

NASA's Plans for Development of Standards for Additive Manufactured Components

Andrew Glendening (speaker)

Materials and Processes Assurance (GSFC)

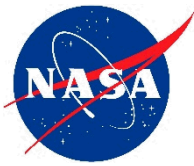
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NASA Technical Fellow for Materials (KSC/LaRC)

Collaboration on Quality in the Space and Defense Industries

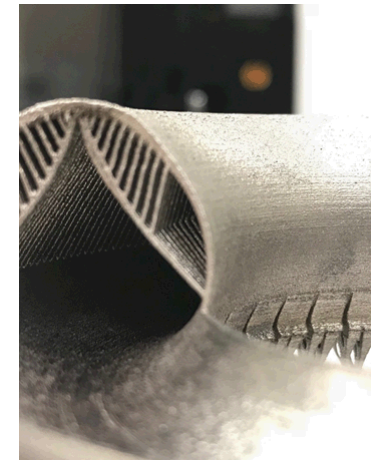
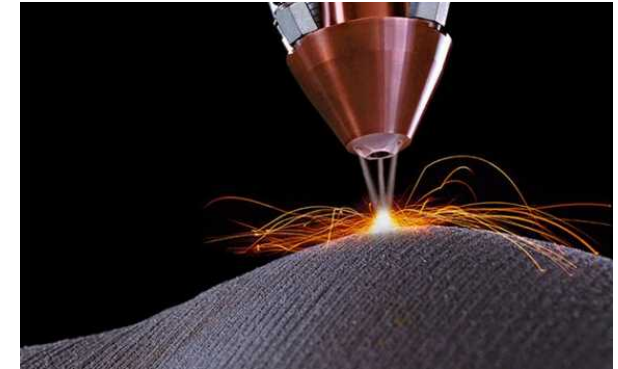
Cap Canaveral, FL

March 9, 2020



NASA's use of Additive Manufacturing

- Additive Manufacturing (AM) is rapidly becoming more attractive
 - Design innovation
 - Cost reduction
 - Time Savings
- There is a critical need to increase NASA's knowledge and understanding of the materials, processes, analysis, inspection, verification and validation methods for AM Parts
 - Standardization
 - Development of qualification and certification methodologies
 - Property validation
 - Specification development
 - Computational materials
 - NDE
 - Process monitoring – (in-situ NDE)

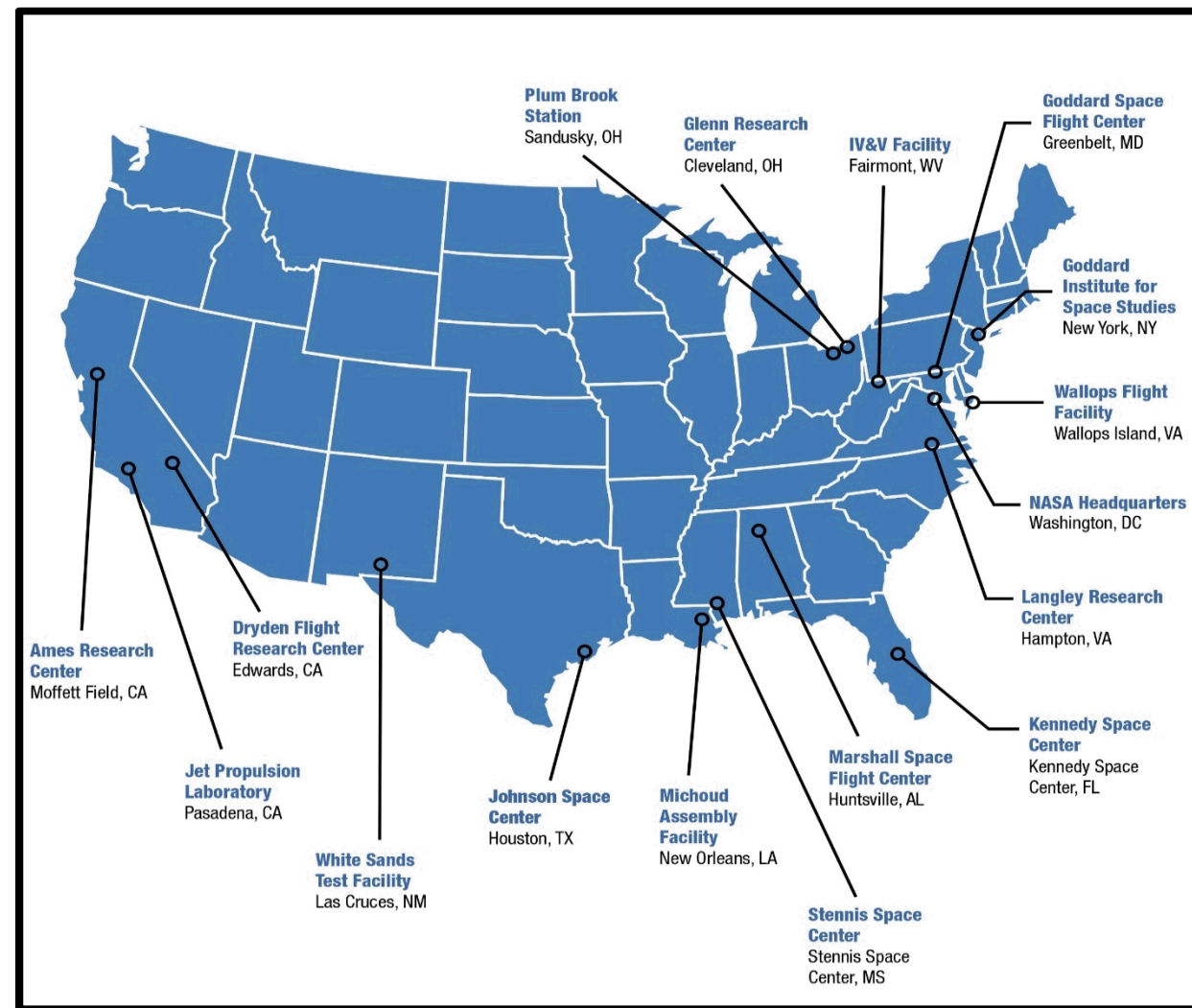


Toroidal Tank Development part



Additive Manufacturing at NASA

- **MSFC** – Metal Powder/Certification
- **LaRC** – Metal Wire/NDE/Computational Materials Modeling & Characterization
- **GRC** – Alloy development/Ceramic Materials/Powder Characterization/Electric Motors
- **JPL** – Aluminum Powder/Gradient Materials
- **Ames** – Non-metallic materials/Simulations
- **KSC/JSC/GSFC** – Product certification
- **WSTF** – Flammability testing

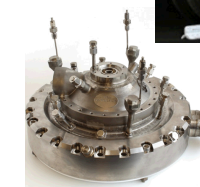




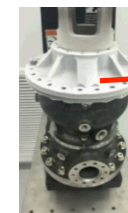
Marshall Space Flight Center (MSFC)

- 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 3 years, and soon to have directed energy deposition
- Has committed significant engineering manpower resources
- NASA AM Objectives
 - Decrease production lead time & costs
 - Develop Flight Certification Standards
 - Process development and characterization
 - Share of knowledge and data in pursue of smart vendor base for AM mfg.
 - Design optimized components & test at relevant conditions
 - Appropriate Application
 - High complexity & difficult to manufacture
 - Low production rate
 - Long lead time & high cost

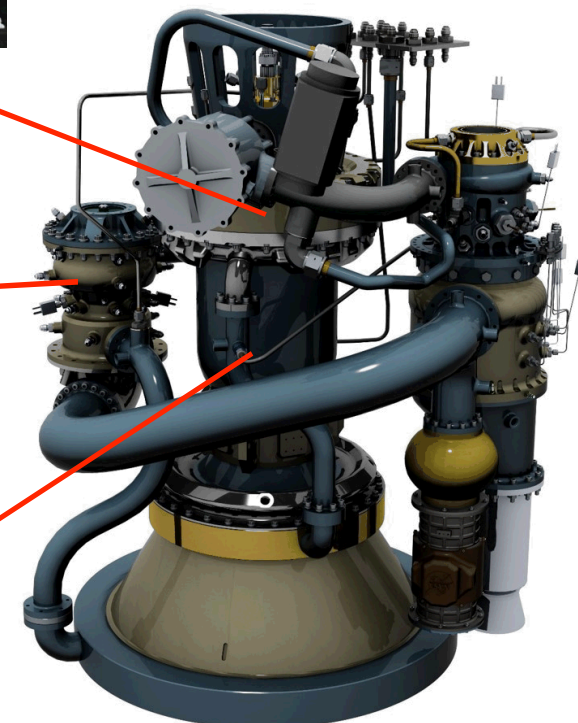
Injector



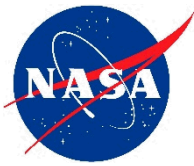
FTP



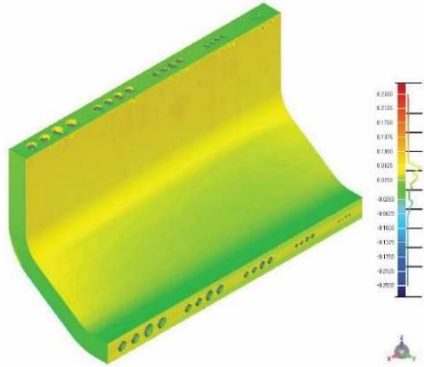
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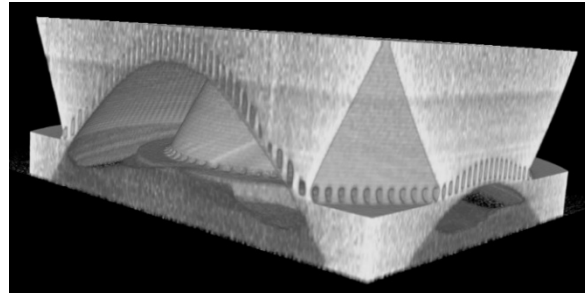
MSFC-STD-3716 &
MSFC-SPEC-3717



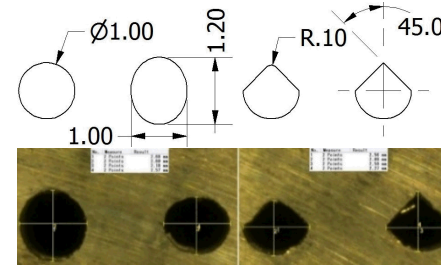
MSFC – Integrated Engineering Framework



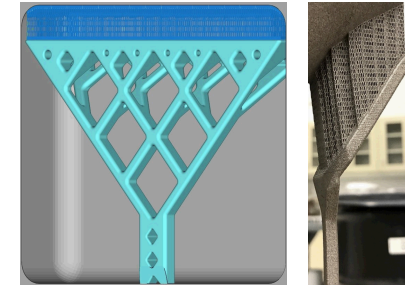
CAD-scan data comparison



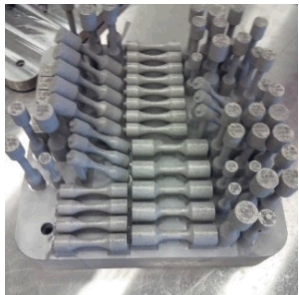
CT showing trapped powder in a manifold



Geometric Constraints



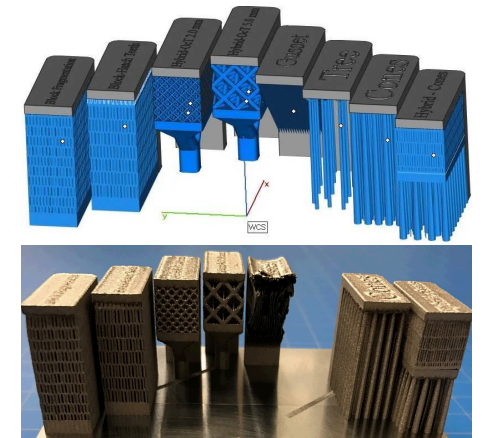
Support Structure Development



Property Development



Thermal Processing



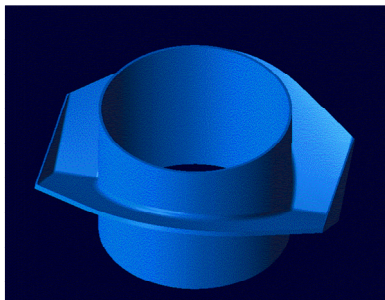
Supports Trials





Langley Research Center (LaRC)

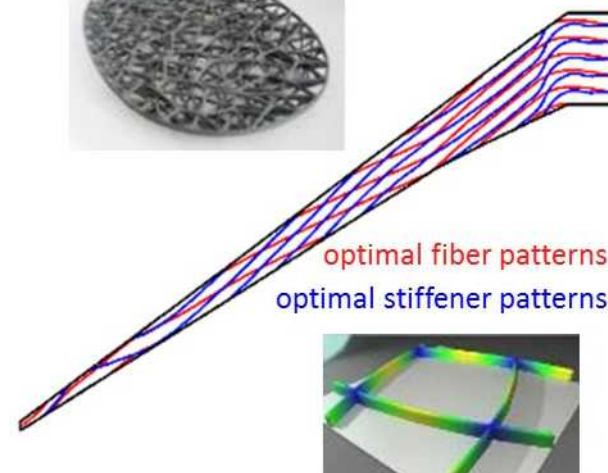
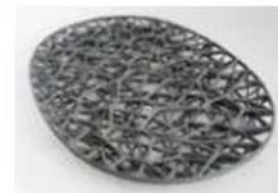
Electron Beam Freedform Fabrication (EBF³) Development



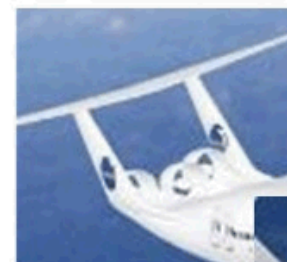
Ground-based system for large structural components



Portable systems for in-space simulation experiments



Tailoring efforts to design for AM in aircraft structures

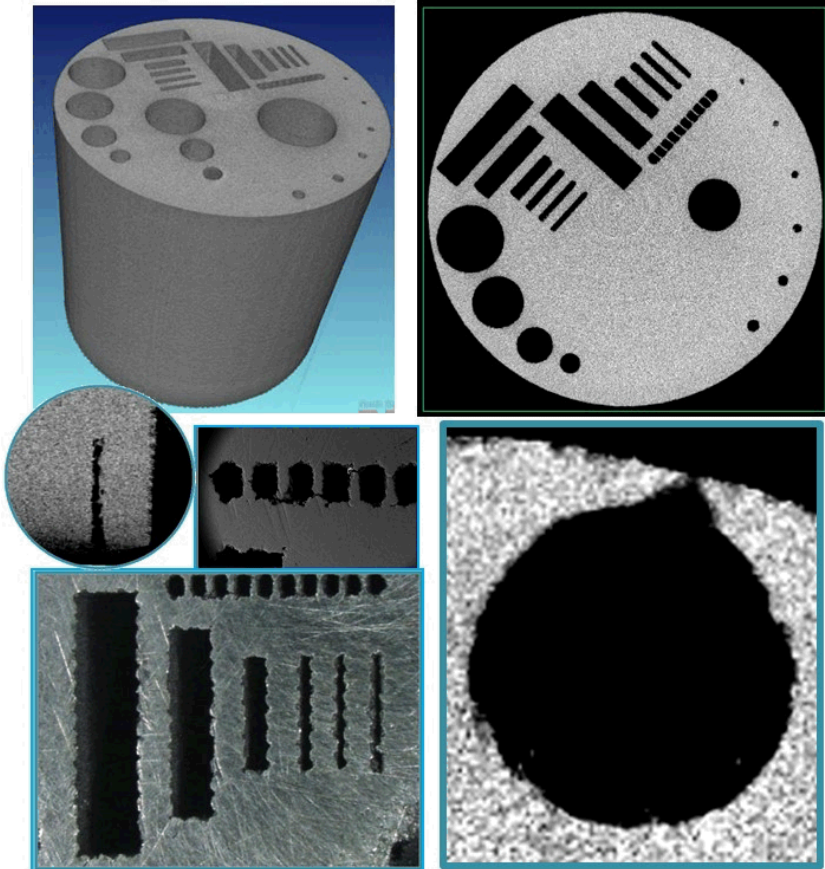


Complex joints for future vehicles (Composites and AM Metallic)

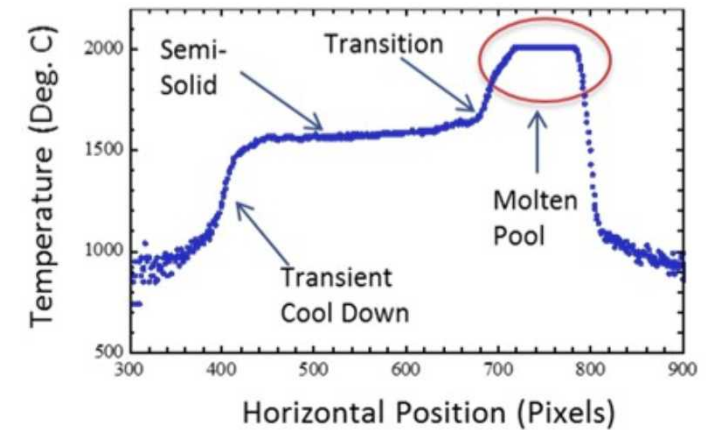
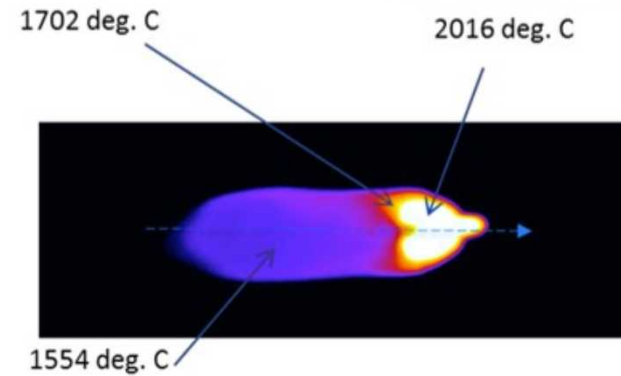




LaRC & GSFC – Nondestructive Evaluation

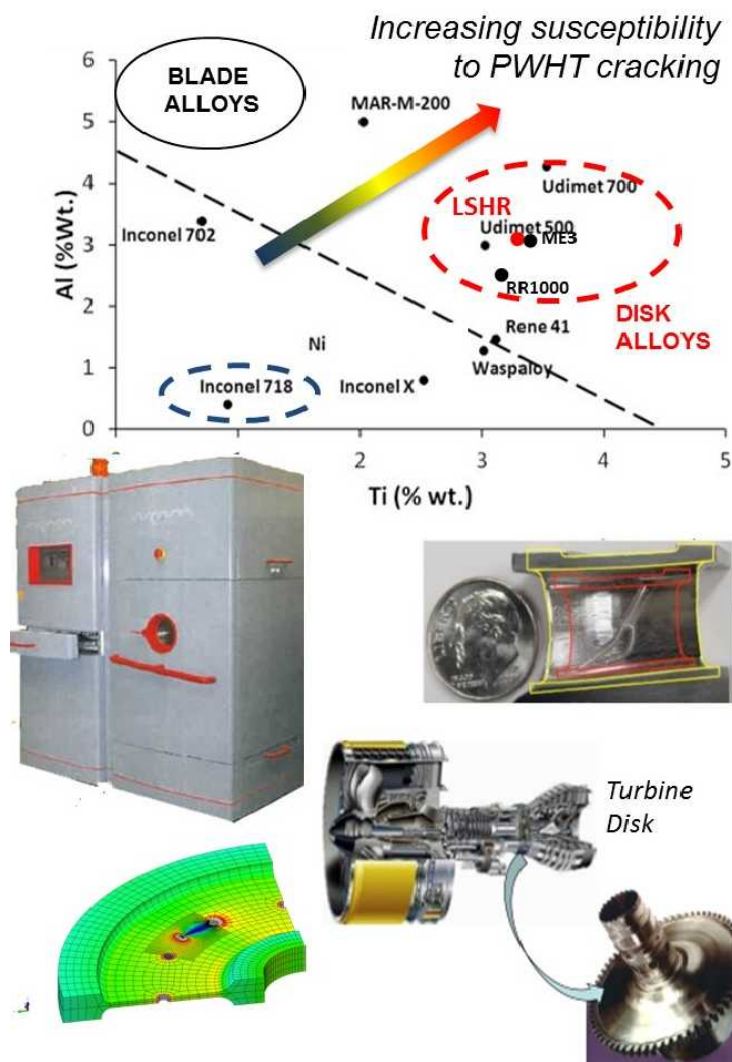


In-Situ Process Monitoring

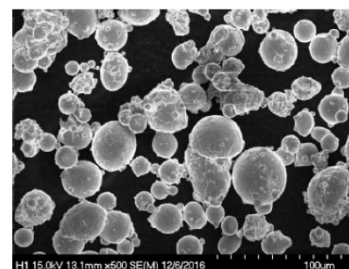
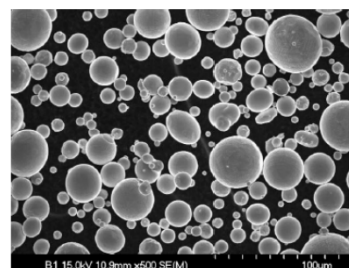


Development of Image Quality Indicators (IQIs)

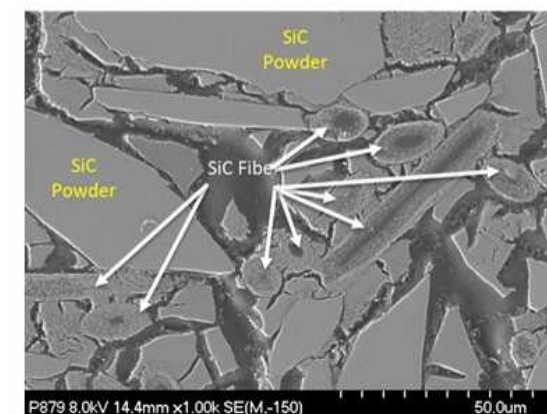
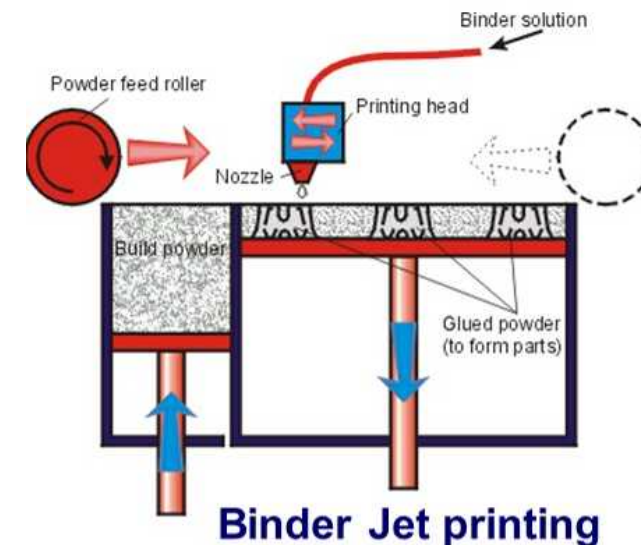
GRC – Alloy/Material Development



SiC Based Ceramics



Powder Characterization



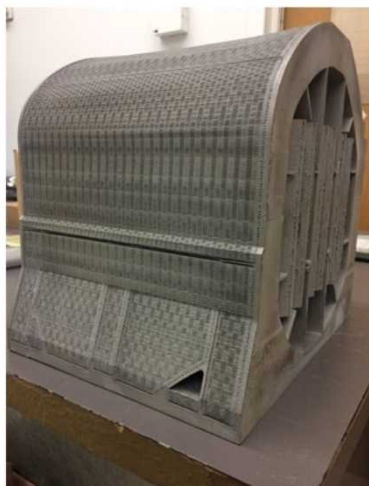
Chopped Fiber Reinforced Ceramic Matrix Composite



Jet Propulsion Laboratory



Aluminum and Titanium Part Development



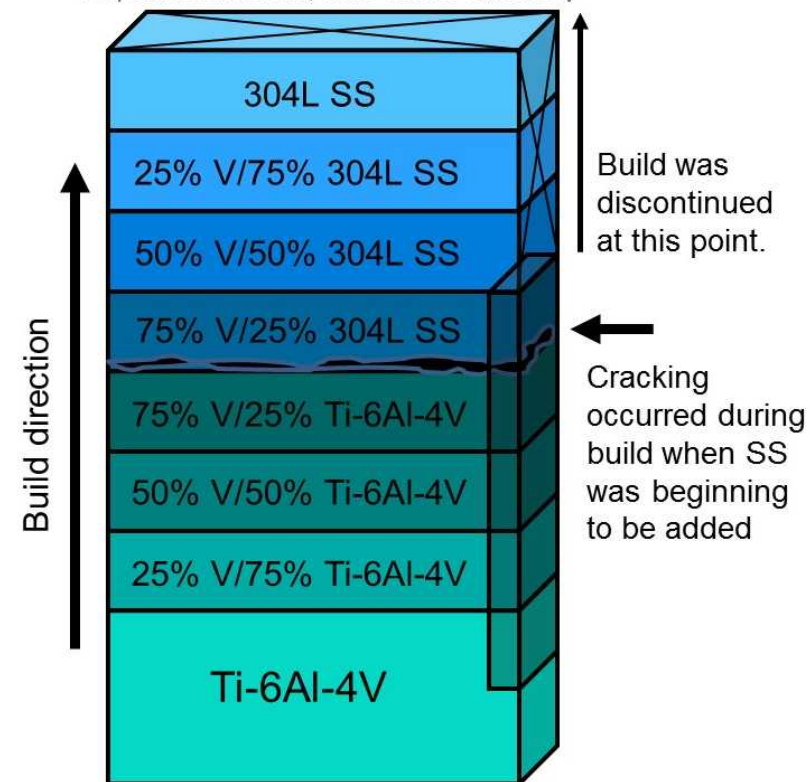
Development Coring Drill, Mars 2020 (Image JPL/NASA)

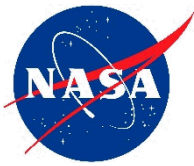


Gradient Alloy Development



Propellant transfer line, Mars Science Laboratory





But That's Not Why You're Here

Let's talk Standards & *REQUIREMENTS!!*



But What Do We Have Now?

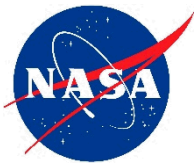
For new programs there is currently a “hook” in NASA-STD-6016A

4.2.4.11 Additive Manufacturing

Guidelines documents and standards for additive manufacturing are in development at this time. The requirements of this NASA Technical Standard on M&P controls, materials design values, metallic and nonmetallic materials, and nondestructive inspection apply to hardware manufactured by additive techniques, just as they do for traditional manufacturing techniques. For nonstructural, nonmetallic 3-D printed hardware, controlled and verified processes are essential; but other M&P aspects like flammability, toxic offgassing, and vacuum outgassing also apply, just as for any other nonmetallic material.

When structural hardware is manufactured by additive manufacturing techniques, **a manufacturing and qualification plan shall be submitted to NASA and approved by the responsible NASA M&P and design organizations.**

Key aspects of producing structural metallic hardware by additive manufacturing techniques, such as direct metal laser sintering (DMLS) and selective laser melting (SLM), include proper development of structural design values and controlled processes, although other requirements, such as stress-corrosion resistance and corrosion control, also apply. Verification of appropriate process control should include first article inspection to verify proper material properties and macro/microstructure and mechanical property testing of integrally manufactured specimens from each hardware unit.



Motivation for NASA Agency Standard Development



- Program partners in manned space flight programs (Commercial Crew, SLS, ISS and Orion) are actively developing AM parts
 - AM parts currently in use for commercial space flight
- NASA is unable to wait for a fully mature ecosystem of industry standards
- NASA is currently using MSFC-STD-3716 and MSFC-SPEC-3717 as the basis of tailoring for all flight programs
 - MSFC documents written for SLS RS-25 restart and cover Laser Powder Bed fusion of metallic powders only
 - The parts that have seen this tailoring range from safety-critical to benign
 - Interim guidance has been released via NESC Technical Bulletin No. 17-01
- NASA needs something that could cover ALL AM Parts



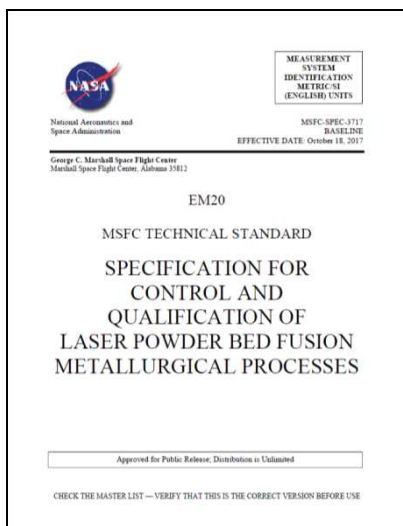
Agency Documents

MSFC-STD-3716



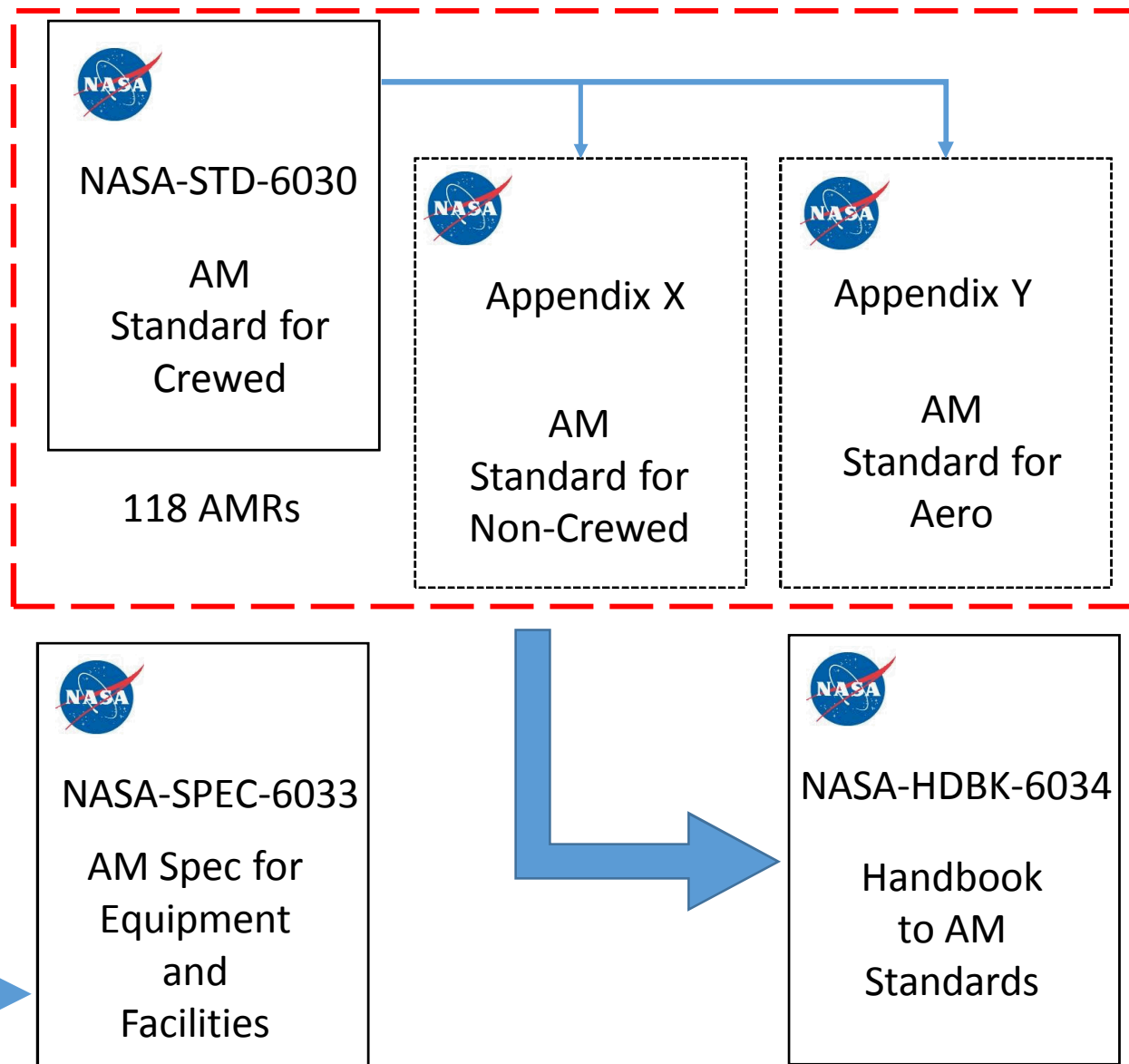
65 AMRs

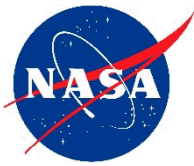
MSFC-SPEC-3717



45 PCQRs for:
Process definition
QMPs

PCQRs for:
Equipment and facility
process control

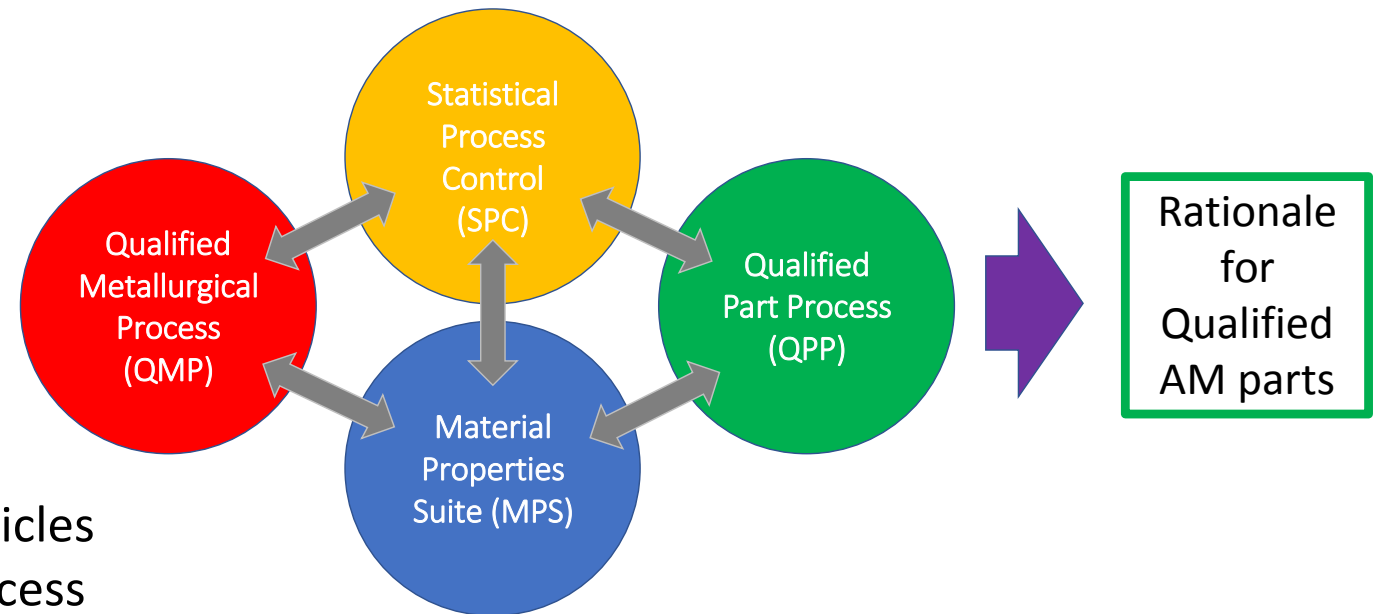


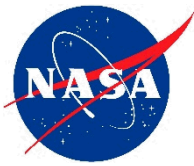


AM Certification: Governing Principles

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

- Have a plan
- Quality Management System (QMS)
- 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





Verification vs Validation

VERIFICATION: “Did I build what I need?”

VALIDATION: “Did I build what I said I would?”

- Verification is important (e.g. tensile tests, proof testing, etc)
- But the vast majority of the effort that goes into meeting the requirements of the new NASA standard could best be described as validation
- i.e. Do you understand your process from initial design to flight worthy part, are you monitoring it, and is it under control.



New NASA Deliverables

- NASA-STD-6030 will require the following deliverables:
 - Additive Manufacturing Control Plan (AMCP)
 - **This is where tailoring happens**
 - Material Usage Agreement (MUA) to approve the Material Property Suite (MPS)
 - Class A and B parts only
 - Part Production Plan (PPP)
 - A summary of everything that informs the final part
 - (Justification for Class C designation)
- Not required by NASA-STD-6030 (but required by contract, and not really new)
 - End Item Data Package (EIDP)
 - Documents compliance to PPP
 - Reviewed by NASA Quality Engineering

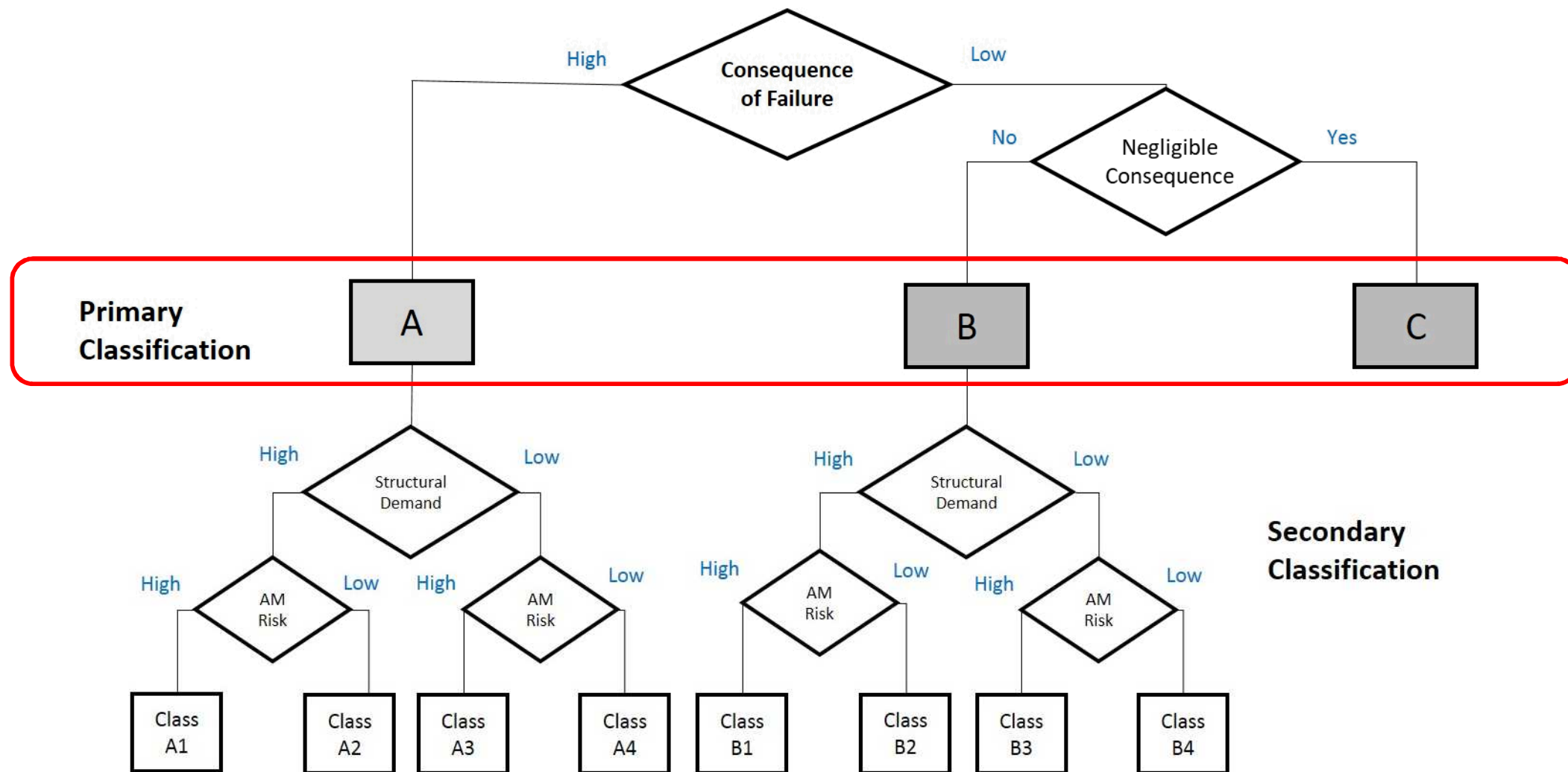
METRIC/SI (ENGLISH)	
 NASA TECHNICAL STANDARD Office of the NASA Chief Engineer	DRAFT NASA-STD-6030
	Approved: 2019-xx-xx
Additive Manufacturing Requirements for Crewed Spaceflight Systems	



AM Technologies Allowed by Standard

Category	Technology	Materials type	Class		
			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

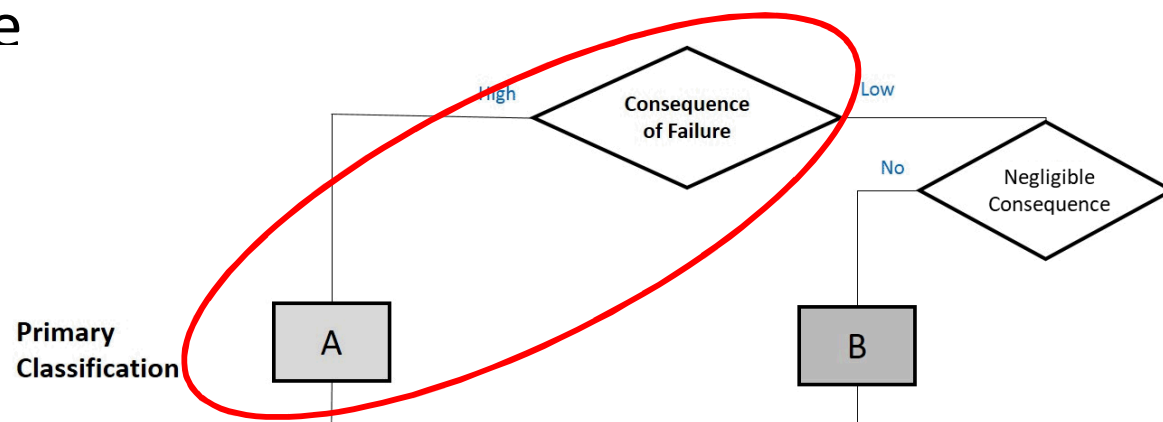
Part Classification





Consequence of Failure

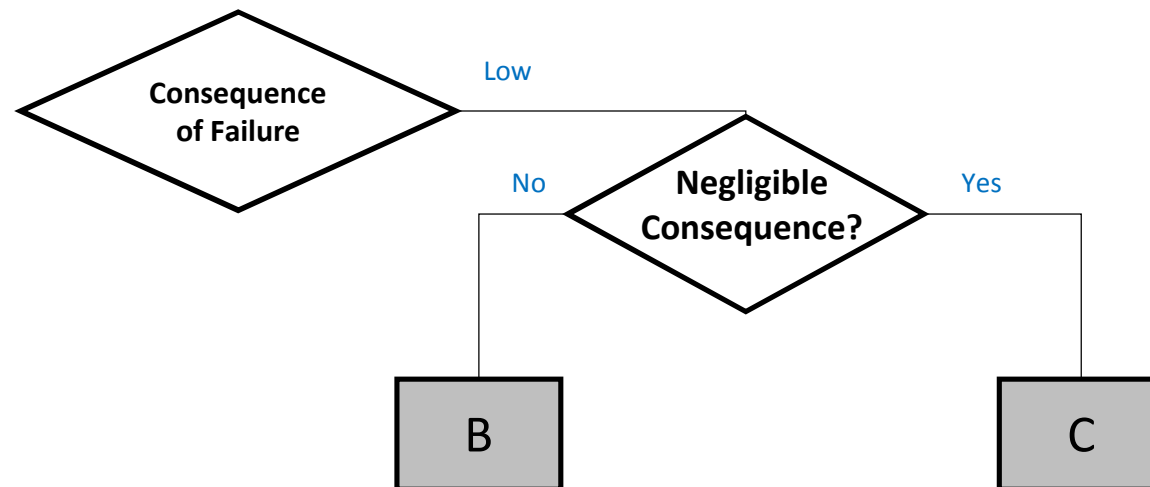
- A part shall be designated as Class A, High Consequence of Failure, if failure of the part leads to a catastrophic hazard or the part is classified as Mission Critical Hardware.
 - If it could hurt someone, it's Class A
 - The Mission Critical part is tailorable
- The following prohibitions shall apply to Class A parts:
 - Non-metallics
 - Fasteners

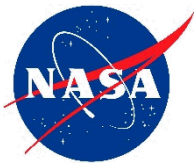




Negligible Consequence

- A Class B Part is defined as a part that is neither Class A nor Class C
 - i.e. we've defined Class B by what it's *not*
- The following prohibition shall apply to Class B parts:
 - Fasteners



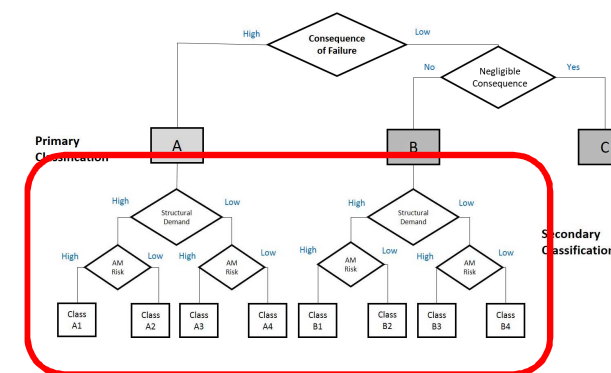
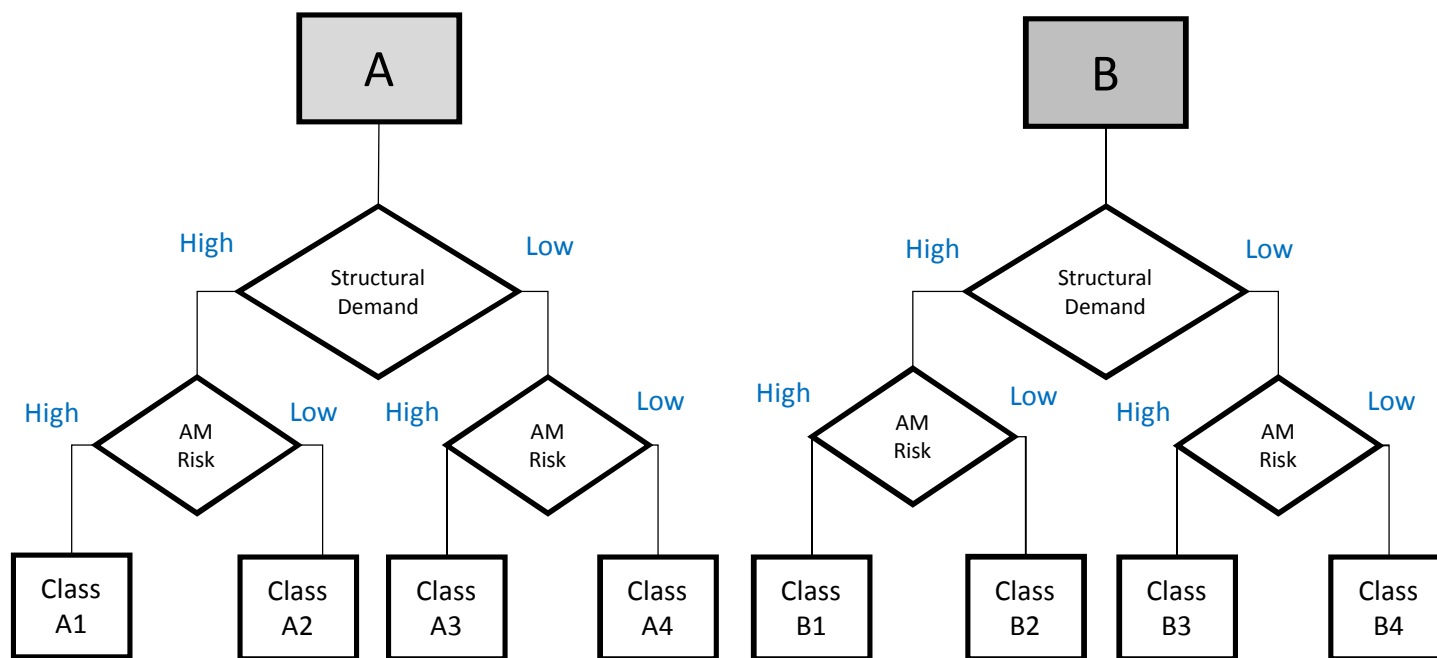


Negligible Consequence

- A part shall be designated as Class C if it is shown to have negligible consequence of failure.
- To accomplish this, ALL of the following criteria must be satisfied.
 - Failure of part does not lead to any form of hazardous or unsafe condition
 - Failure of part does not eliminate a critical redundancy
 - Failure of part does not cause debris or contamination concerns
 - 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 objectives

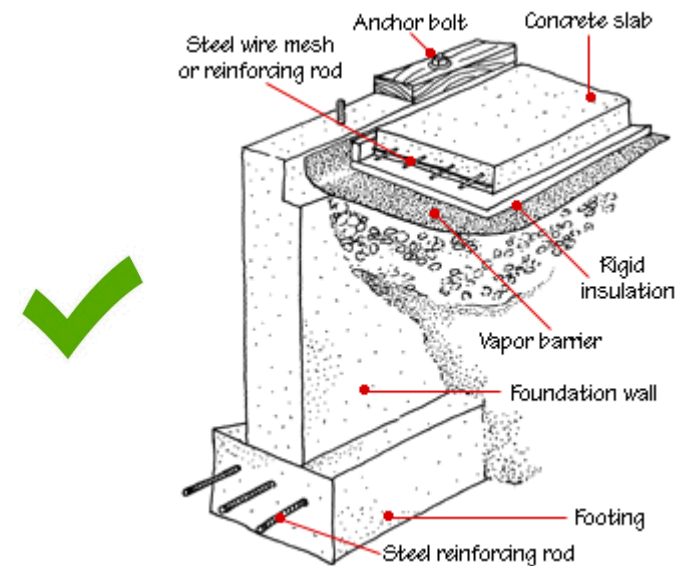
Secondary Classification

- Secondary classification is for Class A and B parts only
- Used to determine appropriate levels of process control
- Also serves as a valuable communication tool between developers and NASA



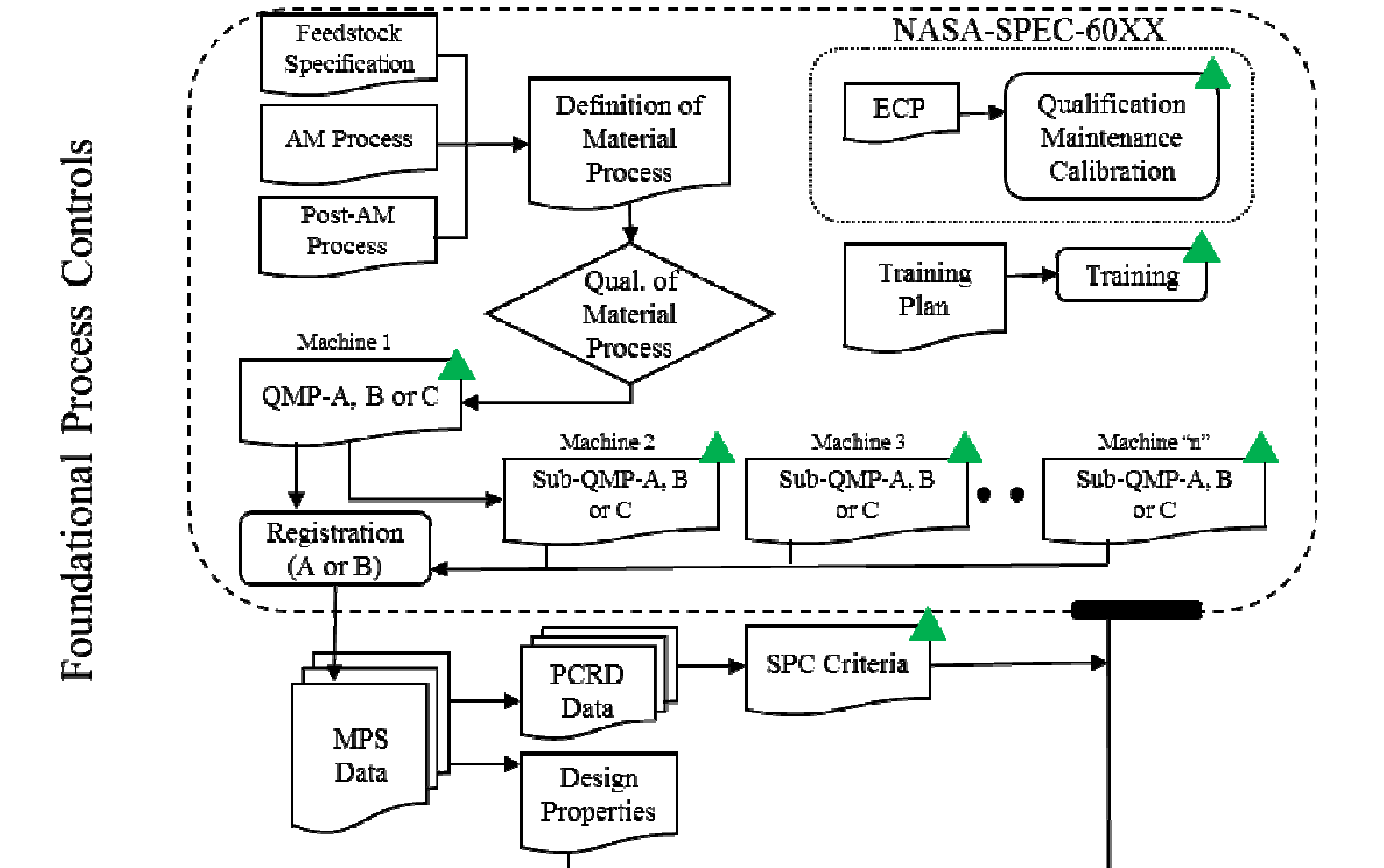
Building a Foundation

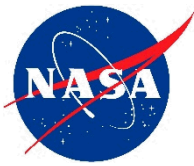
- **Planning for AM certification does NOT start with a part**
- AM Control Plan should define how the foundation for certification is structured and how it operates
 - Equipment and Facility Controls
 - Personnel Training
 - Process/Machine Qualification
 - Material Properties
 - Statistical Process Controls
- Building this foundation can take years
- 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



Foundational Process Controls

- Foundational Process Controls provide the basis for reliable part design and production





Equipment and Facility Control Plan and Training

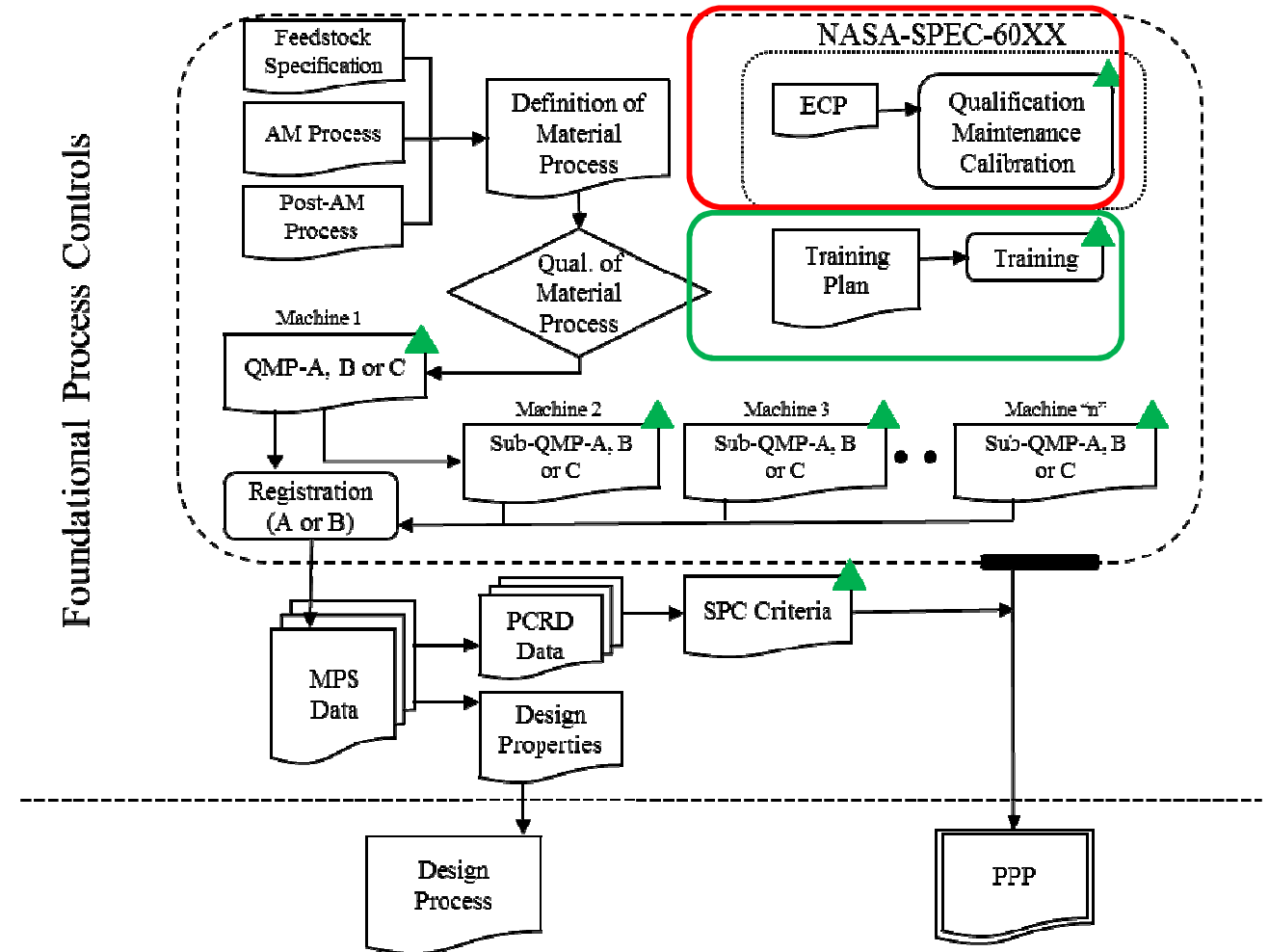


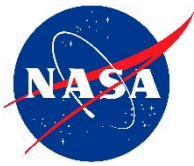
- **EFCP**

- Plan required by Standard
- (but not a deliverable)
- Flexibility in implementation
- Governs AM equipment and facility
 - Qualification
 - Maintenance
 - Calibration

- **Training**

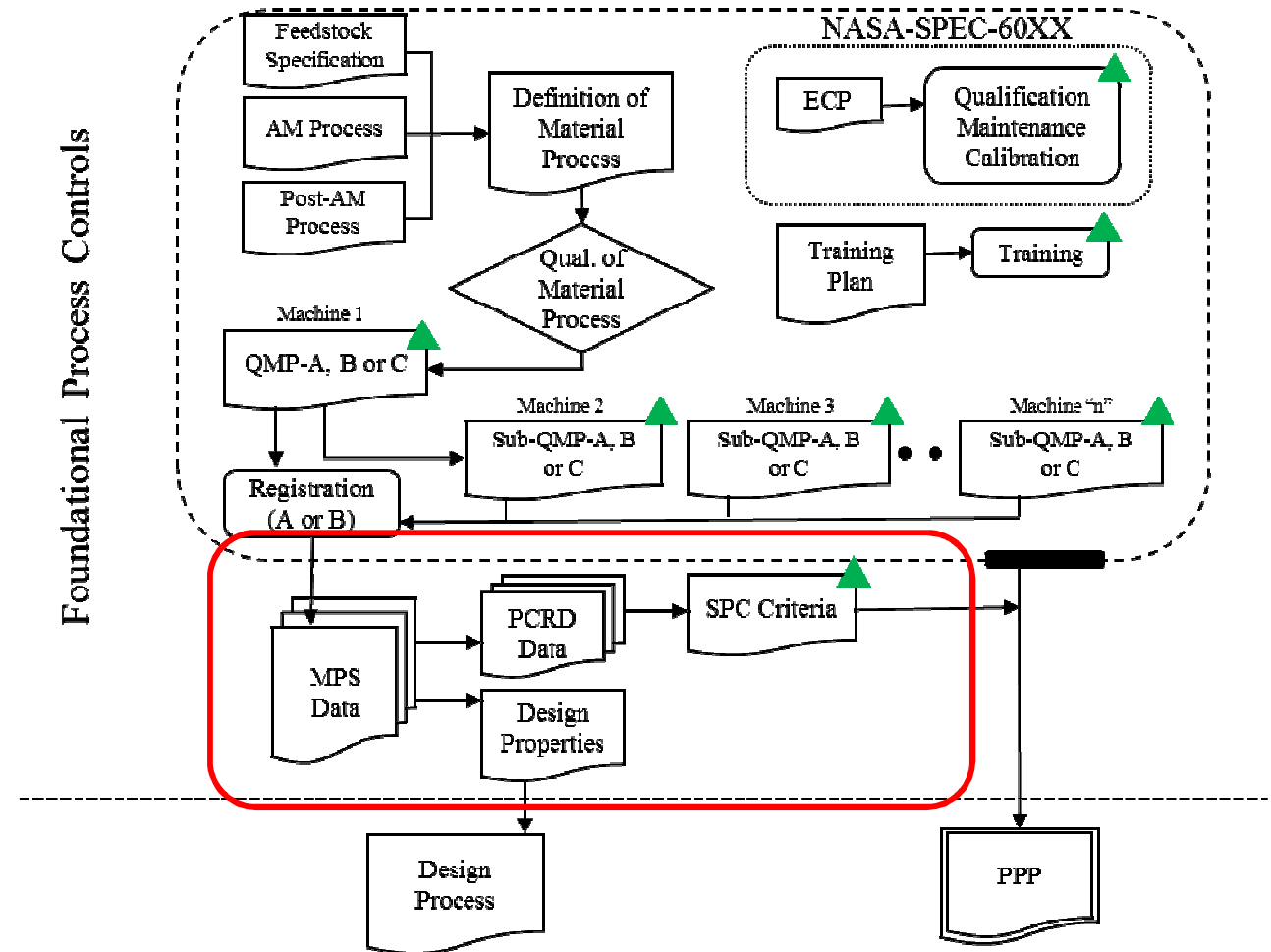
- Training Plan required by Standard
 - Expectations in Specification
- Flexibility in implementation
- Covers all personnel involved in AM





Material Properties

- The Material Property Suite (MPS) consists of five inter-related entities:
 - Data Repository
 - Influence Factors
 - Design Values
 - Process Control Reference Distribution (PCRD)
 - Statistical Process Control (SPC) acceptance criteria for witness testing
- The MPS can be VAST





Material Properties

- Material properties and design values in additive manufacturing require modifications to the approach typical of traditional metallic materials, with requirements more similar to that used in composites
- 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. (Casting analogy)
- **AM Process Vendor is responsible for material integrity**



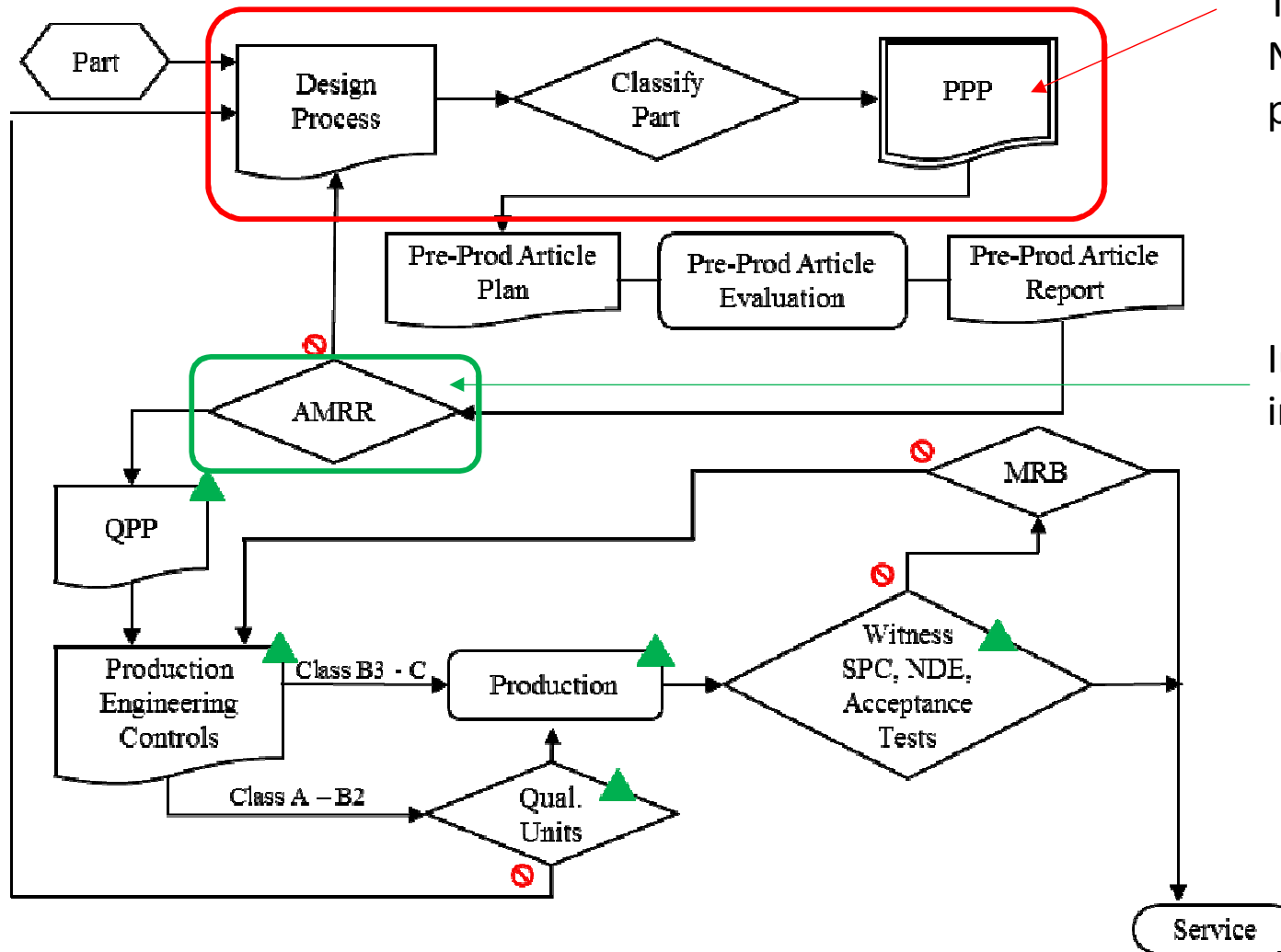
Material Properties – SPC

- Statistical process controls are important in sustaining certification rationale
- *Statistical equivalency evaluations* substantiate design values and process stability build-to-build
 - a) Process qualification
 - b) Witness testing
 - c) Integration to existing material data sets
 - d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts (more on that later)
- The dark and scary place most manufacturers are **NOT** used to operating....



Design Process

Part Production Controls

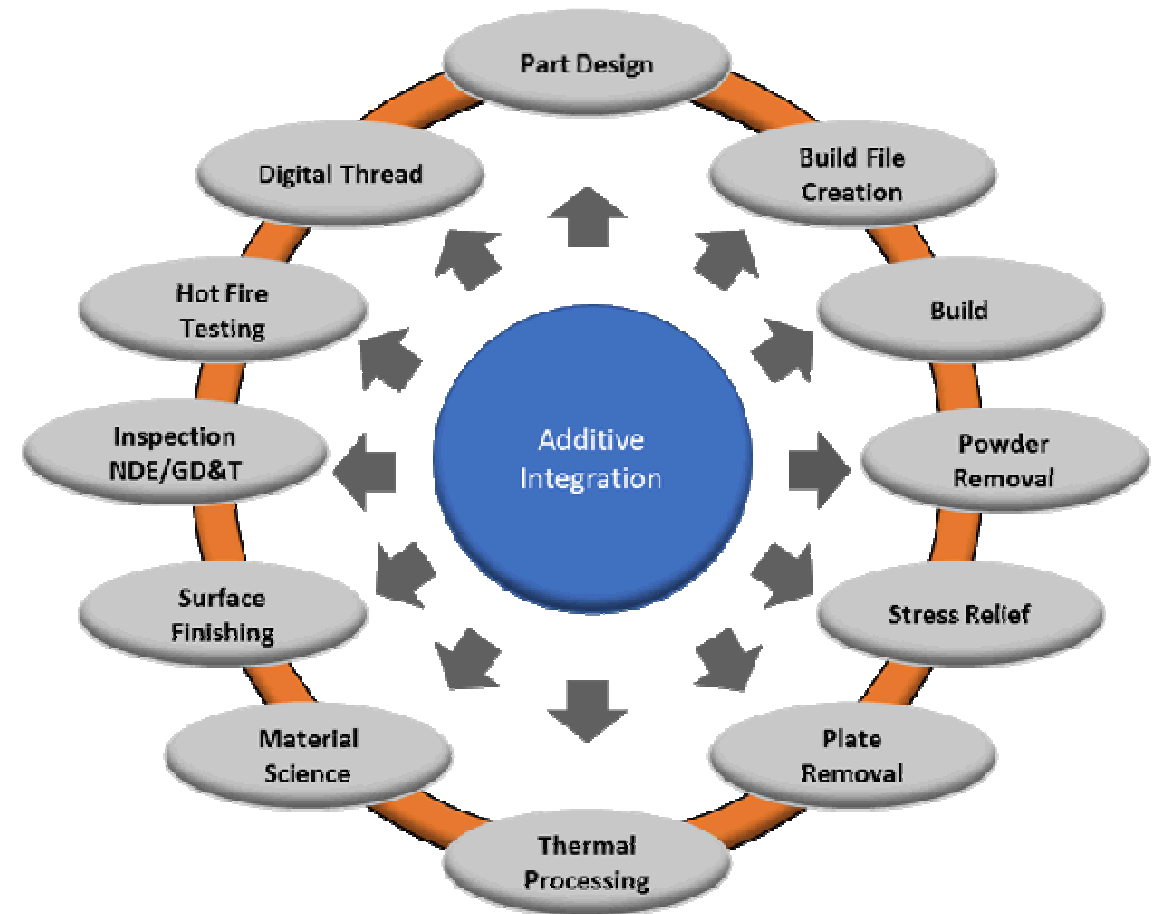


This is the last point where a NASA approval is required prior to the delivery of a part

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

Part Production Plan

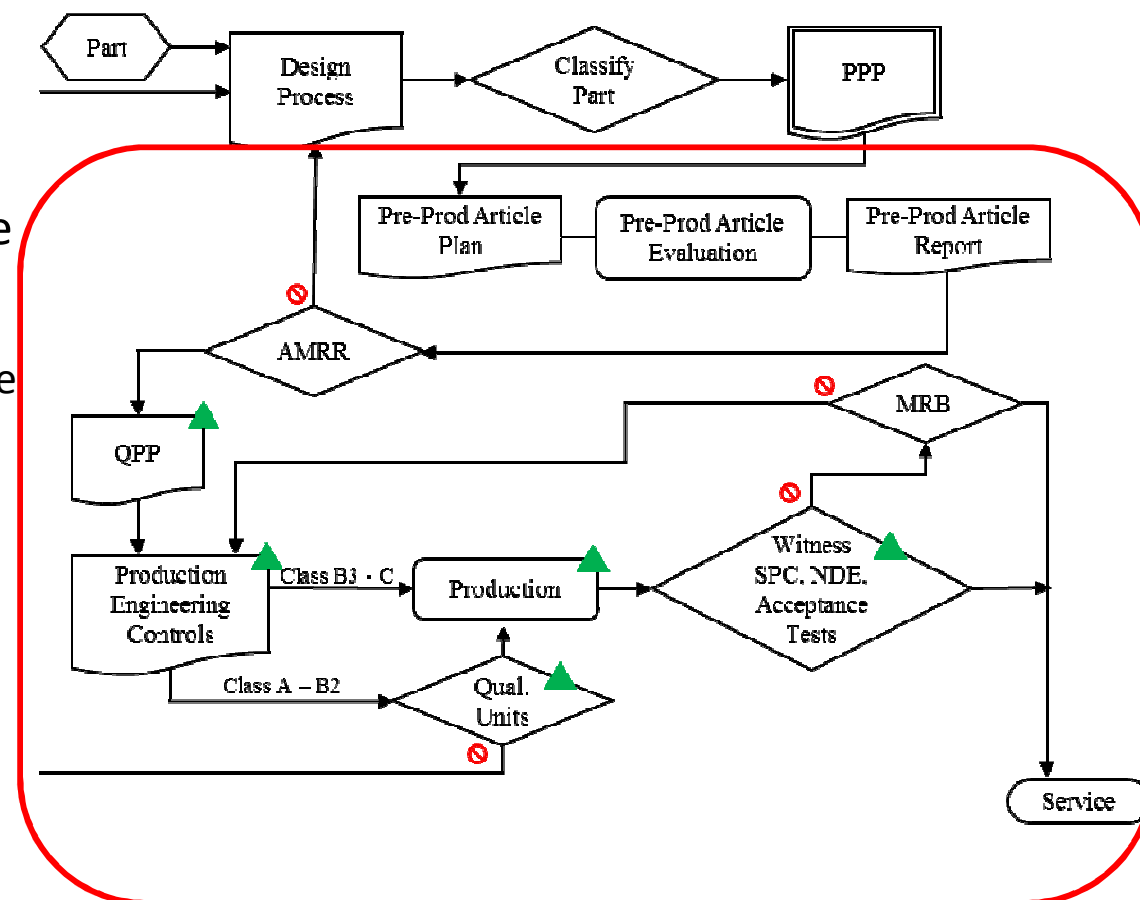
- The last Deliverable before the Part
- Challenge to integrate all required aspects of AM design requirements through drawing content
- Requires many aspects to be integrated
 - Part Classification
 - Integrated Structural Integrity Rationale
 - Build layout
 - Specification of qualified process ID
 - Witness test and acceptance
 - Post processing details
 - Inspection requirements and limitations
- Requiring a AM Part Production Plan as a drawing companion is best option currently



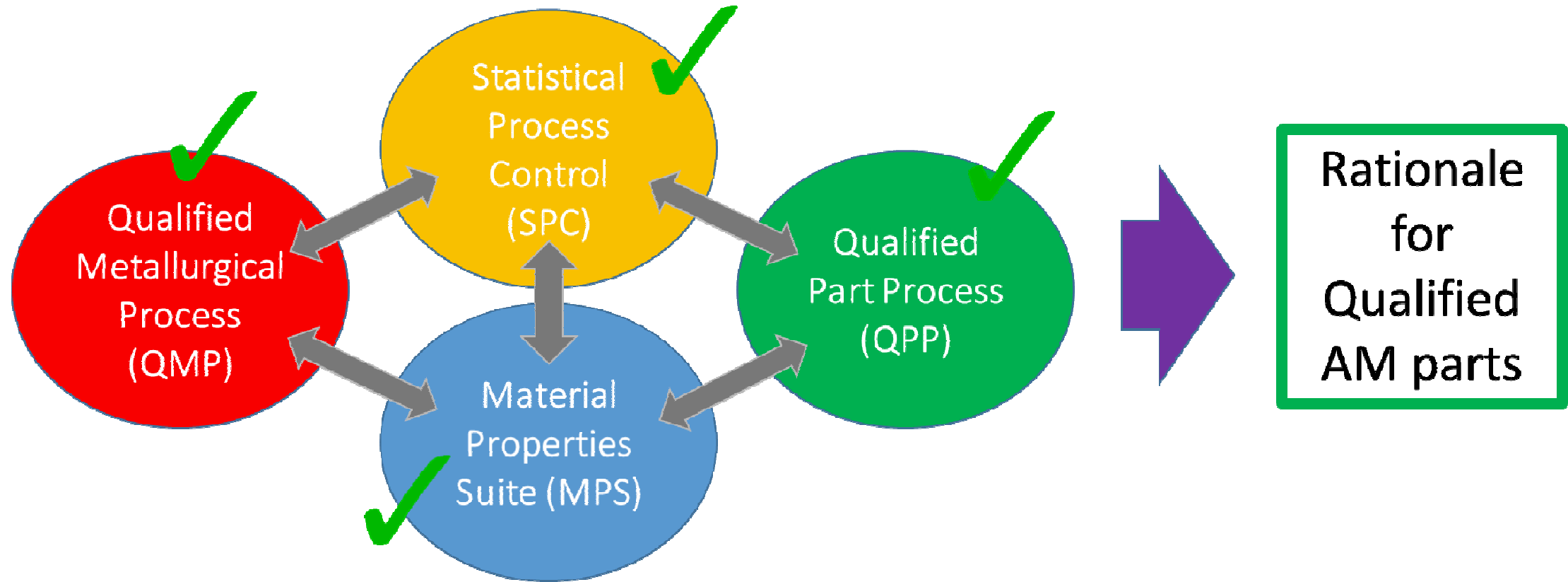


AM Part Production

- **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



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

- Certification rationale is most heavily rooted in the foundational controls
 - Having a Plan
 - Fully involved Quality Management System
 - Equipment and Facility Controls
 - Training
 - Process/machine qualifications
 - Material properties
 - Statistical Process Control
- 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

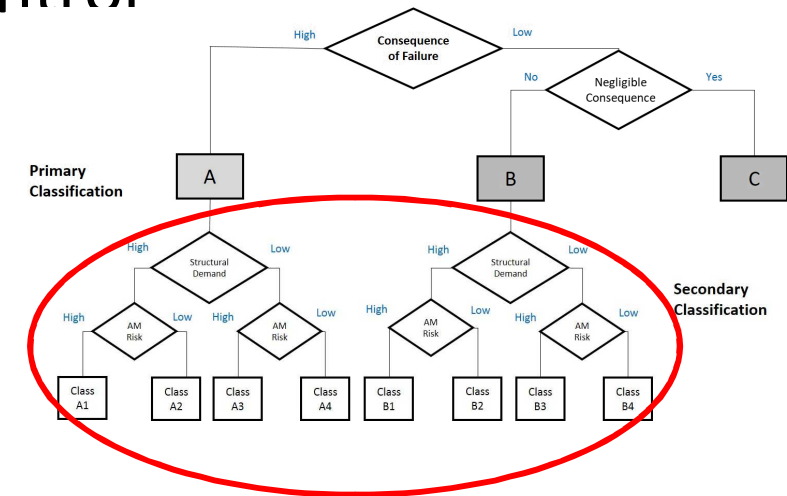
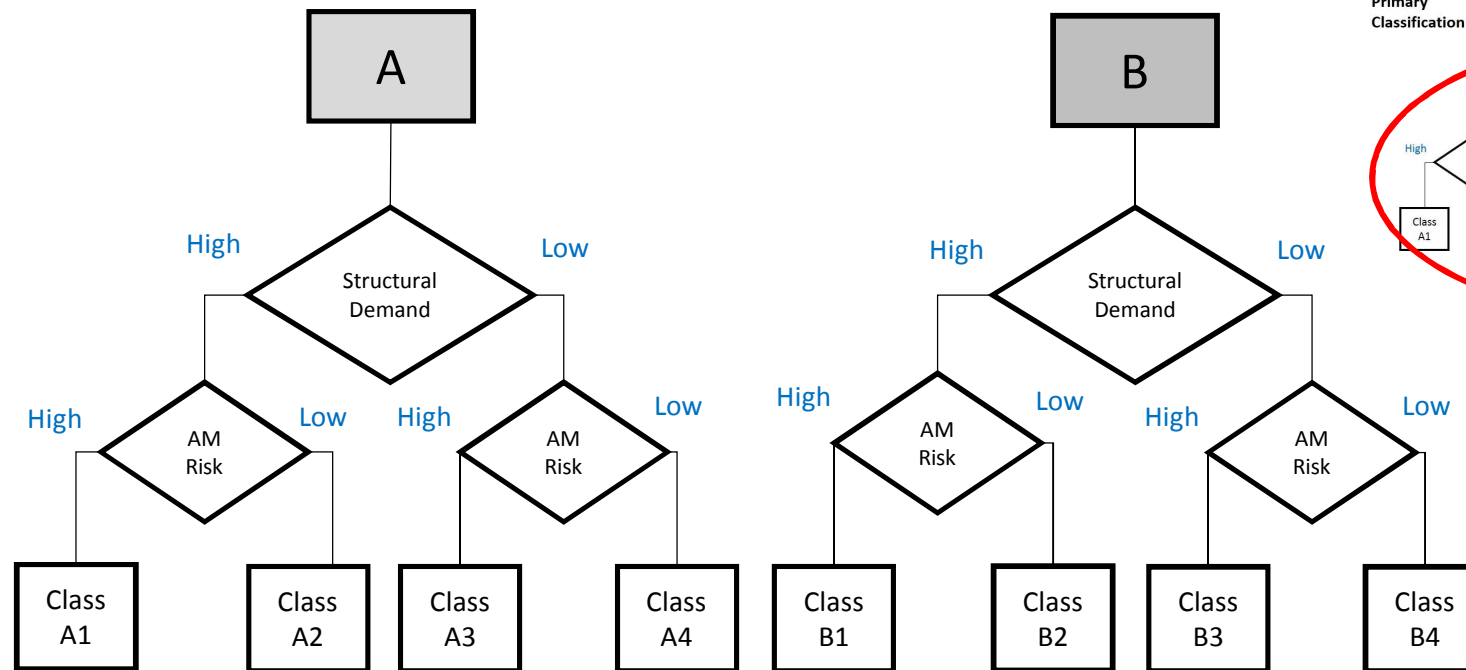


Backup



Secondary Classification

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

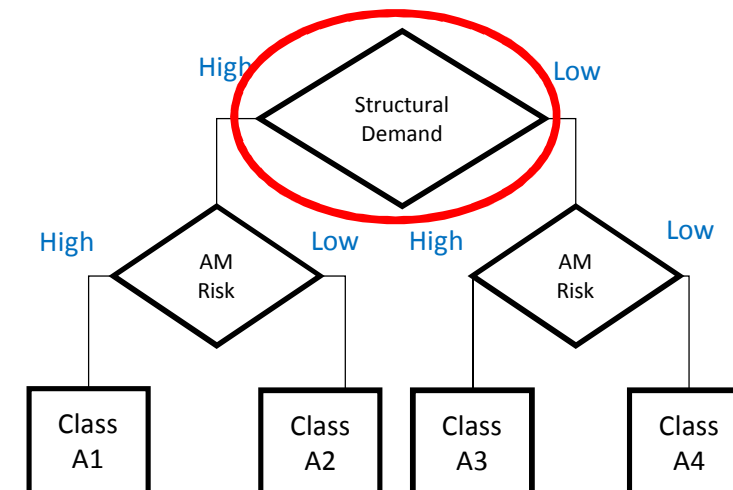




Structural Demand - Metals

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) $\leq 80\%$ of applicable fatigue limit
High Cycle Fatigue, As-built Surfaces	Cyclic stress range (including any required factors) $\leq 60\%$ 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 = $[\sigma_{\text{design}} / (\sigma_{\text{operation}} * \text{safety factor})] - 1$.





Structural Demand - Polymers

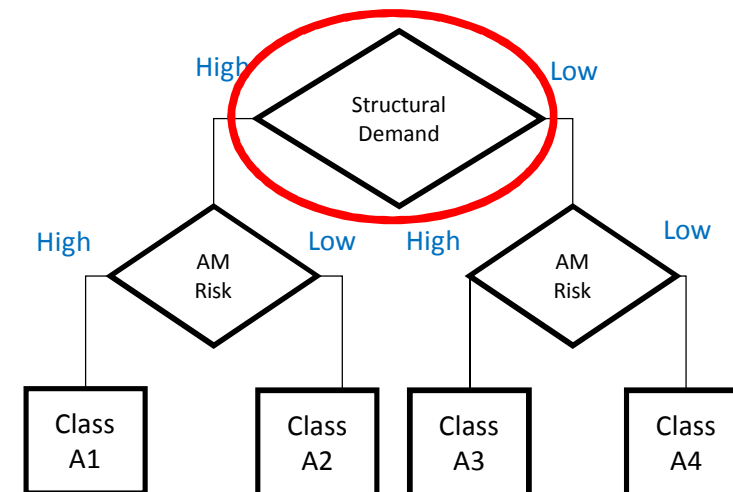
Analysis Input/Material Property	Criteria for Low Structural Demand
All Materials	
Loads Environment	Well defined or bounded loads environment
Environmental Degradation	Only due to temperature and moisture, if specific environmental performance data exist. Design environment temperature does not cross the Tg.
Fatigue	Cyclic stress range (including any required factors) $\leq$ 50% of applicable fatigue limit
Sustained stress / creep strain	No sustained stress [†] and No predicted creep strain
Material with elongation at failure $\geq$ 3% in application environment	
Ultimate Strength	Minimum margin* $\geq$ 0.5
Yield Strength [‡]	Minimum margin* $\geq$ 0.3
Material with elongation at failure $<$ 3% in application environment	
Ultimate Strength [#]	Minimum margin* $\geq$ 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 = $[\sigma_{\text{design}} / (\sigma_{\text{operation}} * \text{safety factor})] - 1$.



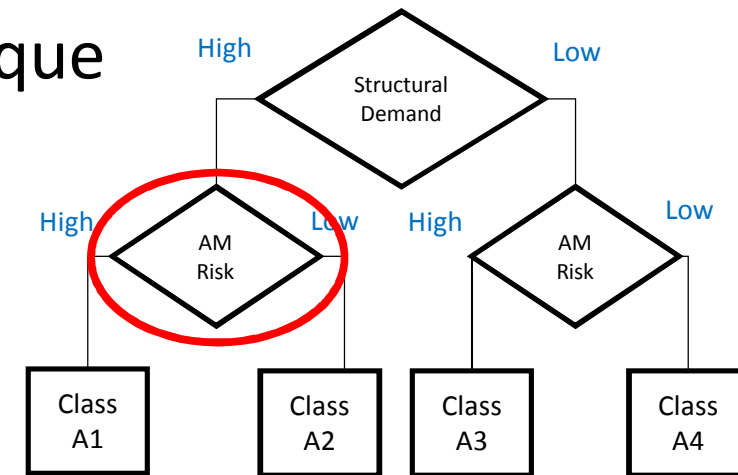


AM Risk

- 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

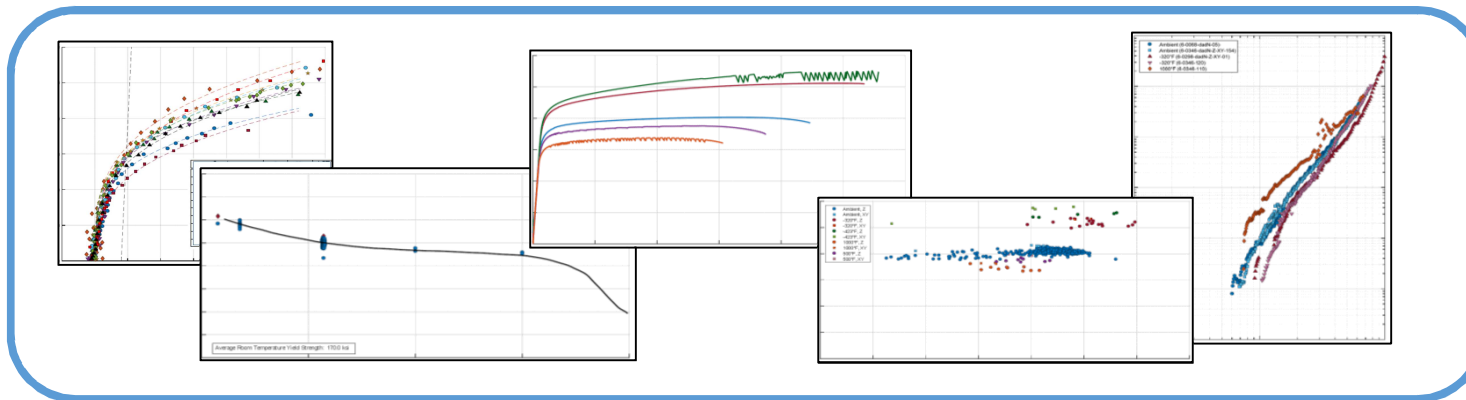
Additive Manufacturing Risk	Yes	No	Score
All critical surface and volumes can be reliably inspected , or the design permits adequate proof testing based on stress state?	0	5	
As-built surface can be fully removed on all fatigue-critical surfaces?	0	3	
Surfaces interfacing with sacrificial supports are fully accessible and improved?	0	3	
Structural walls or protrusions are $\geq 1\text{mm}$ 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



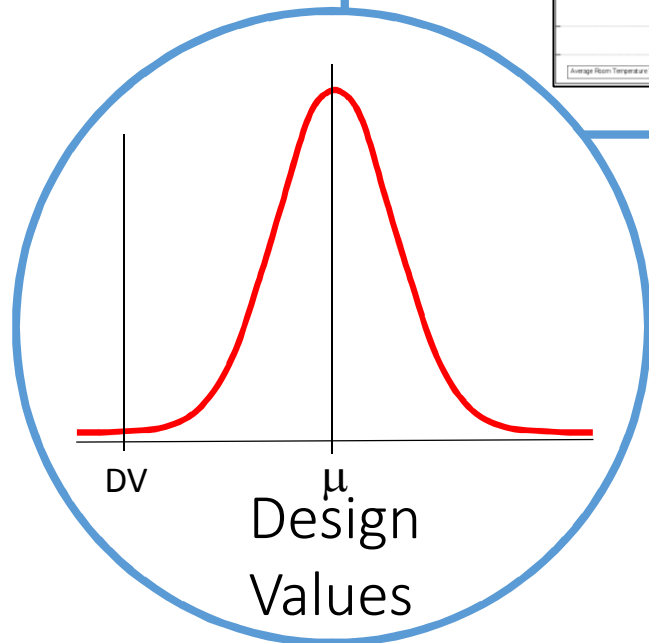
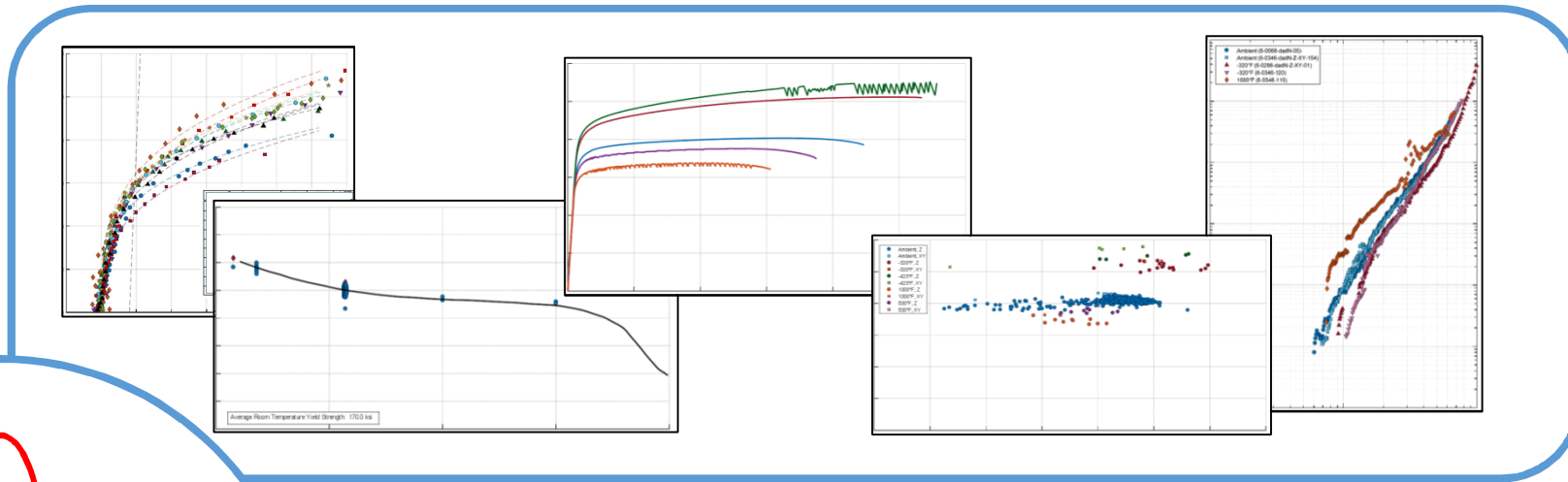


MPS Backup – Data Repository



- Includes data from
 - Qualification testing
 - Material Characterization
 - Pre-production Article Evaluations
 - Contains all data needed for
 - Setting Design Values
 - Property equivalence evaluations and QMP Registration
 - Setting the Process Control Reference Distribution
- Grouping of data
- Group data by
- QMP = Material/process/heat treat
 - “Combinable” conditions for design

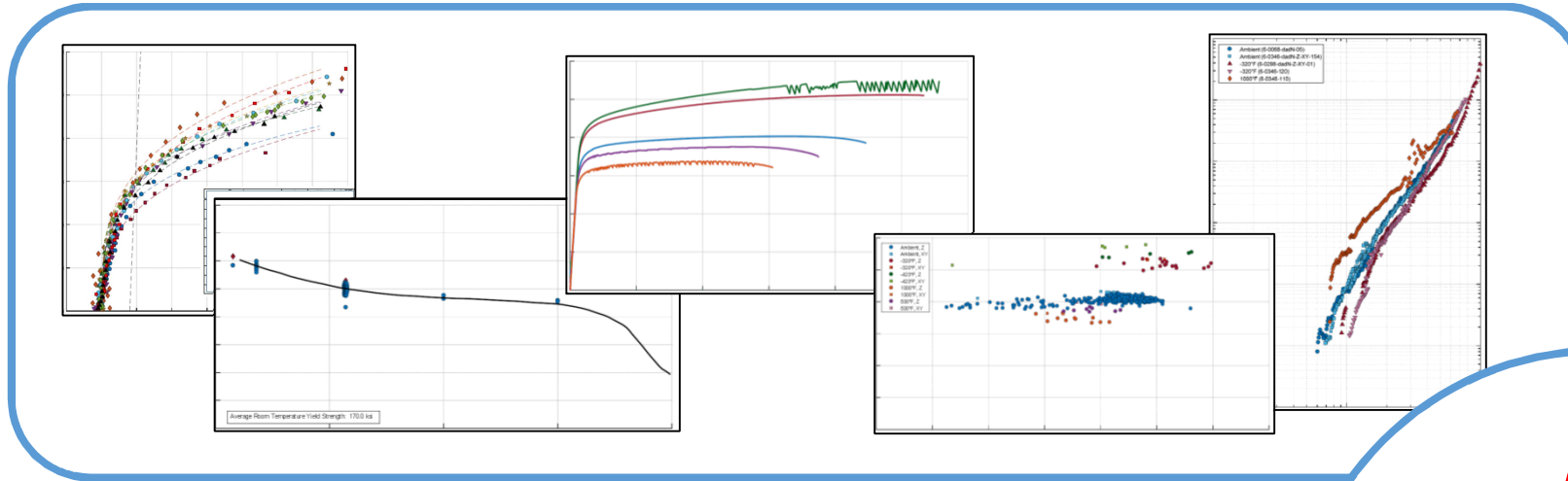
MPS Backup – Design Values



Design Values

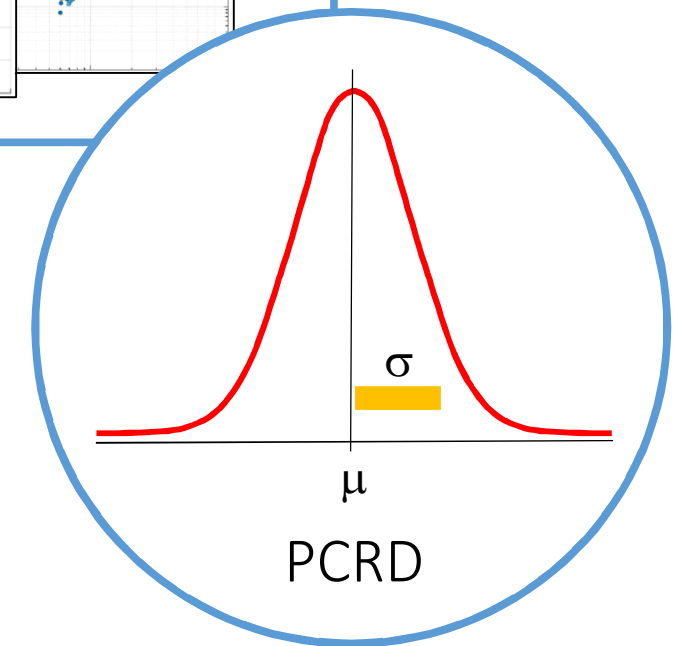
- Statistically substantiated
- Applicable sources of variability included
- Utilizes all appropriate data sources in Repository
- May include additional margin for safety

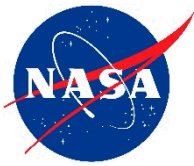
MPS Backup – PCRDR



Process Control Reference Distribution

- 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



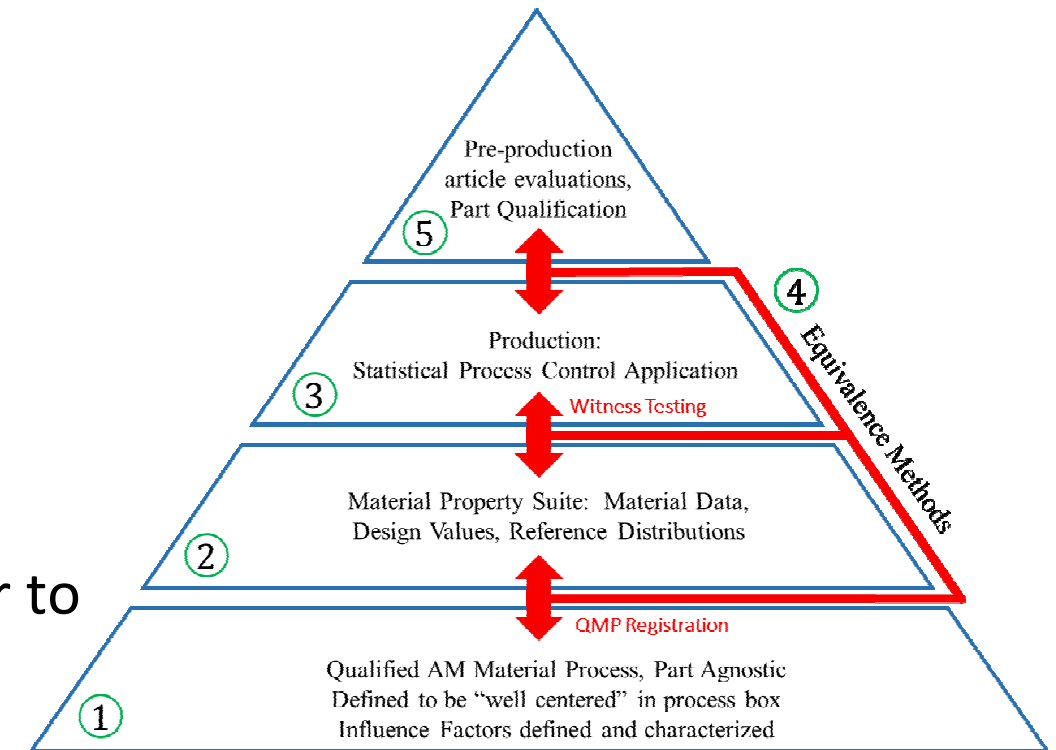


MPS Backup – SPC



Statistical process controls are important in sustaining certification rationale

- *Statistical equivalency evaluations* substantiate design values and process stability build-to-build
 - a) Process qualification
 - b) Witness testing
 - c) Integration to existing material data sets
 - d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts



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

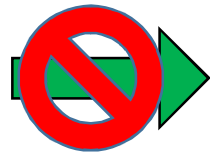
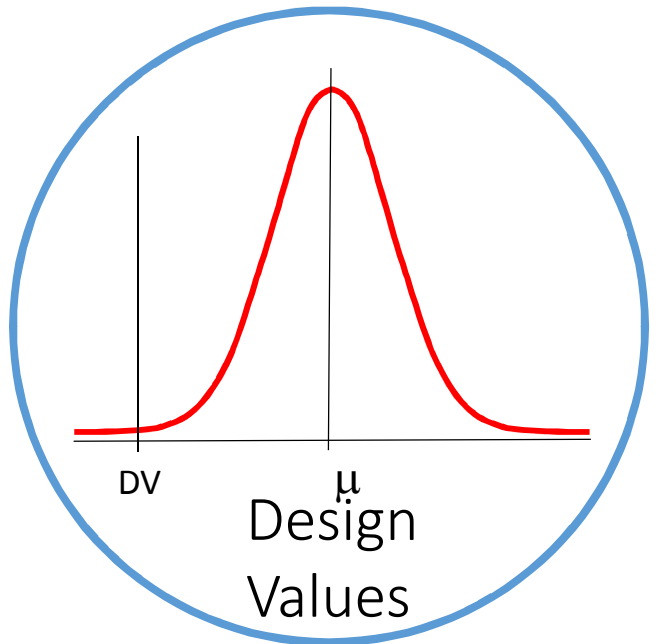
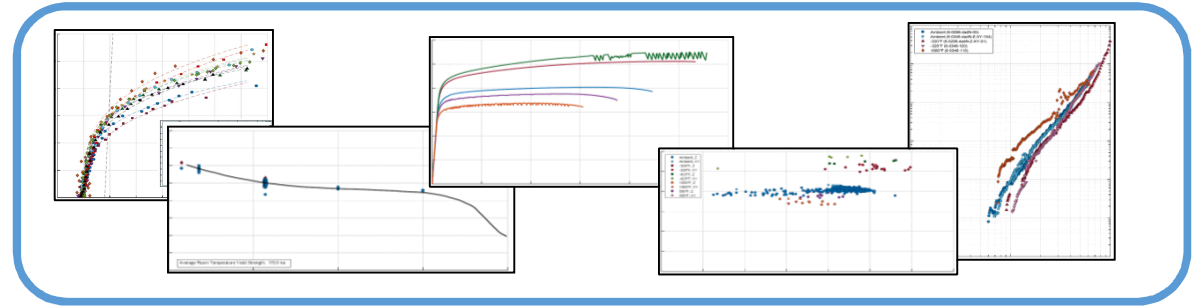


MPS Backup

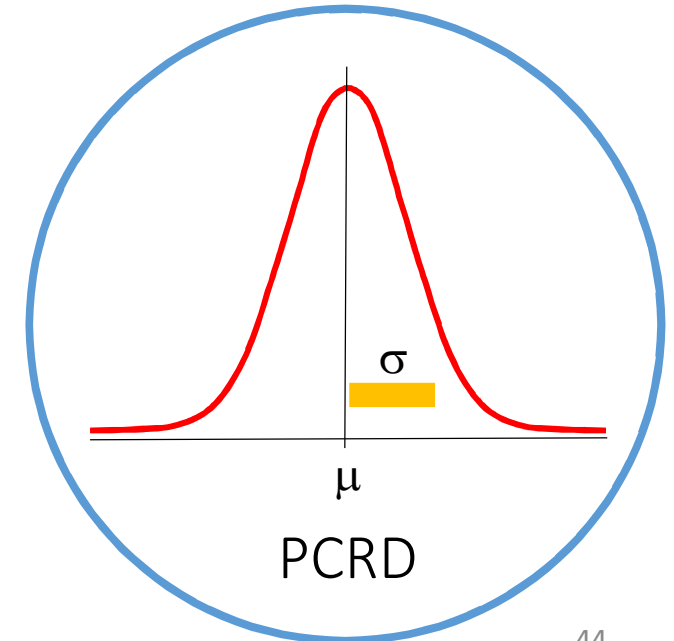
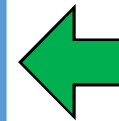


Statistical Process Control Acceptance Criteria

- Derived from PCR~~D~~
- Acceptance criteria for witness tests



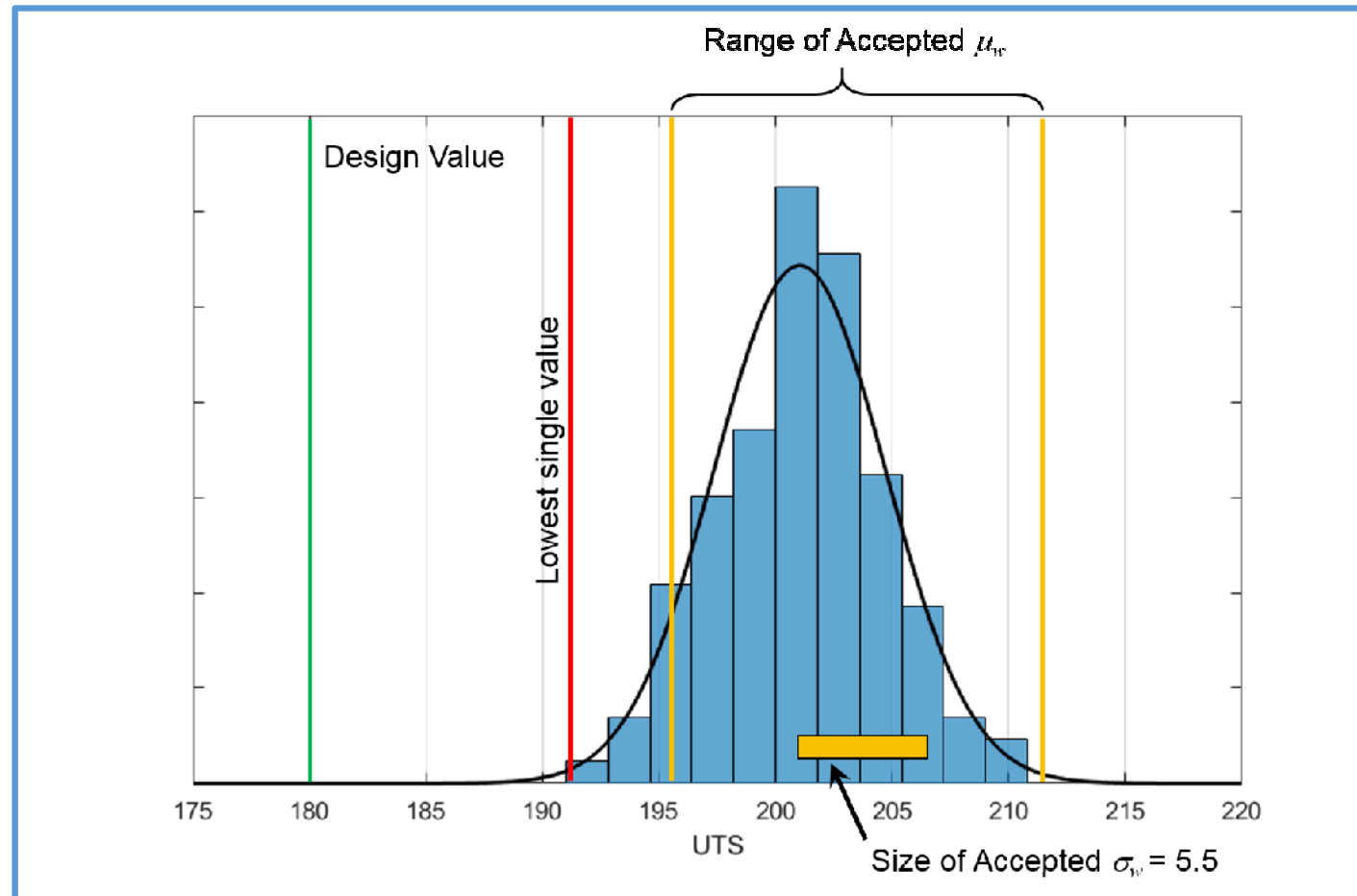
SPC Acceptance
Criteria for
Witness Testing





MPS Backup – PCRD and SPC Criteria

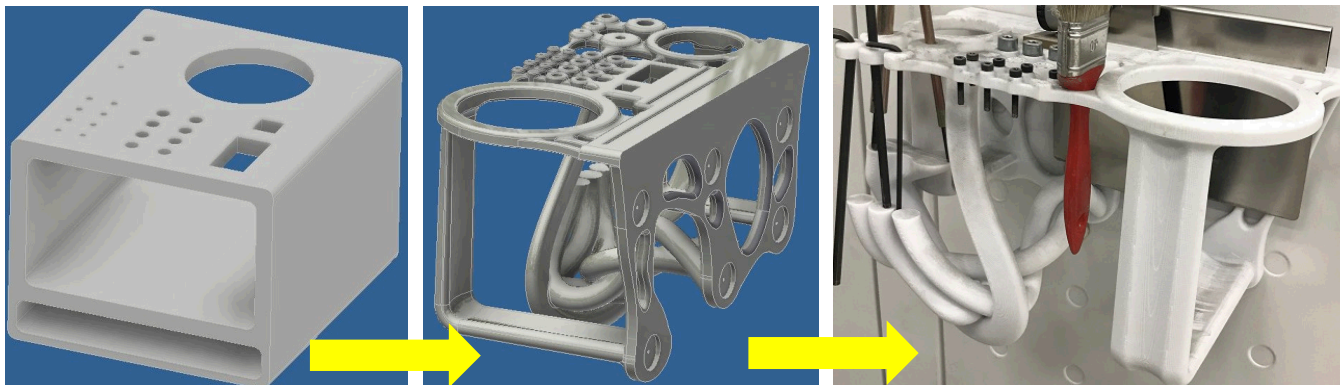
- Witness test acceptance is **not** intended to be based upon design values or “specification minimums”
- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values
- Suggested approach
 - Acceptance range on mean value
 - Acceptance range on variability (e.g., standard deviation)
 - Limit on lowest single value



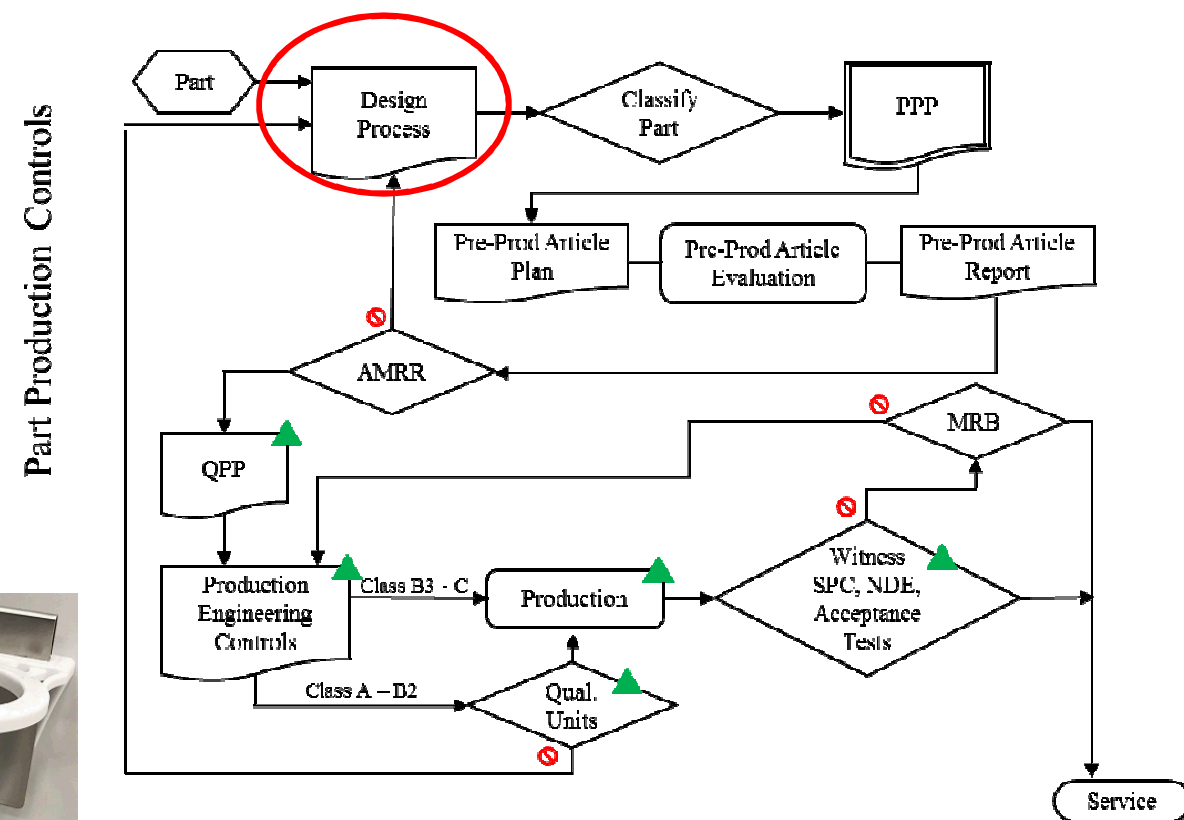
Design Process

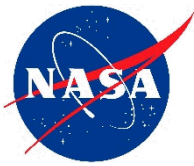
Design For Additive Manufacturing Paradigm Shift

- 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

Part Production Controls

