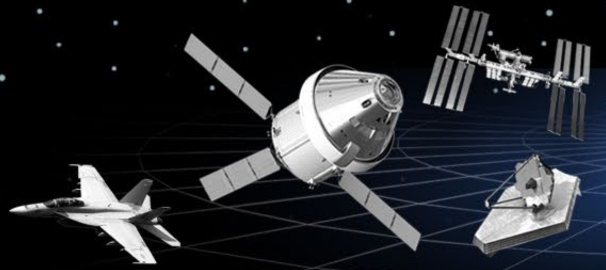

Additive Manufacturing Qualification for Spaceflight

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NASA Engineering & Safety Center

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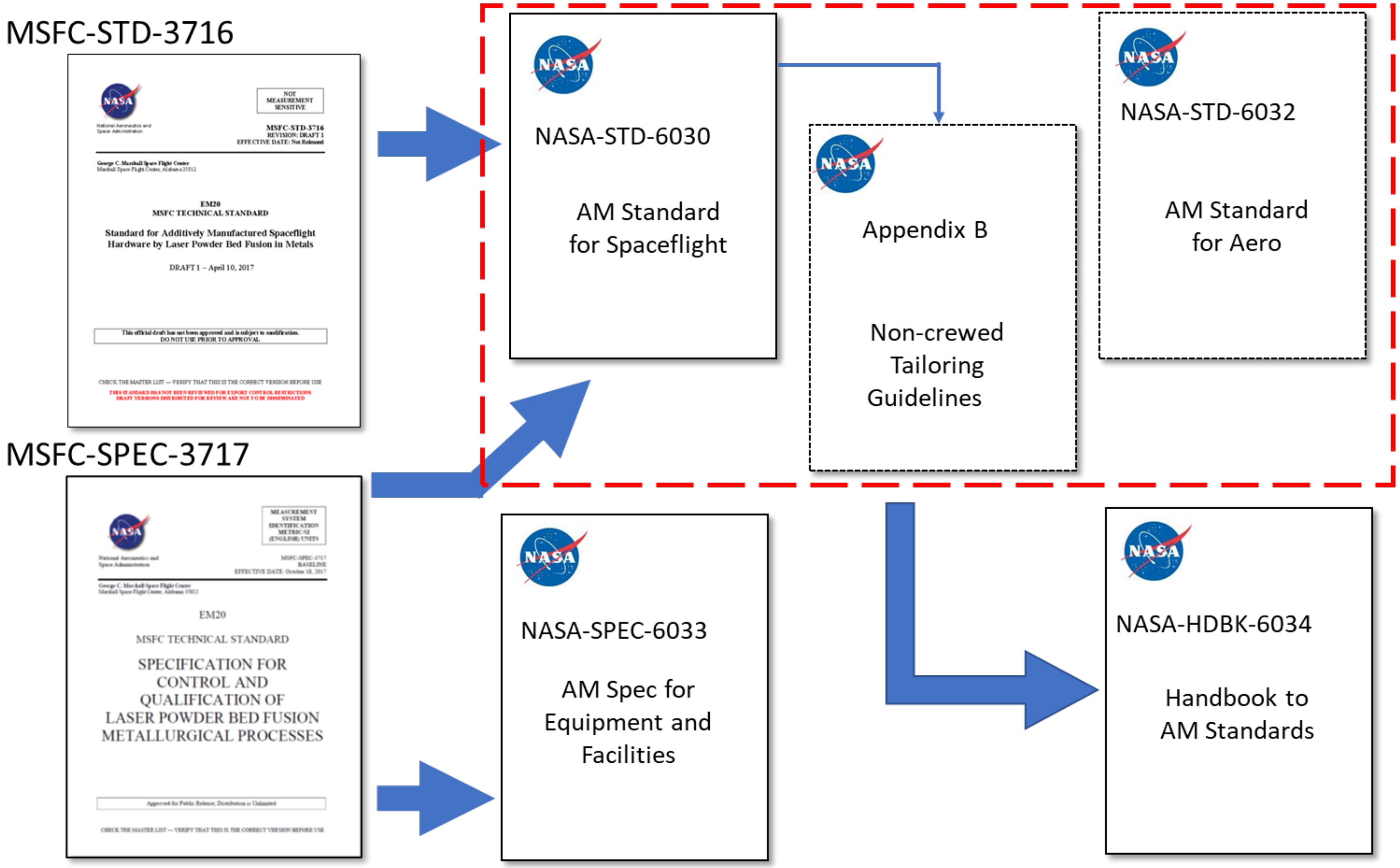
Agenda

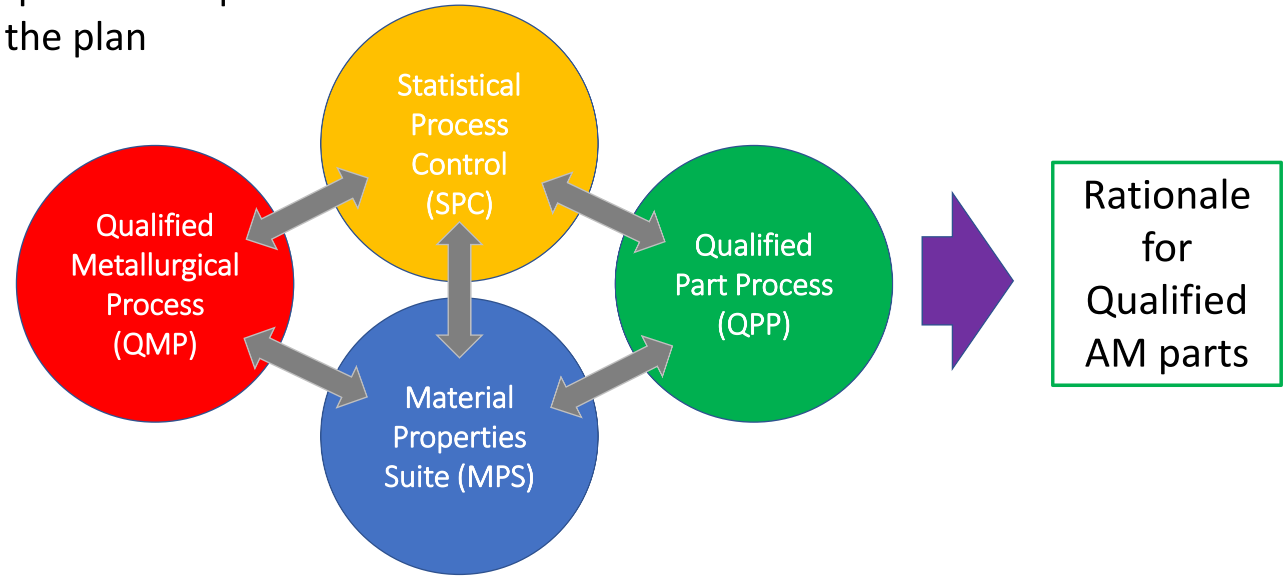
- NASA Additive Manufacturing (AM) Standards
  - Hierarchy
  - Application
- Examples of Implementation
  - Planetary Instrument for X-Ray Lithochemistry (PIXL)
  - Europa Clipper
- Application Specific Needs
- Conclusions

NASA Additive Manufacturing Standards

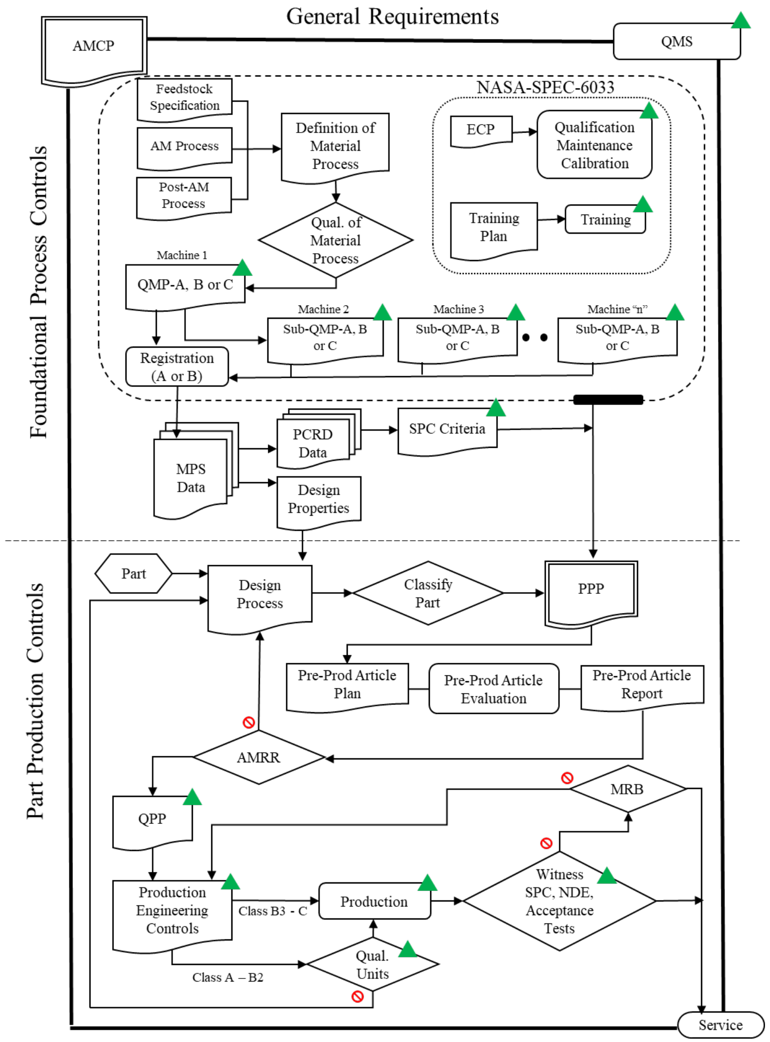


Guiding Principles

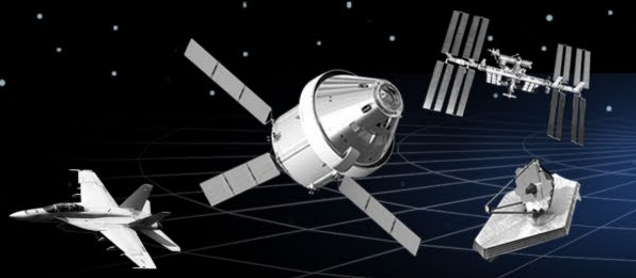
- Planning is key
- Integrate a Quality Management System (QMS)
- Build a foundation
  - Equipment and Facility
  - Training
  - Process and machine qualification
  - Material Properties / Statistical Process Control (SPC)
- Plan each Part
  - Design, classification, pre-production articles
  - Qualify and lock the part production process
- Produce to the plan – Stick to the plan



Summary of Methodology



Currently Applicable Technologies



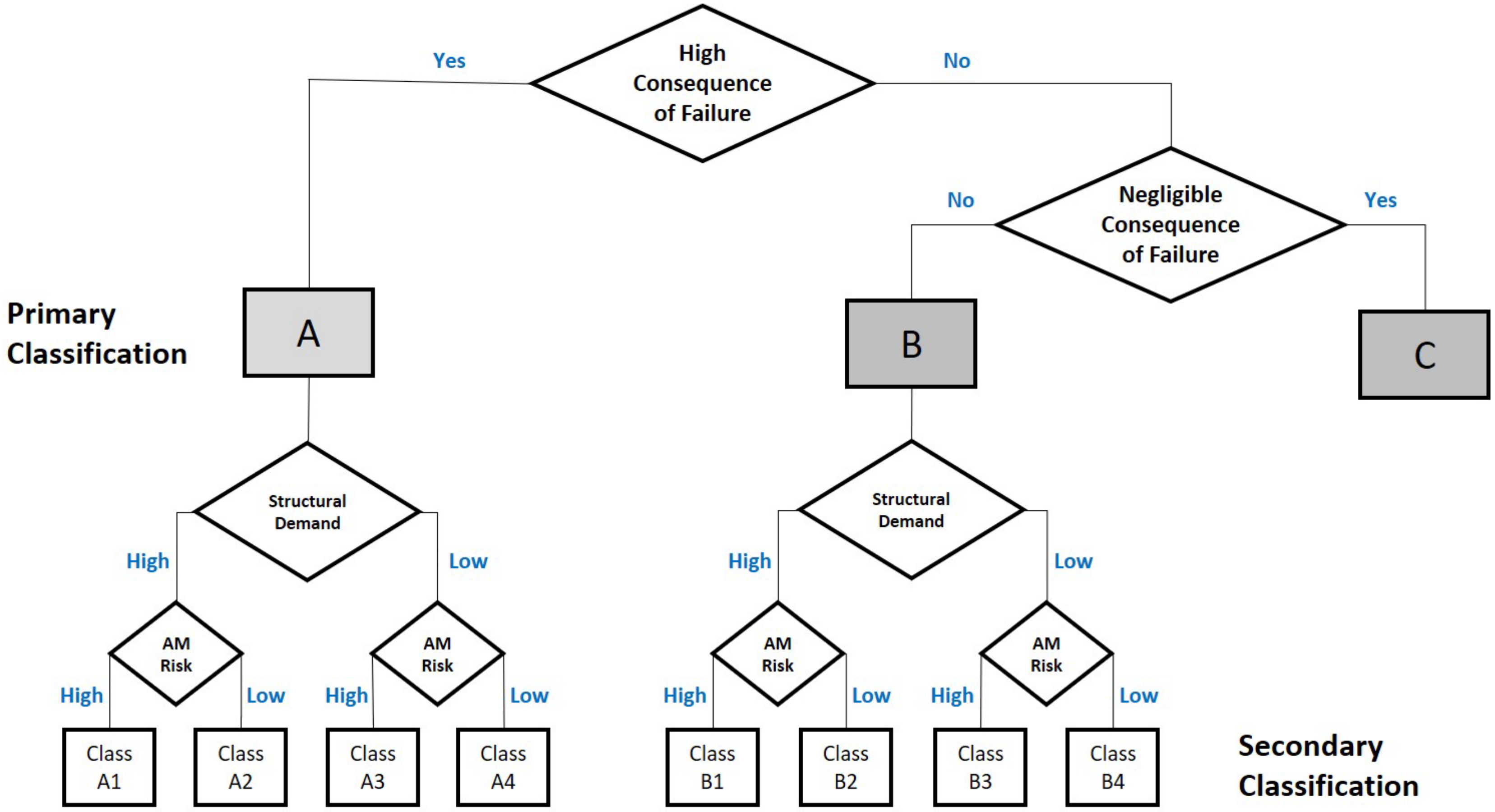
			Class		
Catogory	Technology	Materials type	A	B	C
Metals	L-PBF	Powder	X	X	X
	DED	Wire	X	X	X
	DED	Blown Powder	X	X	X
Polymers	SLS	Polymer Powder		X	X
	SLA	Photopolymer Resin			X
	FFF	Fused Filament Fabrication			X

<u>Adaptive technologies</u>—where process parameters change based on active feedback during the manufacturing process—are not allowed without a tailored, point-design methodology.

- e.g. Electron beam powder bed fusion (E-PBF)

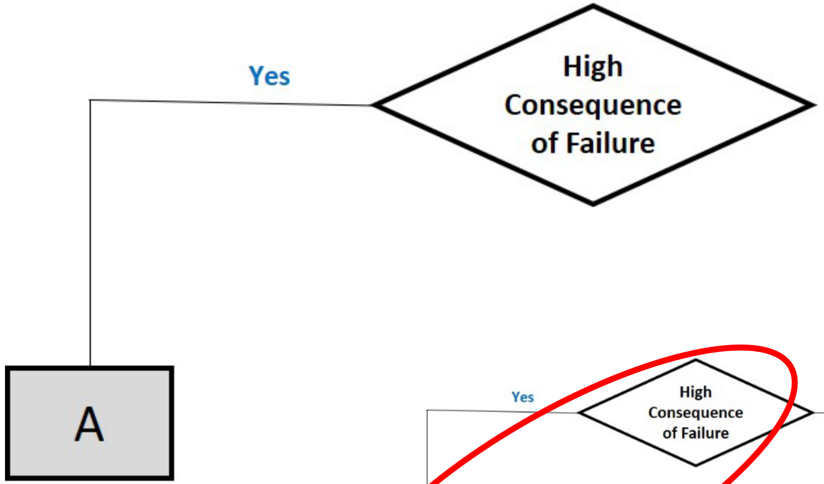
<u>Micro technologies</u>—where the output are small scale, non-structural components (i.e. MEMS, sensors) from alternate approaches, can be handled on a case-by-case basis.

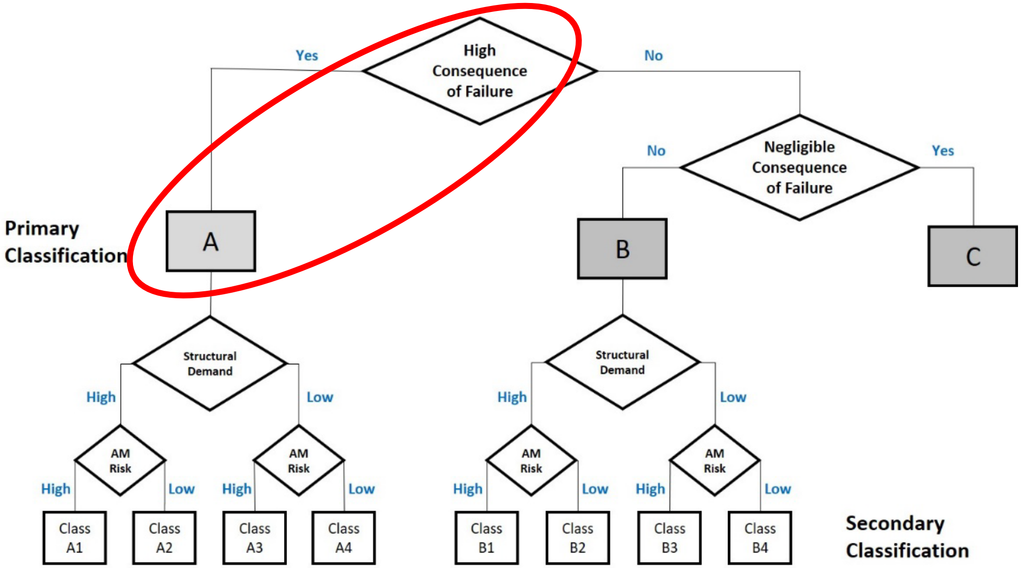
Currently Applicable Technologies



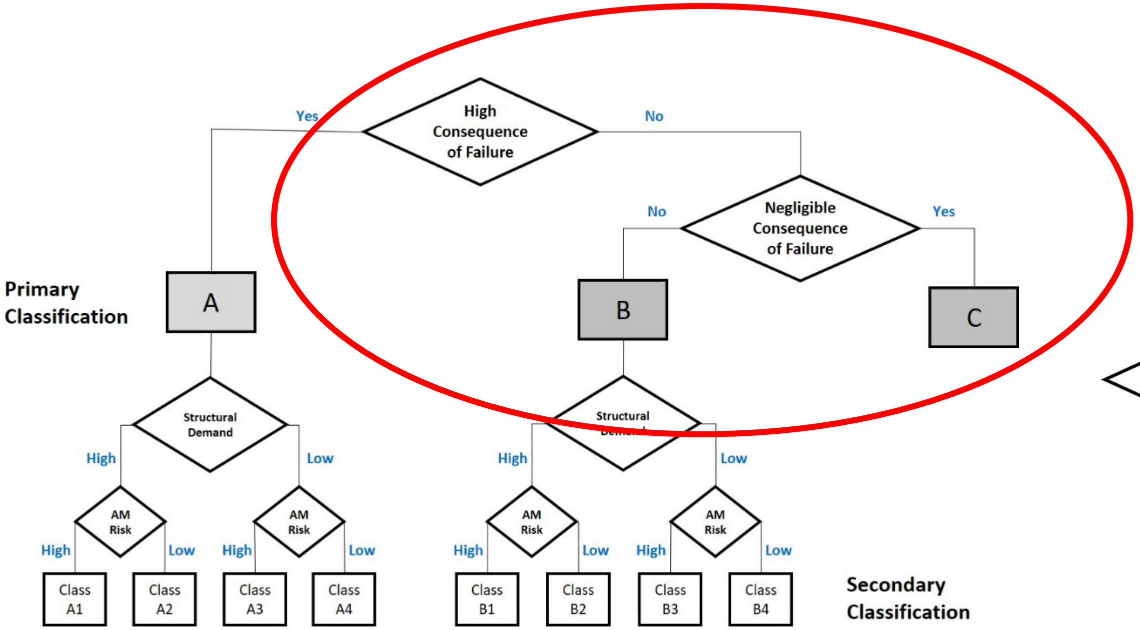
High Consequence of Failure

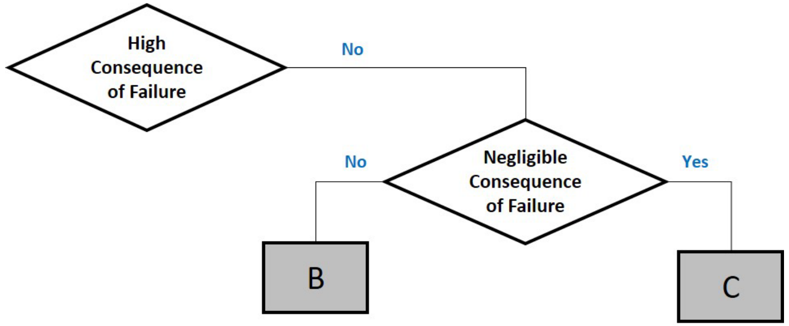
- A part **shall** be designated as Class A, High Consequence of Failure, if failure of the part leads to a catastrophic hazard or the part is defined as Mission Critical Hardware by the Program Office.
- Class A parts **shall** not:
  - Be made from polymeric materials
  - Be fasteners
  - Contain printed threads.





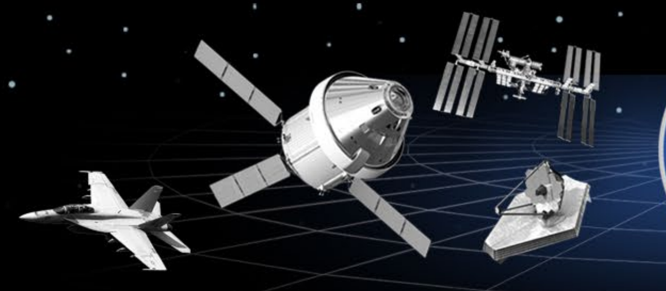
Negligible Consequence of Failure



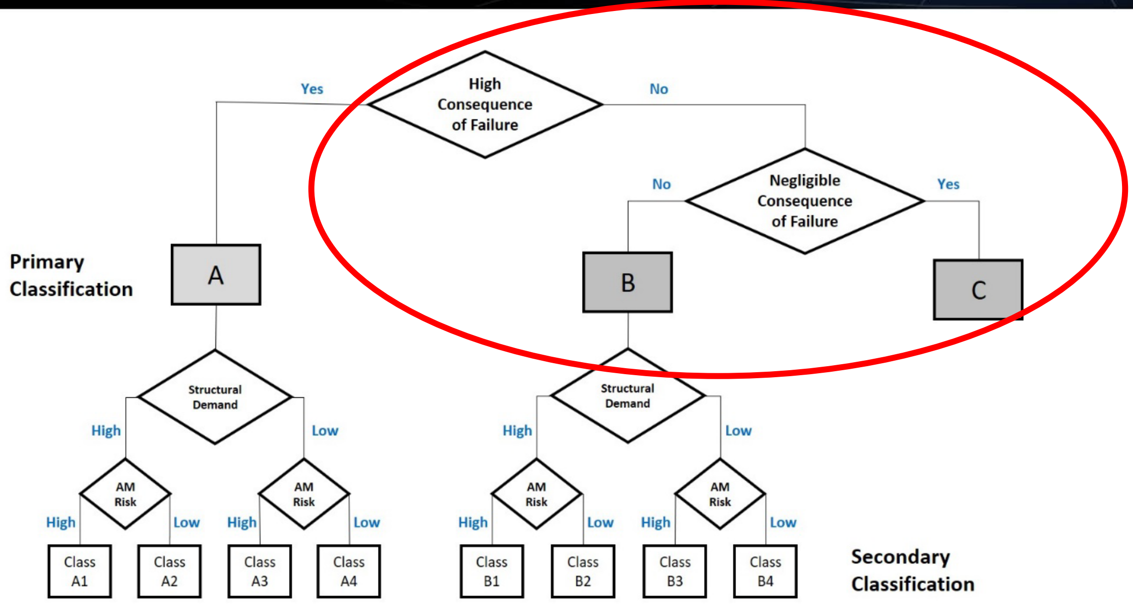


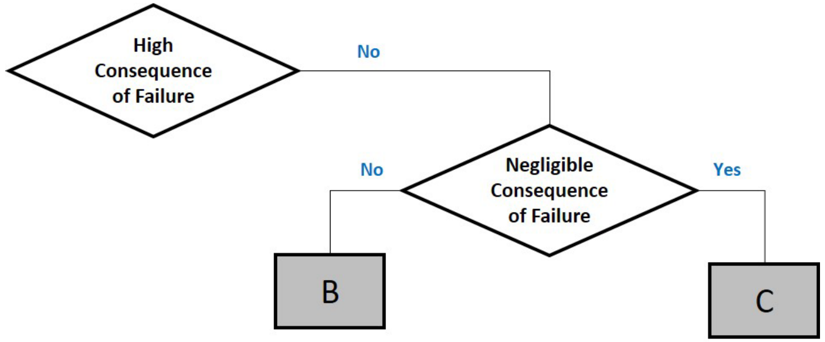
- Parts not designated Class A or Class C **shall** be designated as Class B.
- Class B parts **shall** not:
  - Be fasteners
  - Contain printed threads.

Negligible Consequence of Failure



- A part **shall** be designated as Class C, Negligible Consequence of Failure, provided that <u>ALL</u> of the following criteria (see the next slide) are satisfied:
  - Failure of part does not lead to any form of hazardous or unsafe 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.
  - Part is not designated “Non-Hazardous Leak Before Burst” per NASA-STD-5019.
  - Failure of part does not cause debris or contamination concerns per NASA-STD-6016.
  - Part meets requirements for off-gassing, flammability, and compatibility requirements as described in NASA-STD-6016.
  - 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.





Formal checklist in Appendix B for non-crewed missions.

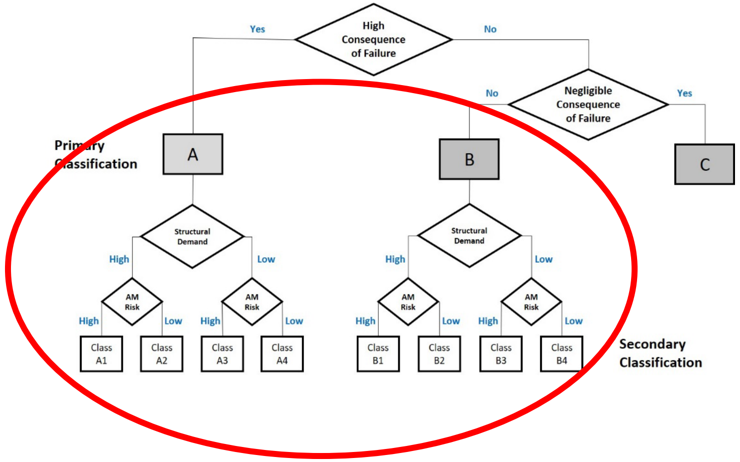
Checklist (Appendix B)

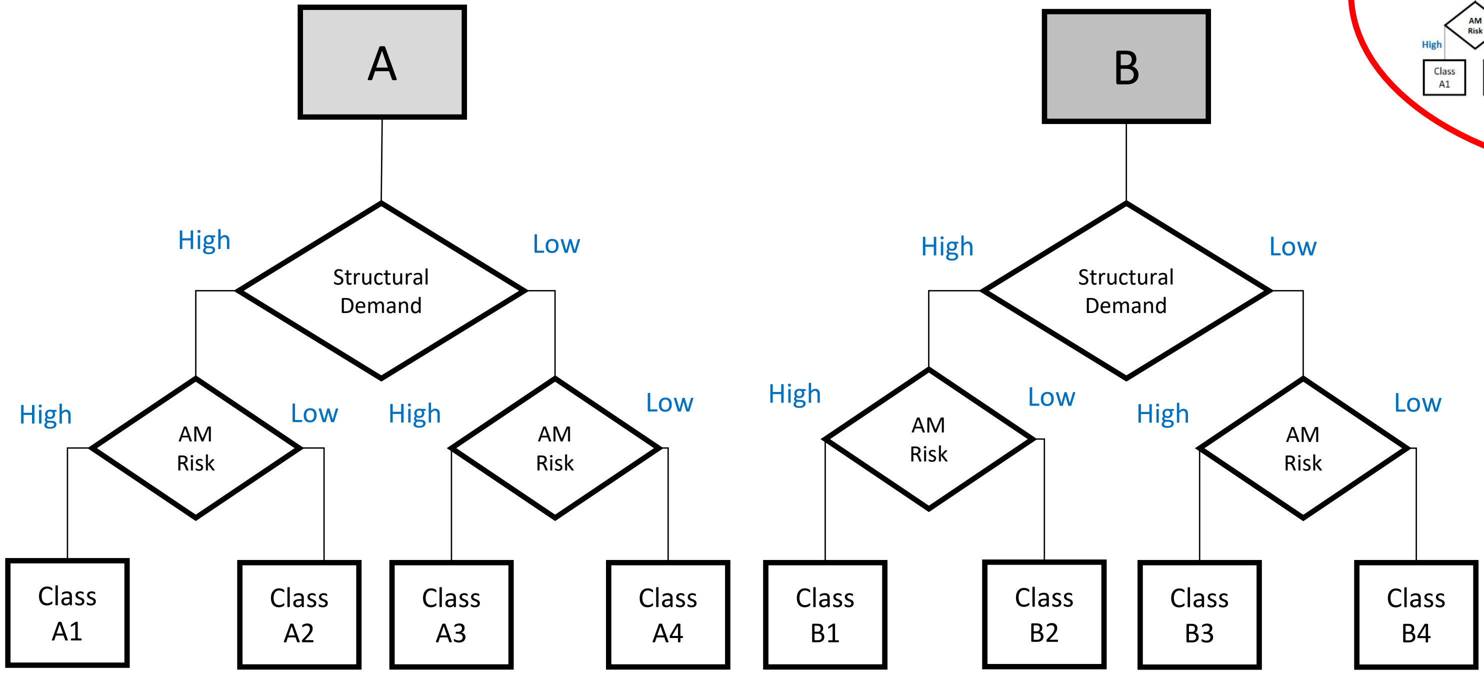
Table 22—Listing of Requirements that Can and Cannot be Tailored for Class C Part Characterization; Specifications that Can be Tailored are Denoted "Y"

Section 4.3.13 Requirements	Mission Class		
Subsection	**A/B**	**C**	**D**
Failure of part does not lead to any form of hazardous or unsafe condition	N	N	N
Failure of part does not adversely affect mission objectives	N	N	N
Failure of part does not adversely affect other systems or operations	N	N	N
Failure of part does not alter structural margins or related evaluations on other hardware	N	N	N
Failure of part causes only minor inconvenience operations	N	N	N
Failure of part does not cause debris or contamination concerns	N	N	Y
Failed part would not require repair or replacement	N	Y	Y
Part is not a protoflight article	N	N	Y
Load environments are defined	N	Y	Y
Part is not exposed to environment with potential for material degradation over the expected service life	N	Y	Y
Part is not primary structure	N	Y	Y
Part does not serve as redundant structure for fail-safe criteria per NASA-STD-5019	N	Y	Y
Part is not designated "Non-Hazardous Leak Before Burst" per NASA-STD-5019	N	Y	Y
Part does not serve as primary or secondary containment	N	Y	Y
Part is not subjected to impact loads	N	Y	Y
Part has no printed threads	N	Y	Y
Part is not a fastener nor does it serve the purpose of a fastener	N	Y	Y
If a structural analysis is required, margin of safety ultimate tensile strength (UTS) >6 on local maximum principal tensile stress	N	Y	Y

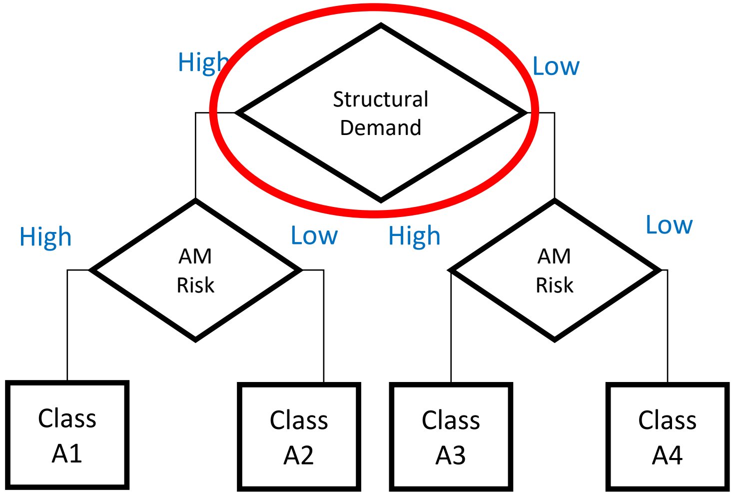
Secondary Classification

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





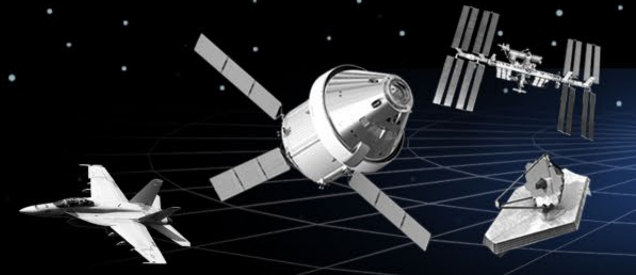
Structural Demands (Metals)



Material Property	Criteria for Low Structural Demand
Loads environment	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

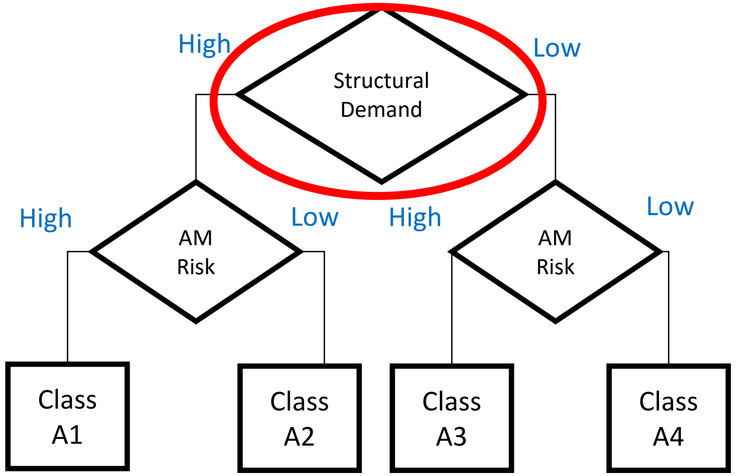
*Margin = $[\sigma_{design}/(\sigma_{operation} * \textit{safety factor})] - 1$

Structural Demands (Polymers)



Analysis Input/Material Property	Criteria for Low Structural Demand
All Materials	
Loads Environment	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

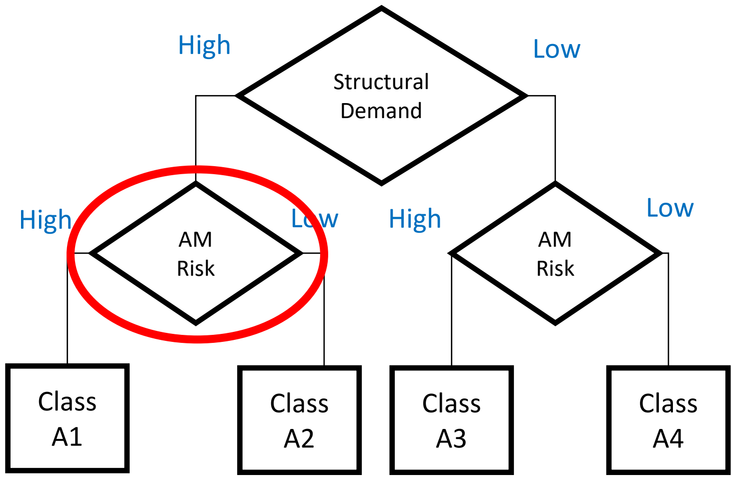
†Includes assembly stress (tight snap fit connections, shrink fits, fastener preloads) and operational stress
‡Yield strength defined by secant modulus to specified strain, by specified offset strain, or as otherwise defined by structural assessment requirements
#Ultimate strength assessed against local 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

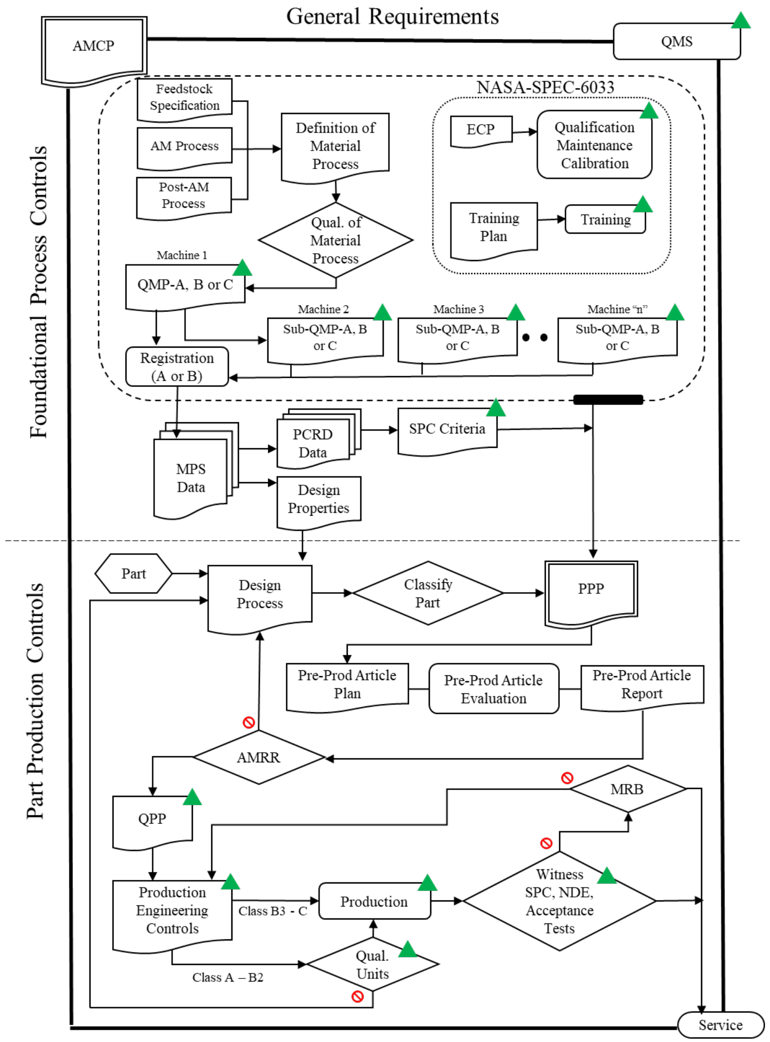
	Metallic		Polymer			
	L-PBF	DED	L-PBF	Score For		
Additive Manufacturing Risk				Yes	No	Score
All surfaces and volumes can be reliably inspected, or the design permits adequate proof testing based on stress state?	X	X	X	0	5	
As-built surface can be fully removed on all fatigue-critical surfaces?	X	X		0	3	
Surfaces interfacing with support structures are fully accessible and the as-built surface removed?	X	X	X	0	3	
Structural walls or protrusions are the equivalent of ≥ 8 trace, (e.g., melt pool, bead, scan path) widths in cross section?	X		X	0	2	
Structural walls or protrusions are the equivalent of ≥ 2 trace, (e.g., melt pool, bead, scan path) widths in cross section?		X		0	2	
Critical regions of the part do not require support structure?	X	X	X	0	2	

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



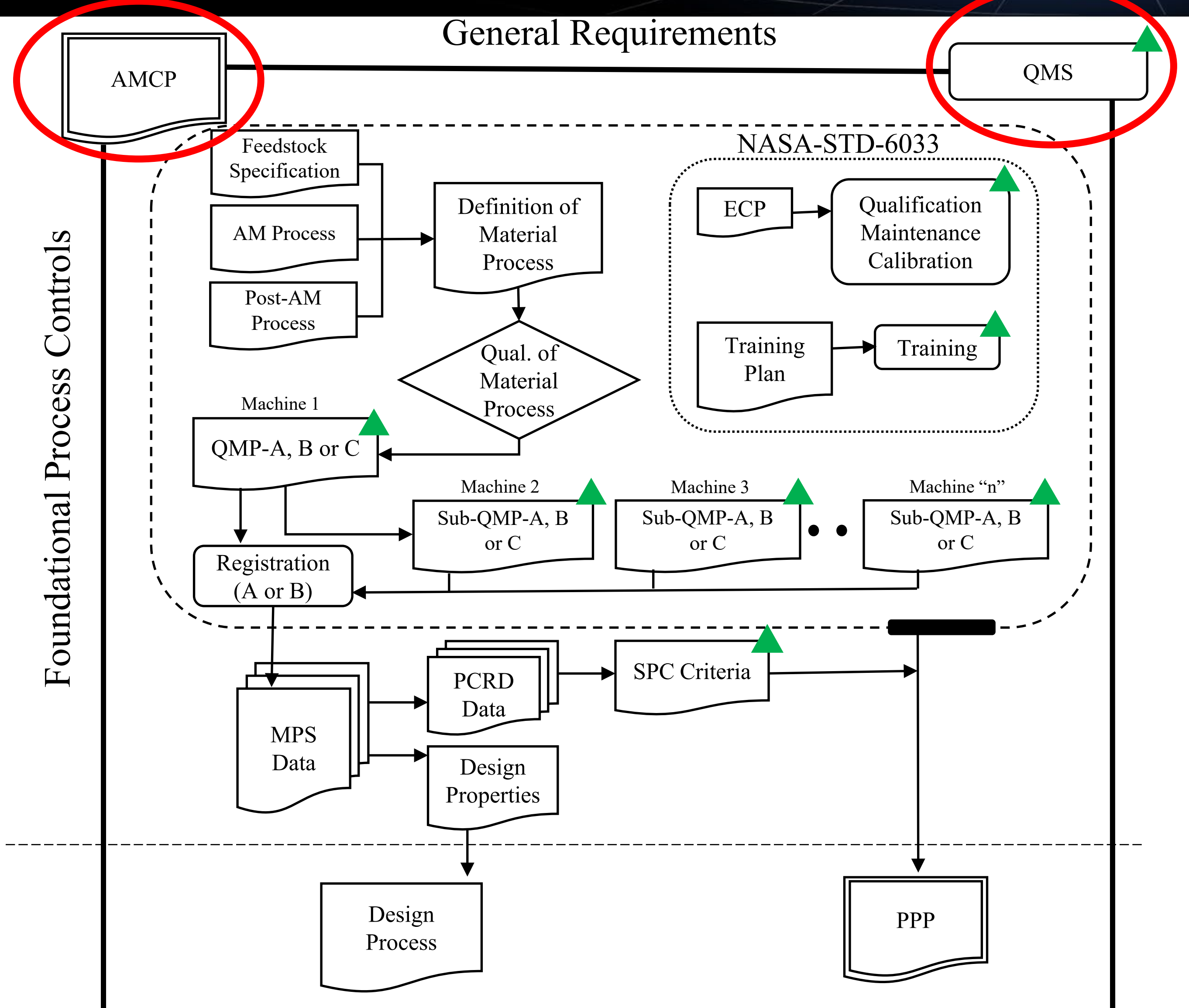
Additive Manufacturing Risk determination will be unique to each material and type of process

Summary of Methodology



General Requirements

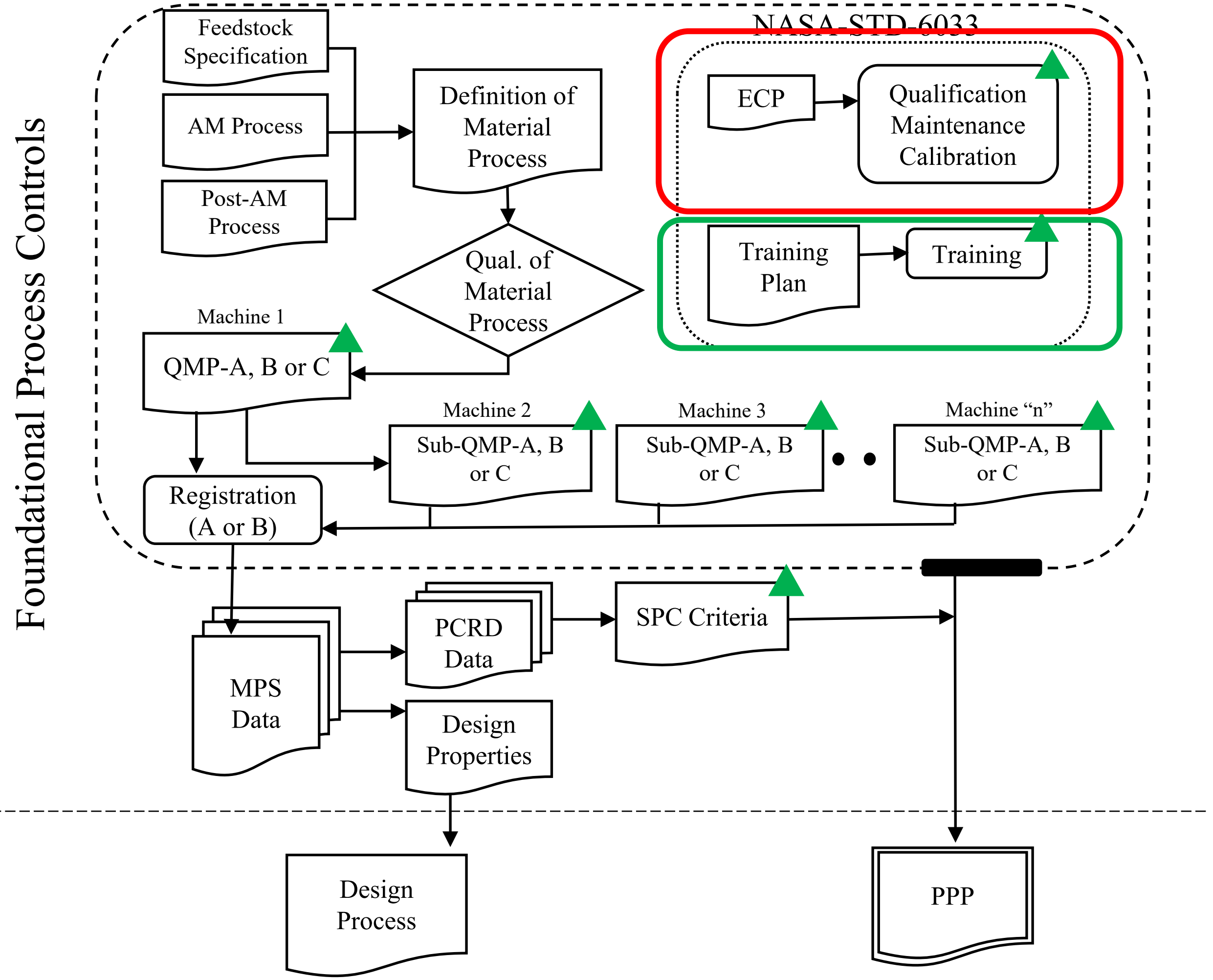
- Additive Manufacturing Control Plan (AMCP)
  - Critical to define implementation policies for program or project
  - Describes implementation of all requirements
    - Includes tailoring of requirements
  - Becomes governing document in place of standards
- Quality Management System (QMS)
  - Critical to maintain consistent implementation policy
  - Ensures you stick to your plan and tailoring
  - Ensures consistent training, processes and procedures
- Foundational Process Controls provide the basis for reliable part design and production



Equipment & Facility Control Plan and Training

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

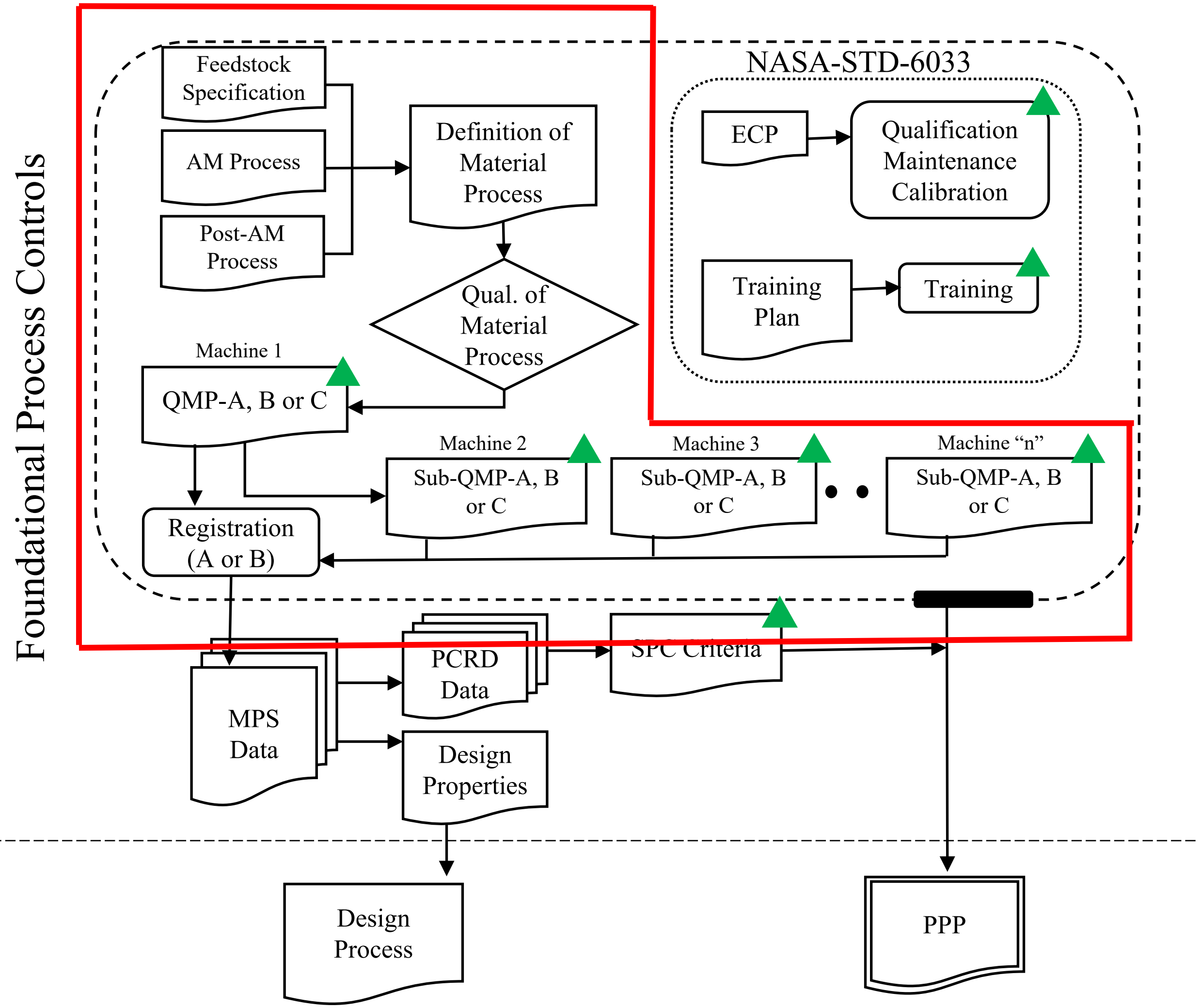
- **Training**
  - Training Plan required by Standard
    - Expectations in Specification
  - Flexibility in implementation
  - Covers all personnel involved in AM



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



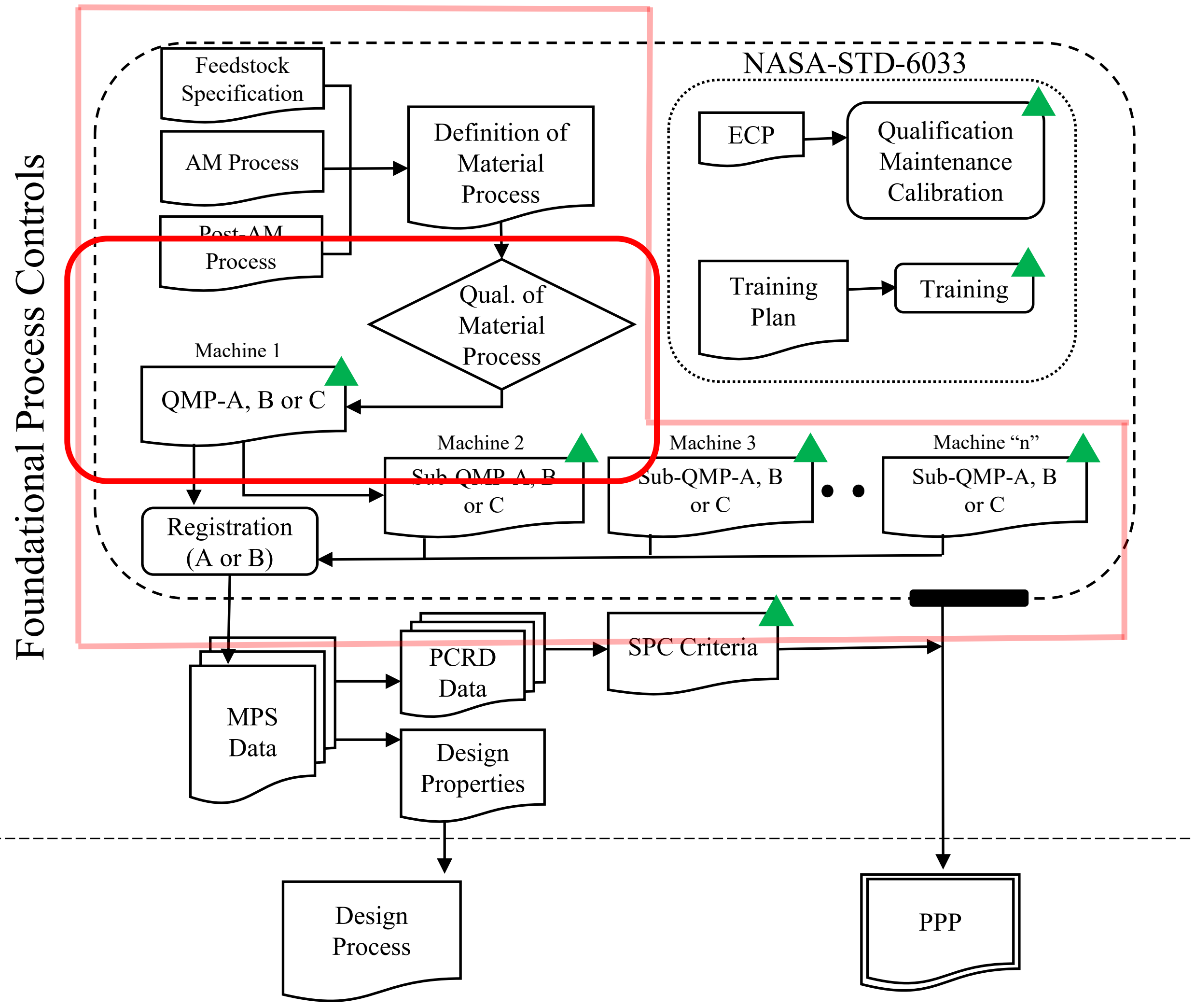
Qualified Materials Process

- Qualification of the Candidate Material Process
  - Establishes a QMP: Qualified Material Process
  - Requirements vary based on classification

Step 1: Material qualification

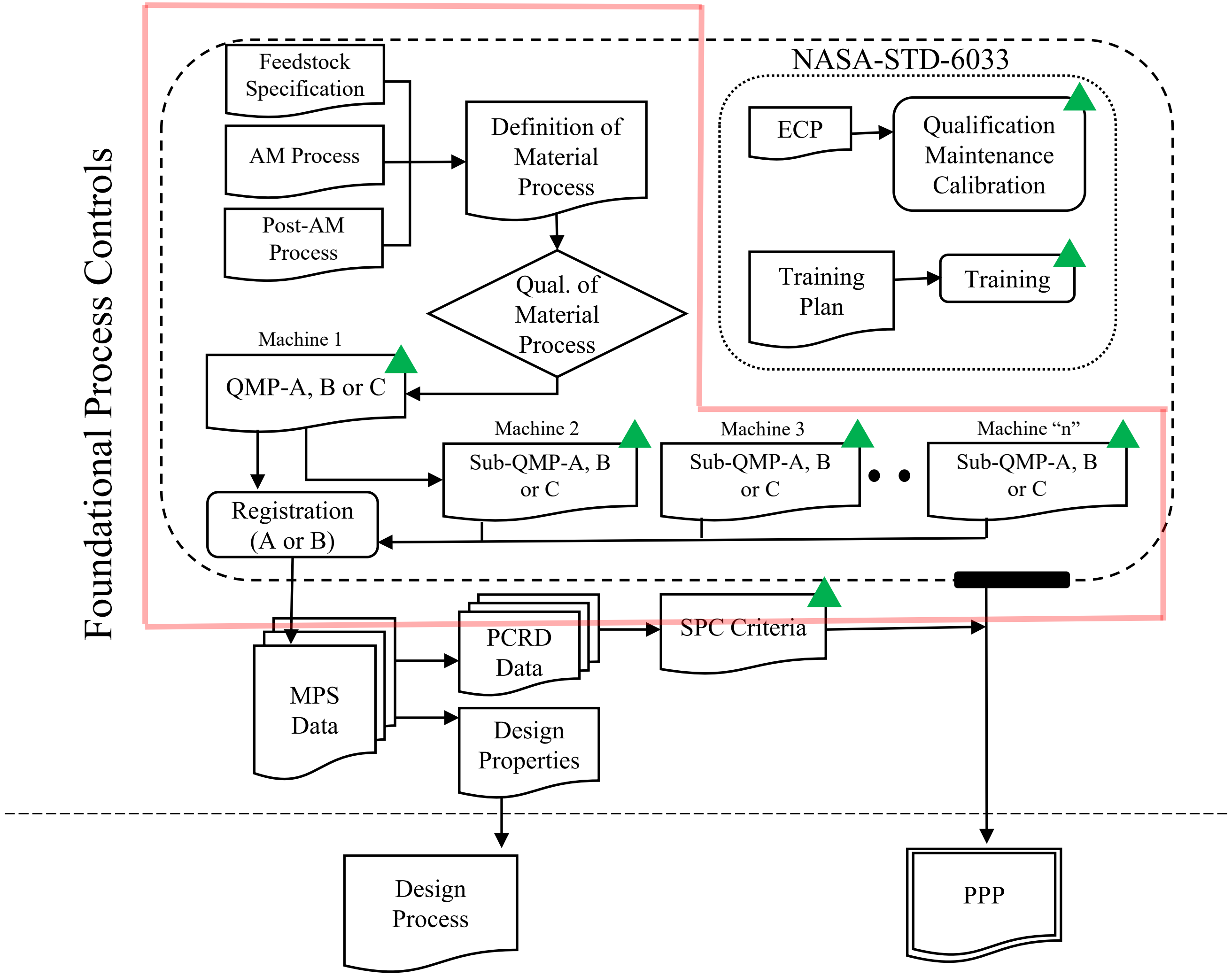
Step 2: Surface texture and detail resolution

Step 3: Mechanical properties



Subsequent QMPs

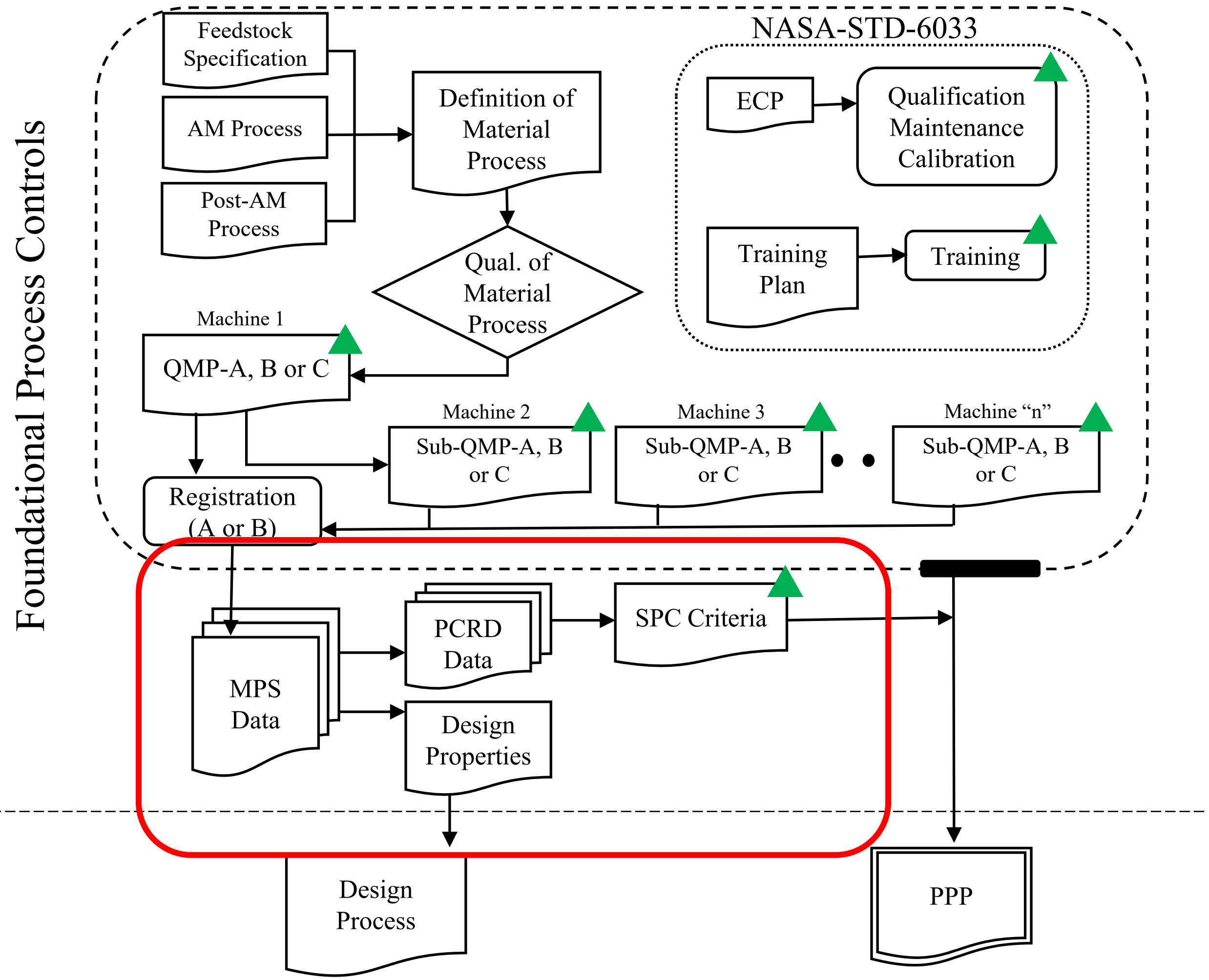
- A Subsequent QMP (Sub-QMP) shall be developed for any candidate AM material process that meets all of the following commonality criteria for an existing QMP:
  - Feedstock controls are identical.
  - AM build process definition is identical
  - Post AM process definition is identical
- Sub-QMPs have a reduced testing requirement compared to the QMP
  - Varies based on classification



Material Properties

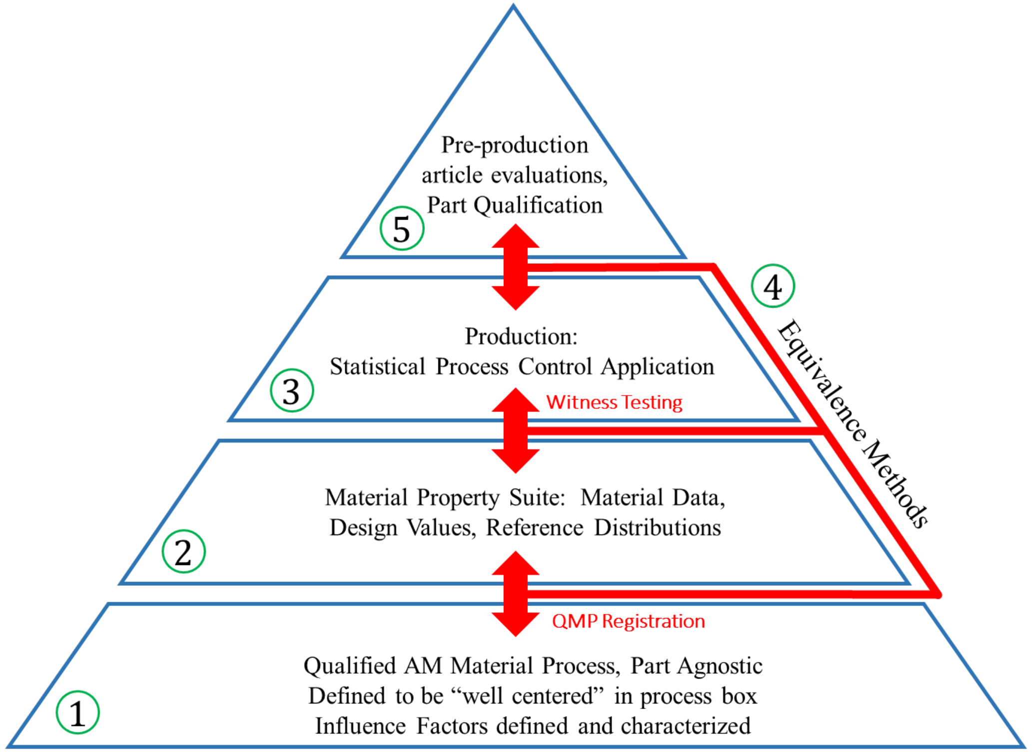
The Material Property Suite (MPS) consists of four inter-related entities:

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



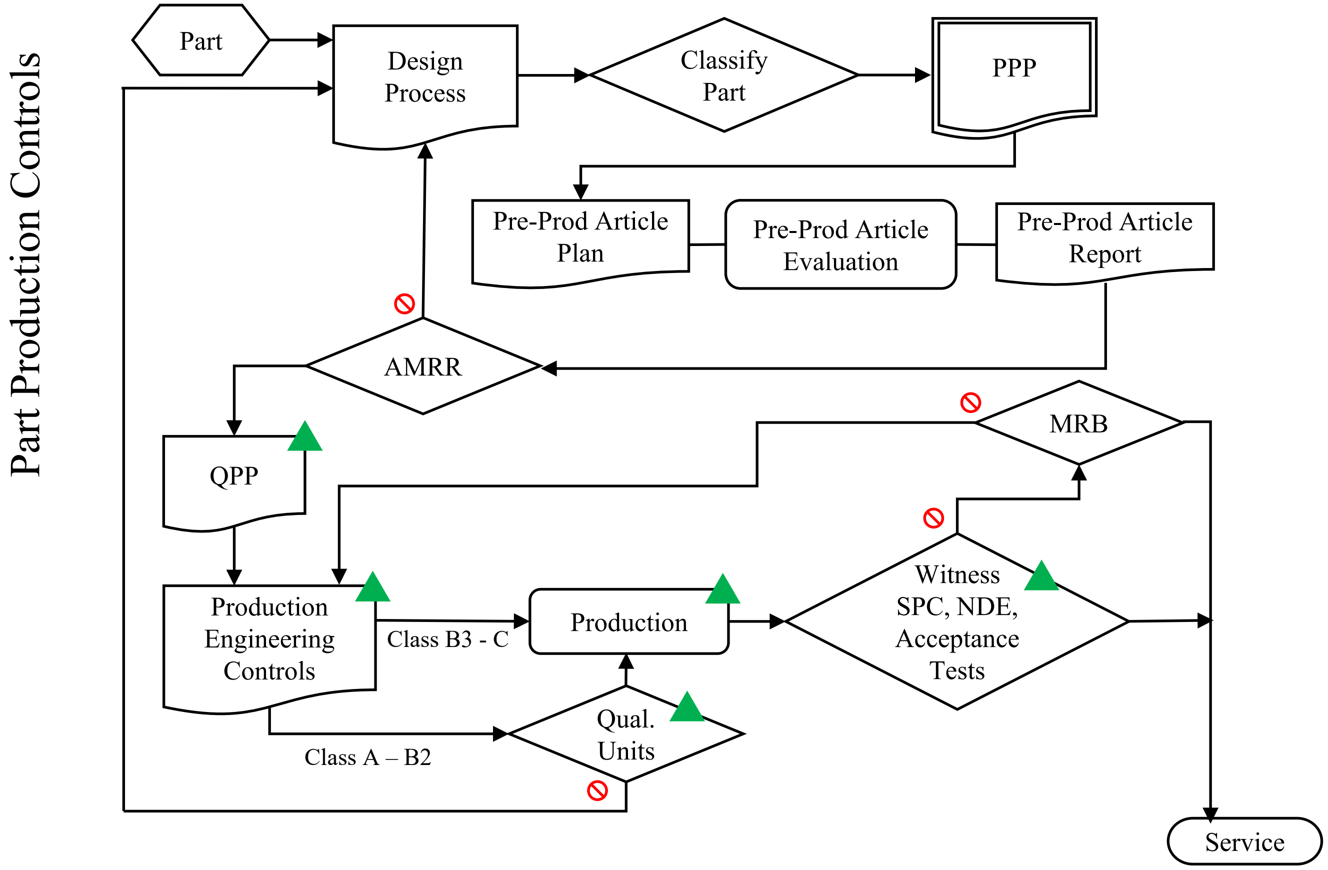
Materials Properties - SPC

- *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



Part Production Controls

- **Part Production Controls** are typical of aerospace operations and include design, part classification, pre-production and production controls

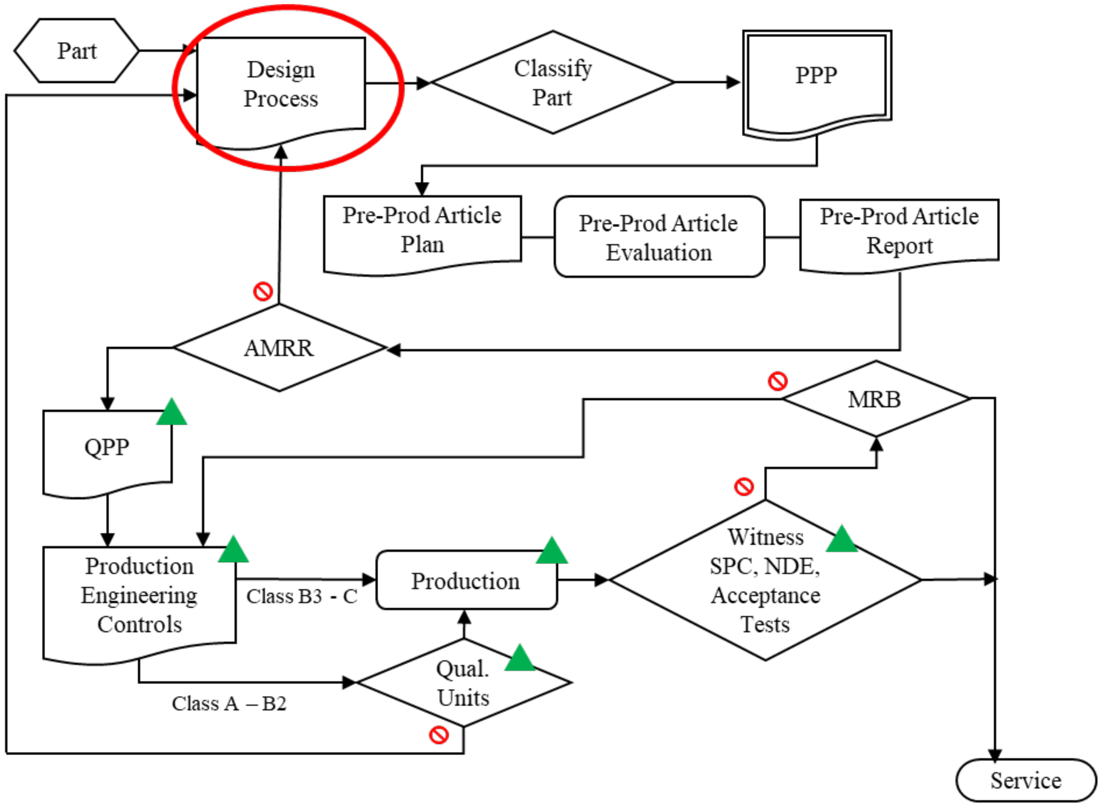


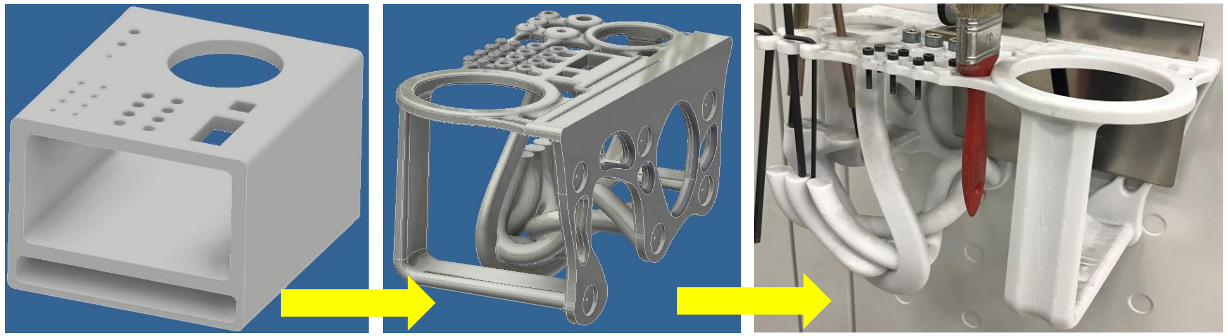
Design Process

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

Part Production Controls

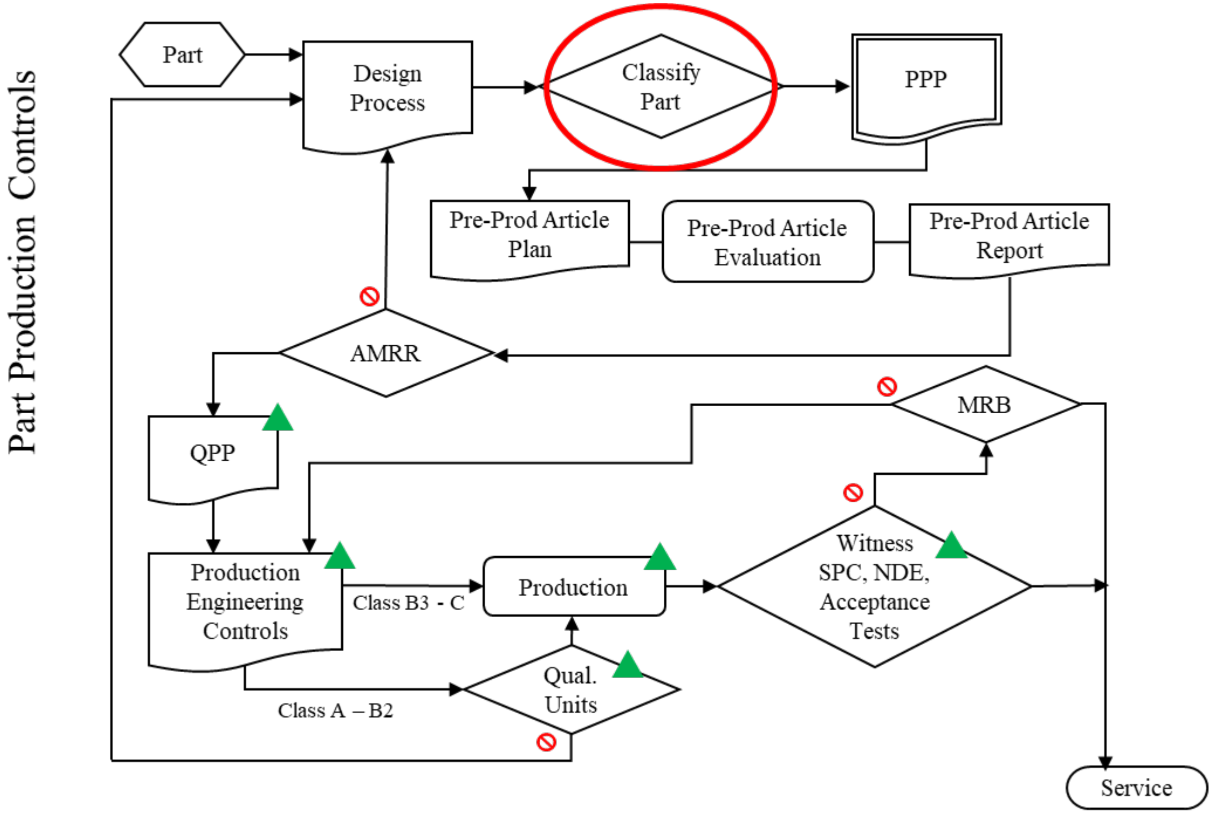




Topology Optimization FDM Tool Rack

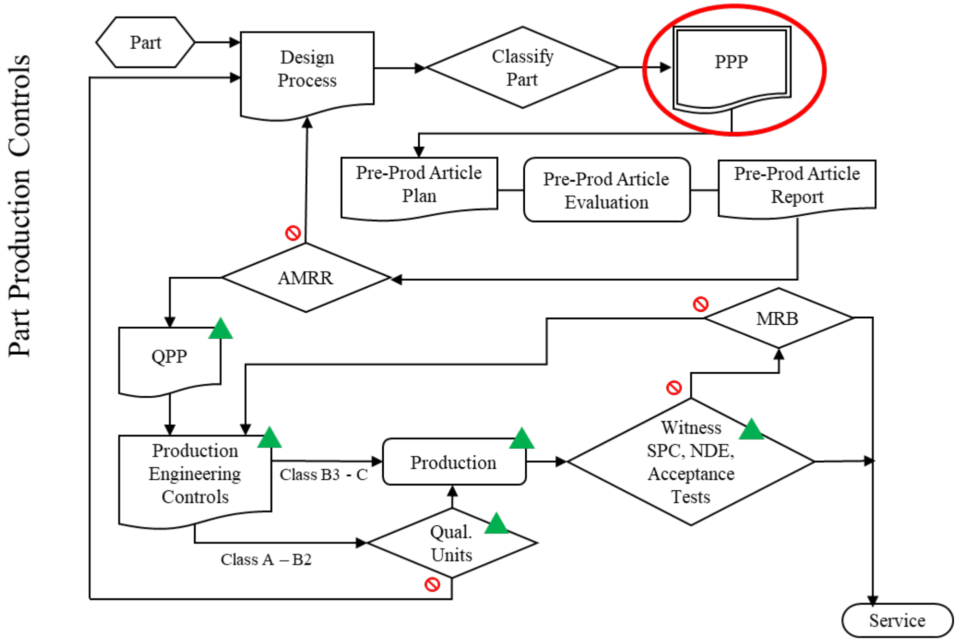
Part Classification

- 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



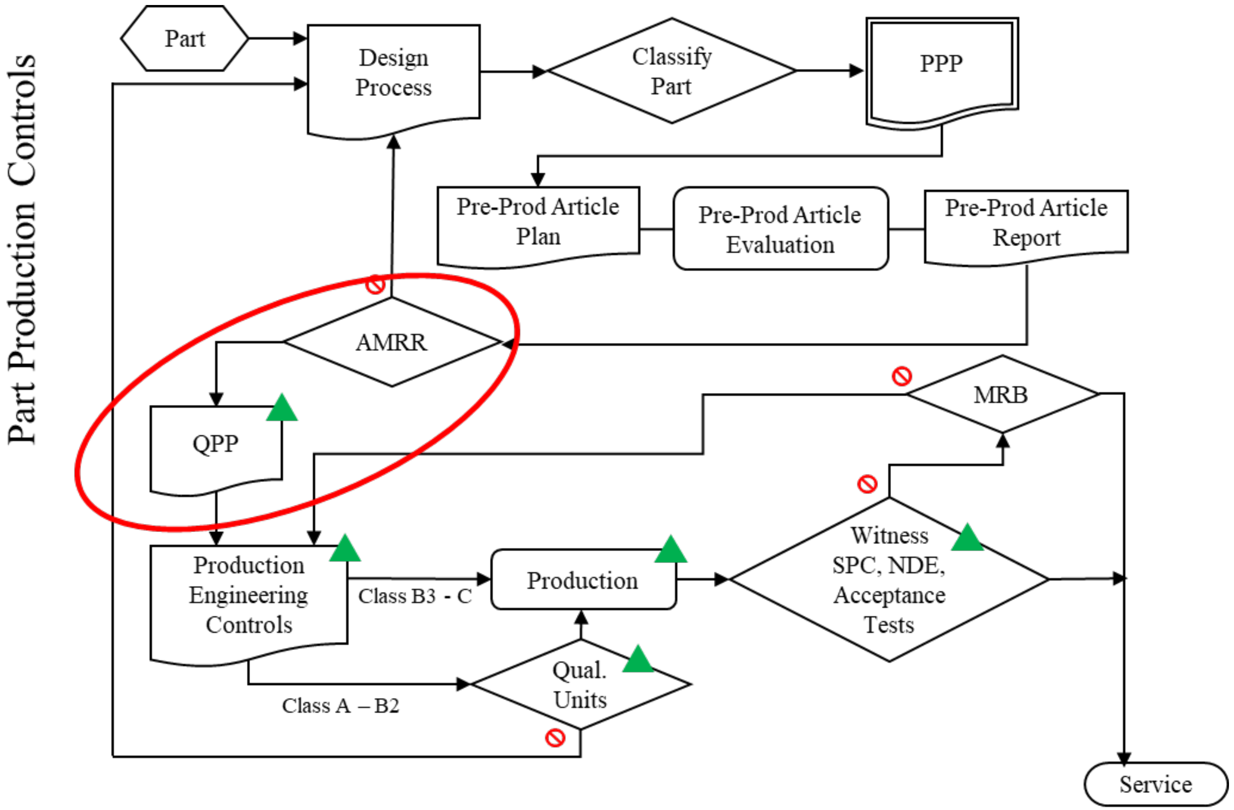
Part Production Plan

- 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
    - *<u>Inspection requirements and limitations</u>*
- Requiring a AM Part Production Plan as a drawing companion is best option currently

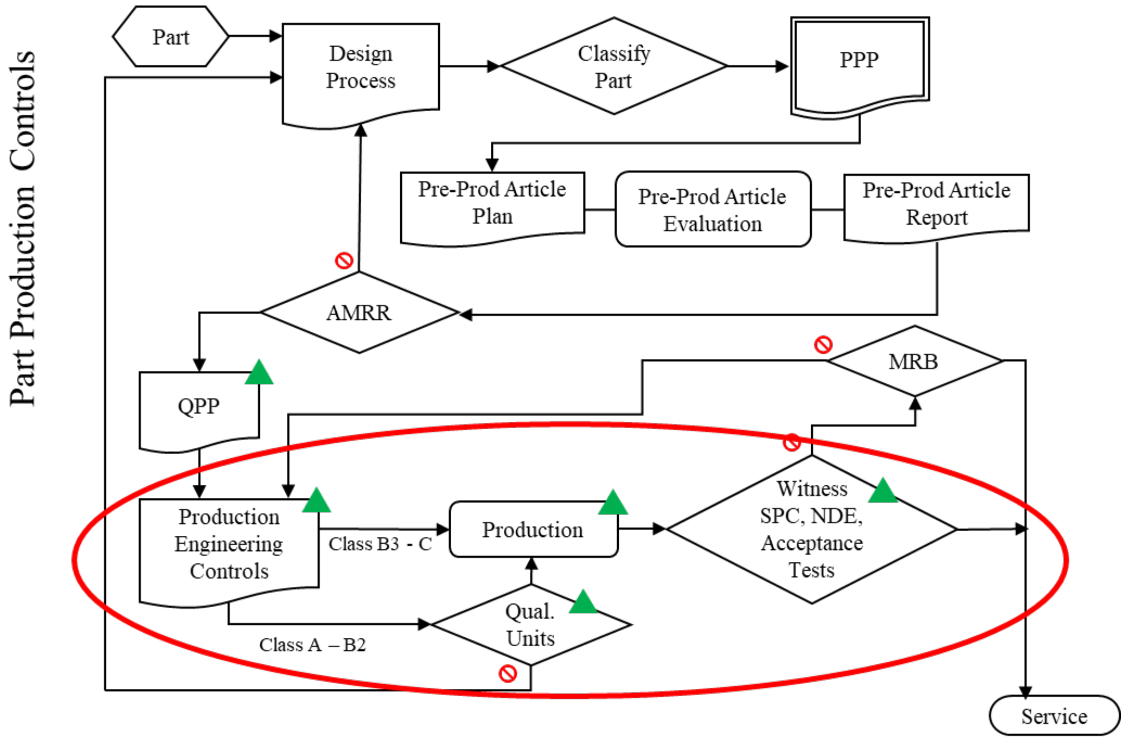


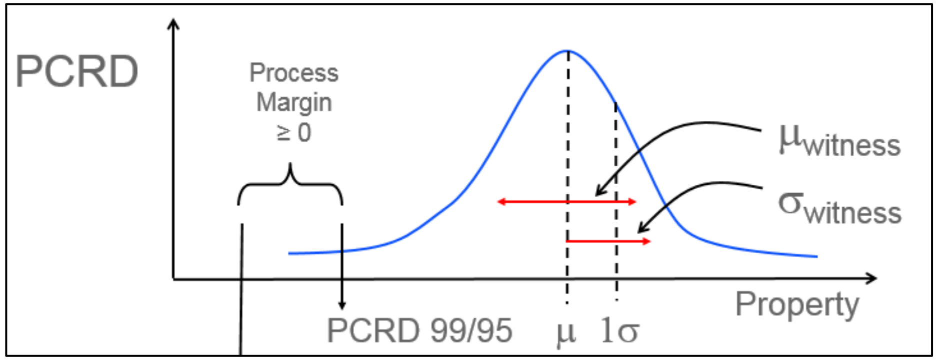
Qualified AM Part Process

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

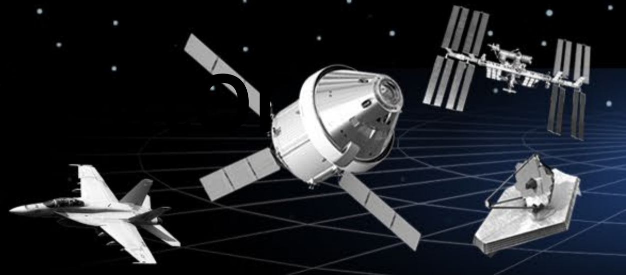


AM Part Production





Strategic Vectors



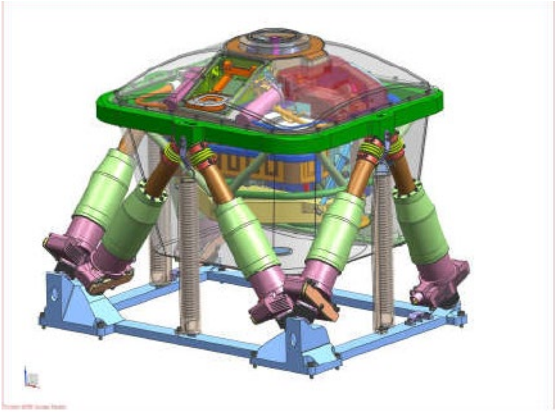
	Near Term	Far Term
NASA Leverage – Commercial or Other Government Agency	New Materials for Turbine/SCRAMjet engine applications (Commercial/Defense Advanced Research Projects Agency (DARPA)/Air Force) New structural materials for supersonic transports and hypersonic vehicles (Commercial/DARPA/Air Force) Advanced photovoltaic solar energy conversion cell materials. Development of high-strength aluminum alloys for additive manufacturing	Advanced battery system materials – beyond Li ion Advanced energy storage system materials for extreme environments Materials to enable highly efficient, lightweight electrical systems for electrified aircraft power and energy storage.
NASA Partner – Outsource and provide oversight on development	Modeling and analysis tool development (Academia) Additive processes for rocket engine components (Commercial) New aeroshell shapes, decelerators and control methods (joint Commercial development) Habitat Materials (joint Commercial development) Space Suit Materials (joint Commercial development) High throughput manufacturing methods and certification to support VTOL/UAM supply chain	High power density materials for surface operations. Multifunctional and gradient materials - Load/Energy/Thermal Combinations (Collaborative Development Academia/Commercial).

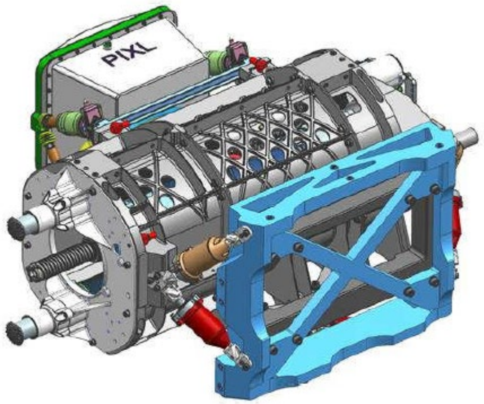
Engagement with STMD will be key

- Materials workforce contains both technologists and flight engineering expertise
- Continued development of materials within the Agency (e.g. GRX-810) will help retain those skills, and allows for a bench of technologists to help flight personnel review materials development from external partners
- Need to be able to spot flaws in development programs; the lessons learned from hands-on research experience is needed to spot some challenges
- Excellent way to cross-train technologists and flight engineering staff, enhancing cross-talk
- Initiated discussions with John Vickers (STMD) about looking for future STMD funds for multi-Center Materials research tasks

Planetary Instrument for X-Ray Lithochemistry (PIXL)

- Combination of structural and non-structural parts
- Mission class D instrument, located on a high-value region of a Class A spacecraft
  - Cost sensitive mission, so savings from AM would reduce development time and costs for a braze joint
  - Parts are 100% inspectable with non-destructive evaluation
- Hardware developed prior to NASA-STD-6030 release
  - Used similar methodologies (i.e. process control)
  - Required 100% proof testing of all flight components

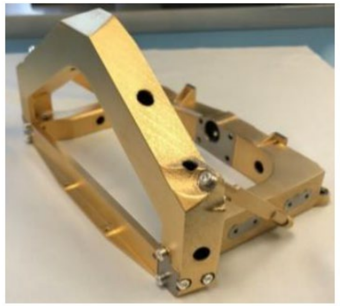




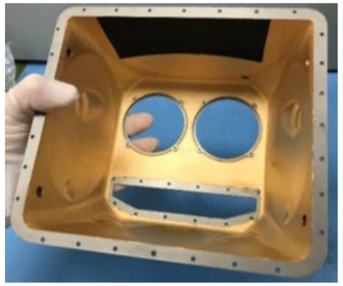
CAD images courtesy NASA/JPL-Caltech

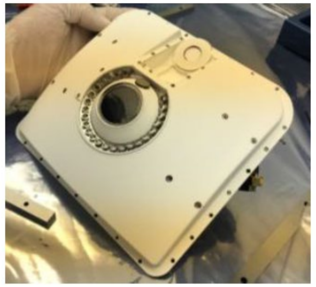
PIXL (cont.)

- Structural Ti-6Al-4V (top row) components
  - Leveraged America Makes B-Basis allowables for EB-PBF
  - Locked machine parameters and powder suppliers to America Makes-qualified suppliers
  - Mounting frame took serious effort for powder removal, given thin walls and hollow box-beam construction
- Non-structural AlSi10Mg (middle row)
  - No commercial database existed
    - Levied significant JPL investment into process control via post-build heat treatment to attain repeatable properties
    - Worked with a trusted vendor
  - Risks to mission were minimal, limited requirements levied on parts (dust shields)
- Reasons for success
  - Process control was implemented
  - Development plans were clearly communicated
  - JPL-led investments provided hard data to engineering review community
    - NDE inspectability and proof testing requirements helped with the narrative
  - Design was mass-constrained; AM provided cost, schedule, and mass relief (i.e. internal driving force)


X-ray bench and support


Mounting frame


Back cover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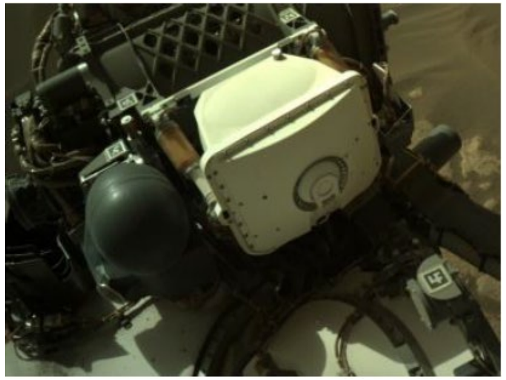
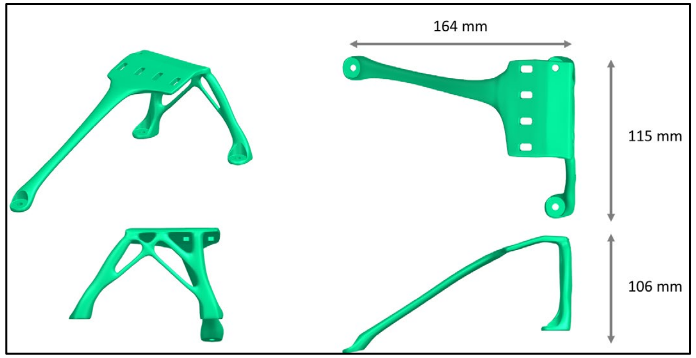
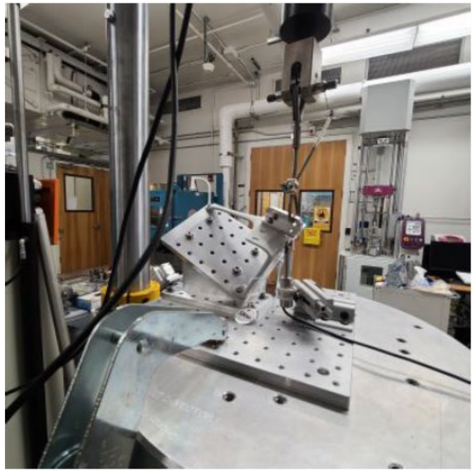


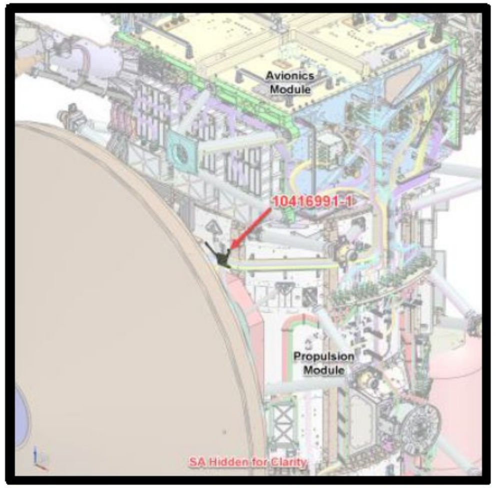
Images courtesy NASA/JPL-Caltech

Europa Clipper

- Europa Clipper mission required a cabling/harnessing bracket
  - Geometry benefited from topological optimization (TO) to reduce mass and provided a useful, low risk case study
  - Part could suffer plastic deformation or cracking without causing a de-mate situation
- JPL's approach was internal printing
  - Qualified Al 6061 RAM2 on a laser powder bed fusion system
  - Met all NASA-STD-6030 requirements
  - Was a successful, low-risk case study to work out process challenges, primarily focused on secondary surface finishing due to the complex geometry





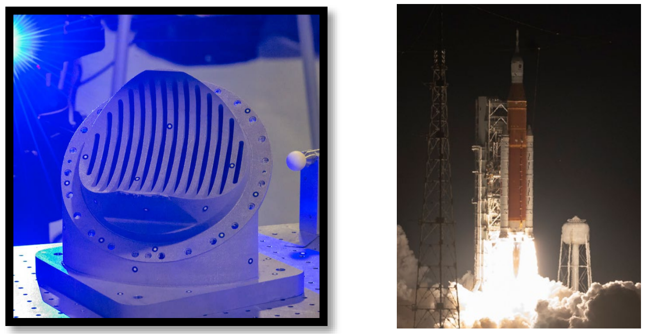


Images courtesy NASA/JPL-Caltech

Conclusions

- NASA-STD-6030 and -6033 are the approach that NASA is using for qualification of additive manufacturing for spaceflight hardware
  - Focus is on process control and risk quantification
  - Can be applied to high-value, high-risk hardware when used appropriately
- The key to successful implementation is detailed process knowledge, including the complete lifecycle of the part
  - Will dictate quality control testing specific to your needs
  - For INL, radiation-induced damage or alteration of behaviors
- NASA's approach is the first "how to qualify additive manufacturing" document
  - Being utilized by the Department of Defense, and other Agencies, as an effective entry point for their needs

GrCop42 thrust chamber assembly



Pogo Z Baffle, flown on Artemis I on the RS-25 engines
Reduced weld count from 127 to 4

Images courtesy NASA

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