistical Process Controls
  - Pre-Production Articles
  - Proof Tests
  - Qualification Tests
  - Part Acceptance

Key AM Qualification Concepts

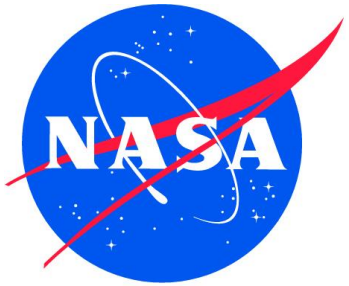


Part reliability rationale comes from the sum of both in-process and post-process controls, weakness in one must be compensated in the other

Conclusions

1. Certification rationale is most heavily rooted in the foundational controls
   - Having a Plan
   - Fully involved Quality Management System(s)
   - Equipment and Facility Controls
   - Training
   - Process/machine qualifications
   - Material properties
   - Statistical Process Control
2. Part Planning must confirm the process produces a good part consistently
3. Part production follows a fixed process with statistical process controls

Control what you do :: Evaluate what you get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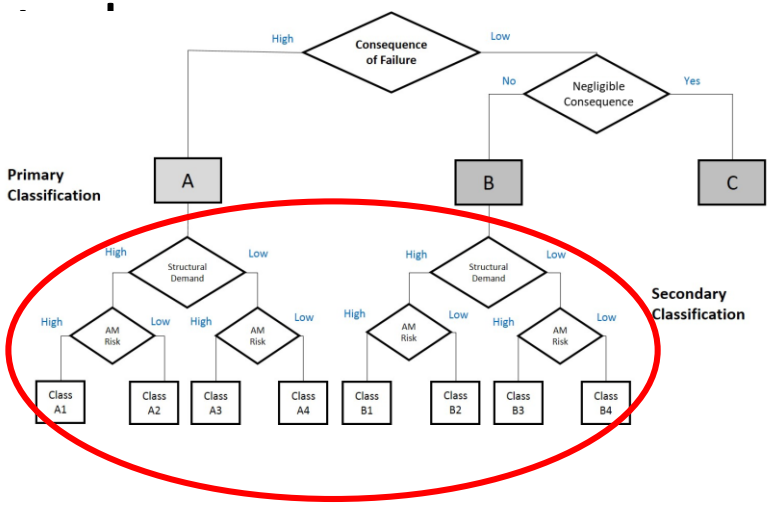
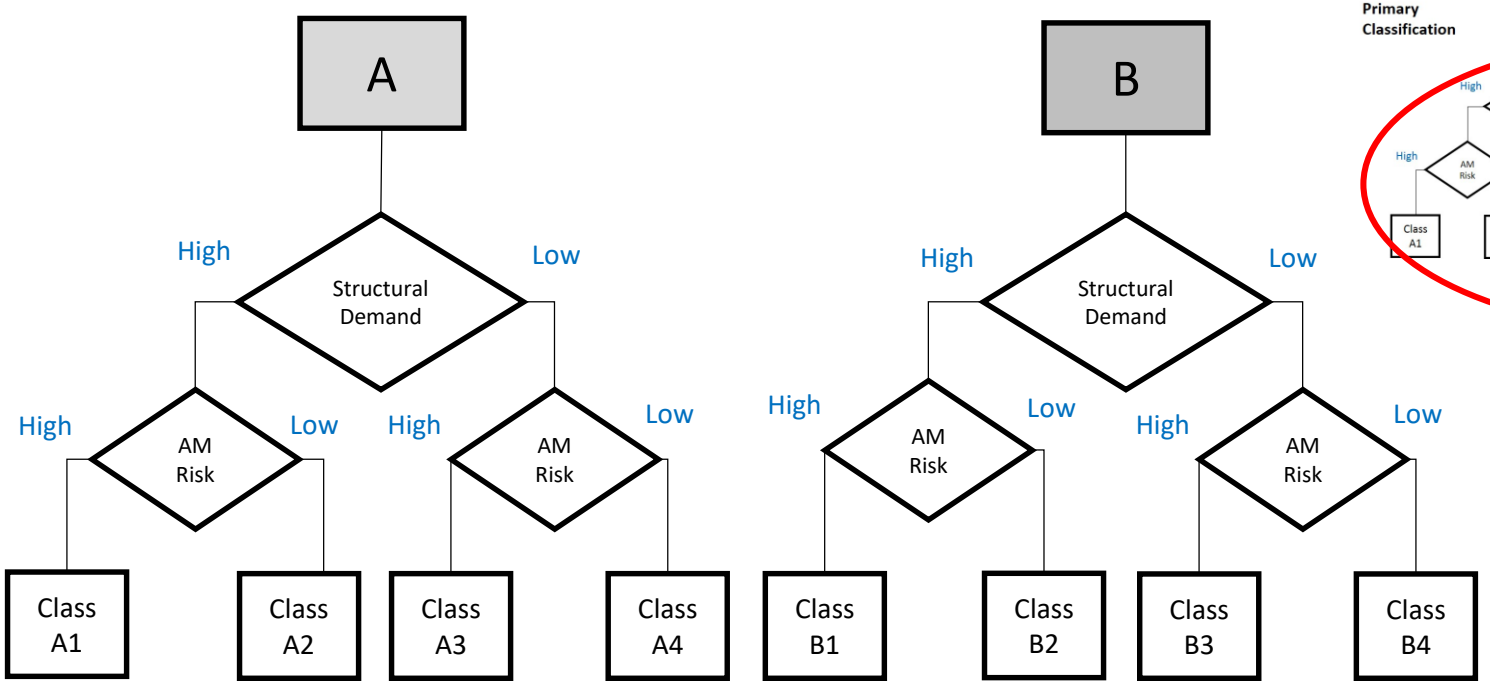
Backup

Secondary Classification

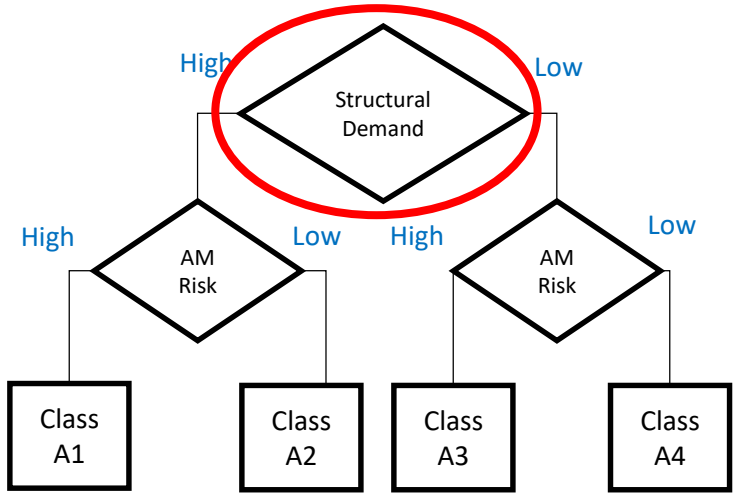
- Secondary classification is for Class A and B parts only and is used to determine appropriate levels of process cor





Structural Demand - Metals

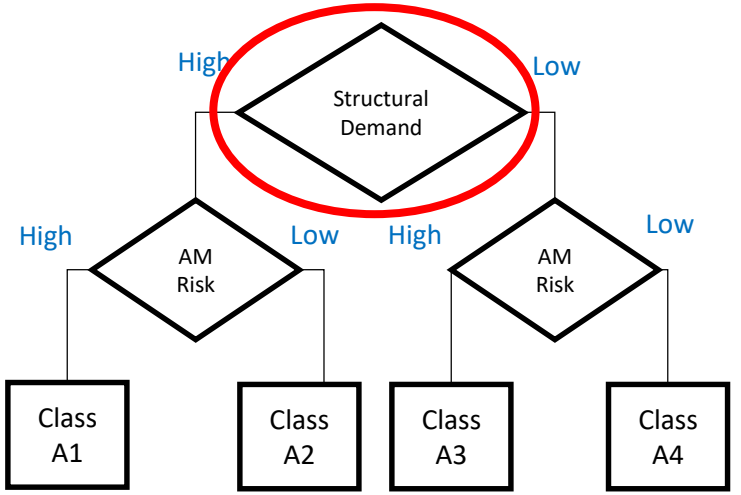
Material Property	Criteria for Low Structural Demand
Loads Environment	Well defined or bounded loads environment
Environmental Degradation	Only due to temperature
Ultimate Strength	Minimum margin* ≥ 0.3
Yield Strength	Minimum margin* ≥ 0.2
Point Strain	Local plastic strain < 0.005
High Cycle Fatigue, Improved Surfaces	Cyclic stress range (including any required factors) ≤ 80% of applicable fatigue limit
High Cycle Fatigue, As-built Surfaces	Cyclic stress range (including any required factors) ≤ 60% of applicable fatigue limit
Low Cycle Fatigue	No predicted cyclic plastic strain
Fracture Mechanics Life	20x life factor
Creep Strain	No predicted creep strain



*Margin = $[\sigma_{design} / (\sigma_{operation} * \textit{safety factor})] - 1.$

Structural Demand - Polymers

Analysis Input/Material Property	Criteria for Low Structural Demand
All Materials	
Loads Environment	Well defined or bounded loads environment
Environmental Degradation	Only due to temperature and moisture, if specific environmental performance data exist. Design environment temperature does not cross the Tg.
Fatigue	Cyclic stress range (including any required factors) ≤ 50% of applicable fatigue limit
Sustained stress / creep strain	No sustained stress† and No predicted creep strain
Material with elongation at failure ≥ 3% in application environment	
Ultimate Strength	Minimum margin* ≥ 0.5
Yield Strength‡	Minimum margin* ≥ 0.3
Material with elongation at failure < 3% in application environment	
Ultimate Strength#	Minimum margin* ≥ 2.0



†Includes assembly stress (tight snap fit connections, shrink fits, fastener preloads) and operational stress

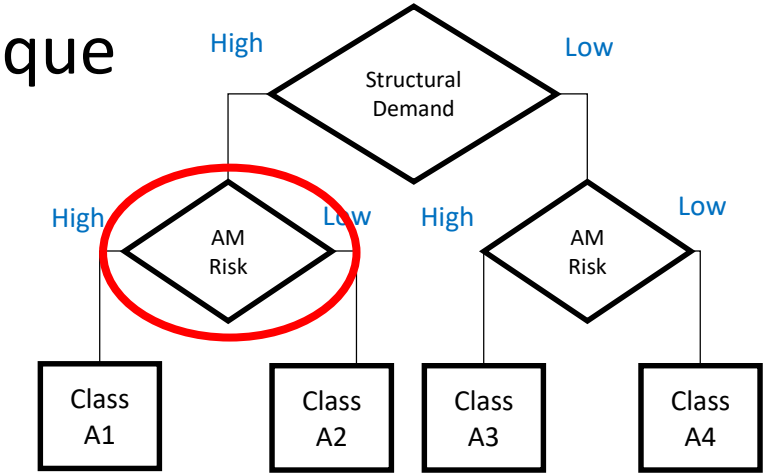
‡Yield Strength defined by secant modulus to specified strain, by specified offset strain, or as otherwise defined by structural assessment requirements

#Ultimate Strength assessed against local maximum principal stress at stress concentrations (brittle material design rules) for low ductility materials

*Margin = $[\sigma_{design} / (\sigma_{operation} * \textit{safety factor})] - 1$.

AM Risk

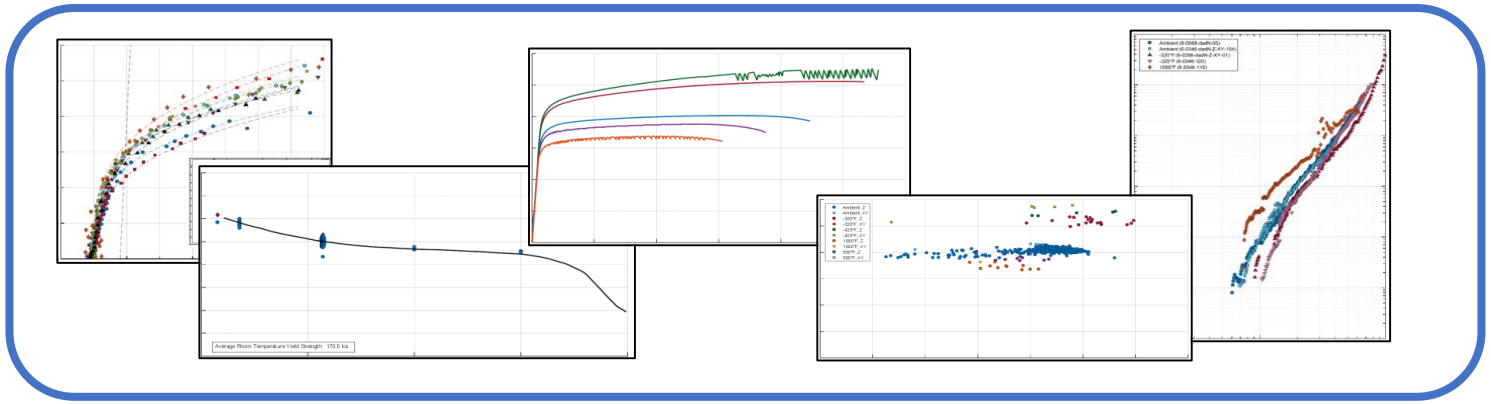
- Additive Manufacturing Risk determination will be unique to each type of process (e.g. powder vs wire)
- The example below is for Laser Powder Bed Fusion



Additive Manufacturing Risk	**Yes**	**No**	**Score**
All critical surface and volumes **can be reliably inspected**, or the design permits **adequate proof testing** based on stress state?	0	5	
As-built surface **can** be fully removed on all fatigue-critical surfaces?	0	3	
Surfaces interfacing with sacrificial supports **are fully accessible** and improved?	0	3	
Structural walls or protrusions are ≥ 1mm in cross-section?	0	2	
Critical regions of the part **do not** require sacrificial supports?	0	2	
		Total	

AM risk = HIGH, if cumulative AM Risk score >=5

MPS Backup – Data Repository



- Includes data from
- Qualification testing
- Material Characterization
- Pre-production Article Evaluations

Grouping of data

Group data by

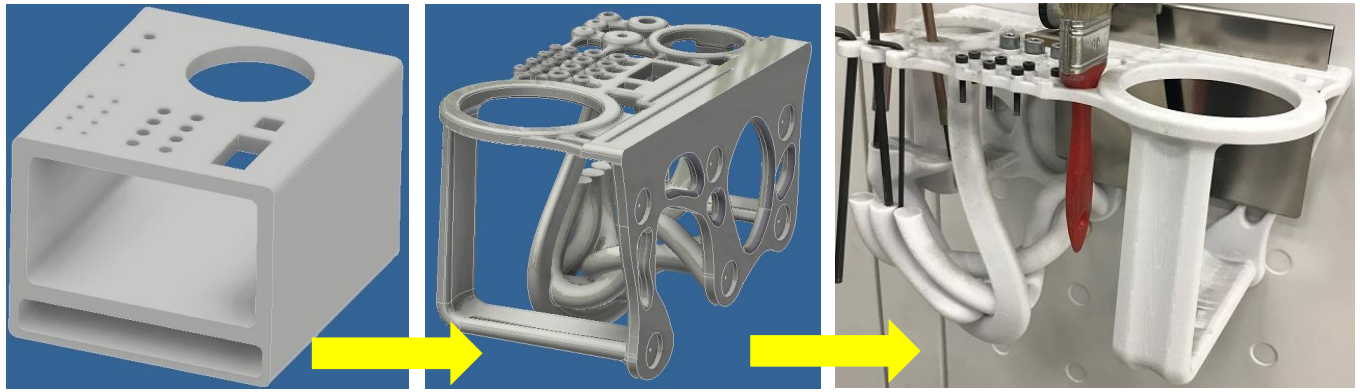
- QMP = Material/process/heat treat
- “Combinable” conditions for design

- Contains all data needed for
- Setting Design Values
- Property equivalence evaluations and QMP Registration
- Setting the Process Control Reference Distribution

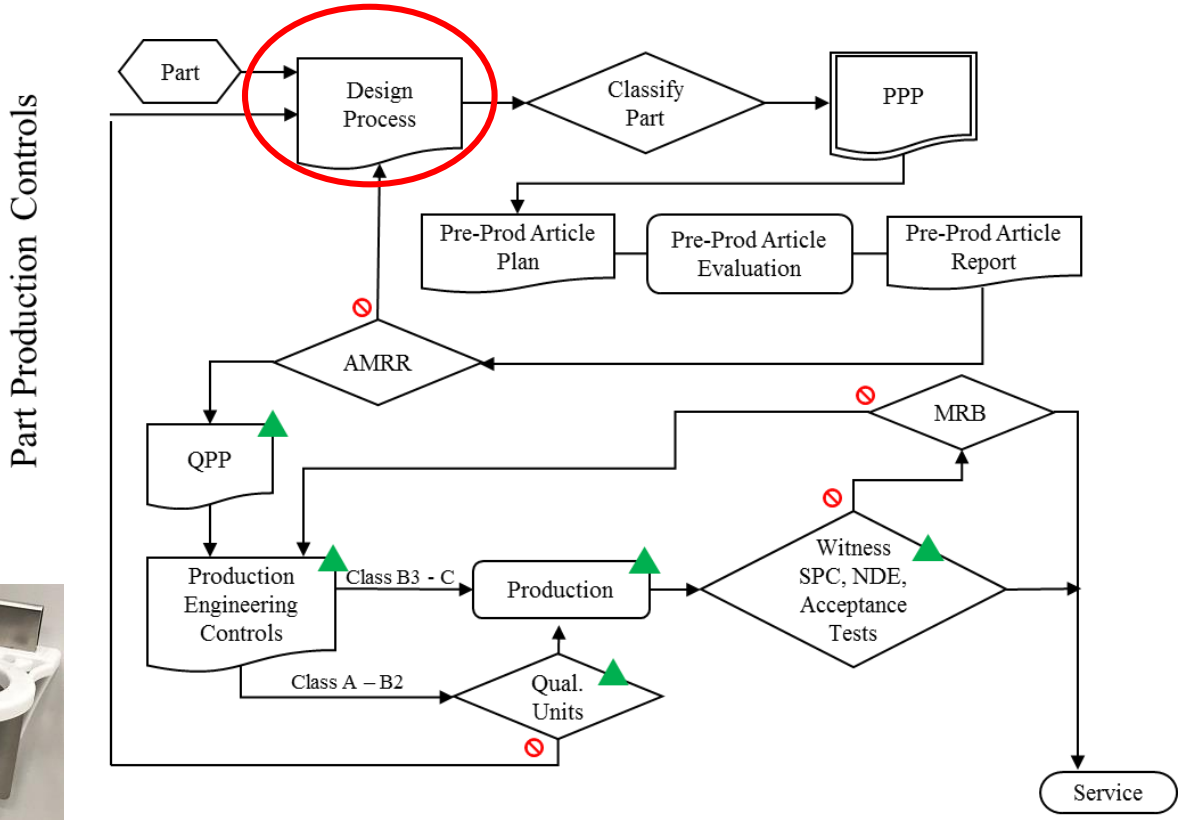
Design Process

Design For Additive Manufacturing Paradigm Shift

- New benefits bring new constraints
- Must decide manufacturing method as early as possible
- Each Process is different with unique constraints: SLM vs DED

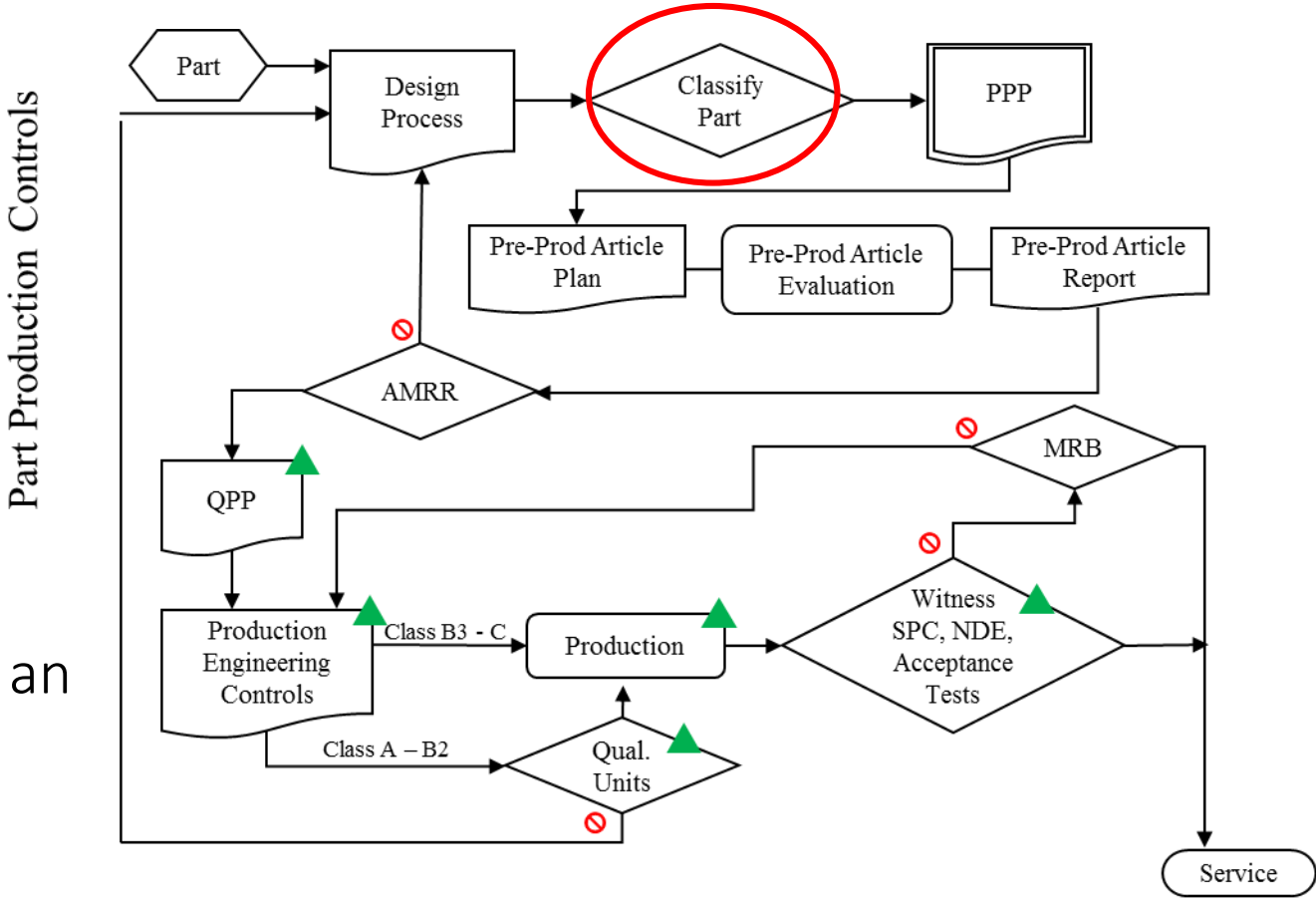


Topology Optimization FDM Tool Rack



Part Classification

- Part Classification system is a ***risk communication*** tool
- 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



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