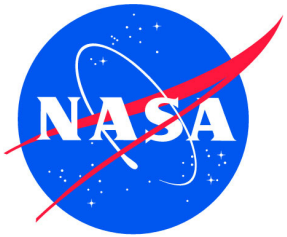


Additive Manufacturing Design, Process and Quality Controls

Doug Wells
MSFC Structural Materials Engineer,
Technical Specialist – Damage Tolerance

Sam Cordner
MSFC Materials Engineer

Andrew Glendening
GSFC Materials and Processes Assurance

Rick Russell
NASA Technical Fellow for Materials

Public Use - Quality Leadership Forum 2021 - 27 May 2021

Outline

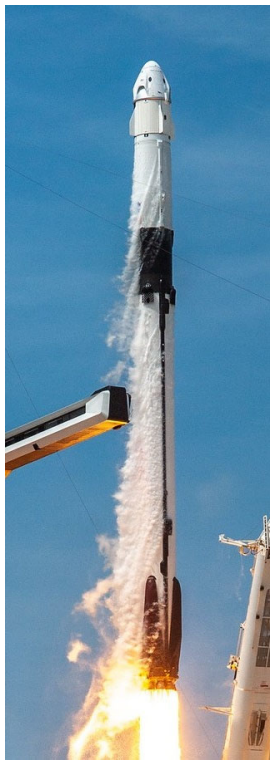
- Introductory Session - 1:00-1:30 pm EDT
- Breakout Sessions – 1:35-2:35 pm EDT
  - Qualified Material Process and Material Property Suite for Additive Manufacturing
    - Doug Wells - MSFC
    - Sam Cordner - MSFC
  - Considerations for Quality Audits of Additive Manufacturing Suppliers
    - Andrew Glendening – GSFC
    - Jeannette Plante – HQ/OSMA

Introductory Session

No Verbal Q&A Until Breakout Sessions

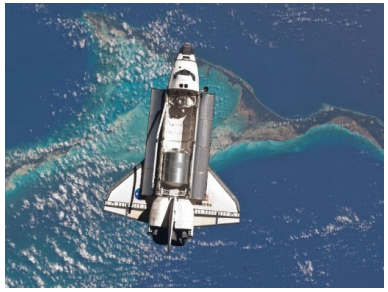
Please take note of any questions you might have so you can ask them in the breakout sessions

Additive Manufacturing: The Future is Now!!

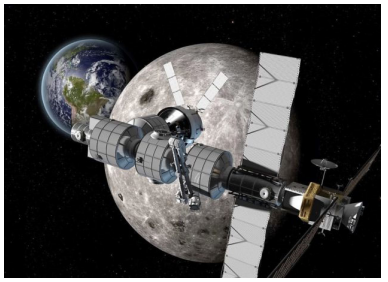


NASA's motivation for AM Standards

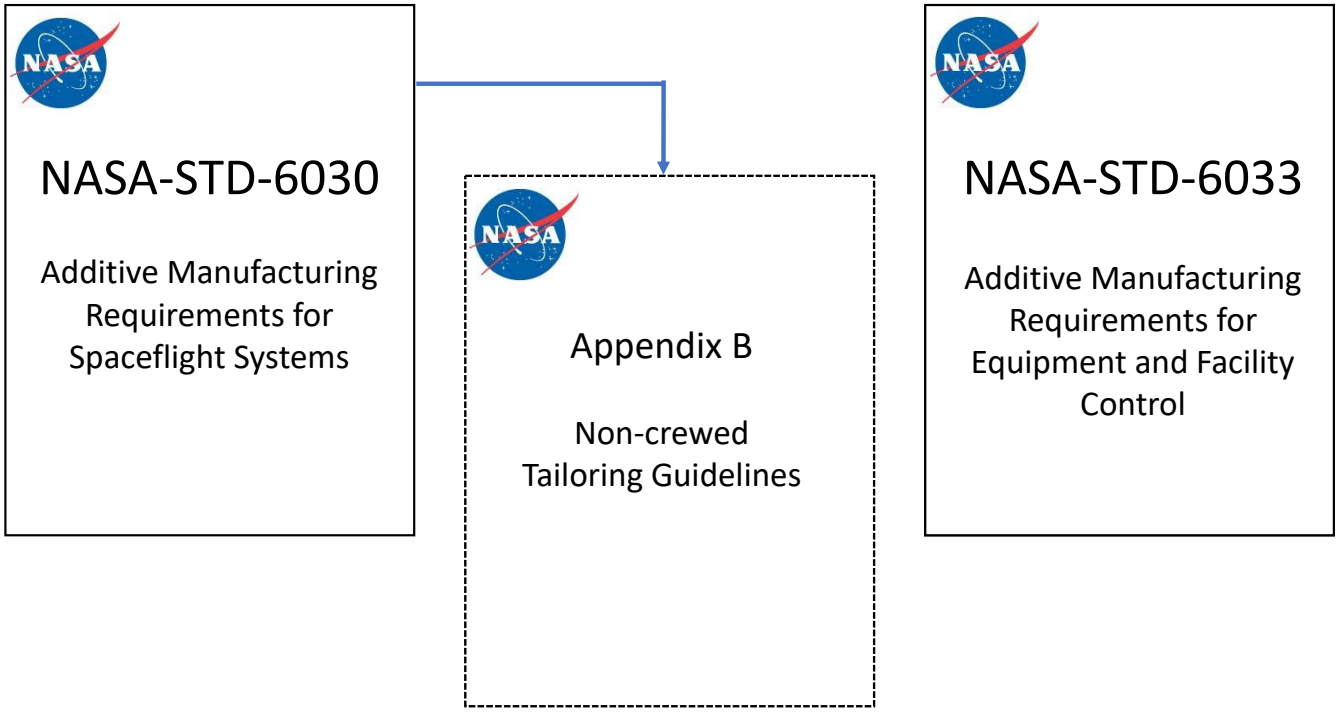
- AM parts are already being use for NASA programs in critical applications
- Human exploration of space, especially deep space, requires extreme reliability



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



The New Standards – April 2021

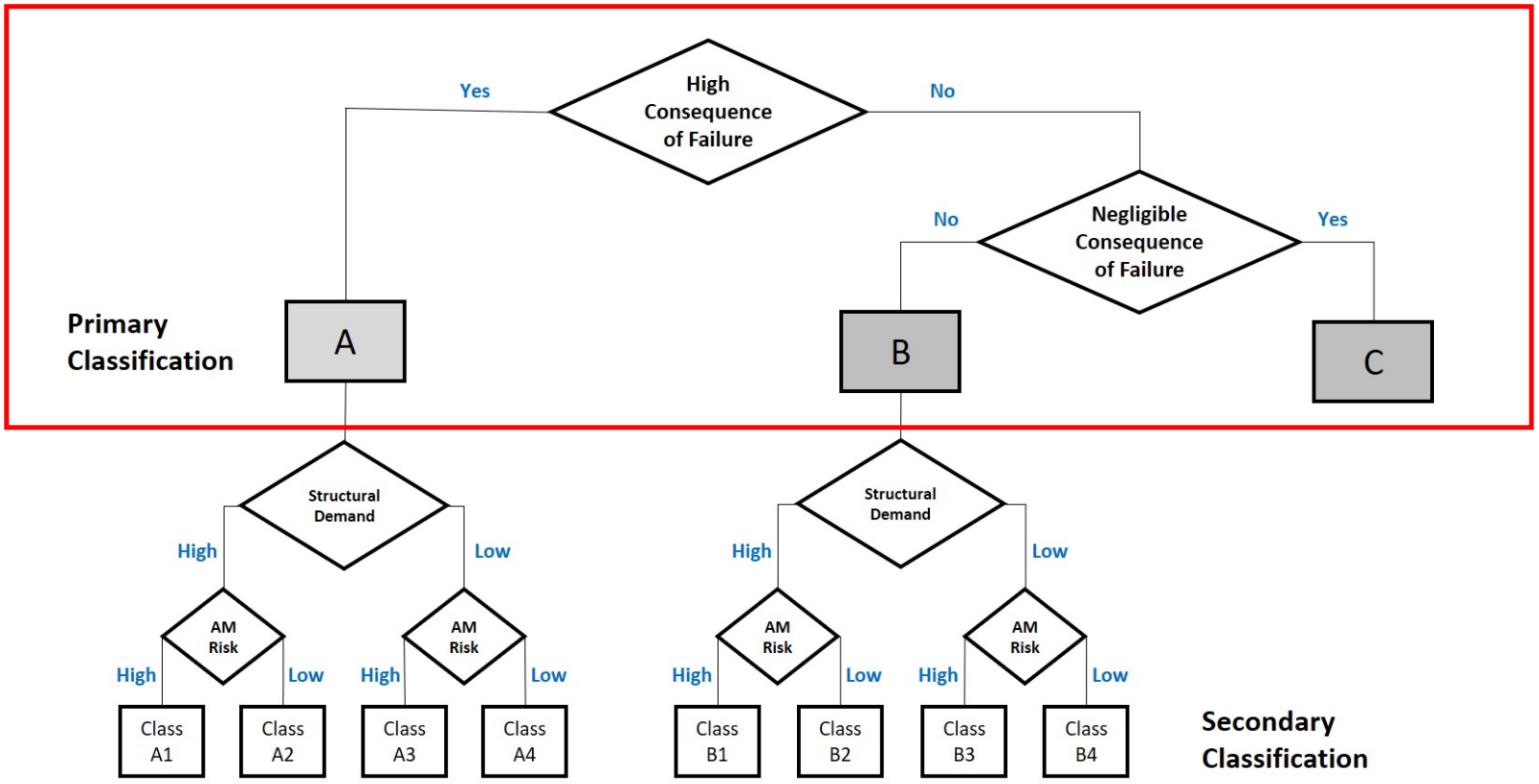


Applicability

			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

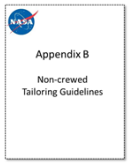
- Adaptive technologies, where the heat input can change during the manufacturing process, are not covered by NASA-STD-6030
  - e.g., Electron beam powder bed fusion (E-PBF)

Classification



High Consequence of Failure

- A part **shall** be designated as Class A, High Consequence of Failure, if failure of the part leads to a **catastrophic**, **critical**, **or** **safety hazard** and/or the part is **defined as mission critical by the program or project**.



- Class A parts **shall not**:
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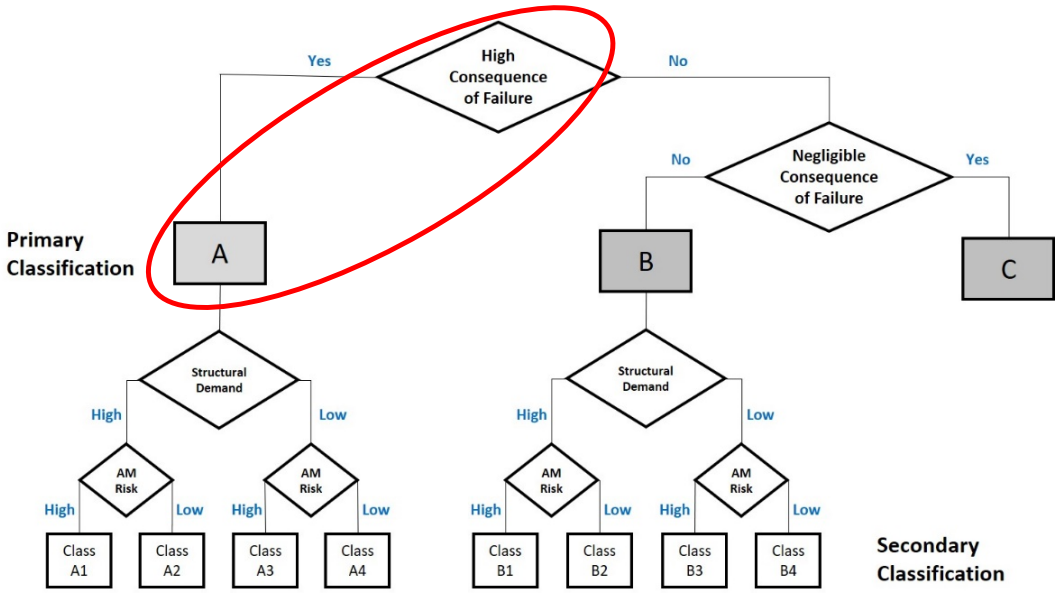
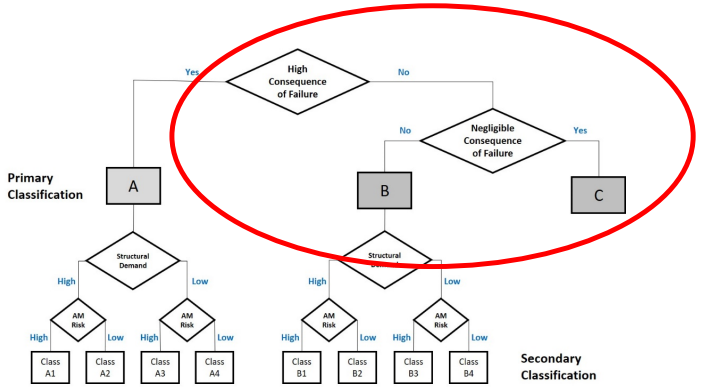
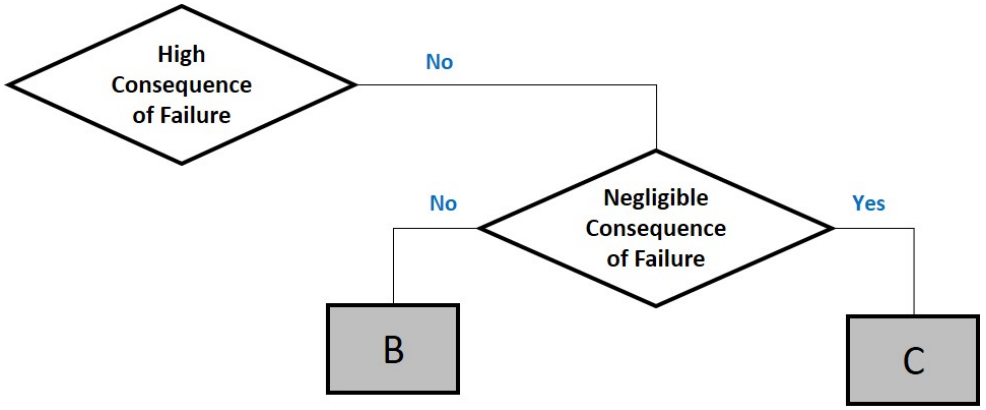
  - Contain printed threads.



Negligible Consequence of Failure

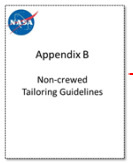




- Parts not designated Class A or Class C **shall** be designated as Class B.
- Class B parts **shall** not:
  - Be fasteners
  - Contain printed threads.

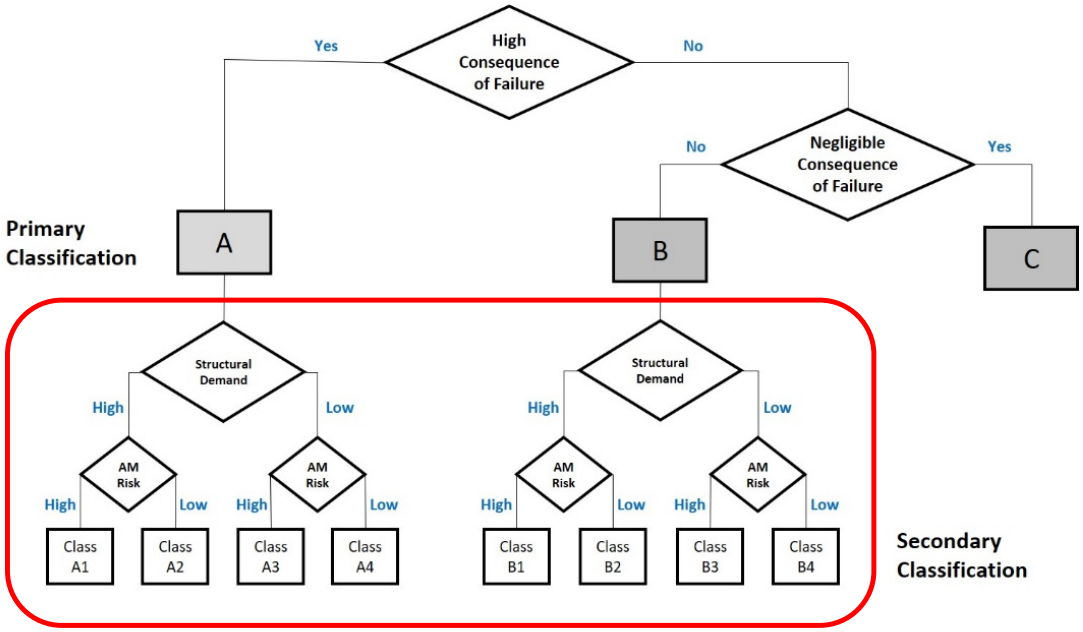
Negligible Consequence of Failure

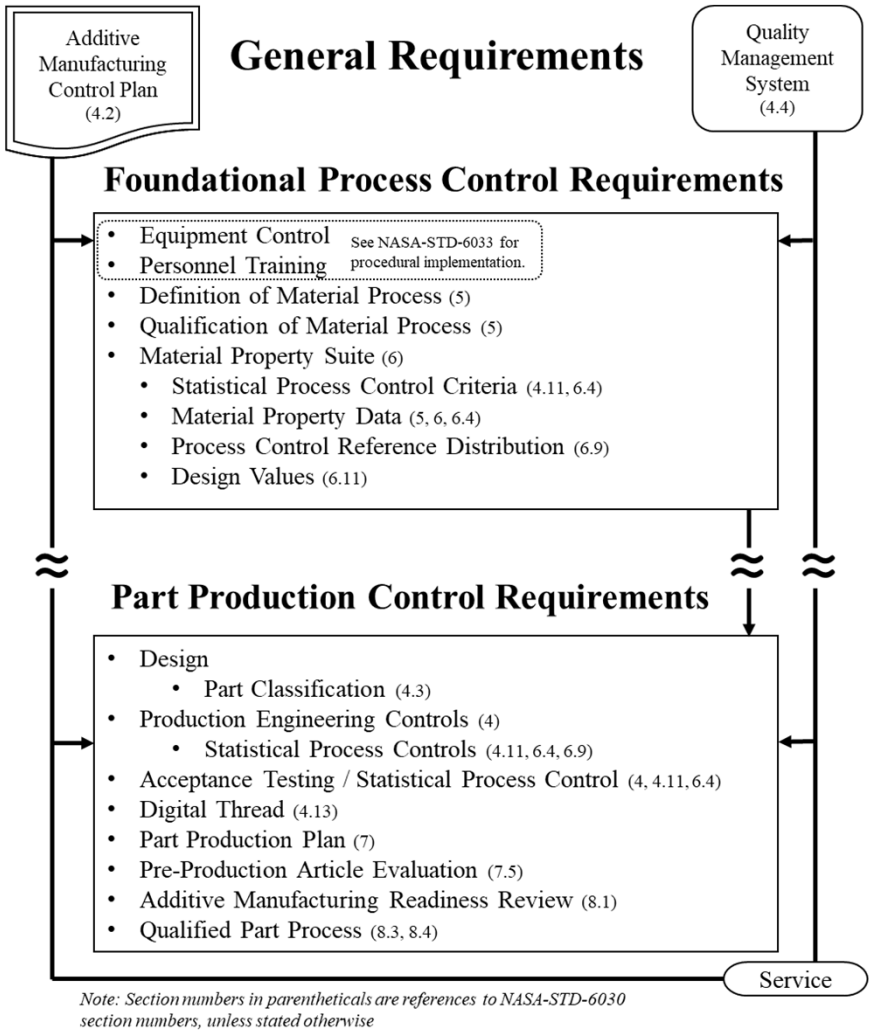
- A part **shall** be designated as Class C, Negligible Consequence of Failure, provided that ALL of the following criteria are satisfied:
  - Failure of part does not lead to any form of hazardous condition.
  - Failure of part does not eliminate a critical redundancy.
  - Part does not serve as primary or secondary containment.
  - Part does not serve as redundant structures for fail-safe criteria per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.
  - Part is not designated “Non-Hazardous Leak Before Burst” per NASA-STD-5019.
  - Failure of part does not cause debris or contamination concerns, as defined by the Non-Fracture Critical Low-Release Mass classification per NASA-STD-5019, NASA-STD-6016, and/or other project/program requirements.
  - Failure of part causes only minor inconvenience to crew or operations.
  - Failure of part does not alter structural margins or related evaluations on other hardware.
  - Failure of part does not adversely affect other systems or operations.
  - Failure of part does not affect minimum mission operations.



Secondary Classification

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

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• 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)

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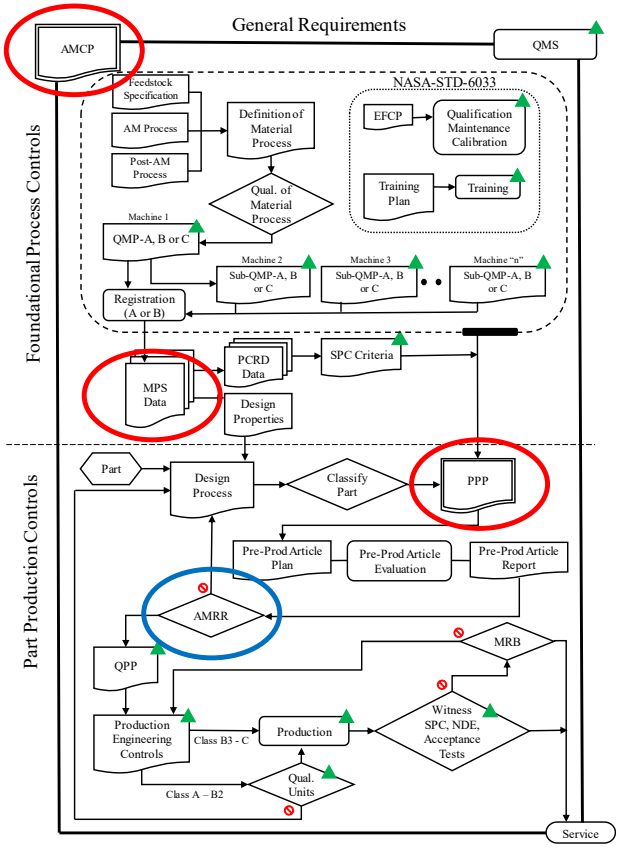
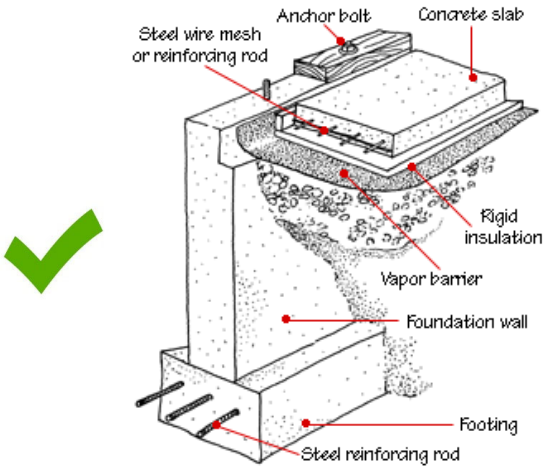
  - NASA's attendance is only required for Class A1 or A2 Parts
  - NASA Approval is NOT required

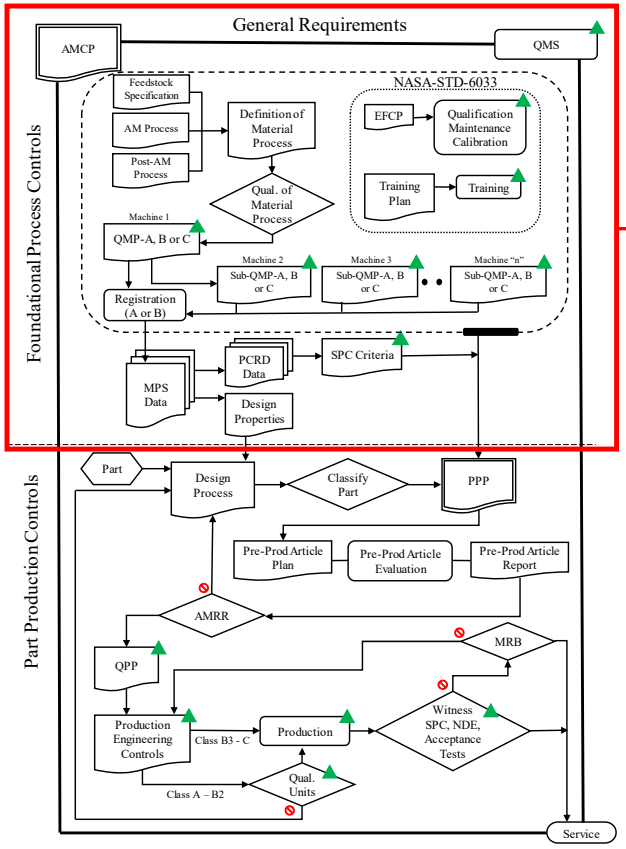


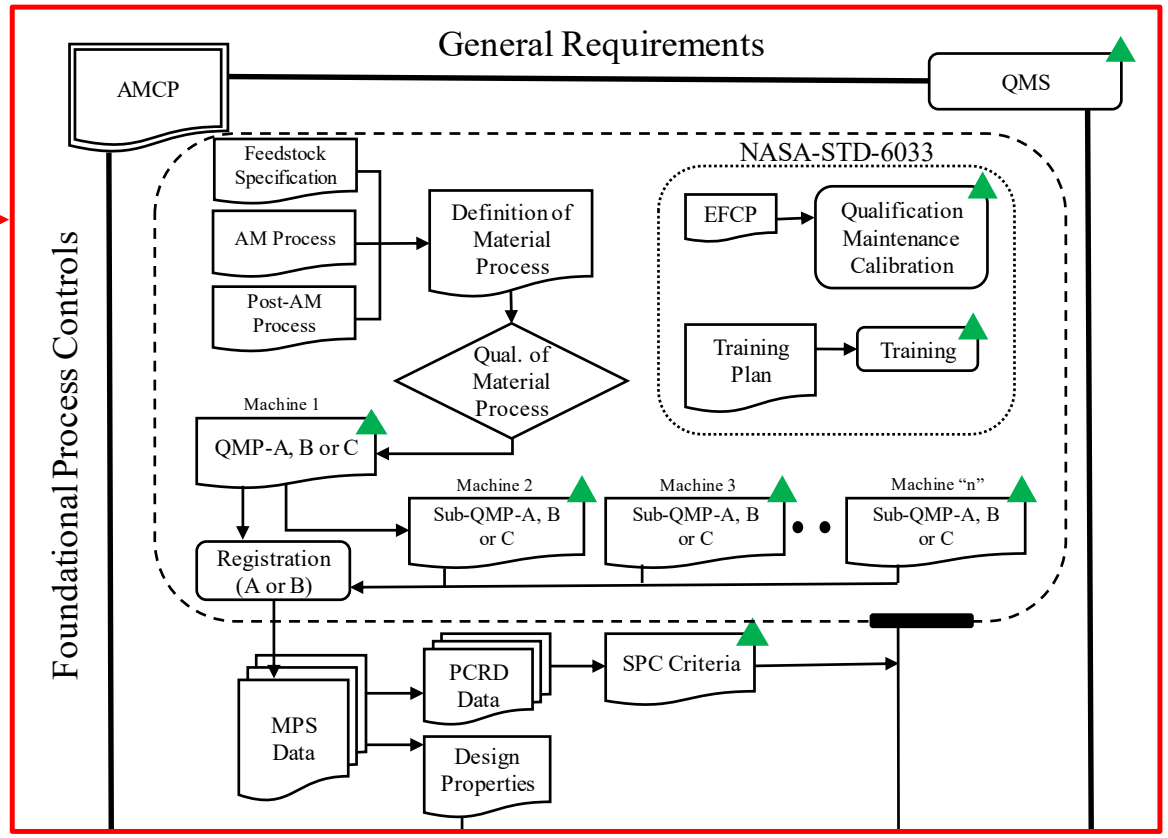
Building a Foundation

- **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.



Summary of Methodology

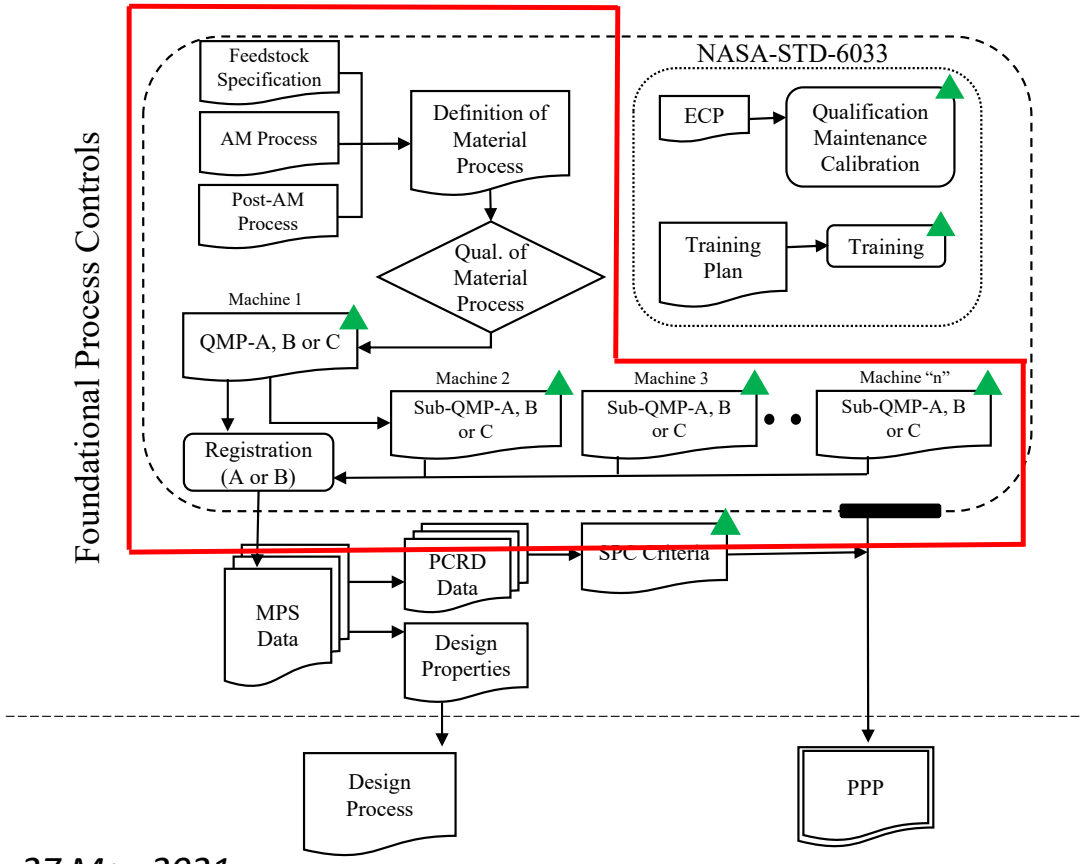




Qualified Material Process (QMP)

- Begins as a Candidate QMP
- Defines aspects of the basic, *part agnostic*, fixed AM process:
  - Feedstock
  - Fusion Process
  - Thermal Process

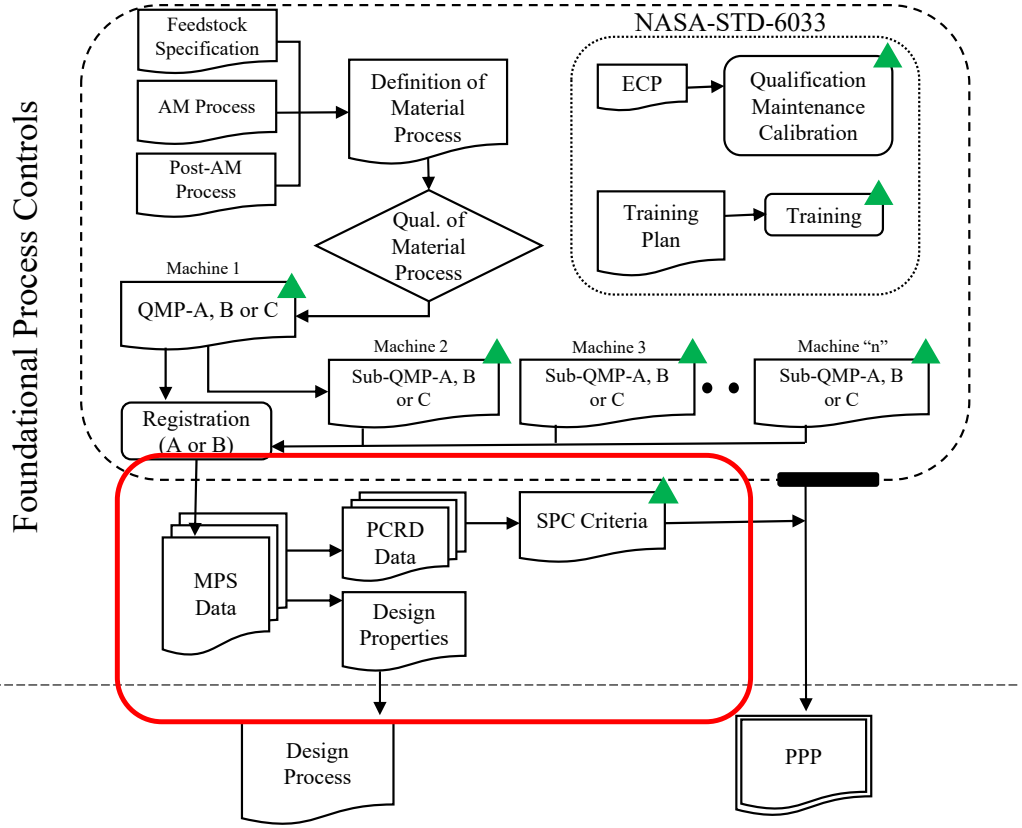
- Enabling Concept
  - Machine qualification and re-qualification, *monitored by…*
  - Process control metrics, SPC, *all feeding into…*
  - Design values



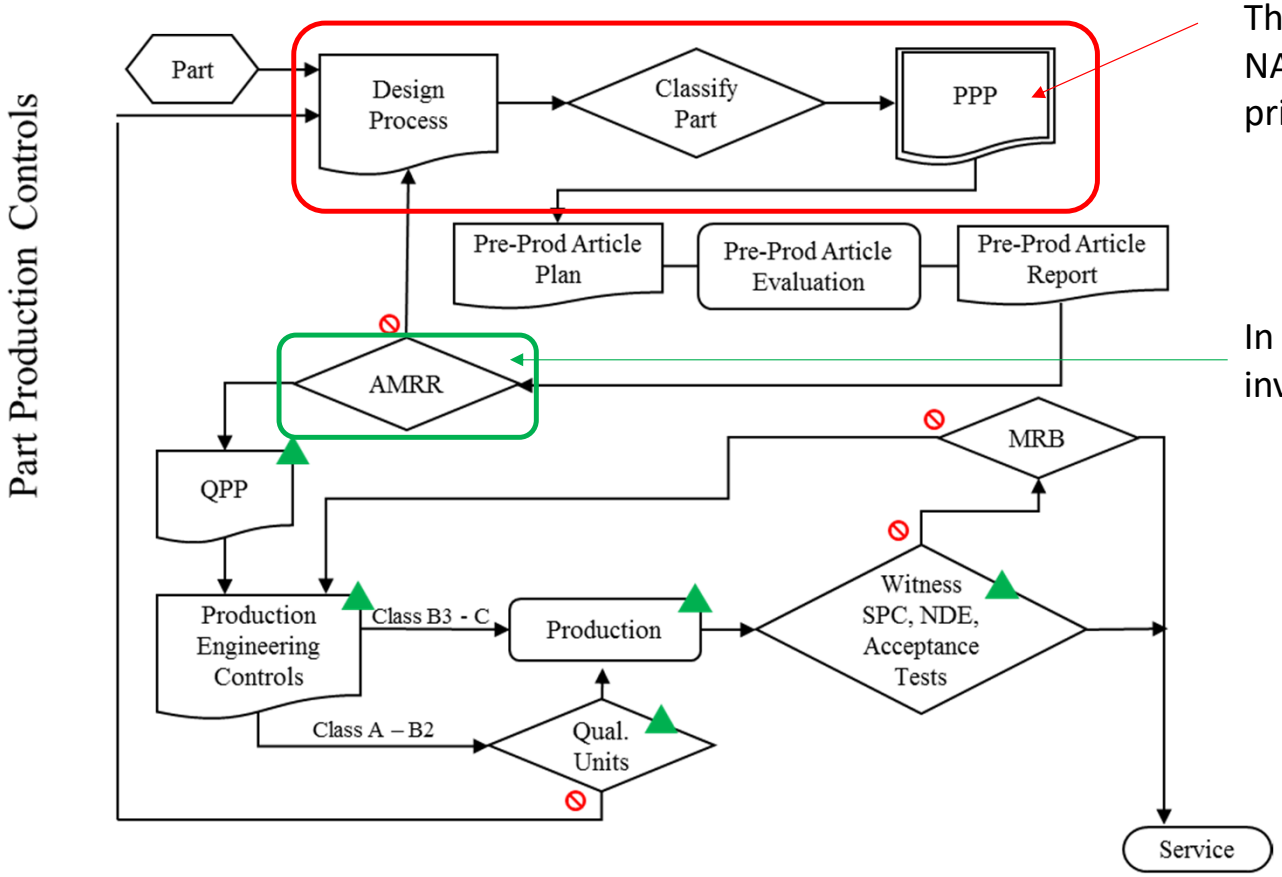
Material Properties

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



Design Process

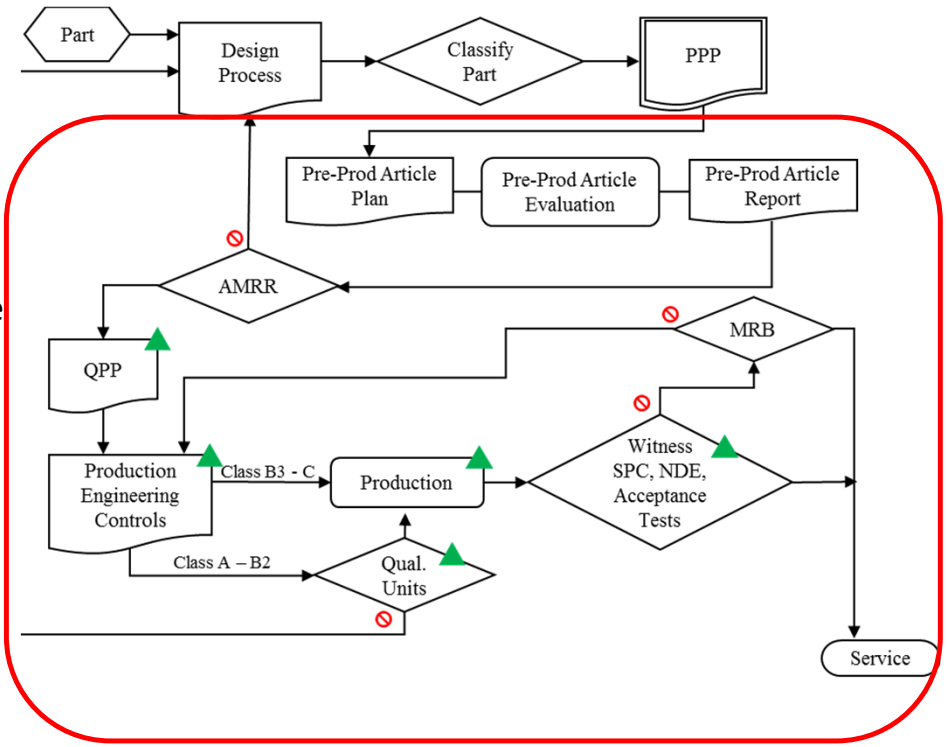


This is the last point where a NASA approval is required prior to the delivery of a part

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

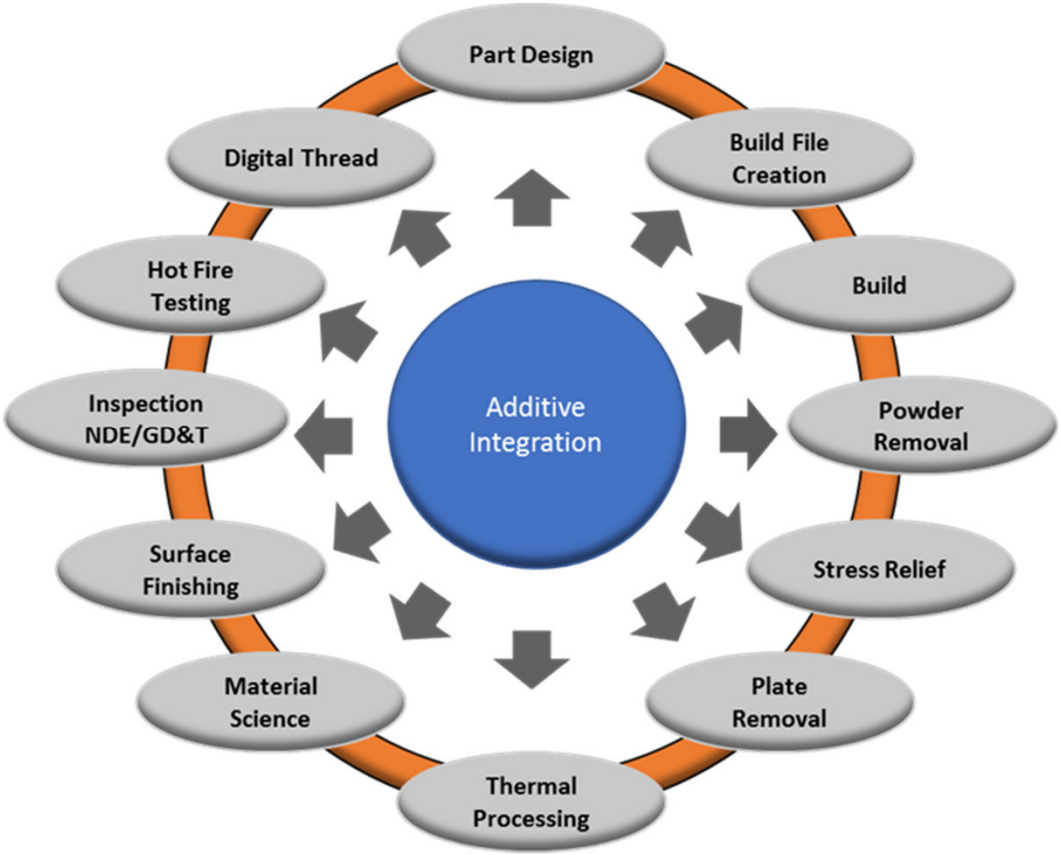
AM Part Production

- **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



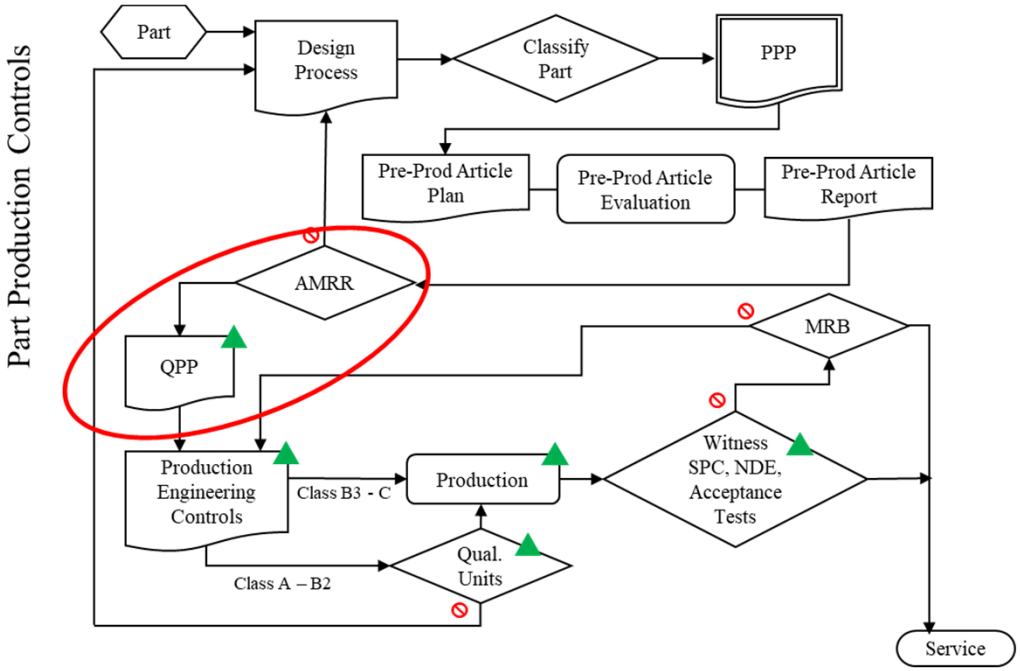
Part Production Plan

- AM parts do not yet have a common industry standard of practice
  - Challenge to integrate all required aspects of AM design requirements through drawing content
  - Requires many aspects to be integrated
    - Build layout
    - Specification of qualified process ID
    - Witness test and acceptance
    - Post processing details
    - *Inspection requirements and limitations*
- Requiring a AM Part Production Plan as a drawing companion is currently the best option



Qualified AM Part Process

1. Agreed upon and approved AM Part Production Plan
2. Pre-production article evaluation
3. AM Manufacturing Readiness Review
   - 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
4. Produce to the Plan and STICK TO THE PLAN

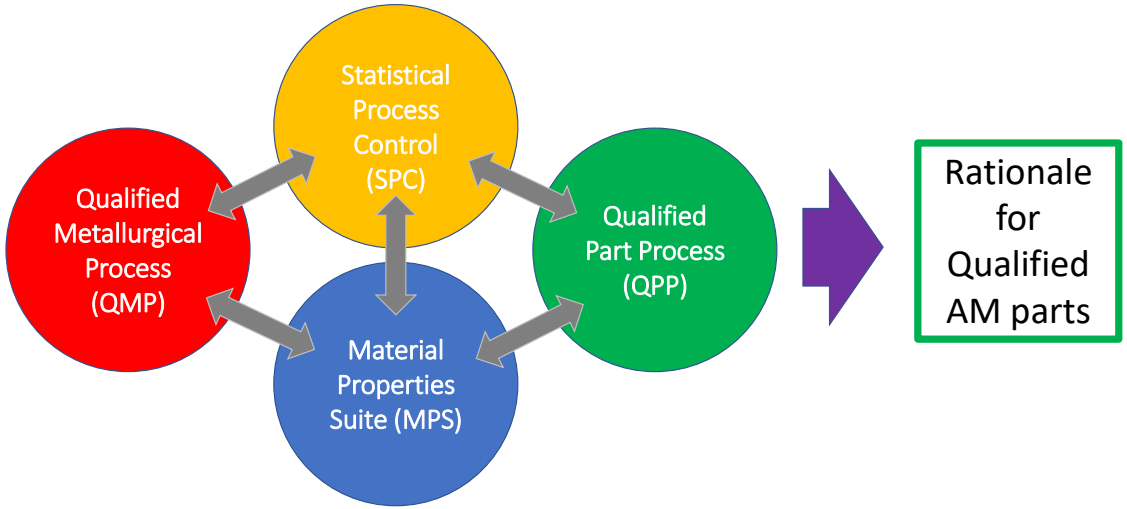


Locked Process Is the QPP! Must be documented in the QMS!

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**



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.

Breakout Sessions will begin in ~5 minutes

Please bring your questions!

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  - #1 Qualified Material Process and Material Property Suite for Additive Manufacturing
    - Doug Wells - MSFC
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  - **#2 Considerations for Quality Audits of Additive Manufacturing Suppliers**
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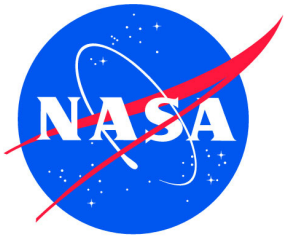

Breakout Session 2

Considerations for Quality Audits of Additive Manufacturing Suppliers

Bring Your Questions!

Andrew Glendening
GSFC Materials and Processes Assurance

Jeannette Plante
NASA Quality Engineering Technical Fellow

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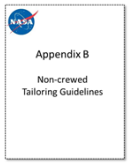

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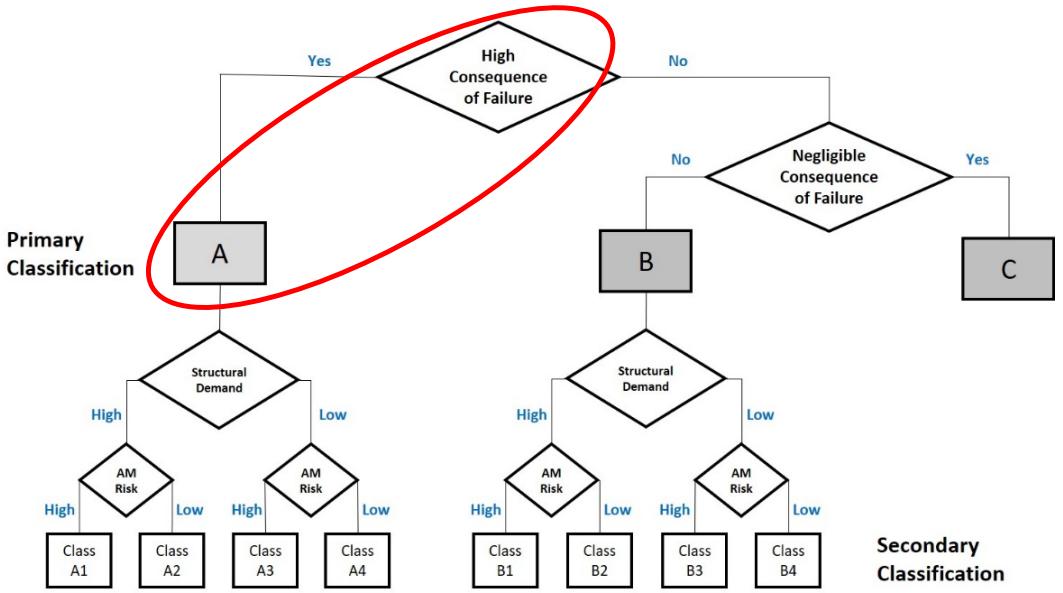

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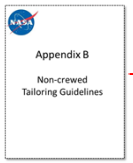

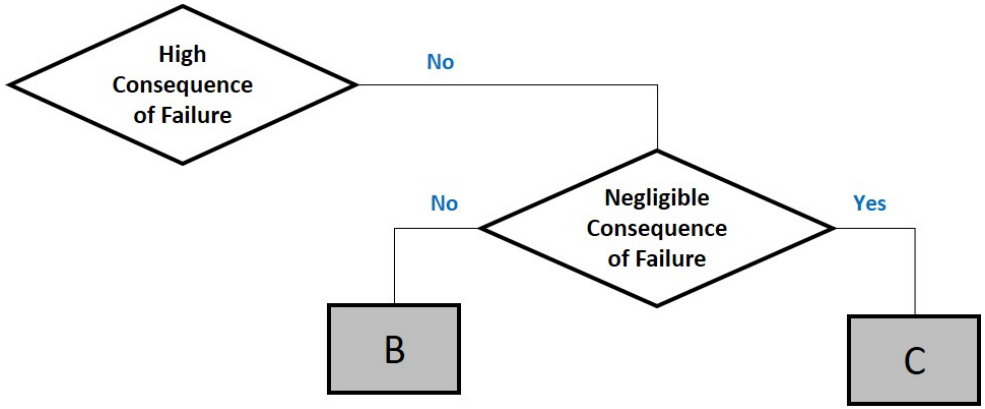

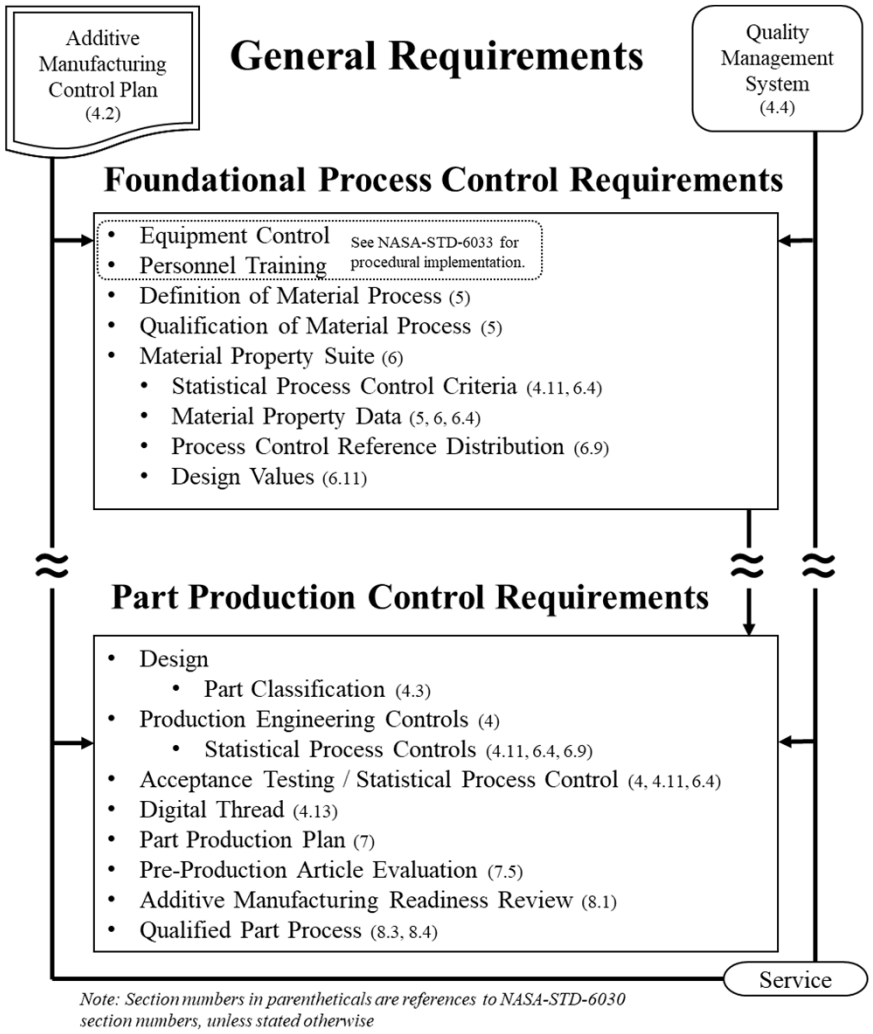
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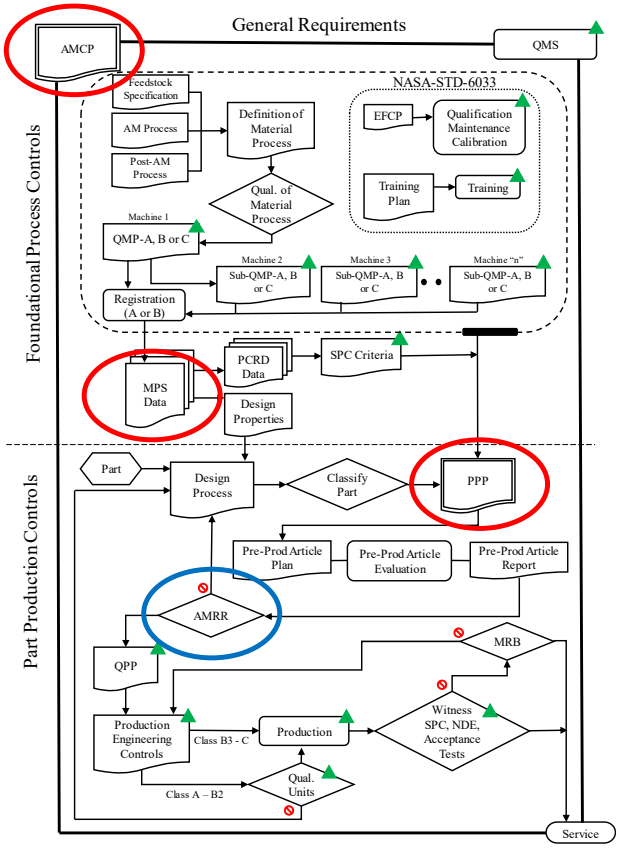
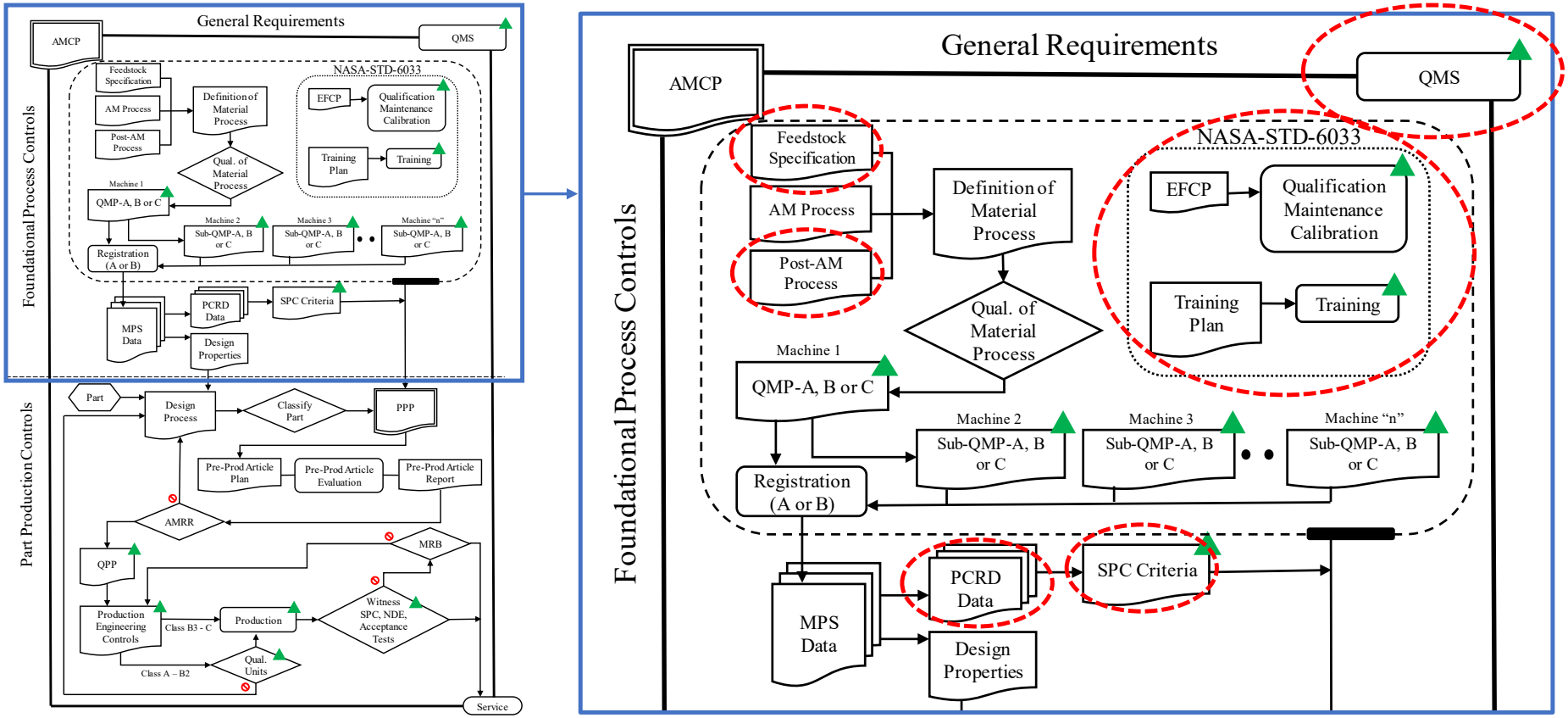
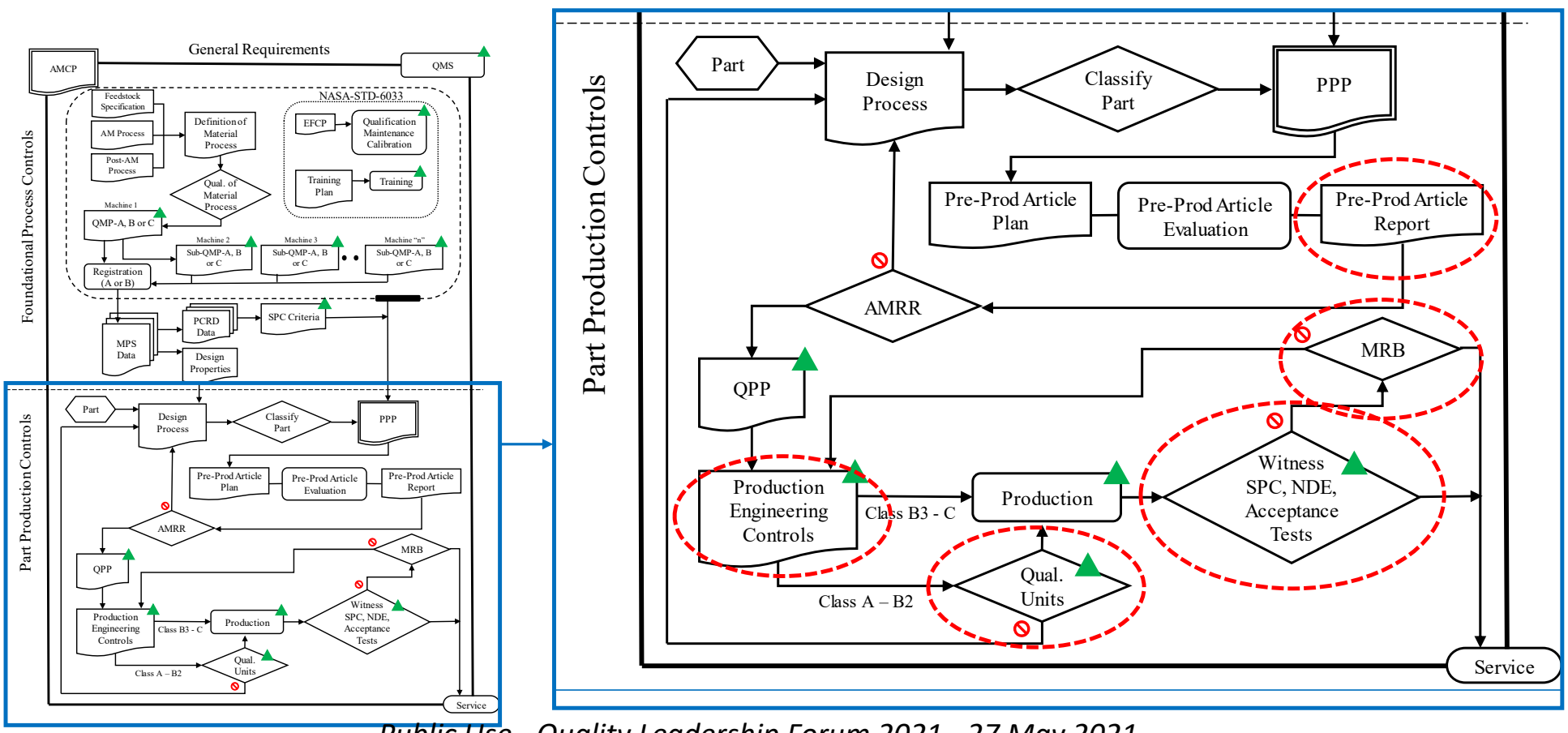


Foundational Process Controls



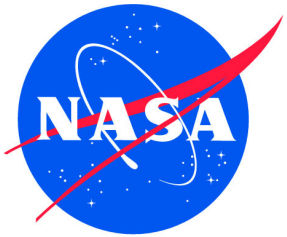
Part Production Controls



Cognizant Engineering Organization (CEO)

NASA-STD-6030, Section 3.2:

<u>Cognizant Engineering Organization</u>: The organization responsible for establishing/maintaining the certified design state of the AM hardware and delivering AM hardware compliant with all levied requirements. The CEO will typically be a supplier to NASA, a subcontractor, or NASA.



Quality Assurance's Role

You don't have to be a Materials Engineer…

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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
  - Note:
    - The specific pass/fail criteria are all manufacturer/CEO defined
    - The pass/fail criteria are related to, and controlled by, the MPS (the *other* breakout session)

- But there are other tests and evaluations that, while NOT defined in detail in 6030/6033, still require formal documentation and implementation
  - Statistical Process Controls (defined by MPS)
  - Pre-Production Articles (defined for NASA in the PPP)
  - Proof Tests (defined for NASA in the PPP)
  - Qualification Tests (defined for NASA in the PPP)
  - Part Acceptance (defined for NASA in the PPP)

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.

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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