Methodologies for Qualification of Additively Manufactured Aerospace Hardware

Aircraft Airworthiness and Sustainment (Australia) Conference
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Welcome and Course Objectives

- NASA's Approach to Additive Manufacturing Certification: Methodologies for Qualification of Additively Manufactured Aerospace Hardware
- This course is intended to provide guidance and practical methodologies on how to establish a qualified process and deliver certifiable hardware per the requirements in MSFC-STD-3716 and MSFC-SPEC-3717
- Course Objectives
  - Reinforce a basic understanding of AM processes
  - Become familiar with MSFC-STD-3716 and MSFC-SPEC-3717 requirements for metallic spaceflight hardware
  - Appreciate integrated path to Qualification and Certification
  - Understand products necessary to get you to Qualification and Certification

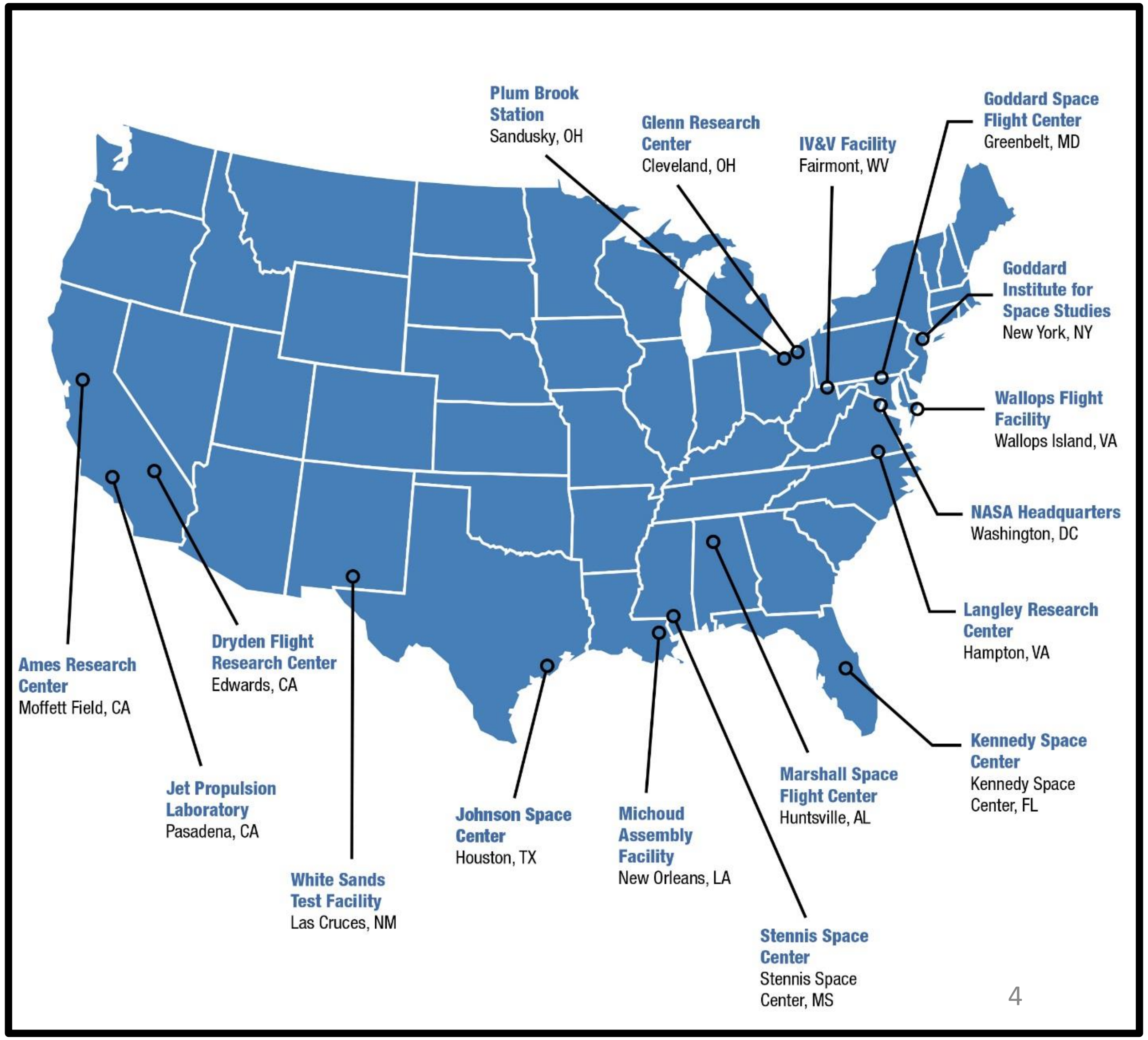
Course Description

Additive Manufacturing (AM) is a disruptive technology that has the potential to revolutionize hardware production and traditional supply chains. For NASA, companies producing human rated liquid rocket engines have been an early adopter of AM. In response the NASA Marshall Space Flight Center has produced MSFC-STD-3716 “Standard For Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion of Metals” and MSFC-SPEC-3717 “Specification For Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes”. These two documents convey the policy and procedures necessary for Marshall to certify components produced using powder bed fusion. The framework established by these documents has been widely accepted by NASA and is being reworked to become NASA Agency level standards which will be written to cover a wider range of AM materials and technologies for all NASA programs. This course will provide guidance and practical methodologies on how to establish a qualified process and deliver certifiable hardware per the requirements in MSFC-STD-3716 and MSFC-SPEC-3717. Where available, examples will be used to demonstrate how a participant could respond to the given requirements.

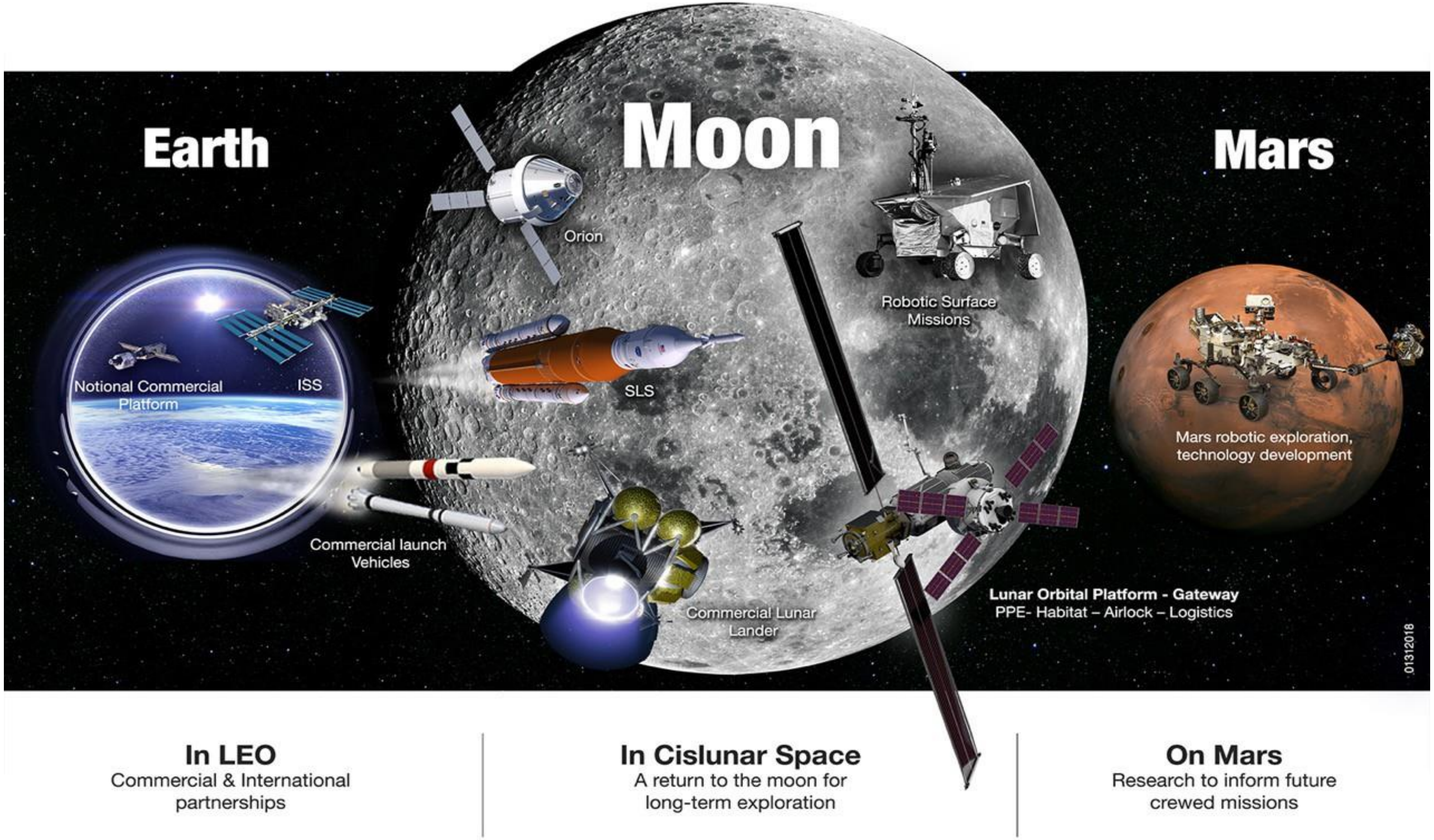
Overview of NASA

NASA is not homogeneous

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



Supporting the Mission

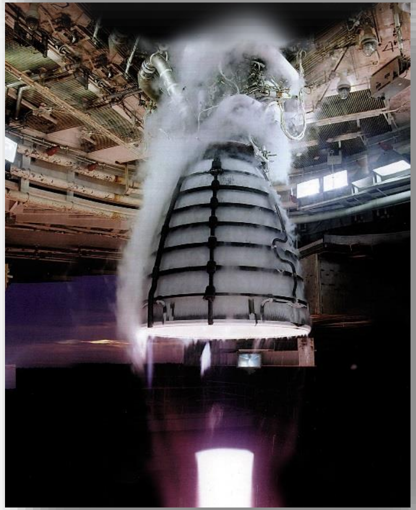


Additive Manufacturing (at MSFC)

- Extensive experience in Additive Manufacturing (AM) technologies, and have been involved in about 30 different AM systems in the past 26 years.
- Over $11.5M capital investments in metallic powder bed systems in the past 5 years, and have committed significant engineering manpower resources
- NASA AM Objectives
  - Decrease production lead time & costs
  - Develop Flight Certification Standards
  - Process development and characterization
  - Share knowledge and data in pursuit of smart vendor base
  - Design optimized components & test at relevant conditions
  - Appropriate Application
    - High complexity & difficult to manufacture
    - Low production rate
    - Long lead time & high cost

Additive Manufacturing at NASA

For-Space:

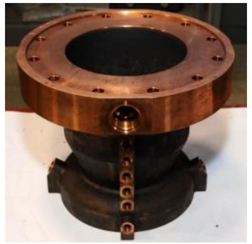


In-Space:

Aerospace Examples

NASA MSFC has also built channel-cooled combustion chambers using L-PBF, but that use bi-metallic additive and hybrid techniques.

- The materials used vary from Inconel® 625 and 718, Monel® K-500, GRCop-84, and C18150 metal alloys.
- Designs tested ranged from 200 to 1,400 psia in a variety of propellants and mixture ratios, producing 1,000 to 35,000 lbf thrust.

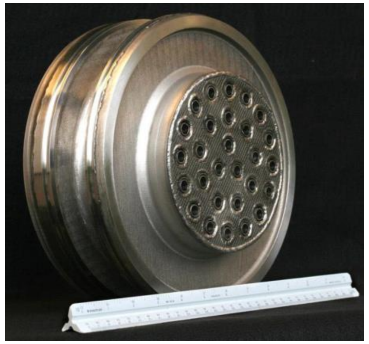





https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625

NASA MSFC rocket injectors made by AM resulting in a 70% reduction in cost.

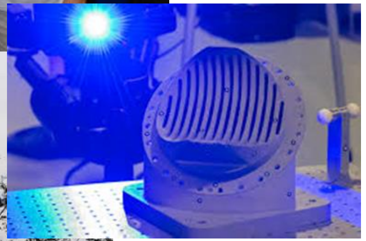
- Using traditional manufacturing methods: 1 Year, 163 parts
- With AM, 4 months. only 2 parts

28-element Inconel® 625 fuel injector built using an laser powder bed fusion (L-PBF) process

https://www.nasa.gov/press/2014/august/sparks-fly-as-nasa-pushes-the-limits-of-3-d-printing-technology/
https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625





RS25 Prime Contractor, Aerojet Rocketdyne, technician exhibits the RS-25 pogo accumulator (top and middle), which was subsequently hot-fire tested (bottom)

- Over 100 Weld Eliminated
- Nearly 35% Cost Reduction

https://www.nasa.gov/exploration/systems/sls/nasa-tests-3-d-printed-rocket-part-to-reduce-future-sls-engine-costs

NASA MSFC AM Standards

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

- Space Launch System
- Orion Spacecraft
- Commercial Crew Program

COMMERCIAL CREW PROGRAM

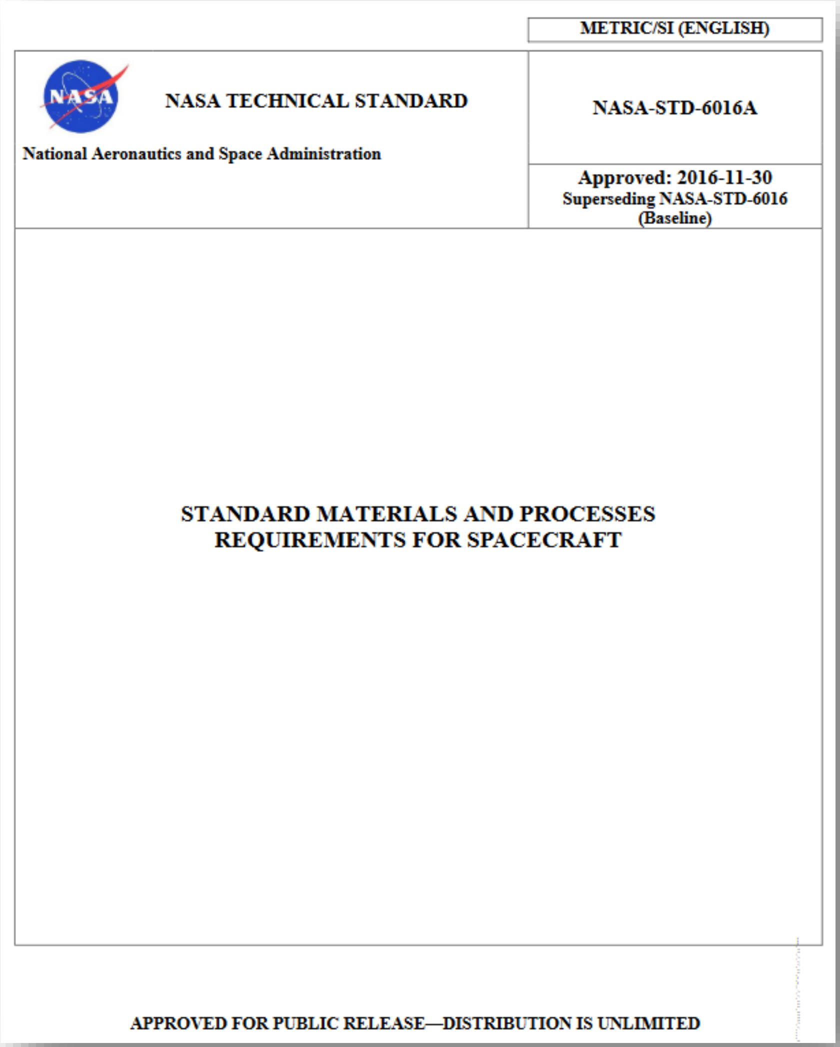
ORION

As a Human Space Flight Center we were faced with the near term action of " How can we trust and certify these parts?"

Definition of Additive Manufacturing

(NASA-STD-6016A Standard Materials and Processes Requirements For Spacecraft)

Additive Manufacturing: Any process for making a three-dimensional object from a 3-D model or other electronic data source primarily through processes in which successive layers of material are deposited under computer control.



METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD National Aeronautics and Space Administration	NASA-STD-6016A
	Approved: 2016-11-30 Superseding NASA-STD-6016 (Baseline)

STANDARD MATERIALS AND PROCESSES REQUIREMENTS FOR SPACECRAFT

APPROVED FOR PUBLIC RELEASE—DISTRIBUTION IS UNLIMITED

NASA-STD-6016A

Standard Materials and Processes Requirements For Spacecraft§

- *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.*

	METRIC/SI (ENGLISH)
NASA TECHNICAL STANDARD National Aeronautics and Space Administration	NASA-STD-6016A
	Approved: 2016-11-30 Superseding NASA-STD-6016 (Baseline)

§ guidance (italics) and requirements excerpts from NASA-STD-6016A

NASA-STD-6016A

Standard Materials and Processes Requirements For Spacecraft§

	METRIC/SI (ENGLISH)
NASA TECHNICAL STANDARD National Aeronautics and Space Administration	NASA-STD-6016A
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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.

§ guidance (italics) excerpts from NASA-STD-6016A

Active Standards for AM within NASA

MSFC-STD-3716 & MSFC-SPEC-3717

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-STD-3716
BASELINE
EFFECTIVE DATE: October 18, 2017

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

STANDARD FOR ADDITIVELY MANUFACTURED SPACEFLIGHT HARDWARE BY LASER POWDER BED FUSION IN METALS

Approved for Public Release; Distribution is Unlimited

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

Policy: MSFC-STD-3716

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-SPEC-3717
BASELINE
EFFECTIVE DATE: October 18, 2017

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES

Approved for Public Release; Distribution is Unlimited

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

Procedure: MSFC-SPEC-3717

https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.pdf

https://www.nasa.gov/sites/default/files/atoms/files/msfcspec3717baseline.pdf

What are the key ingredients?

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

- Most of the traditional certification framework remains consistent
- Only a few items are unique to additive manufacturing certification
- Some roles and responsibilities are transitioned
  - Production facilities now largely responsible for material integrity
  - Statistical process controls required in environments unaccustomed to it

What are the key ingredients?

Some roles and responsibilities are transitioned

Subtractive Forging Process

CoC

1. **Ingot Making**
2. **Cutting**
3. **Heating**
4. **Forging**
5. **Heat Treating**
6. **Machining**
7. **Inspection**
8. **Delivery with CoC**

Additive SLM Process

1. **Powder Making**
2. **Printing**
3. **HIPing**
4. **Heat Treating**
5. **Machining**
6. **Inspection**
7. **Final Part**

Production facilities now largely responsible for material integrity

Statistical process controls required in environments unaccustomed to it

What are “Qualification” and “Certification”?

- Answer varies by industry and even by culture within industries
- The following interpretations are fairly common:
  - Qualification applies to
    - Parts and components
    - Processes
  - Certification applies to
    - Design (e.g. status following Design Certification Review)
    - Subsystems (e.g. engine level certification test series)
    - Integrated system (Collective certification)

Certification is granted by the responsible reviewing authority when the verification process is complete, assuring both design and as-built hardware will meet the established requirements to safely and reliably complete the intended mission.

Overview of Certification Framework

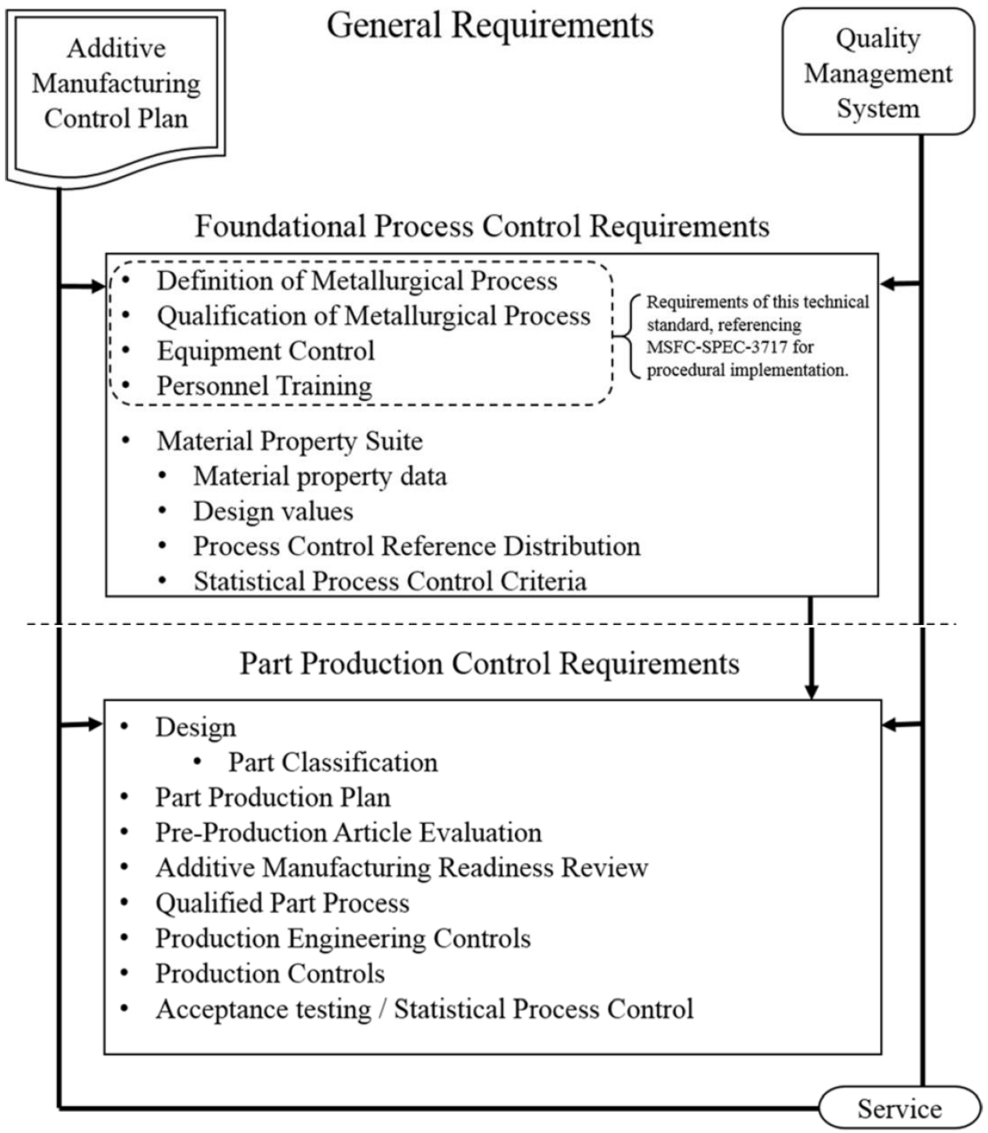
- Have a plan
- Integrate a Quality Management System (QMS)
- Build a foundation
  - Equipment and Facility
  - Training
  - Process and machine qualification
  - Material Properties / SPC
- Part planning
  - Design, classification, Pre-production articles
  - Qualify and lock the part production process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

MSFC-STD-3716 Outline

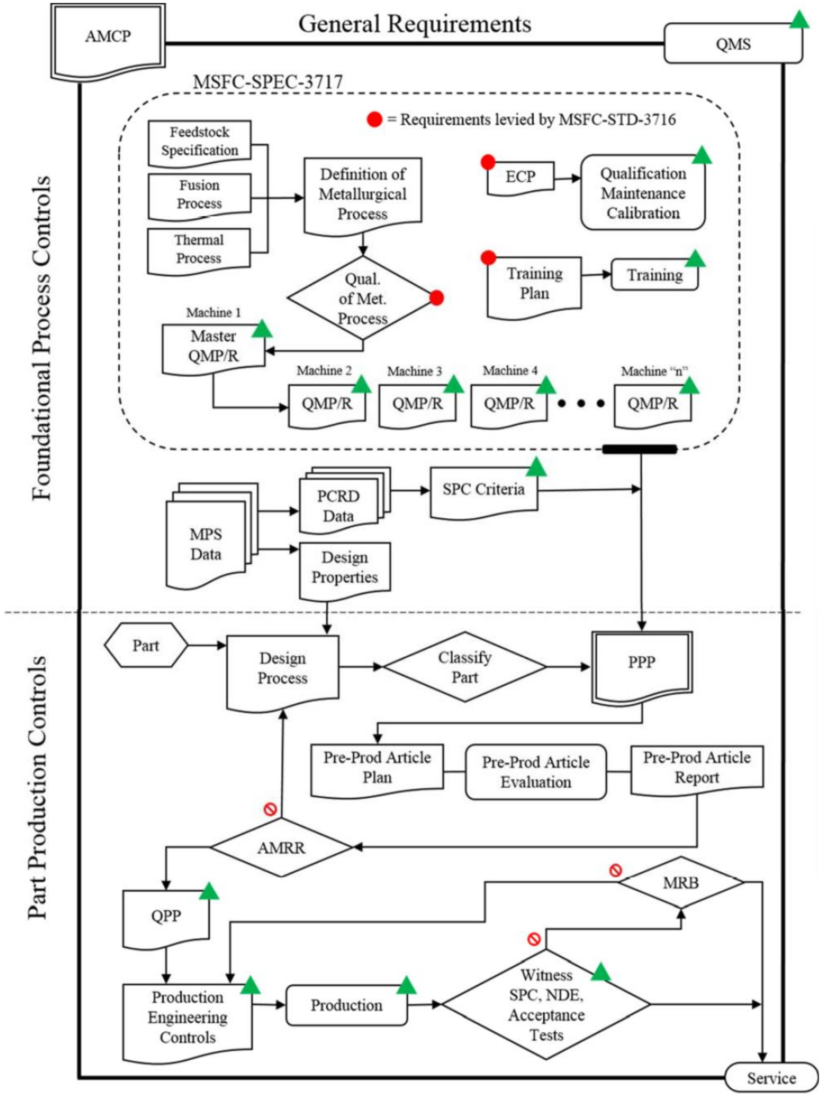
- General requirements in the AMCP govern the engineering and production practice and are paralleled by a Quality Management System (QMS).

- Process control requirements provide the basis for reliable part design and production and include:
  - qualified metallurgical processes (QMPs)
  - equipment controls (ECP)
  - personnel training
  - material property development

- Part Production Control requirements are typical of aerospace operations and must be met before placing a part into service.



MSFC-STD-3716/MSFC-SPEC-3717 Outline



First Part of Class:

Foundational Process Controls

provide the basis for reliable part design and production

Identifies key points of QMS involvement.

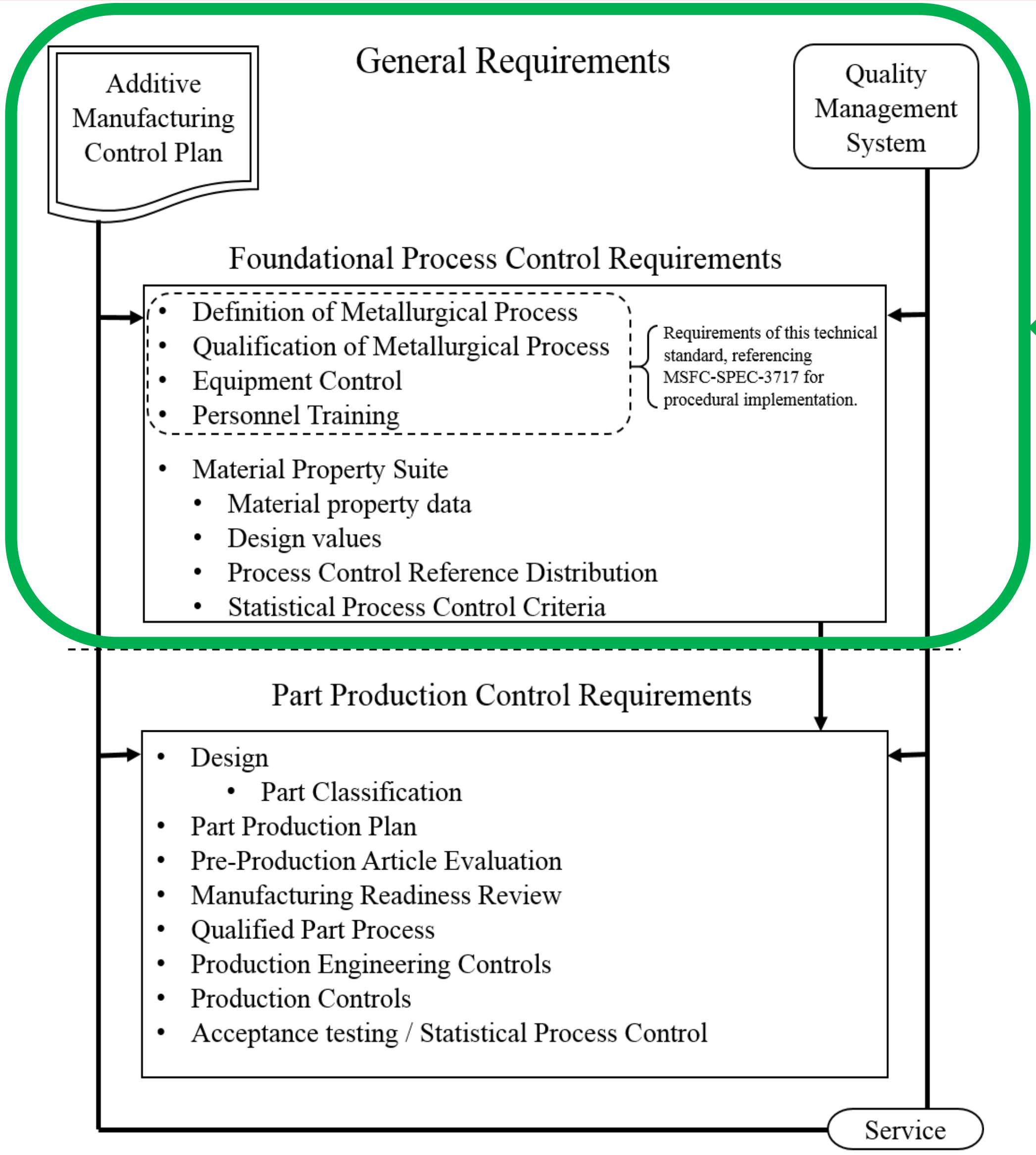
Identifies PBF requirements levied by MSFC-STD-3716 with procedures in MSFC-SPEC-3717

Negative outcome of decisional action

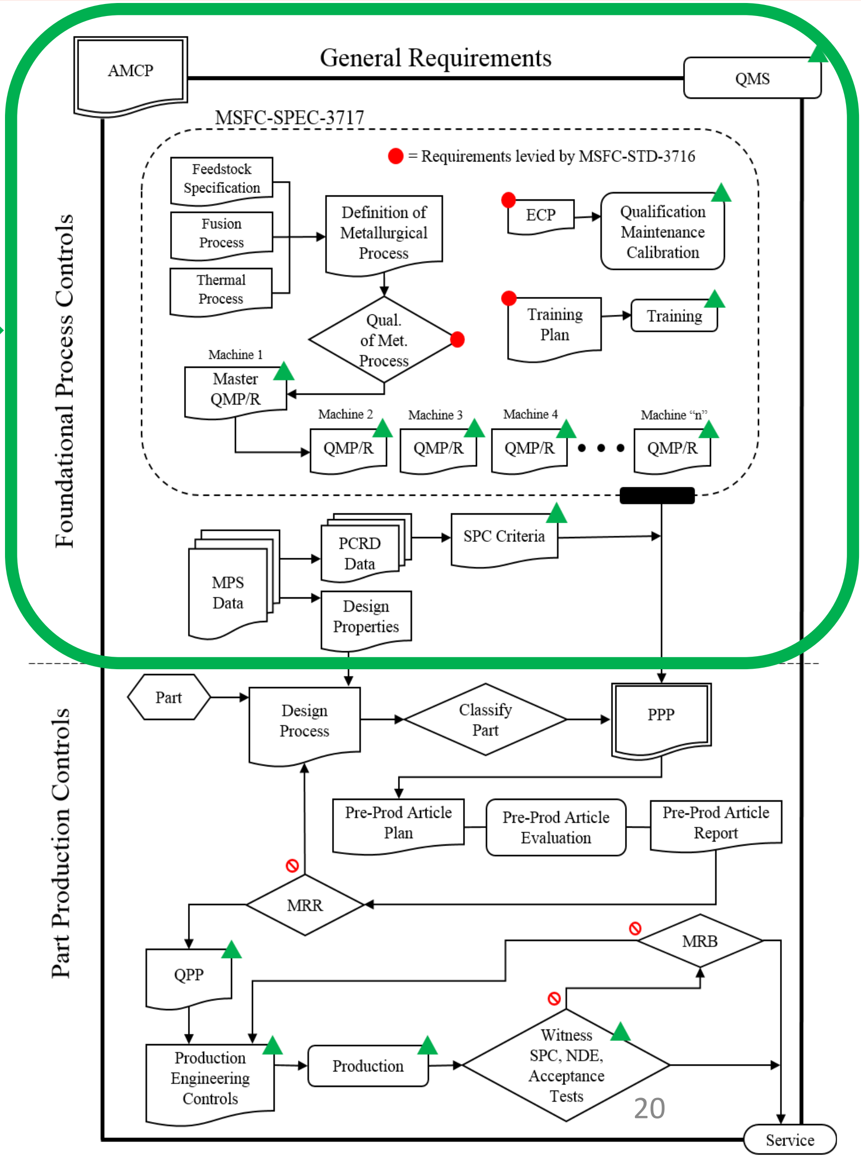
Second Part of Class:

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

Overarching and Foundational Controls



Foundational Process Controls



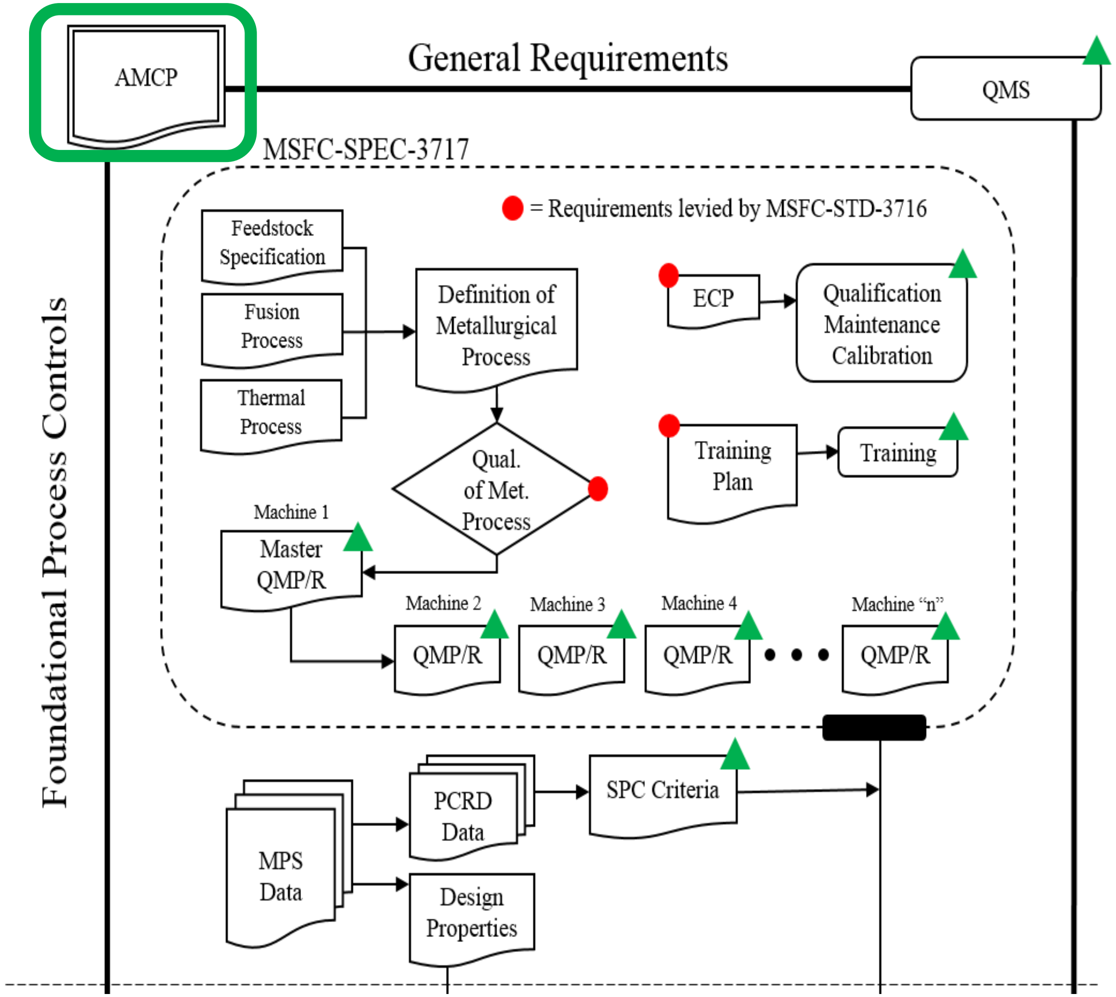
General Requirements
and
Foundational Process Controls

Have A Plan!

Overarching and Foundational Controls

<u>A</u>dditive <u>M</u>anufacturing <u>C</u>ontrol <u>P</u>lan

- 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



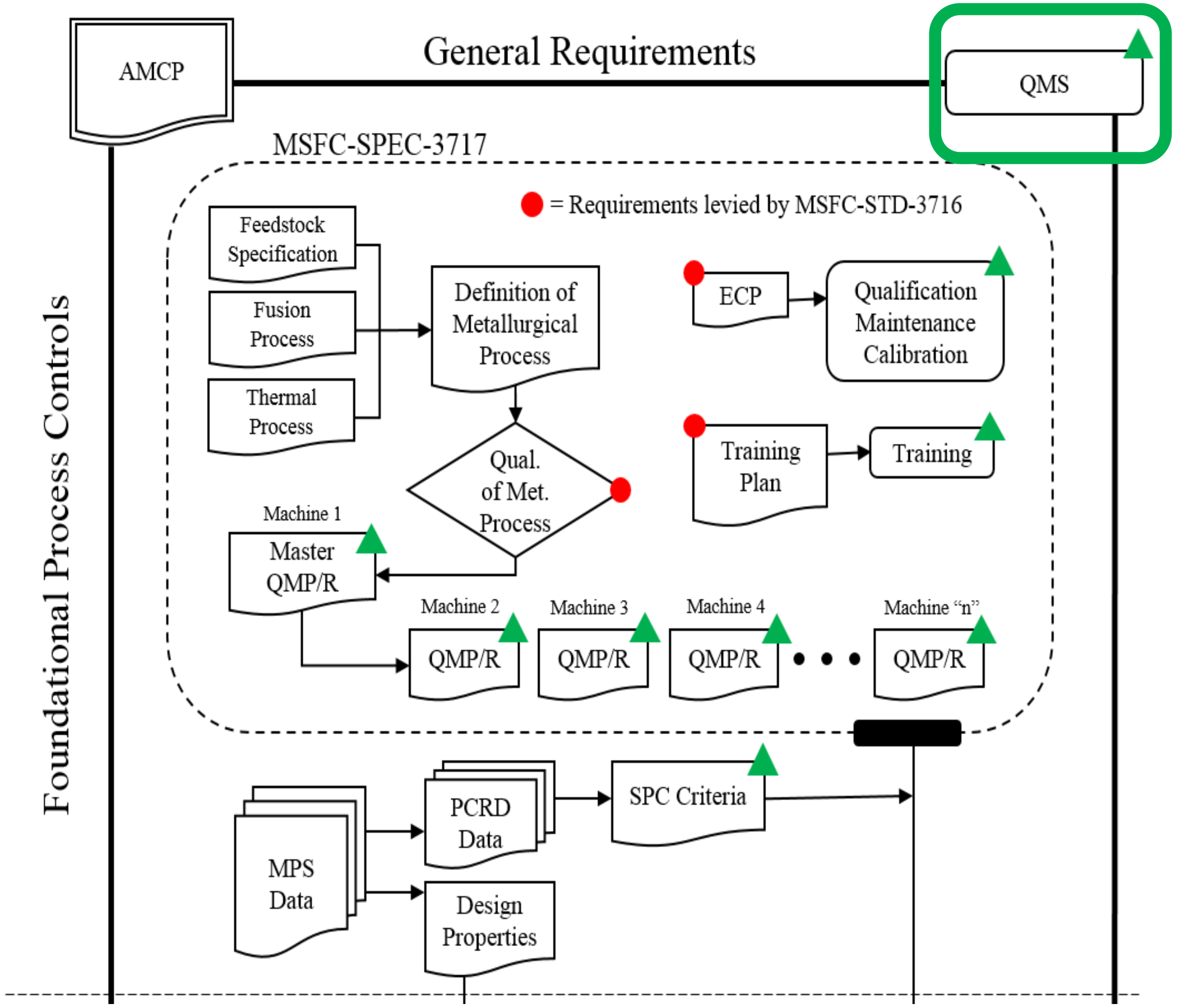
Have a Plan

- Start with a “Big Picture” plan for handling AM
- AM Control Plan
  - Write it down – Communicate it.
  - Authored by the Cognizant Engineering Organization, CEO (The Buck Stops Here)
- Plan should establish practice and policy for all aspects of AM design, production, and part acceptance – tailors policy relative to risk acceptance of the company, organization, or project
- Ensures everyone is on the same page
  - Provides for consistency – particularly important in off-nominal situations
  - Heightened importance when design and production entities are not the same
  - Delineates roles and responsibilities

Overarching and Foundational Controls

Quality Management System

- Critical to maintain consistent implementation policy
- Ensures you stick to your plan and tailoring
- Ensures consistent training, processes and procedures



Integrate a Quality Management System

- The Quality Management System (QMS) must be pervasive
- Long, perilous chain of controls needed
  - Design documentation
  - Feedstock
  - Facility control
  - Machine calibration
  - Digital Thread
  - Inspection
  - Statistical process controls…

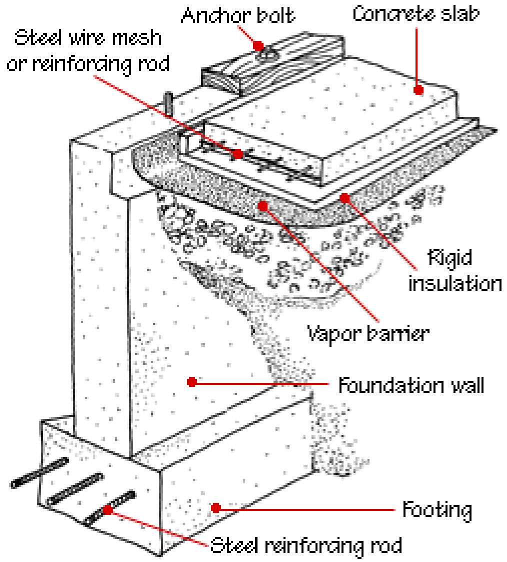
Source: https://www.orielstat.com/blog/medical-device-qms-overview/

- AM is a new process – No common-knowledge standards of practice
- Prepare for "Uh-oh, I ain't never seen that before…" (commonly heard in a North Alabama accent…)

Build a Foundation

Planning for AM certification does NOT start with a part!

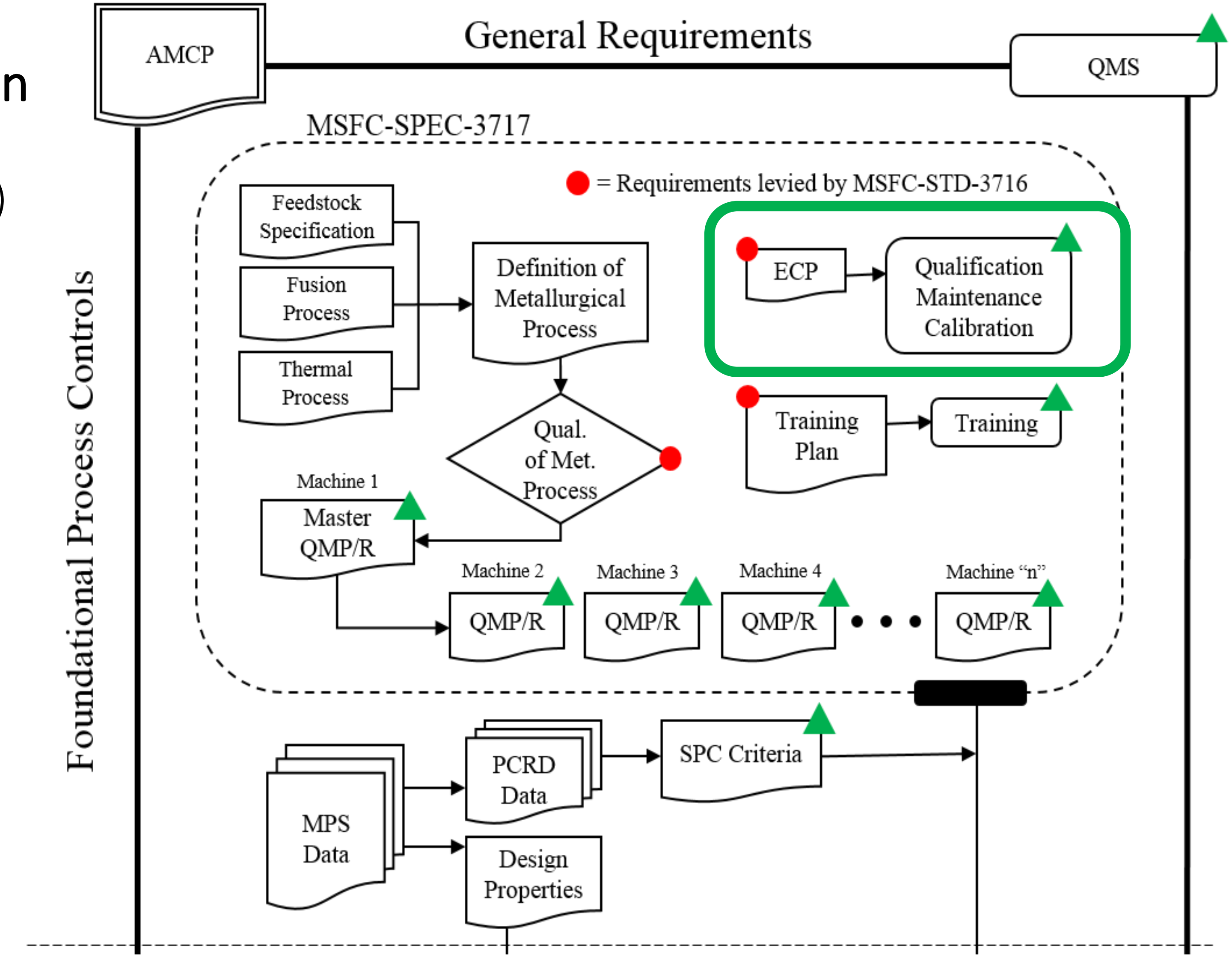
- AM Control Plan should define how the foundation for certification is structured and how it operates
  - Equipment and Facility Controls
  - Personnel Training
  - Process/Machine Qualification
  - Material Properties
  - Statistical Process Controls



Overarching and Foundational Controls

Equipment and Facility Control Plan

- Plan required by Standard (3716)
  - Procedures in Specification (3717)
- Flexibility in implementation
- Governs AM equipment and facility
  - Qualification
  - Maintenance
  - Calibration



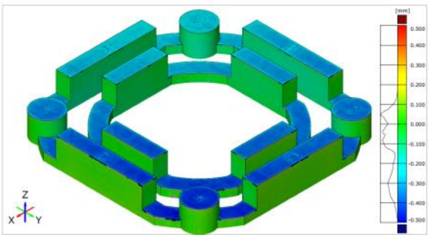
Equipment and Facility Control

Foundation

- Well documented and governed by QMS
- Controls for all AM equipment and facilities
- Significant list of controls needed:
  - Tracking machine configuration status
  - Tracking machine qualification status
  - Maintenance intervals, or unplanned
  - Calibration intervals
  - Feedstock storage and handling
  - Contamination controls
  - Computer security / cybersecurity
  - Standard operating procedures/checklists
  - Handling of Nonconformance in equipment

Concept Laser/GE

EOS M290 Calibration Build 3



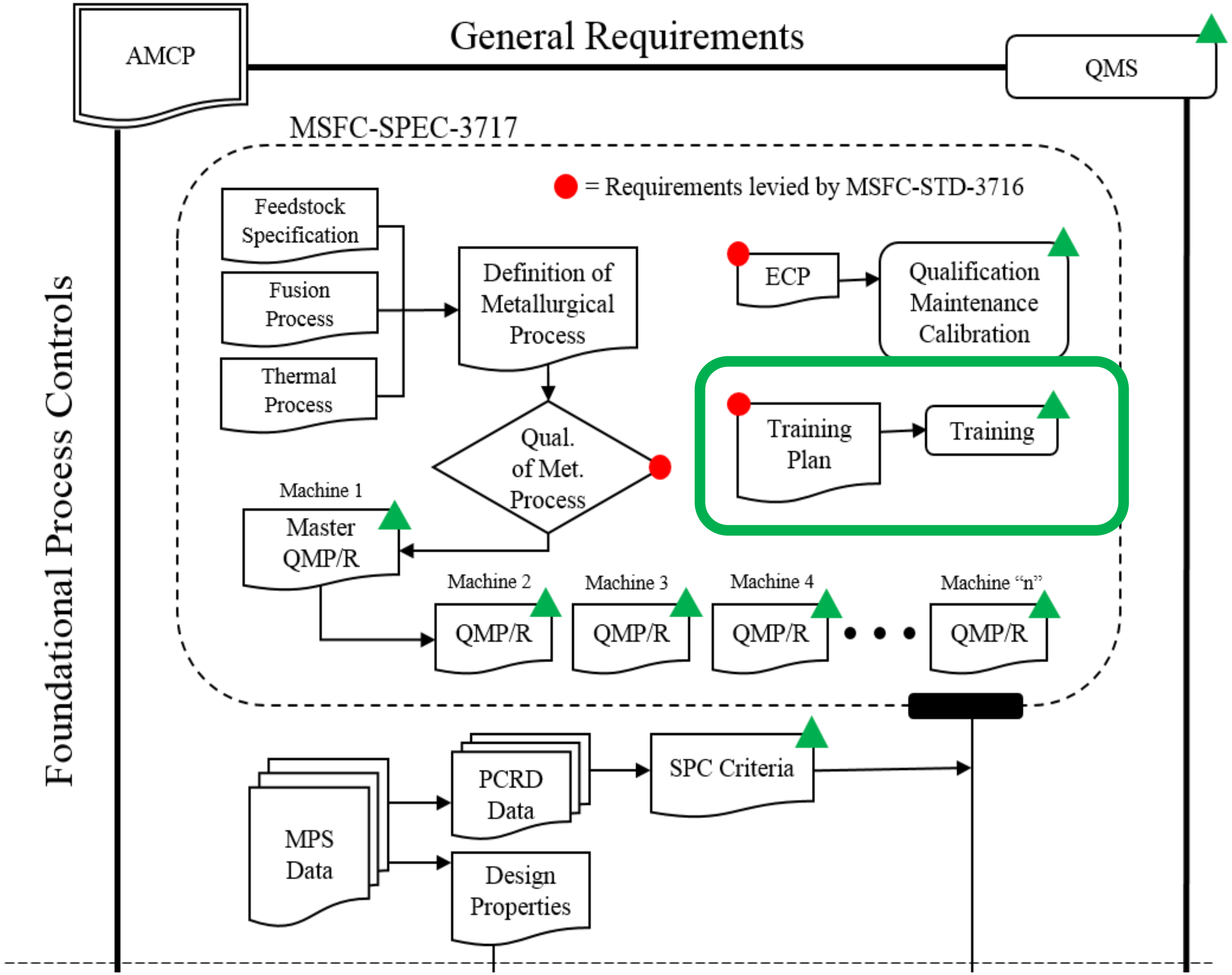
http://vac-u-max.com/view_product.cfm?prod=39

Overarching and Foundational Controls

Foundation

Personnel Training

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



Training

Foundation

Training program to be defined, maintained, and implemented to provide:

- A consistent framework of requirements for training and certification
- Content regarding the importance, purpose, and use of the QMS for all certifications
- Operators with all necessary skills, knowledge, and experience to execute the responsibilities of their certification safely and reliably
- Operator evaluations that demonstrate adequacy in skills, knowledge, and experience to grant certifications to personnel, ensuring only properly trained and experienced personnel have appropriate certifications
- Clear delineations of abilities and responsibilities associated with granted certifications (Technician, maintenance, Engineer)
- Records of all training and certifications

NASA Training Certification Examples

Based On Vendor Training

EM40-OWI-081

Basic Concept Laser Operator

11. PERSONNEL TRAINING AND CERTIFICATION

SHE 102: MSFC SHE PROGRAM REFRESHER TRAINING
SHE 228: RADIATION SAFETY - IONIZING RADIATION PRODUCING DEVICES
SHE 302: CHEMICAL MANAGEMENT TRAINING
SHE 317: MSFC ENVIRONMENTAL COMPLIANCE TRAINING
CONCEPT LASER OPERATOR CERTIFICATION, LEVEL 1, 2

Based On "On the Job Training"

EM40-OWI-077

Structured Light Scanning and Photogrammetry

1. PERSONNEL TRAINING AND CERTIFICATION

1.1. Operator Certifications

1. Only certified operators or someone under the supervision of a certified operator shall operate equipment.
   a. If it is determined that data was collected by a person not having proper or expired certification, a review shall be conducted to determine the validity of the data.
   b. This review shall be conducted by the NASA Team Lead, or delegate. This review will determine whether the data shall be discarded or used.
2. An operator's certification shall be revoked when:
   a. The individual is no longer employed by NASA or one of its contractors
   b. The reason is documented and concurred with by the following:
      i. The Team Lead of the Additive Manufacturing and Digital Solutions Team
      ii. The Branch Chief of the Advanced Manufacturing Branch
      iii. The Division Chief of the Nonmetallic Materials & Advanced Manufacturing Division
3. Certifications shall be valid for two (2) years from the date of certification.
4. A list of certified operators shall be maintained and stored in accordance with the Records Section of this document.
5. For a person to receive or renew their certification, the following shall be met and or demonstrated:
   a. Level 1 Certification
      i. Read this Organizational Work Instruction in its entirety
      ii. Complete training classes as provided by the hardware vendor, or provided by a certified operator. Areas listed below shall be addressed in this training
         1. Photogrammetry best practices and application
         2. Structured light scanning best practices and application
      iii. Complete a six (6) month mentorship under a certified engineer
      iv. Candidate shall exhibit the following:
         1. The ability to unpack and setup the equipment
         2. Power up equipment
         3. Calibrate scanner
         4. Change volumes on scanner
         5. Change cameras and focus cameras
         6. Pick the correct scan volume to receive desired accuracy
         7. Place photogrammetry targets (coded and uncoded) and scale bars, perform photogrammetry, and have the session solve with a scale bar deviation of less than 0.002 inches.
         8. Conduct full lens calibration and set up
         9. Demonstrate the ability to collect structured light scan data on an object that has had photogrammetry data collected.

   b. Level 2 Certification
      i. Obtain Level 1 Certification
      ii. Complete an additional six (6) month mentorship under a certified Level 3 certified person
      iii. Candidate shall exhibit the following:
         1. Ability to conduct basic analysis of structured light data
         2. Ability to generate point cloud data
         3. Conduct Geometric dimensioning and tolerancing analysis
         4. Demonstrate ability to align complex datasets
   c. Level 3 Certification
      i. Obtain level 2 Certification
      ii. Candidate shall exhibit the following:
         1. Demonstrate ability to set up and collect structured light and photogrammetry data on large complex structures
         2. Ability to conduct detailed geometric analysis of large structures
         3. Demonstrate ability to utilize automation in data processing

Qualified Metallurgical Process

Foundation

Qualified Metallurgical Process

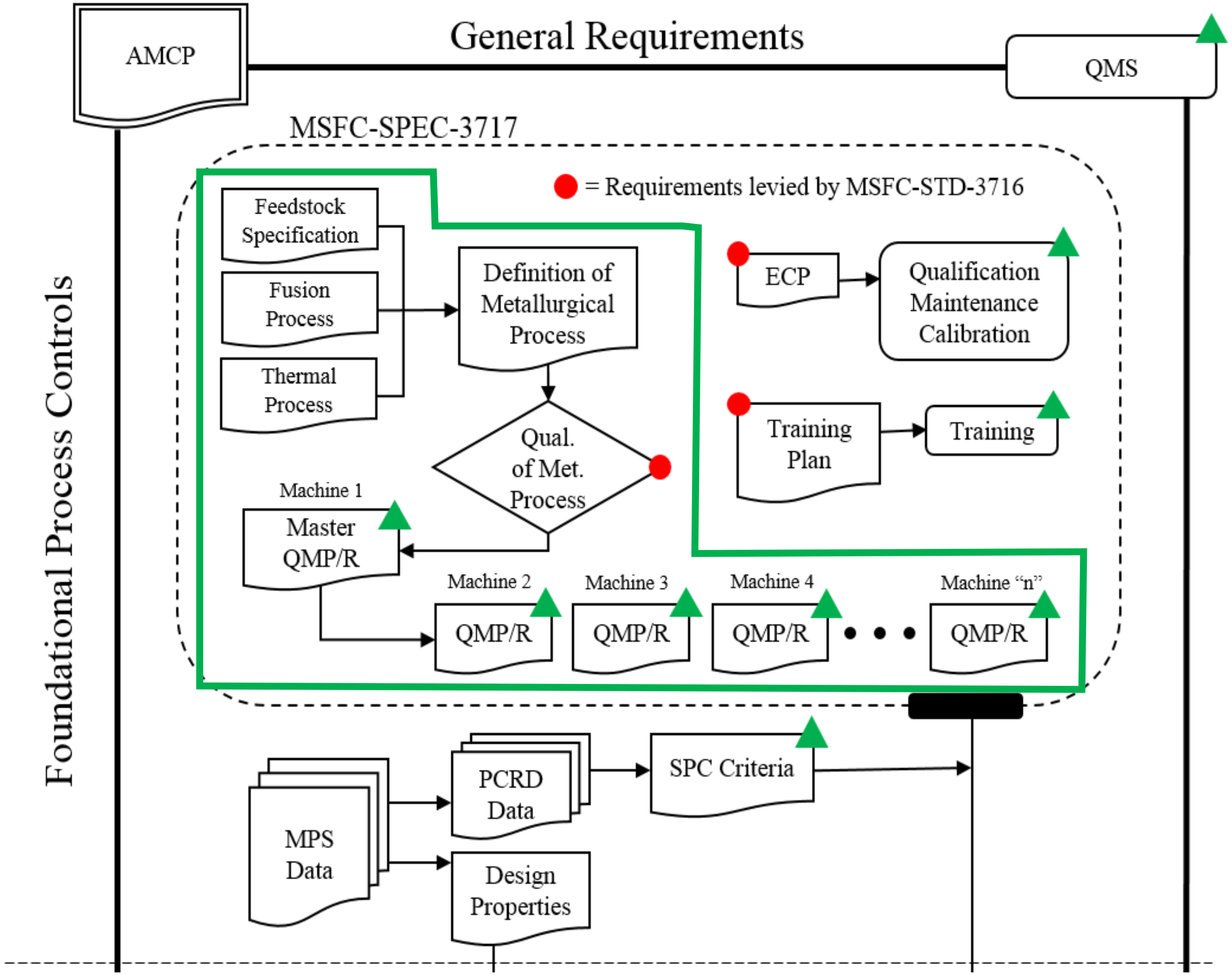
Begins as a ***Candidate*** Met. Process

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

- Feedstock
- Fusion Process
- Thermal Process

Enabling Concept

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



Process/Machine Qualification

Foundation

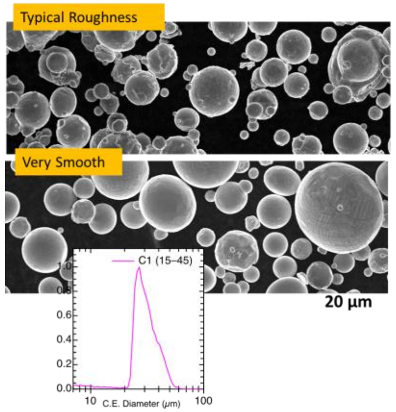
Currently in AM, machine and process are indelibly linked

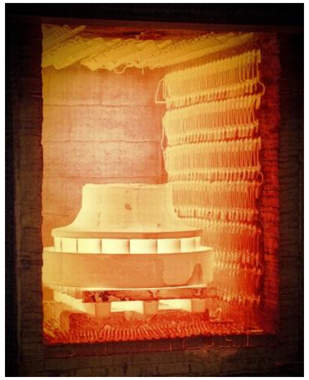
Step 1. Define a candidate process

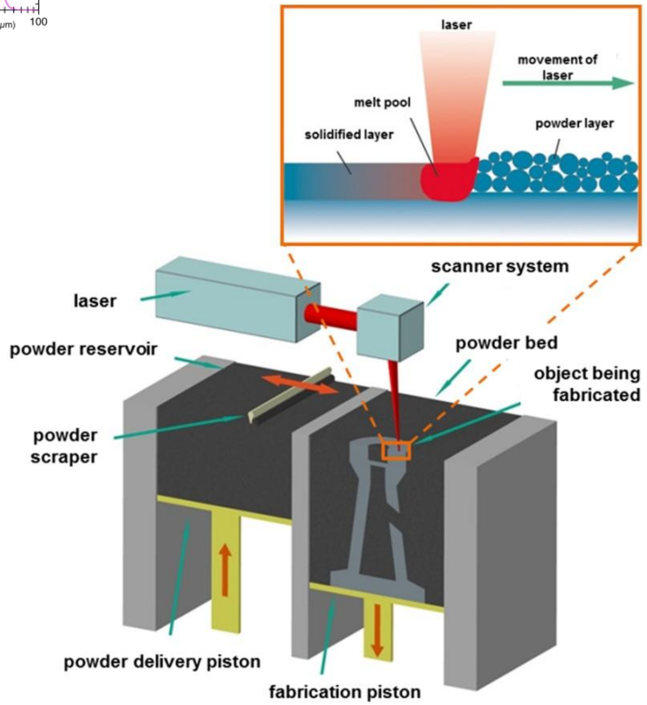
a) Material feedstock controls
b) AM process conditions and machine configuration
c) Post-processing that influences material performance

Step 2. Qualify the candidate process to well-defined metrics, for example:

a) As-built material quality (fill and interfaces)
b) Consistency throughout build envelope
c) Appropriate detail and surface quality
d) Tolerance to inherent process perturbations (thermal or otherwise)
e) Mechanical and/or physical properties







Candidate Metallurgical Process

Foundation

Definition of Metallurgical Process

Feedstock Controls

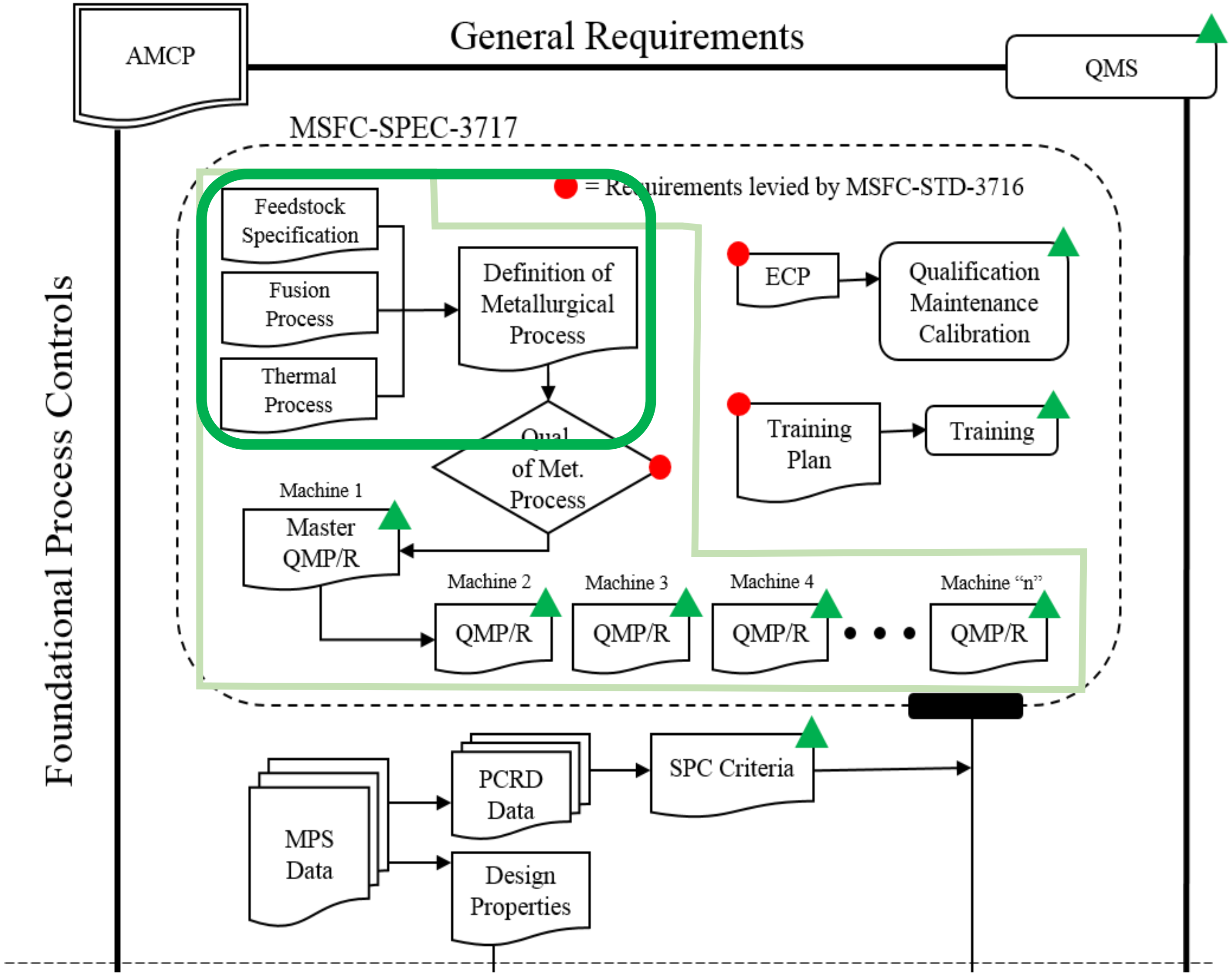
- What you are Building with

Fusion Process

- How a machine operates

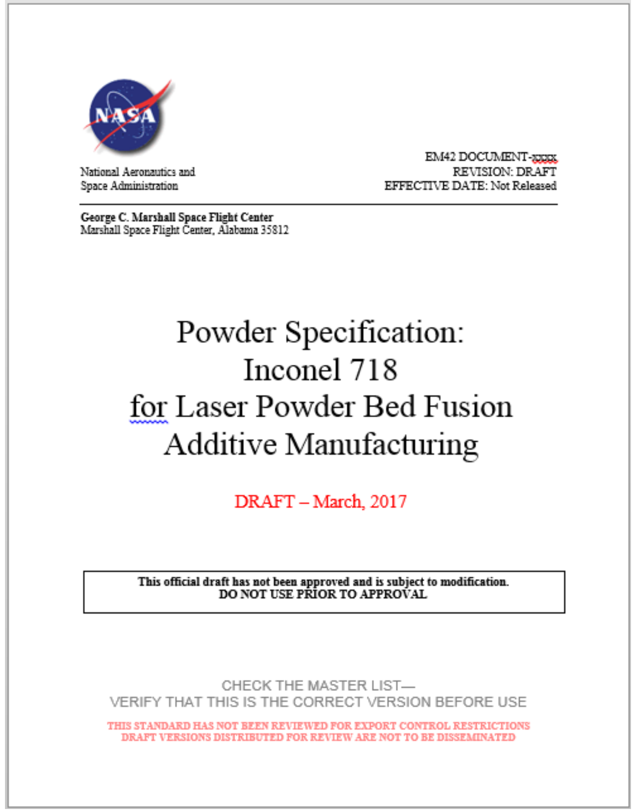
Thermal Process

- Control what Evolves your Material State



Feedstock Controls

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



National Aeronautics and Space Administration

EM42 DOCUMENT-xxxx
REVISION: DRAFT
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Powder Specification:
Inconel 718
for Laser Powder Bed Fusion
Additive Manufacturing

DRAFT – March, 2017

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
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THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
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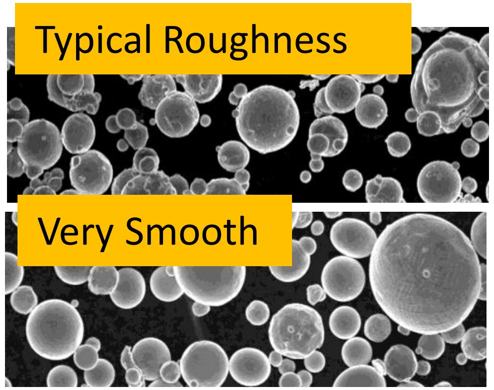
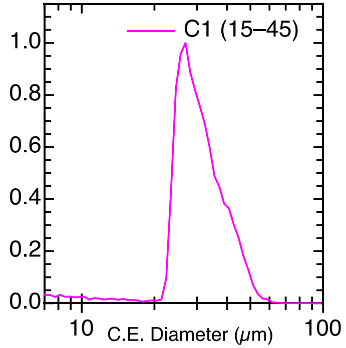
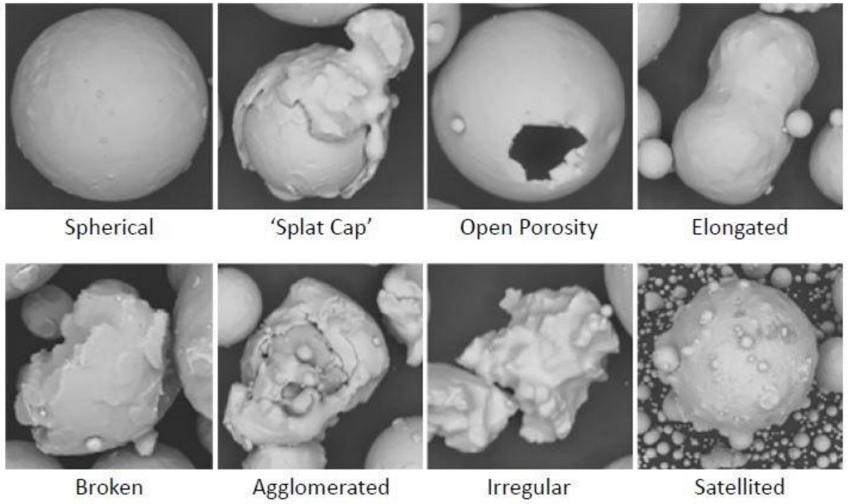




20 μm



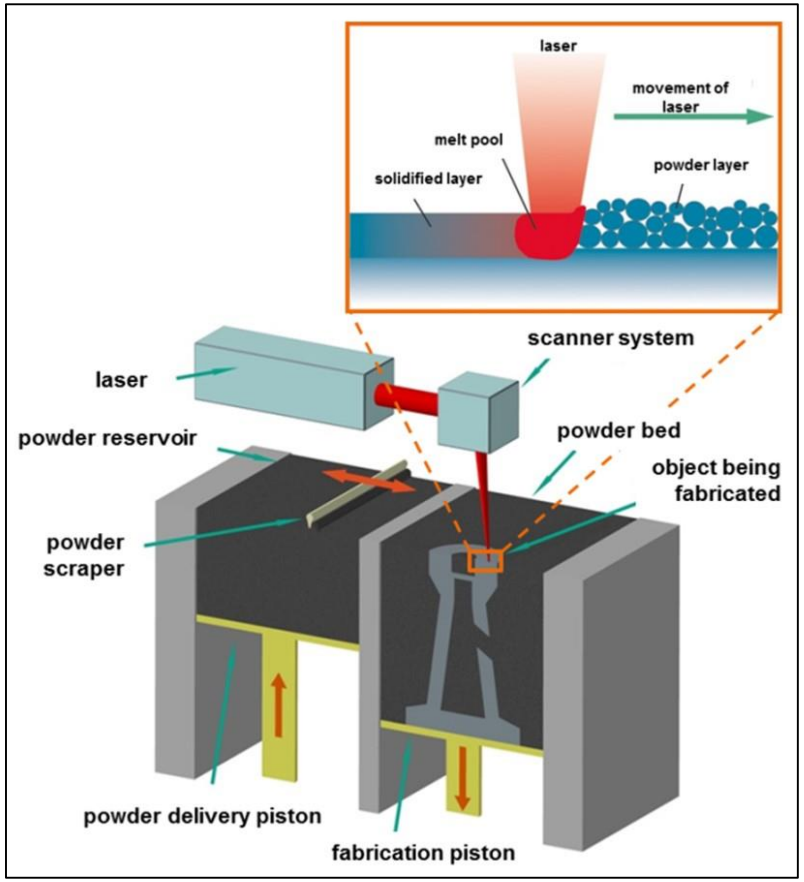
Powder Morphology. Courtesy Metal AM, Winter 2017.

Candidate Metallurgical Process

Foundation

Fusion Controls

- Equipment:
  - Make, Model, *Serial Number*
  - Software/Firmware versions
  - Settings (dosing, recoater speed)
- Atmosphere Controls
  - Oxygen limits
  - Ventilation flow rate
  - Gas quality (purity, dew point)
- Fusion Parameters
  - Layer thickness
  - Power, speed, hatch, contours…
- Table I, MSFC-SPEC-3717



Source: Fraunhofer IWU

<u>Any Machine Parameter that affects Material Quality must be Controlled!</u>

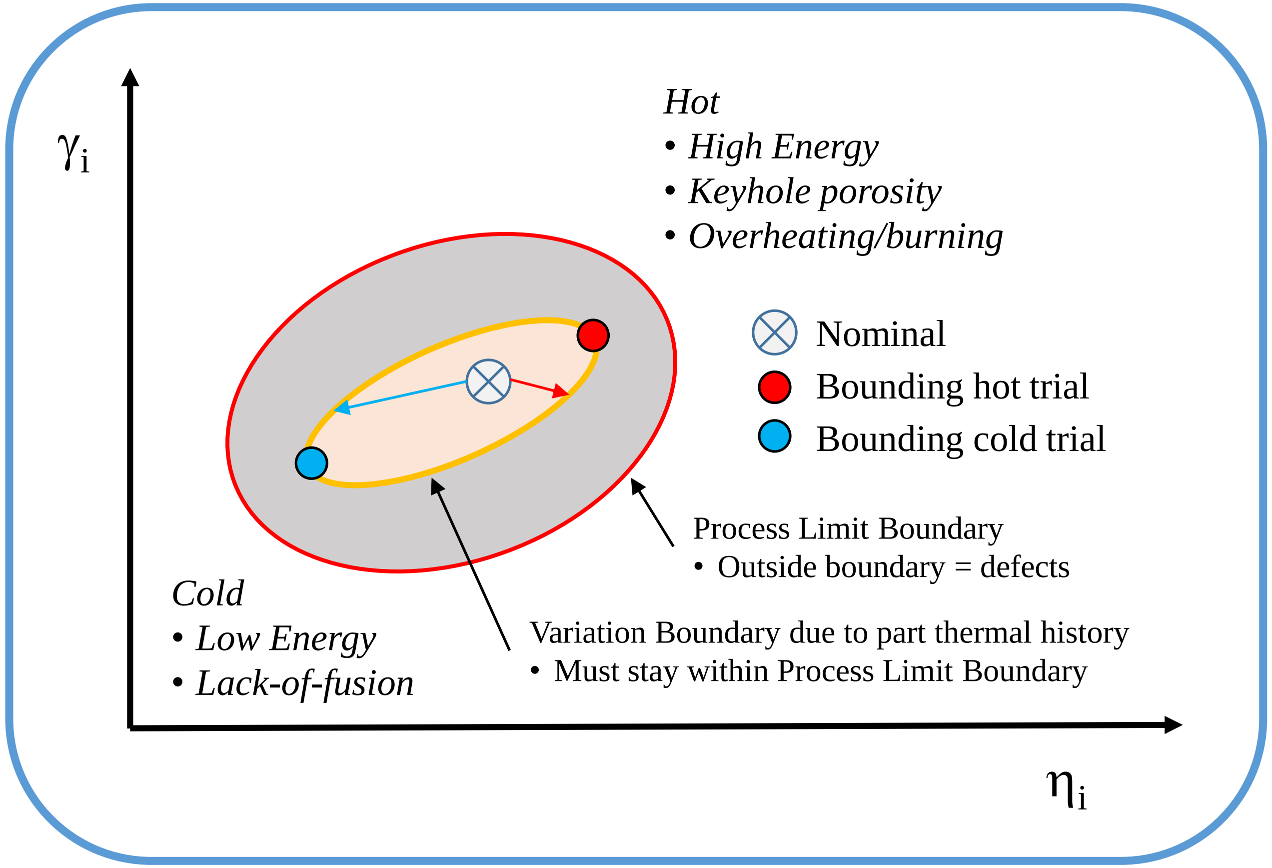
Candidate Metallurgical Process

Foundation

Fusion Controls

<u>Tolerance to variation</u>

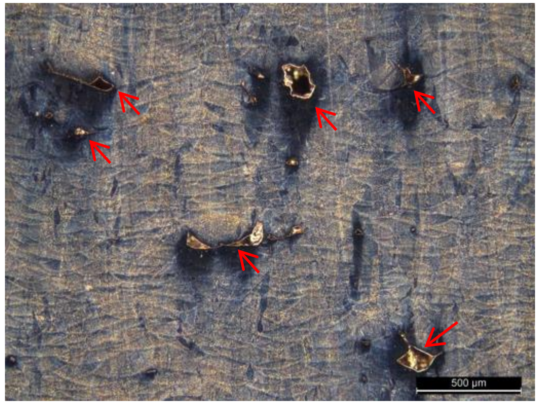
- Part build scenarios create variation in process conditions
  - Thermal history effects
  - Scan patterns
- “Process Box” evaluation for qualification
- QMP needs to be “centered” in the process box to allow robust part build capability
- Process Restarts



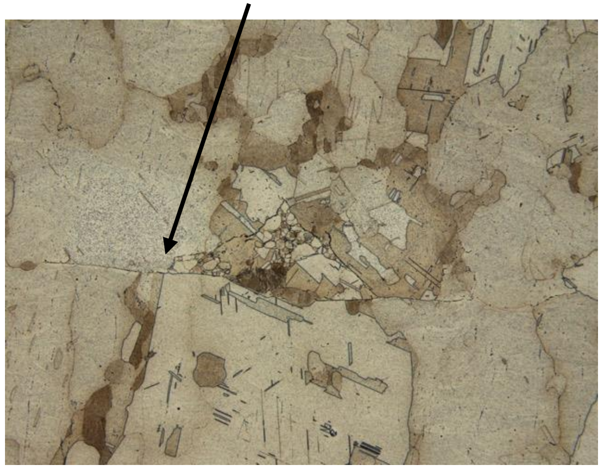
Process Box: Resulting variations in nominal commanded process due to part geometry, scan pattern and thermal history
Axis: Representative of any parameters, i.e. power, speed

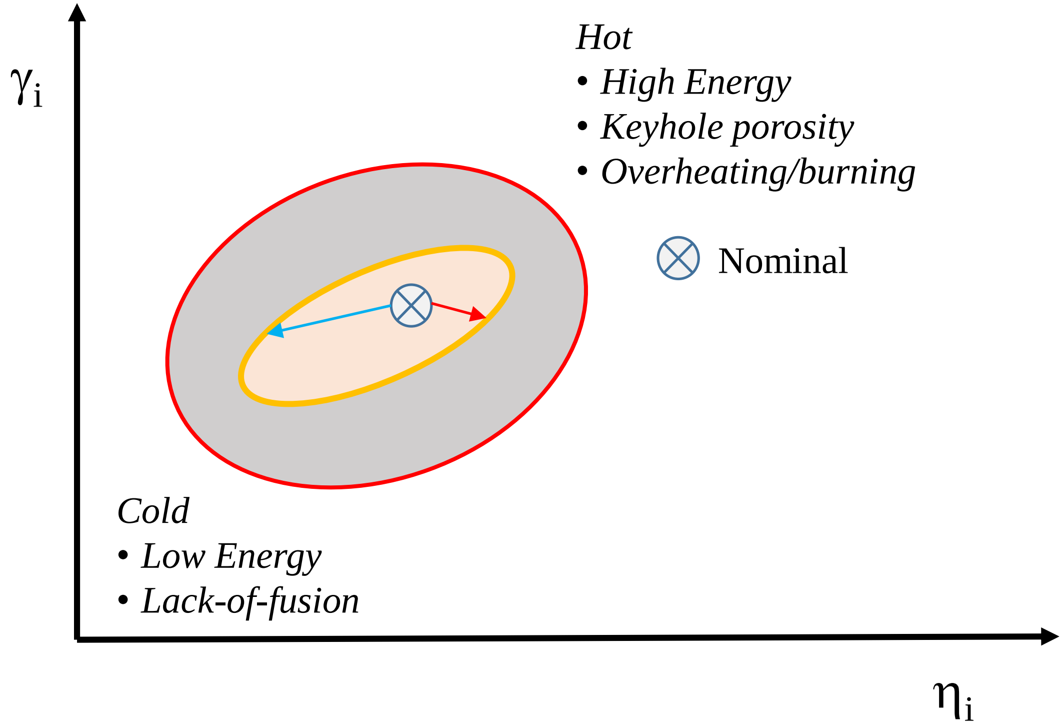
Parameter Influence on Defects

Lack of Fusion Defect



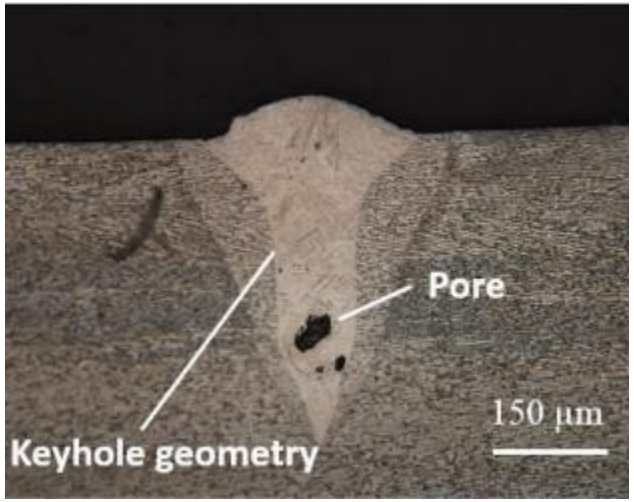
Lack of Fusion Defect after HIP



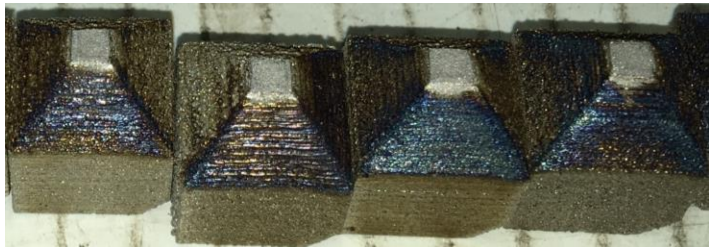


Process Box: Resulting variations in nominal commanded process due to part geometry, scan pattern and thermal history

Axis: Representative of any parameters, i.e. power, speed



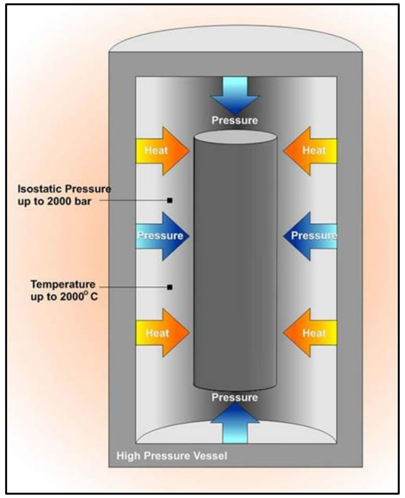
Everton, Sarah & Dickens, Philip & Tuck, Christopher & Dutton, B. (2019). IDENTIFICATION OF SUB-SURFACE DEFECTS IN PARTS PRODUCED BY ADDITIVE MANUFACTURING, USING LASER GENERATED ULTRASOUND.

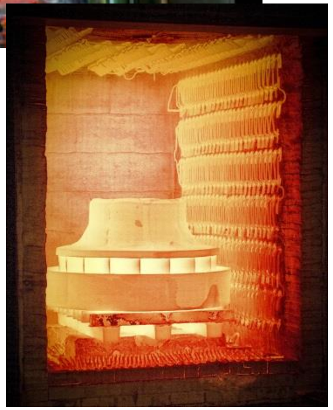


Thermal Process

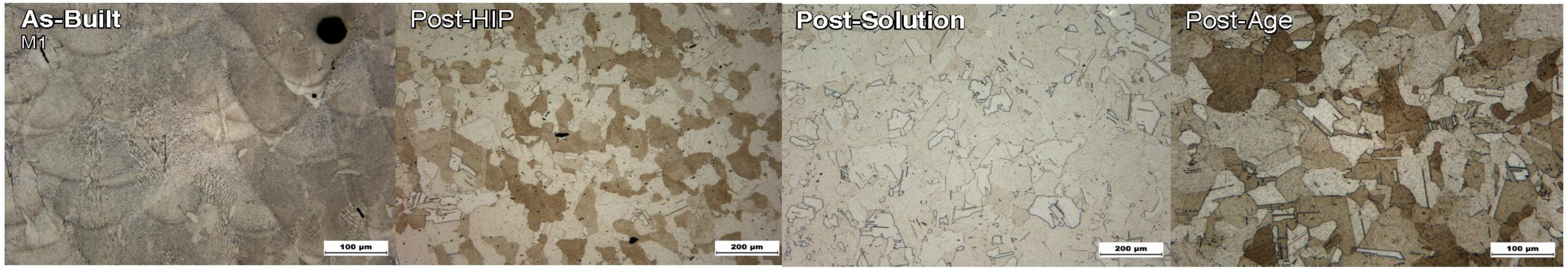
<u>Post-build Thermal Processing</u>

- Includes definition of all thermal process steps
- ***Evolution of microstructure*** *with acceptance criteria for As Built and Final*
- Stress Relief, Hot Isostatic Pressing, Solution Treating, Aging, etc.





IN718 Microstructural Evolution



Candidate Metallurgical Process

Foundation

- Reference QMP for Example Only

L-PBF Qualified Metallurgical Process Record

QMP Title: QMP-MSFC-M290-INC718-SR-HIP-5664-0	
QMP Record Number: QMP-MSFC-M290-INC718-SR-HIP-5664-0	
Check as applicable: x Master QMP ☐ QMP, based upon Master QMP: ☐ Customized QMP (Complete Customized L-PBF Metallurgical Process Definition Section)	
General Description: Powder bed fusion Inconel 718	
RESTRICTIONS ON USE: N/A	
QMP Approval Statement: All necessary data for qualification of this metallurgical process to the requirements of MSFC-SPEC-3717 has been reviewed, judged acceptable, and archived.	
L-PBF Process Vendor Approval:	Date:
CEO Approval: Brian West	Date:3/1/19

L-PBF Metallurgical Process Definition

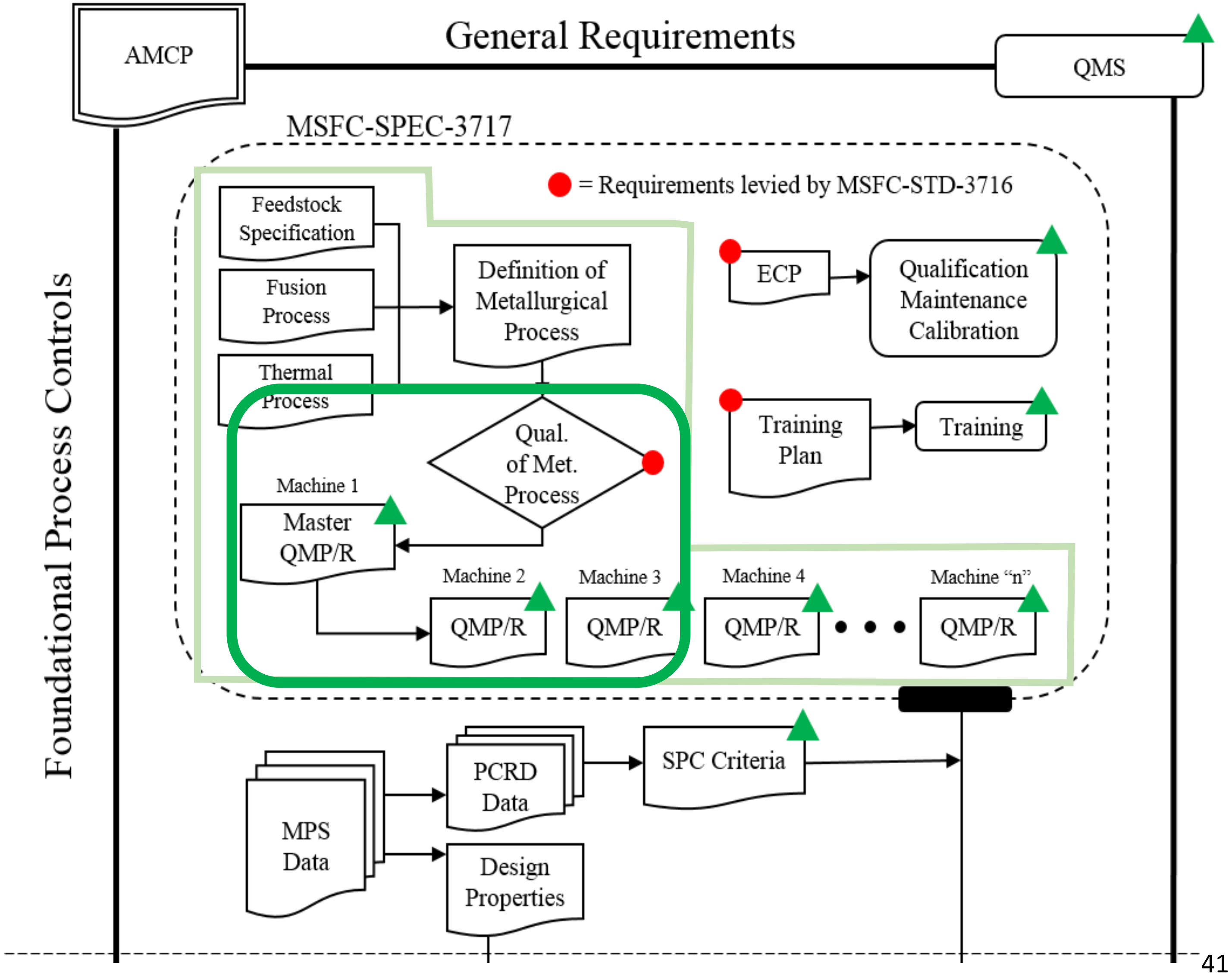
Powder Feedstock			
Feedstock Specification:	EM-42 Additive Manufactured Inconel 718 Powder Specification		
Reuse protocol:	50 Cycles		
Fusion Process Controls			
Machine ID:	M 290	Model/Model:	EOS M 290
Serial Number:	SI 2669	Configuration Date:	10/30/2017
Software Version:	EOSPRINT1.5	Firmware Version:	2.4.14.0
Recoater Configuration:	Carbon fiber		
Build platform material:	Stainless steel		
Preheat temperature:	80℃		
Nominal dosing range:	Variable		
Purge Gas composition:	Argon		
Ventilation flow rate:	TBD		
Ventilation setting:	15%-20%		
Diffuser configuration:	Stock		
Dew point limit:	N/A		
Oxygen limit:	N/A		
Temperature limits:	N/A		
Fusion Parameter File:	2017-0998 M290 QualBuild.eosjob	Hash:	D189F7FFC70D8BCF5CBE34A6D3F92542
Layer thickness:	0.04 mm		
Other:	N/A		
Thermal Process	Builds processed per this QMP will receive the following thermal treatments: 1. Stress Relief: 1950°F ± 25°F for 1.5 hrs. -5/+15 min., furnace cool with venting to air as soon as allowable. Foil wrapping of parts required. 2. Hot Isostatic Press (HIP): Foil wrapping of parts required. 3. Solution Treatment (AMS 5664): 1950°F ± 25°F for 1 hour (or time commensurate with cross sectional area) in an inert atmosphere, followed by cooling at a rate of air cooling or faster. Precipitation Treatment (AMS 5664): 1400°F ± 15°F for 10 hrs ± 0.5 hrs, furnace cool to 1200°F ± 15°F, hold at 1200°F ± 15°F until a total aging heat treatment time of 20 hours has been reached, cool.		

Qualified Metallurgical Process

Foundation

Qualification of the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

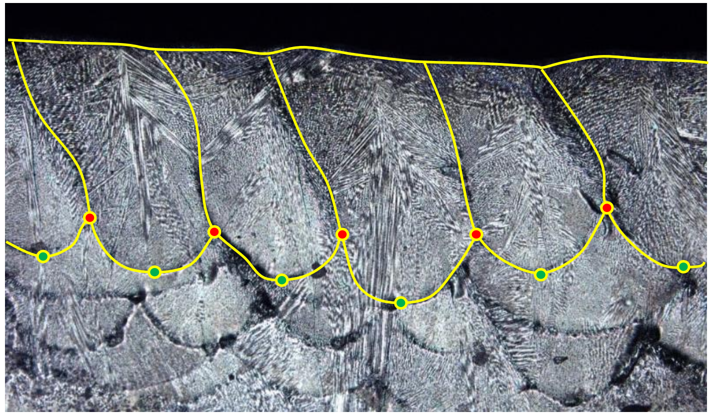


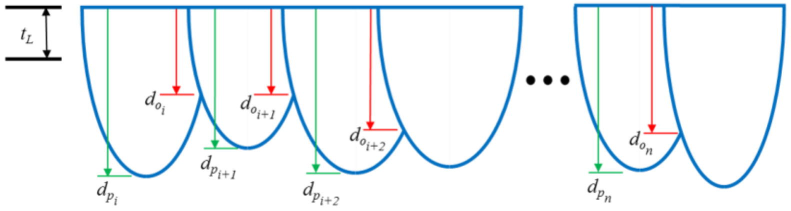
Qualified Metallurgical Process

Foundation

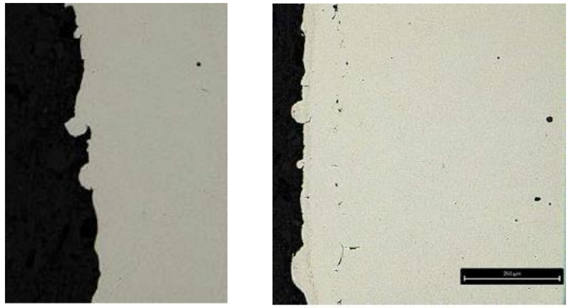
Step 1: Metallurgical Qualification

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

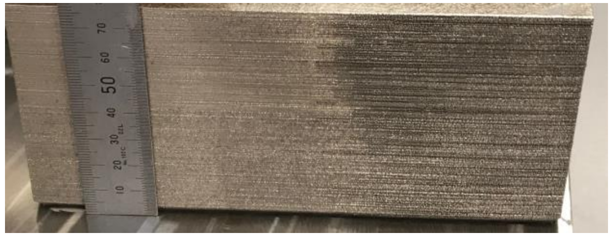




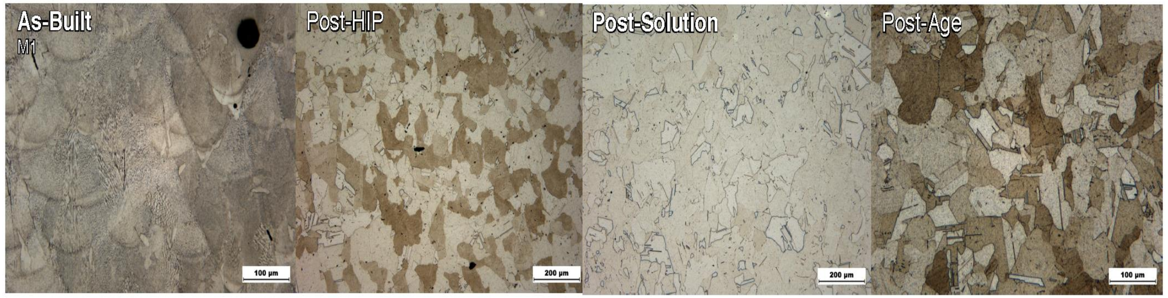
Melt Pool Evaluation



Contour Evaluation



Transition Zone



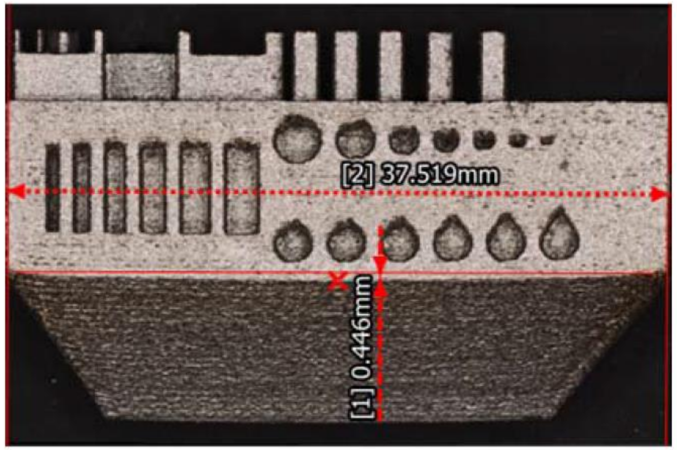
Microstructure Evolution

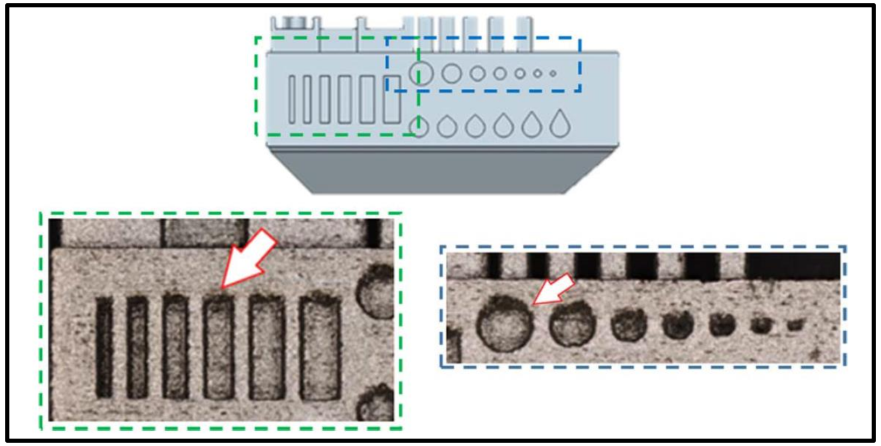
Qualification of the Candidate Metallurgical Process

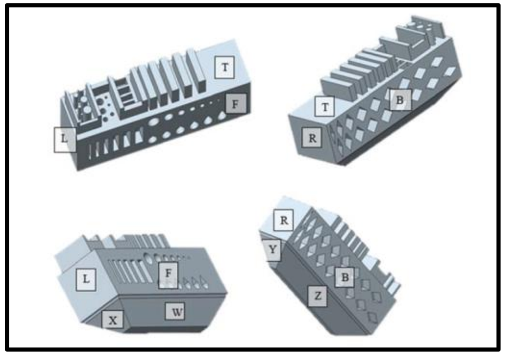
Establishes a QMP: Qualified Metallurgical Process

Step 2: Surface texture and detail resolution

- Reference Parts
- Mix of qualitative and quantitative measures





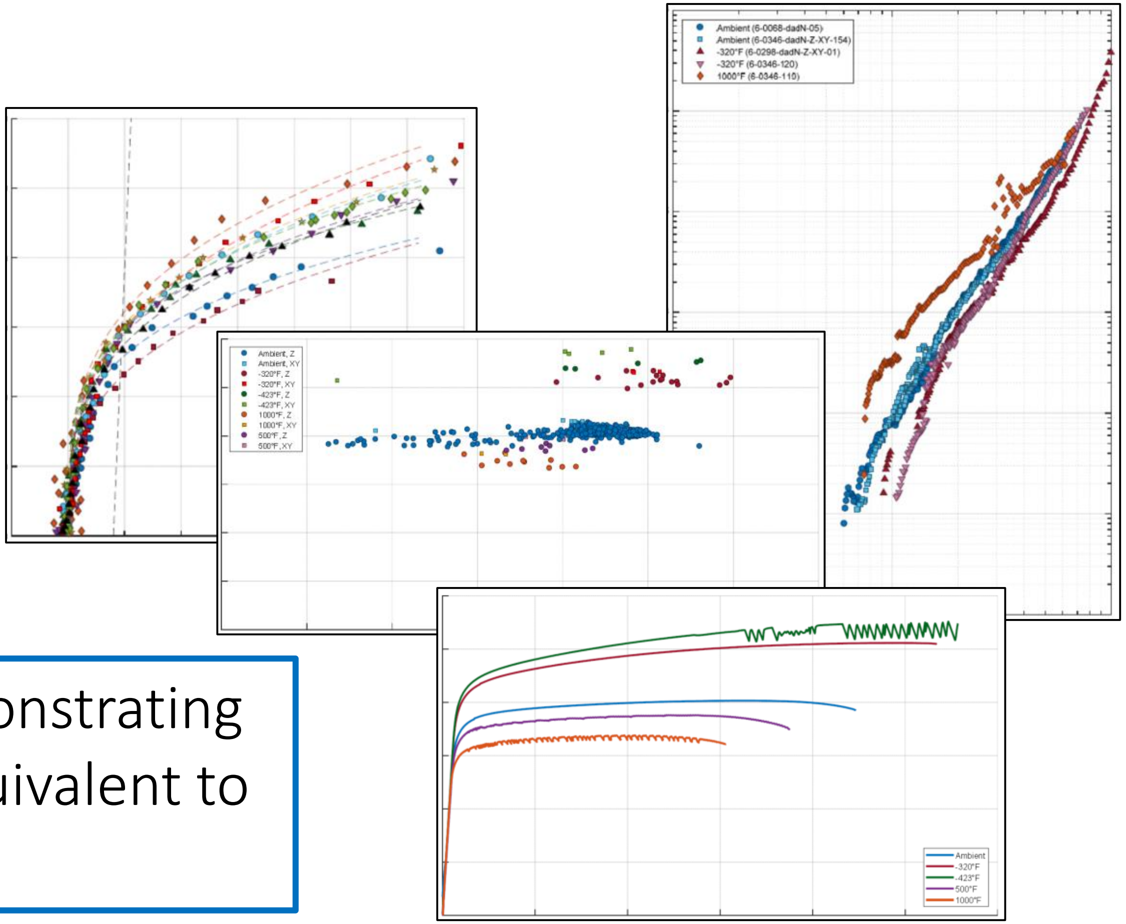


Qualification of the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

Step 3: Mechanical properties

- Tensile, fatigue, toughness…
- Registration through Equivalence
  - Material Property Suite (MPS): Actively maintained, alloy and condition specific material property information that includes material test data, design values, and SPC criteria
  - “In-family” performance



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

Qualified Metallurgical Process

Foundation

What do I need to build to produce a QMP?

Master QMP

TABLE II. Minimum mechanical property evaluation requirements for qualification of candidate metallurgical processes as a Master QMP.

Item	Property	ASTM Standard*	Quantity	Notes
1	Tensile	E8/E8M	15	Survey of build area and materials from "hot" and "cold" processes variants per Section 4.2.3.1 (b)
2	Tensile, With process restart	E8/E8M	5	Required if process restart is allowed. Tensile testing of process restart interface. Item 2 tests not required if restart is included in testing for Item 1
3	High Cycle Fatigue	E466	10	Five (5) tests to MPS PCRD fatigue condition, and five (5) tests at cyclic stress range producing failure > 10^6 cycles that replicate R-ratio and stress range of existing MPS data enabling comparison
4	Low Cycle Fatigue	E606/E606E	5	Five (5) tests at a cyclic strain range represented in MPS data
5	Fatigue, With process restart	E466, E606/E606E	5	Required if process restart is allowed. Fatigue testing of process restart with HCF or LCF, five (5) tests at the MPS PCRD fatigue condition. Item 5 tests not required if restart is included in tests from Item 3 and/or 4.
6	Fracture Toughness	E1820, E399	3	Tests with crack parallel to build plane, loading in Z direction.
7	Tensile (at Temperature)	E21, E1450	6	Three (3) tests per temperature at two or more temperatures – either the high and low bounding temperatures of the MPS or other applicable temperatures.
8	Customized QMP	As specified	2	Test at conditions defined by the candidate metallurgical process required for acceptance, minimum two (2) tests at condition.

*Other test standards approved by the CEO may be used.

Master QMP framework allows for reduced testing requirements in cases where the Metallurgical process is identical

Sub QMP and Requalification

TABLE III. Minimum mechanical property evaluation requirements for qualification of candidate metallurgical processes as a QMP or for reoccurring statistical process control evaluation builds.

Item	Property	ASTM Standard*	Quantity	Notes
1	Tensile	E8/E8M	10	Survey of build area locations
2	Tensile, With process restart	E8/E8M	5	Required if process restart is allowed. Tensile testing of process restart interface. Item 2 tests not required if restart is included in testing for Item 1
3	High Cycle Fatigue	E466	5	Five (5) tests to MPS PCRD fatigue condition,
4	Low Cycle Fatigue	E606/E606M	—	Not required for QMP (only Master QMP)
5	Fatigue, With process restart	E466, E606/E606M	5	Required if process restart is allowed. Fatigue testing of process restart with HCF or LCF, five (5) tests at the MPS PCRD fatigue condition. Item 5 tests not required if restart is included in tests from Item 3.
6	Fracture Toughness	E1820, E399	2	Tests with crack parallel to build plane, loading in Z direction.
7	Tensile (at Temperature)	E21, E1450	—	Not required for QMP (only Master QMP)
8	Customized QMP	As specified	2	Test at conditions defined by the candidate metallurgical process required for acceptance, minimum two (2) tests at condition.

*Other test standards approved by the CEO may be used.

Tables From MSFC-SPEC-3717

If you have 5 M290's running the same process and material this allows you to reduce testing requirements after the first machine is qualified!

Qualified Metallurgical Process

Foundation

- Reference QMP for Example Only

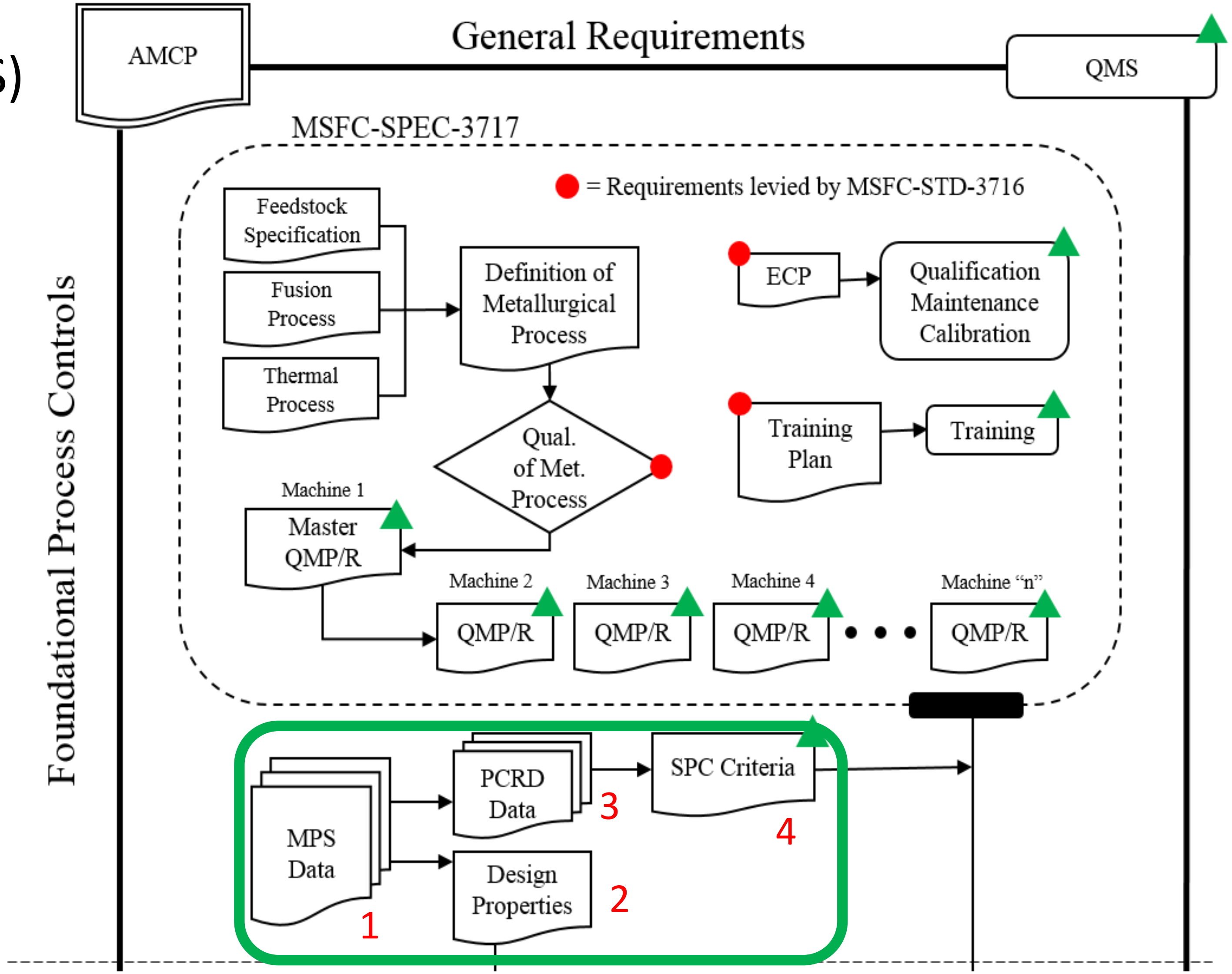
Microsoft Word Document

Material Properties

Foundation

The <u>M</u>aterial <u>P</u>roperty <u>S</u>uite (MPS) consists of four inter-related entities:

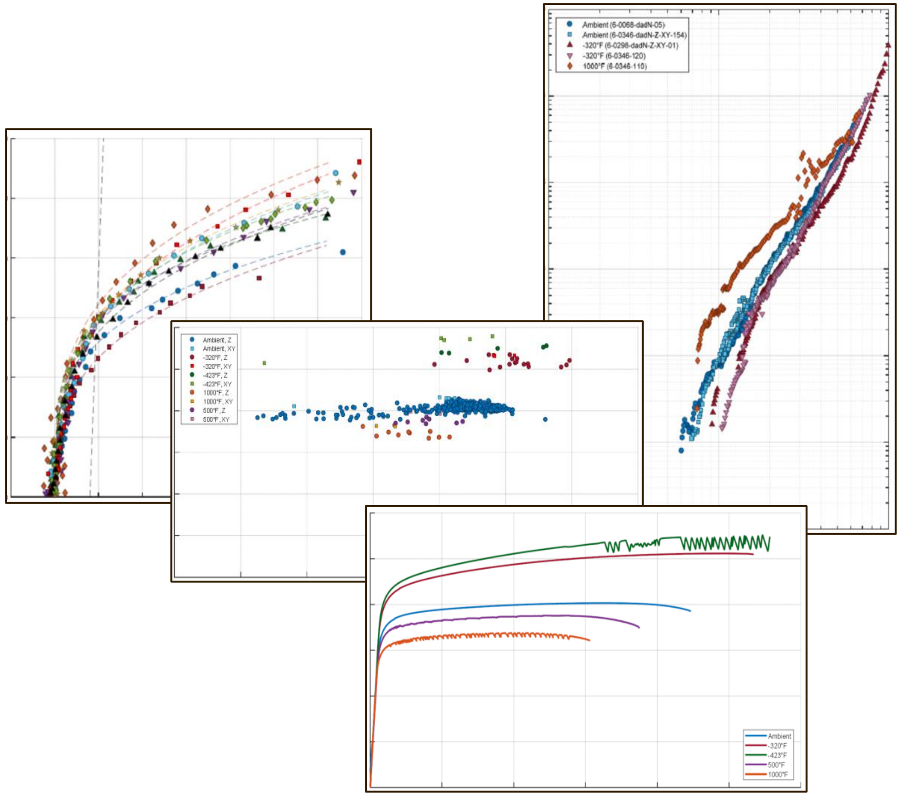
1. Data Repository
2. Design Values
3. Process Control Reference Distribution
4. SPC acceptance criteria for witness testing



Material Properties

Foundation

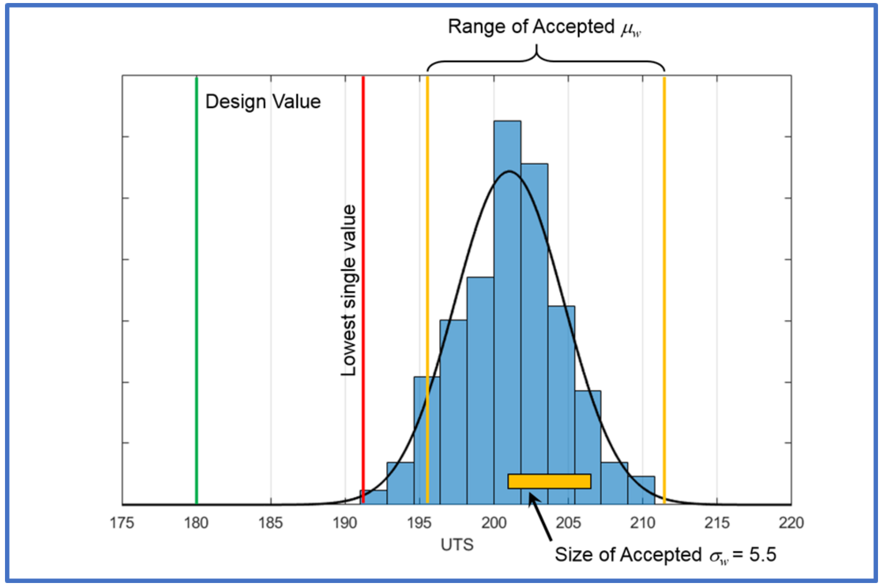
- Material properties and design values in additive manufacturing require modifications to the approach typical of traditional metallic materials, with requirements more similar to that used in composites CMH-17
- Important distinctions arise due to the sensitive nature of the process and individualistic 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. (Casting analogy)
  - **AM Process Vendor responsible for material integrity**



Material Properties

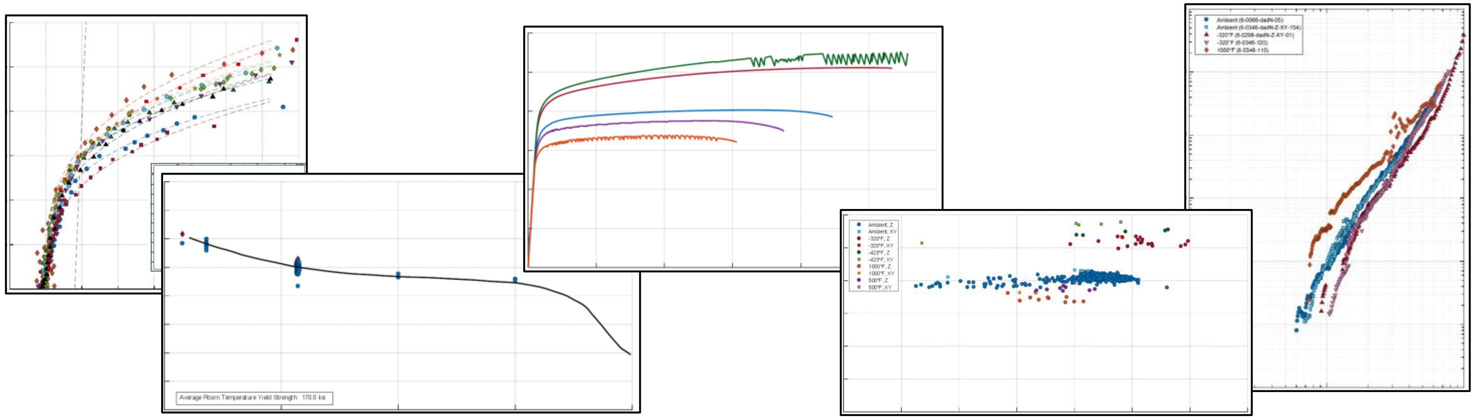
Foundation

- When design and production are not within the same entity, agreements must be reached regarding design value assumptions and associated qualification and monitoring requirements of the AM hardware
- Design values must be continuously substantiated through process qualification and witness requirements
- Material property evaluations are *complicated* by the AM process, leading to new considerations
  - Feedstock lot variability
  - Build-to-build and machine-to-machine variability
  - Coupon to part transferability of properties
  - AM process-specific influence factors
    - Anisotropy, Surface finish effects, Thin walls, Build history effects on material structure, etc.



Material Property Suite

Foundation



Data Repository

Includes data from

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

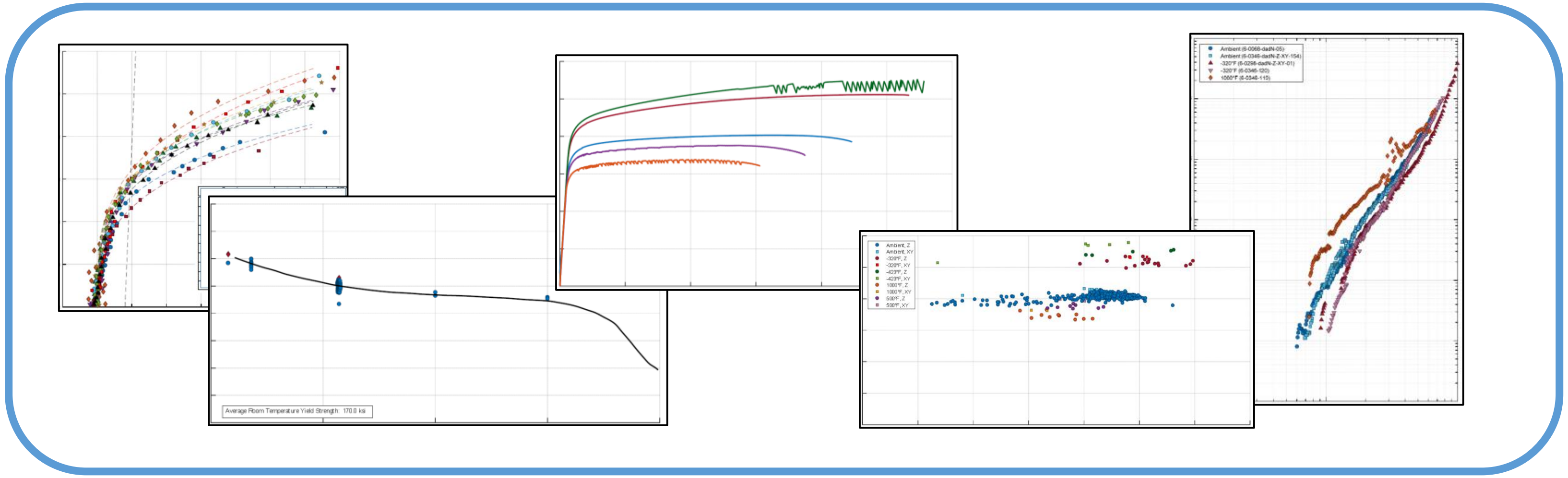
Grouping of data

Group data by

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

Material Property Suite

Foundation



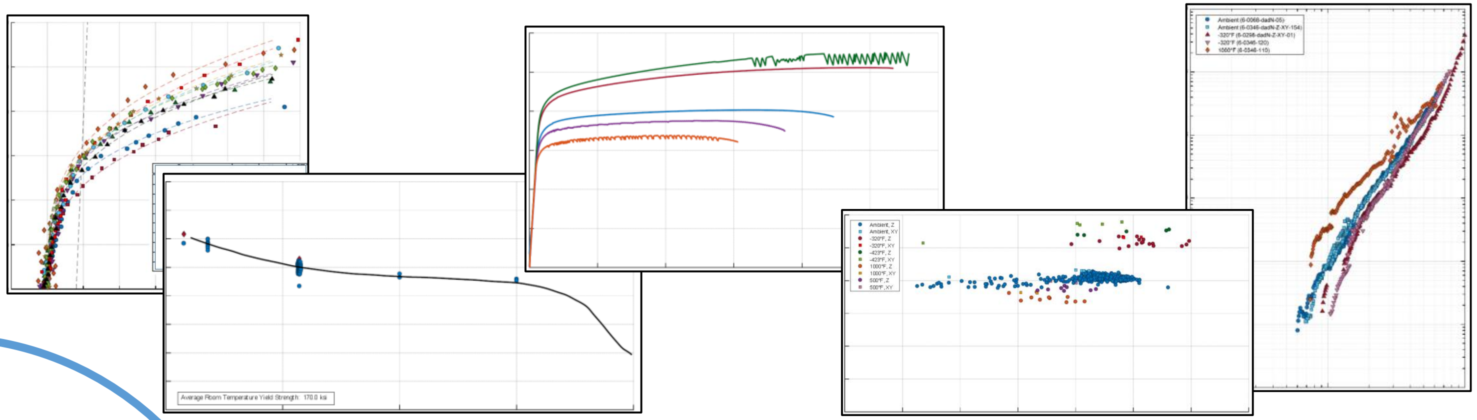
Data Repository, continued

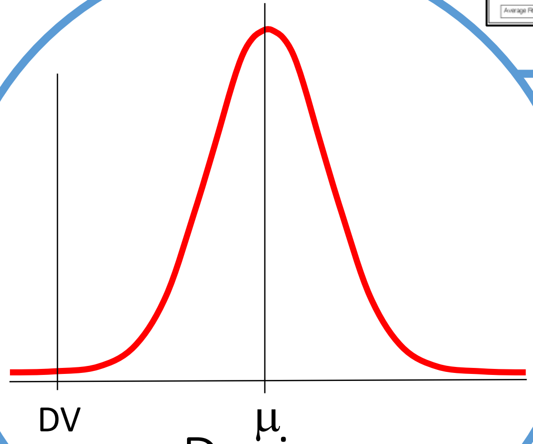
Contains all data needed for

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

Material Property Suite

Foundation





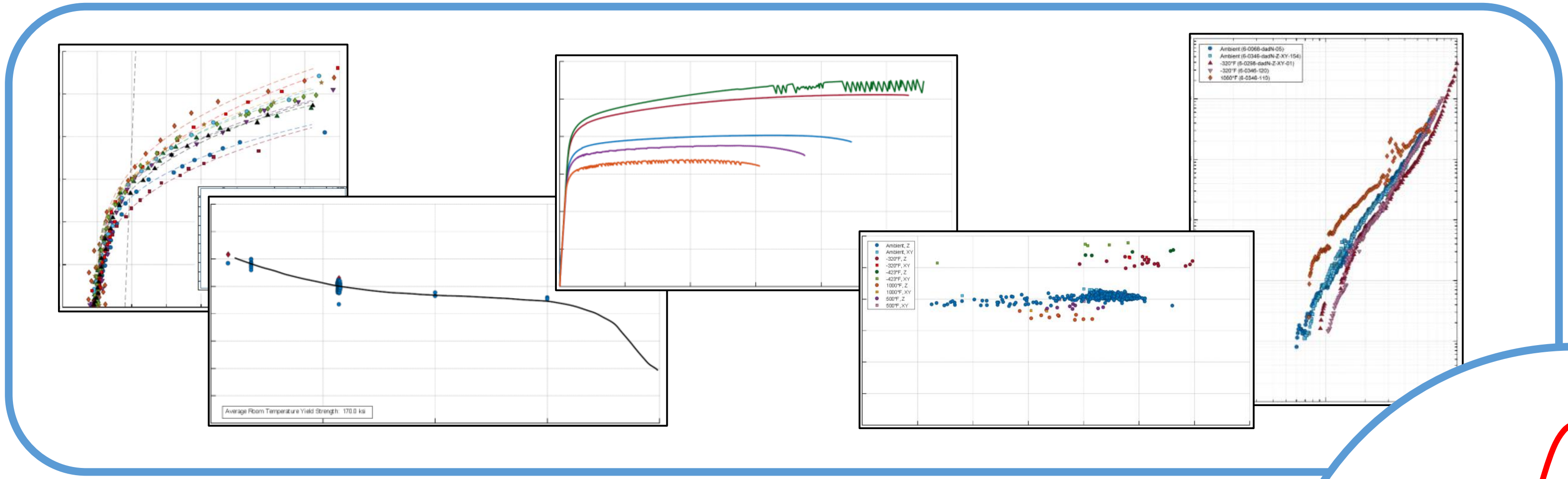
Design Values

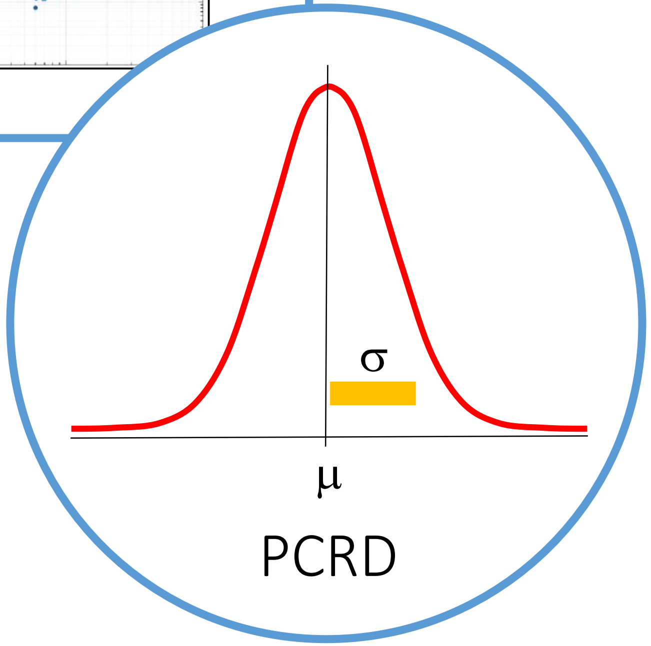
Design Values

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

Material Property Suite

Foundation





Process Control Reference Distribution

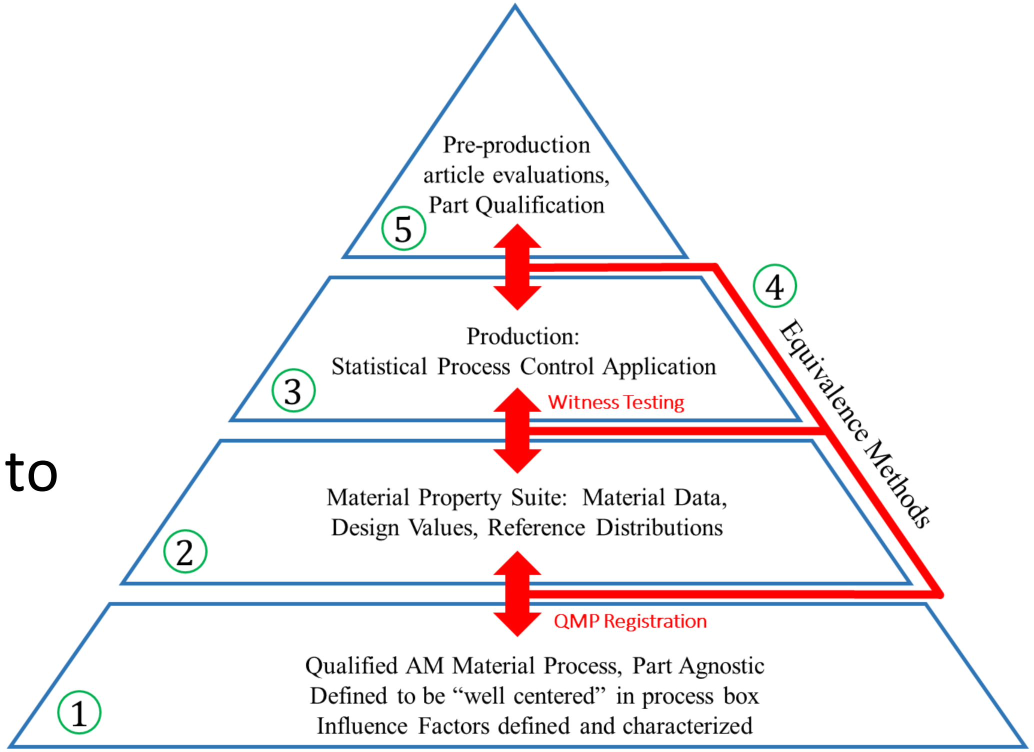
- Statistically describes nominal witness behavior of a machine
- Utilizes all appropriate sources of *witness coupon data* in Repository
- Used to set acceptance criteria for witness tests

Statistical Process Controls

Foundation

Statistical process controls are important in sustaining certification rationale

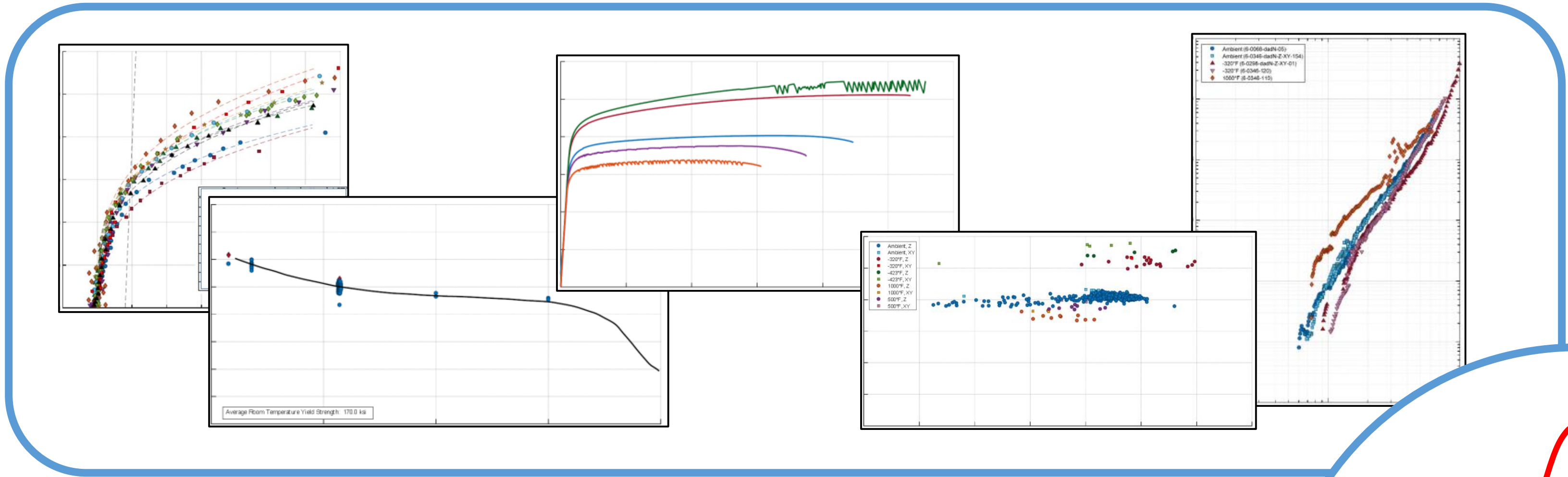
- *Statistical equivalency evaluations* substantiate design values and process stability build-to-build
  a) Process qualification
  b) Witness testing
  c) Integration to existing material data sets
  d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural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



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

Material Property Suite

Foundation

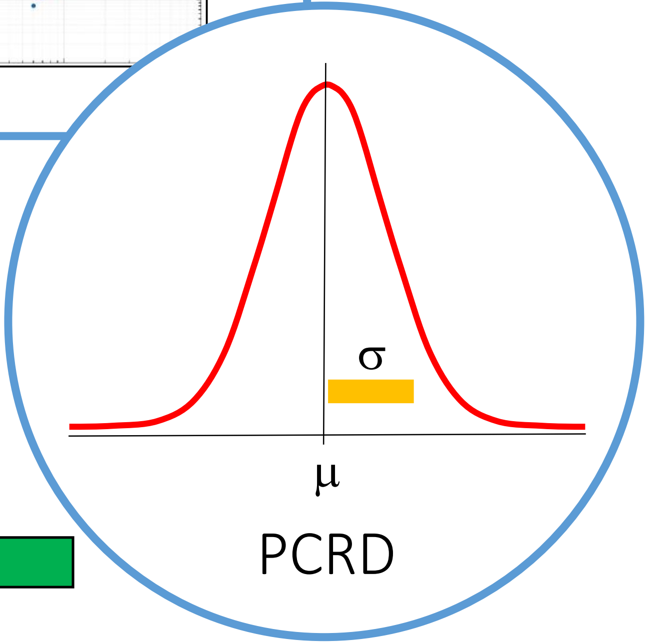


Statistical Process Control

Acceptance Criteria

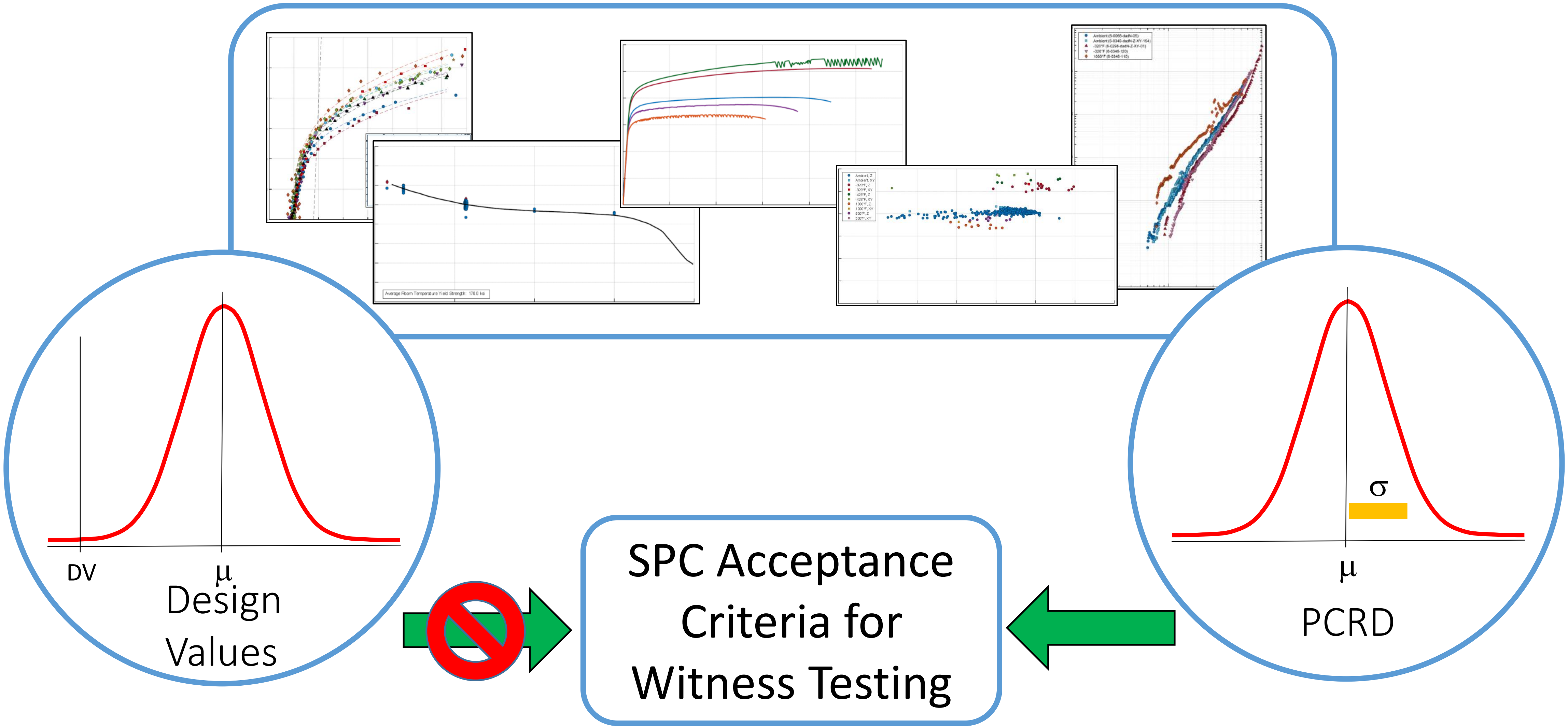
- Derived from PCRD
- Acceptance criteria for witness tests

SPC Acceptance Criteria for Witness Testing



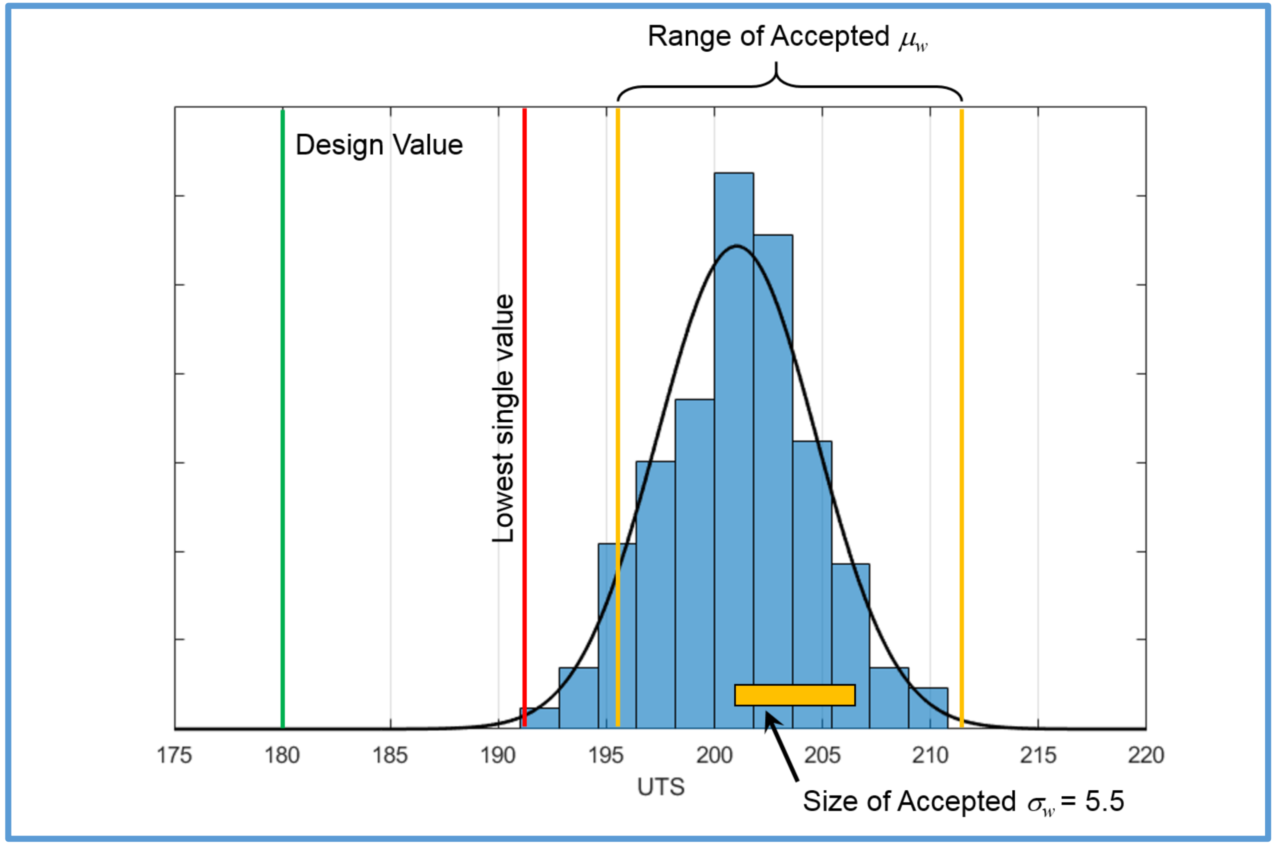
Material Property Suite

Foundation



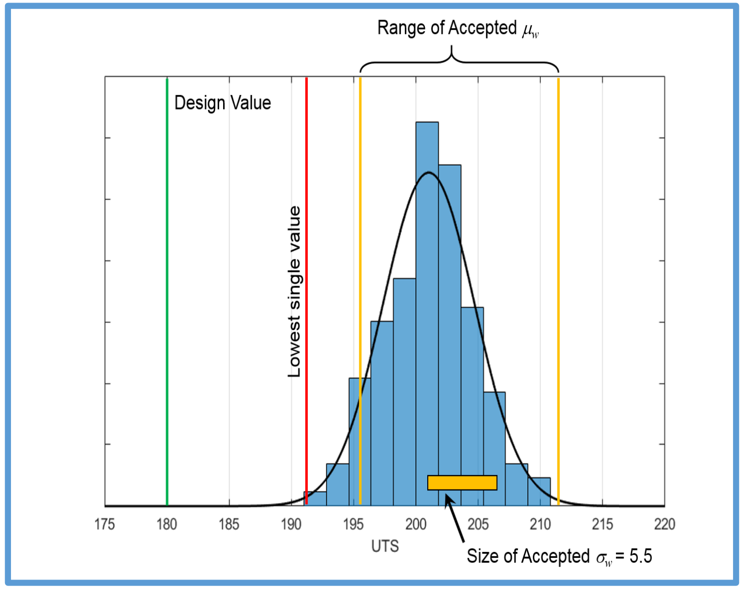
PCRD and SPC Criteria

- 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



Lots Of Data!

- *MPS, Lot-Mature*:
  An MPS that contains data from a minimum of five (5) unique powder feedstock lots and ten (10) build and heat treat lots
  - Nominally balanced distribution across lot data used for all design values
  - Sufficient variability incorporated to be applied to parts of all classes
- *MPS, Lot-Provisional*:
  An MPS that contains data from fewer than five (5) unique powder feedstock lots and ten (10) build and heat treat lots
  - Only applicable to parts of Class B

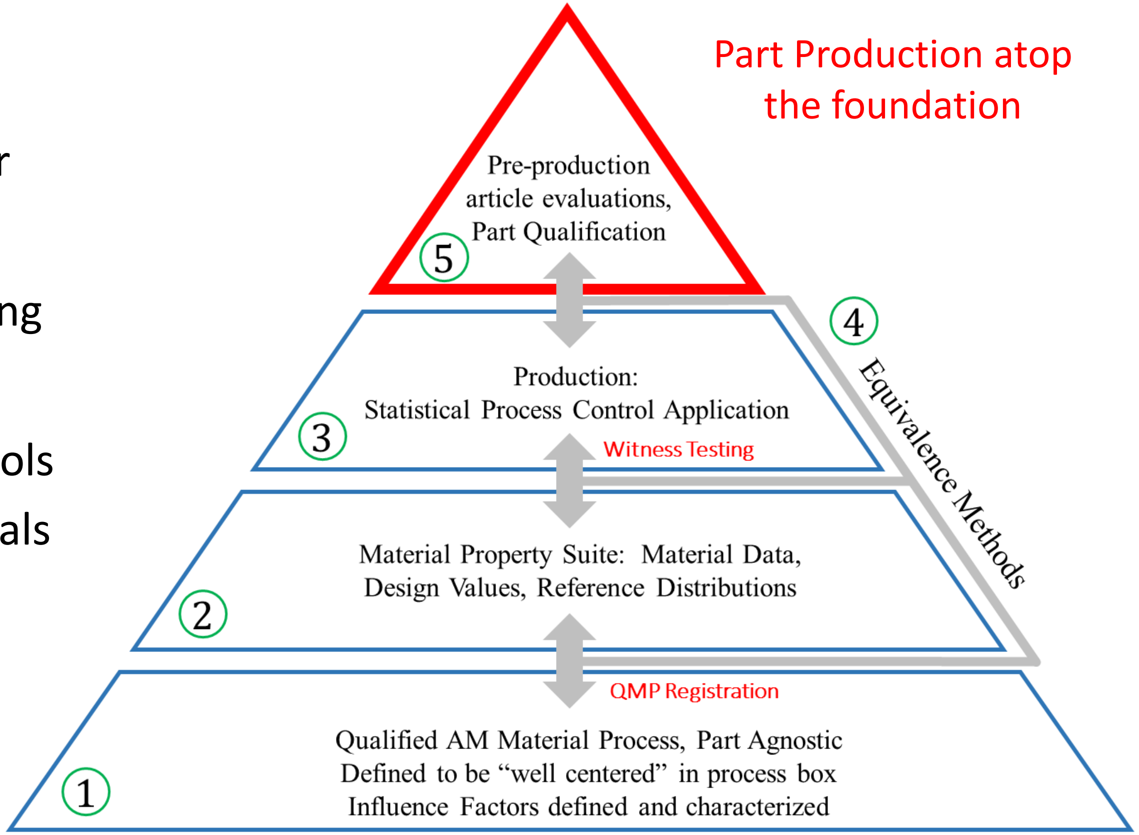


Foundation Complete

A basis to begin designing AM parts with certification intent is feasible once the foundation is laid.

- Equipment and facility understood and controlled
- Well-trained personnel who understand the importance of their role
- Properly qualified machines and processes consistently producing material of known quality
- Understood material capability characterized and process controls established to substantiate the rigor of design values for materials from all qualified machines

Foundation is now ready to support AM part development in an environment with suitable rigor to establish certification.



Part Production Controls

Produce to the plan!
Stick to the plan!

Overview of Current Requirements

Additive Manufacturing Control Plan

General Requirements

Quality Management System

Foundational Process Control Requirements

- Definition of Metallurgical Process
- Qualification of Metallurgical Process
- Equipment Control
- Personnel Training

Requirements of this technical standard, referencing MSFC-SPEC-3717 for procedural implementation.

- Material Property Suite
  - Material property data
  - Design values
  - Process Control Reference Distribution
  - Statistical Process Control Criteria

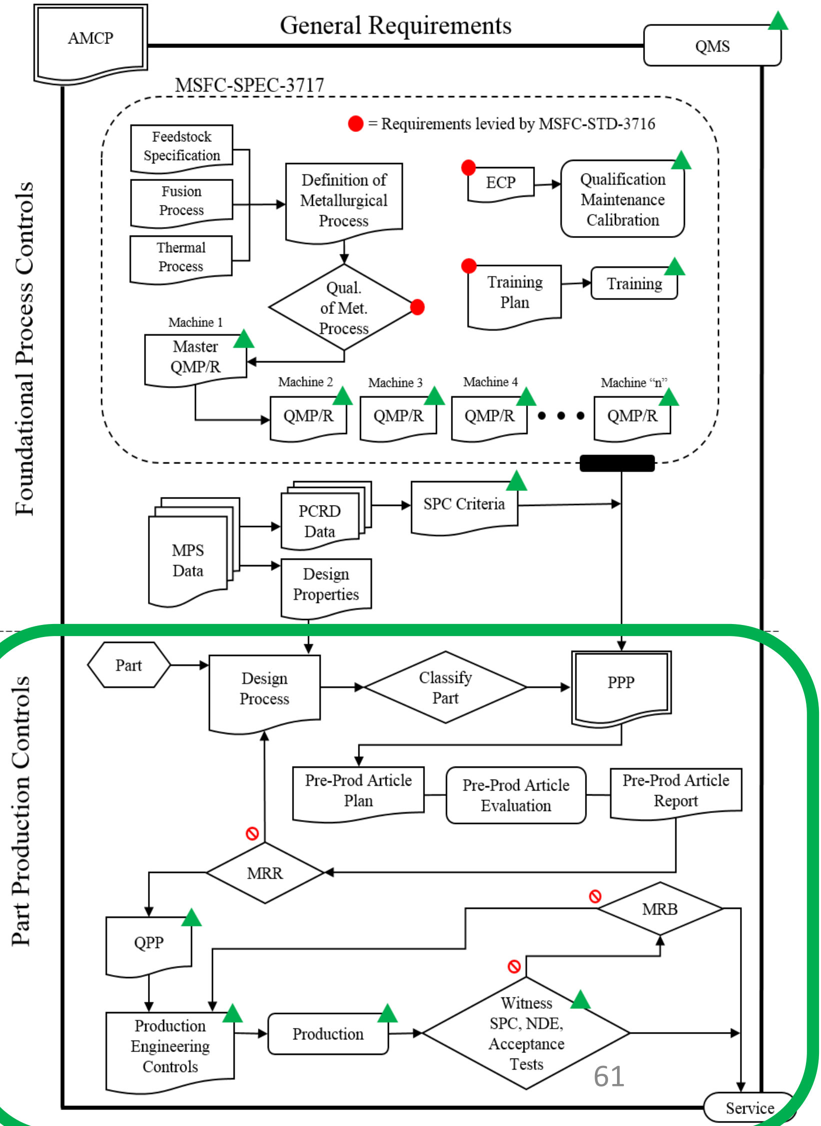
Part Production Control Requirements

- Design
  - Part Classification
- Part Production Plan
- Pre-Production Article Evaluation
- Manufacturing Readiness Review
- Qualified Part Process
- Production Engineering Controls
- Production Controls
- Acceptance testing / Statistical Process Control

Service

Candidate Part

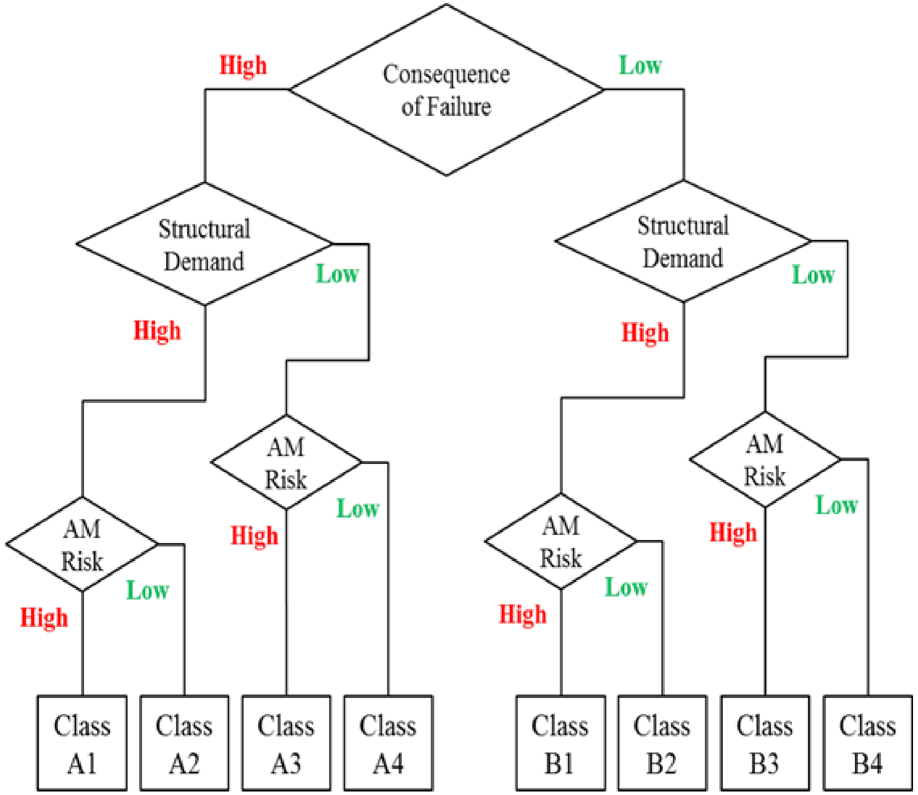
Part Production Controls



Part Planning

AM Part Design

- *Requires integration* across disciplines
  - Manufacturing, Material properties, Inspection
- AM design for manufacturability
  - Ease of build, self supporting, cost effective
  - For certification, NO awards given for most complicated, organic-looking part
  - Prized certification characteristics are ease of *access for verification* and *ability to inspect*
- Classification of parts for risk
  - Consistent ranking and handling of parts based on risk

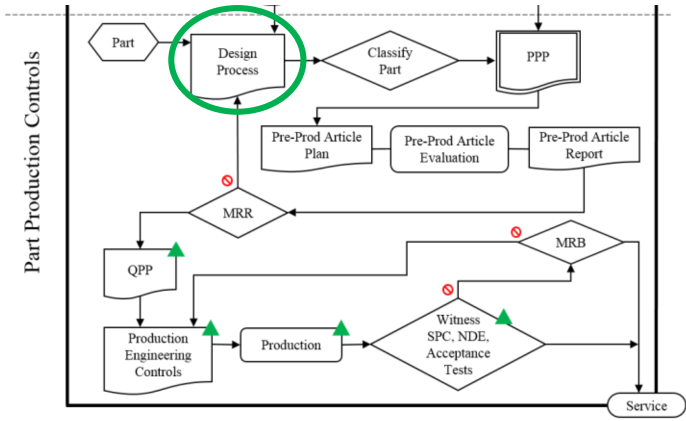


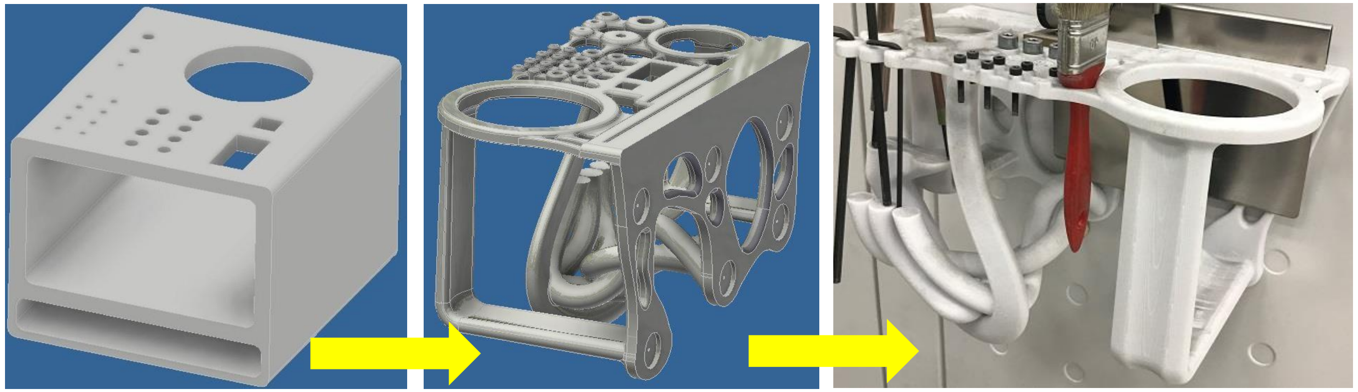
Example AM Part Classification Scheme

Design Process

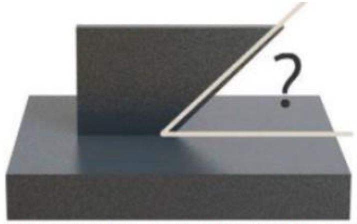
Design For Additive Manufacturing Paradigm Shift

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



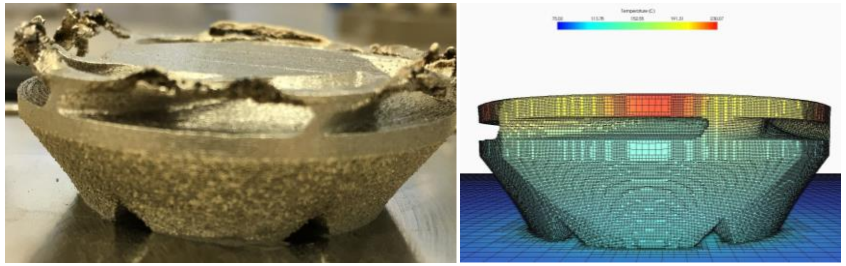


Topology Optimization FDM Tool Rack

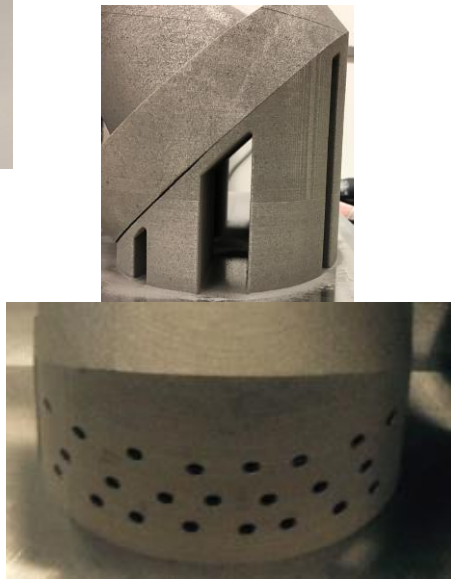


The minimum angles that will be self supporting are approximately:
- Stainless steels: 30 degrees
- Inconels: 45 degrees
- Titanium: 20-30 degrees
- Aluminium: 45 degrees
- Cobalt Chrome: 30 degrees

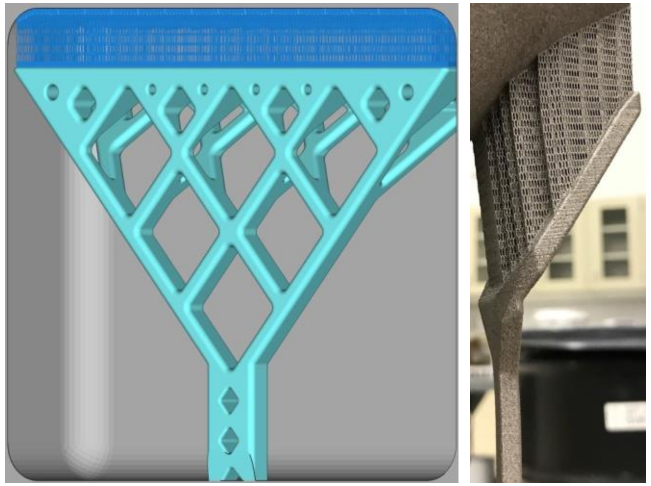
Self-Supporting Angles



Build Simulation

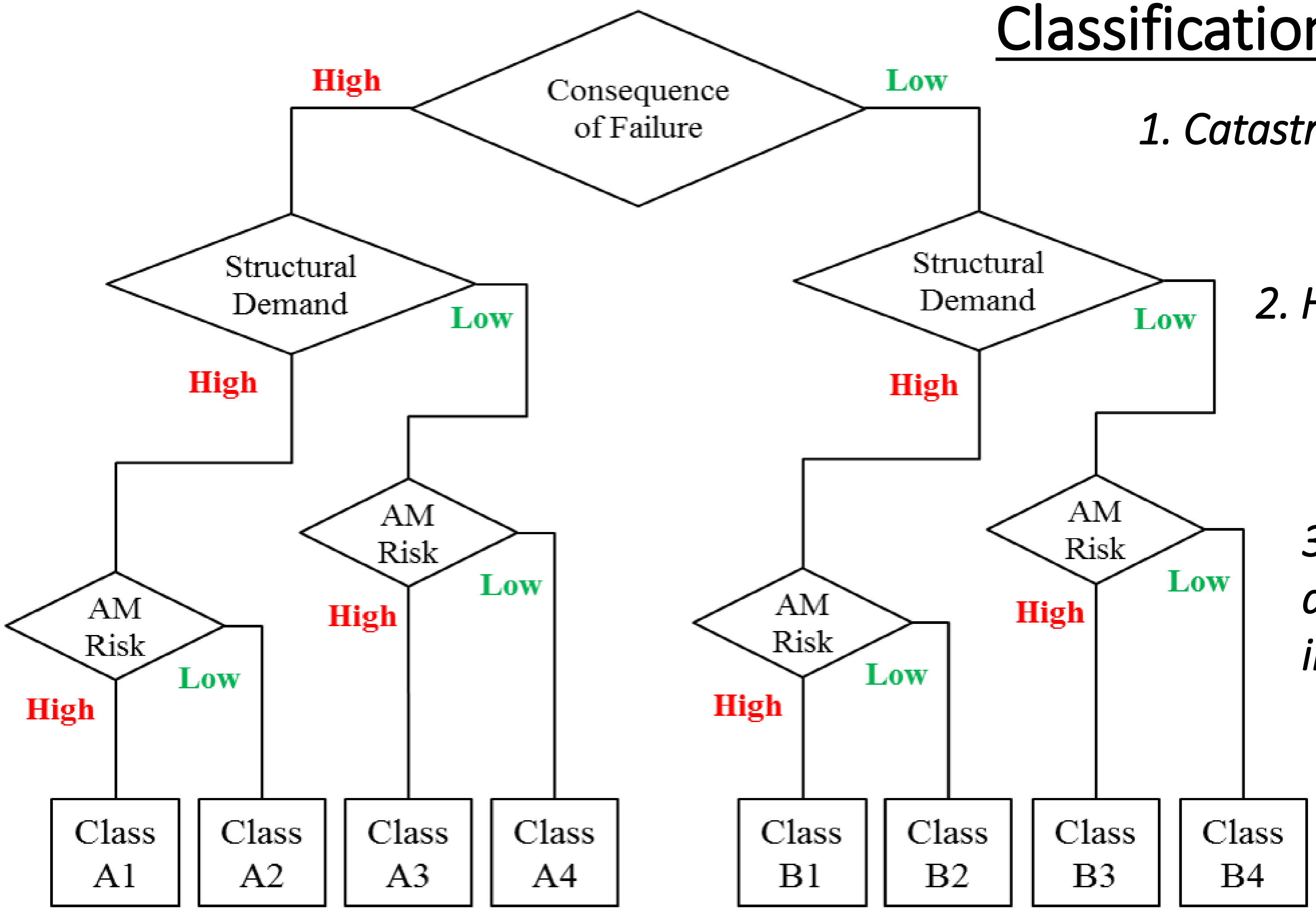


Powder Removal Features



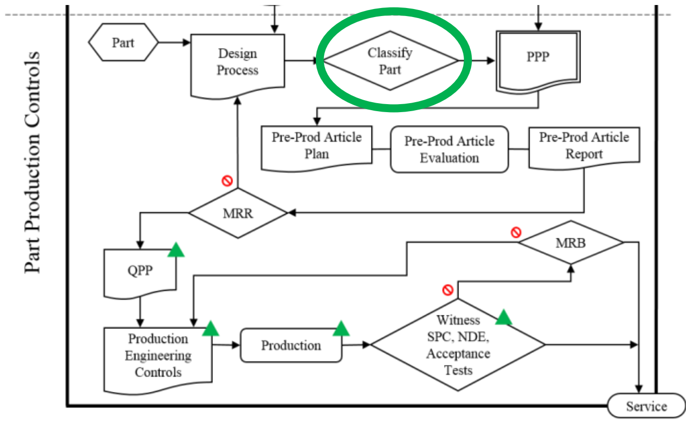
Hybrid crown & perforated block support

Part Classification



Classification System

Classification Questions

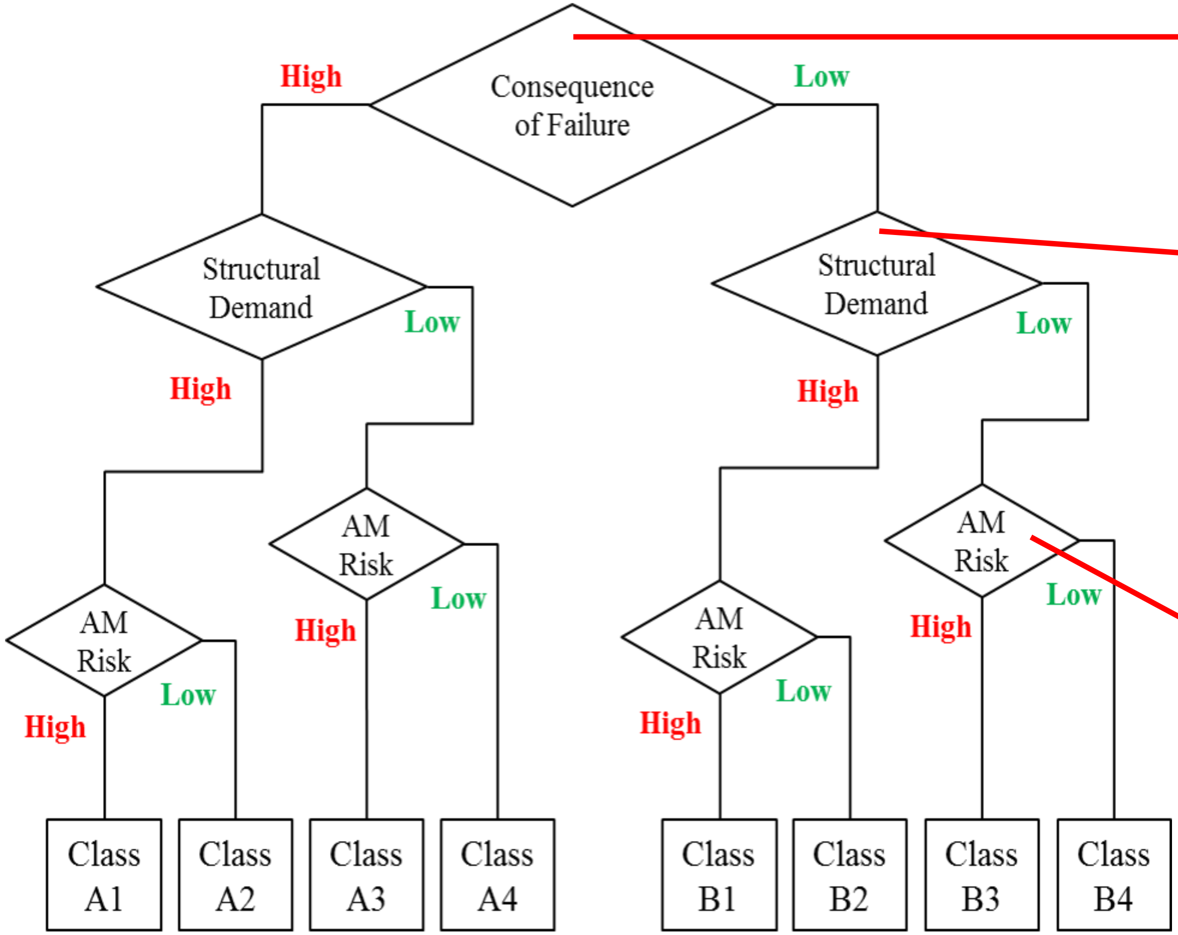


1. Catastrophic Failure?

2. Heavily Loaded?

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

Part Classification



Classification System

The first division among L-PBF parts is based upon the consequence of failure for the part: if failure of the part creates a catastrophic hazard, then consequence of failure is assigned high (Class A); otherwise, consequence of failure is assigned low (Class B).

TABLE I. Assessment criteria to determine structural demand

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

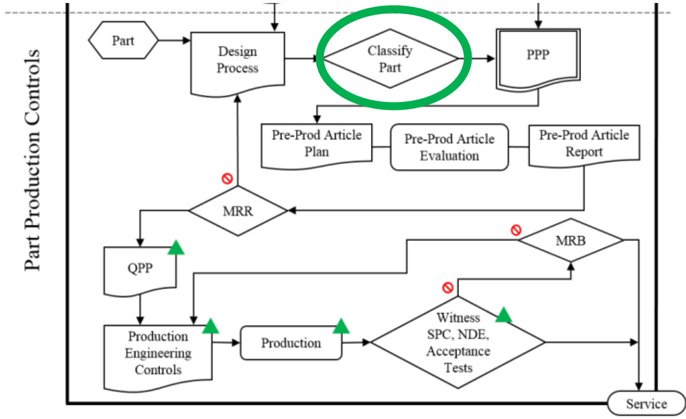
*Margin = $[\sigma_{design} / (\sigma_{operation} * \textit{safety factor})] - 1$.

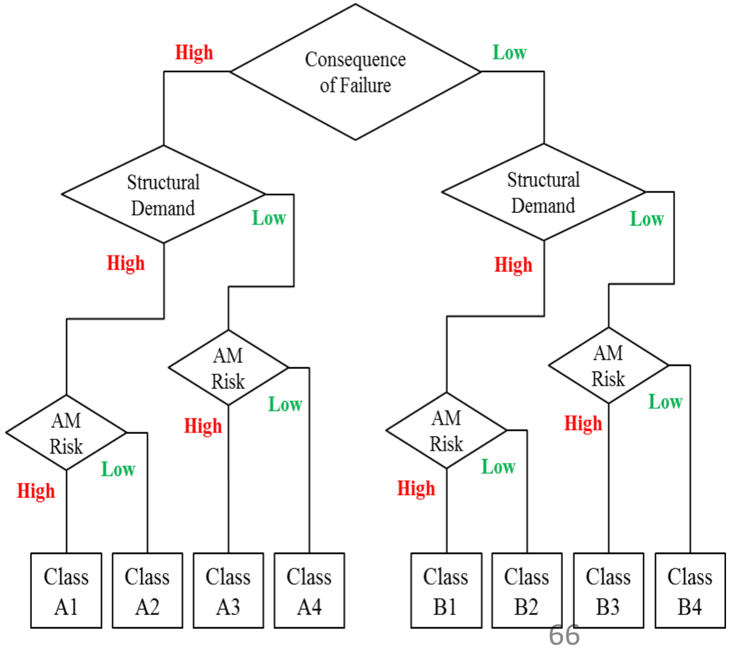
TABLE II. Assessment criteria for L-PBF additive manufacturing risk

L-PBF Risks	Score for Yes	Score for No	Score
All surfaces 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 $\geq$ 1mm in cross-section?	0	2	
Critical regions of the part do not require sacrificial supports?	0	2	
		Total	

Part Classification

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

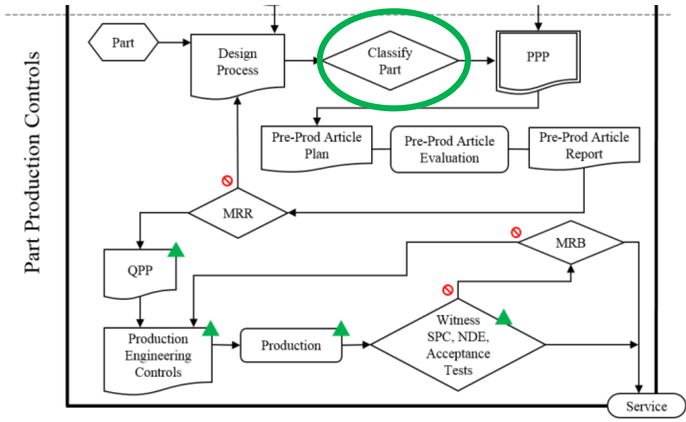




Part Classification

Challenges to the classification system encountered early

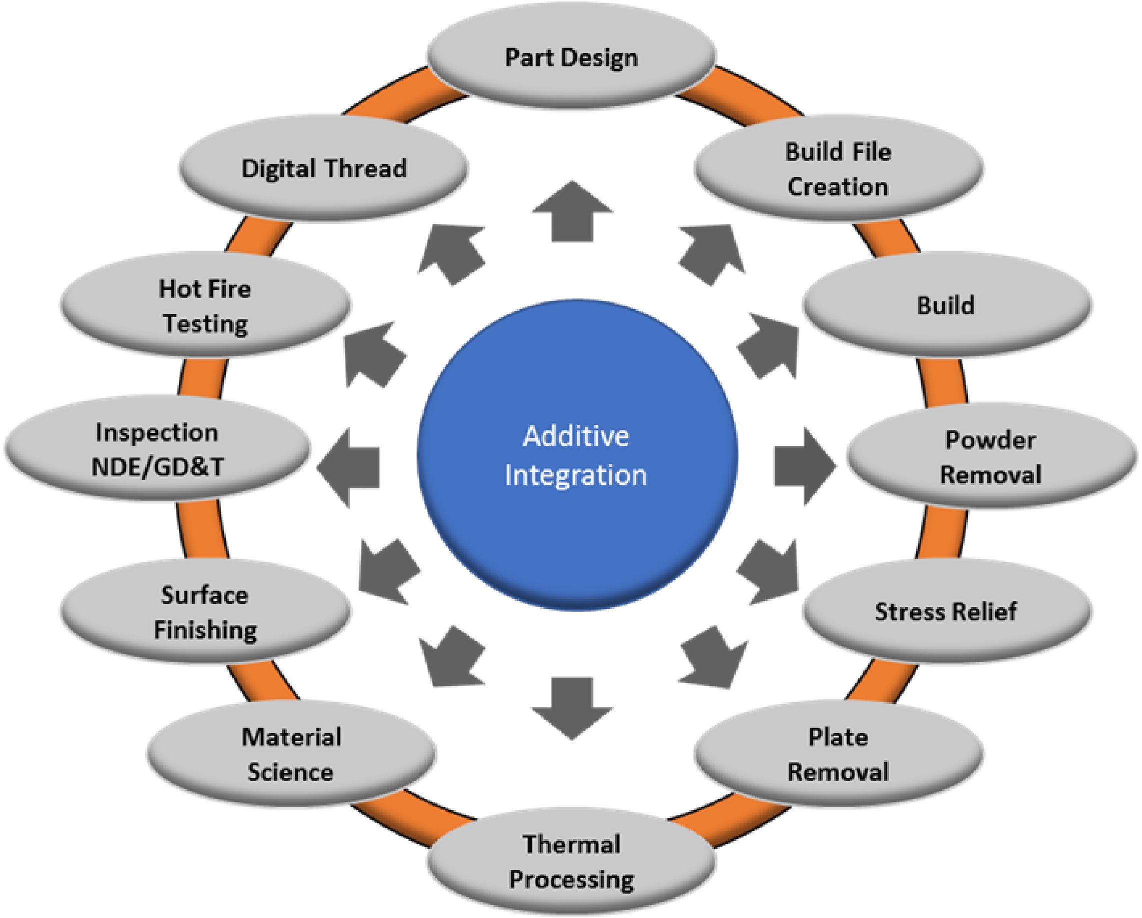
- Draft version contained a Class C for non-service components
  - Intent: fit check parts, demonstrations, visual/design aids
  - Revision now considering a "non-structural" for-service Class C
- Did not account for Science Mission Classes (biased to human-rating perspective)
  - Mission classes A-D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



Part Planning

AM Part Production Plans

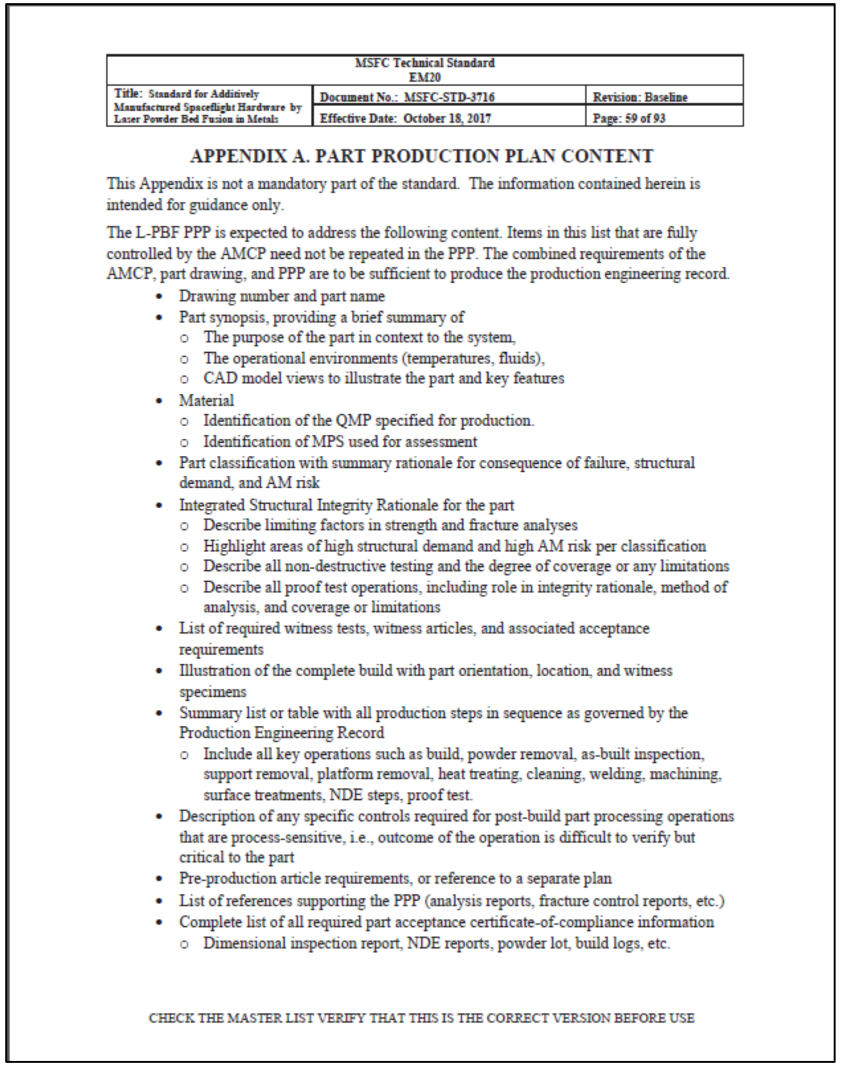
- AM parts do not yet have a common industry standard of practice
  - Challenge to integrate all required aspects of AM design requirements through drawing content
  - Requires many aspects to be integrated
    - Build layout
    - Specification of qualified process ID
    - Witness test and acceptance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



Part Production Plan

<u>P</u>art <u>P</u>roduction <u>P</u>lans force integration of part processing

- Interdependence of layout and downstream requirements
  - Surface finishing
  - Inspection
  - Powder removal



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

APPENDIX A. PART PRODUCTION PLAN CONTENT

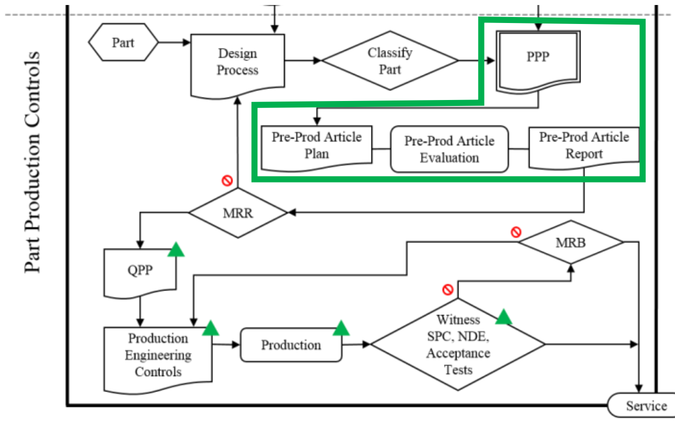
This Appendix is not a mandatory part of the standard. The information contained herein is intended for guidance only.

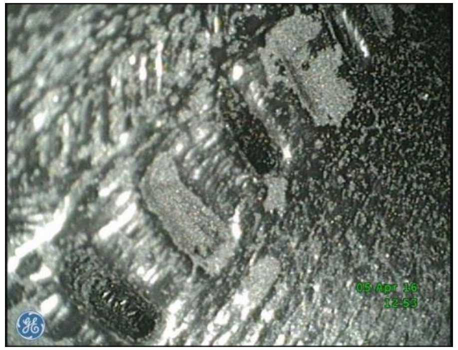
The L-PBF PPP is expected to address the following content. Items in this list that are fully controlled by the AMCP need not be repeated in the PPP. The combined requirements of the AMCP, part drawing, and PPP are to be sufficient to produce the production engineering record.

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

CHECK THE MASTER LIST VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

Reference Appendix A MSFC-STD-3716





Wet Powder

Powder consolidated in Stress Relieve

Part Production Plan

Part Production Plans force integration of part processing

- First five sections describe the part, its classification, and risk

APPENDIX A. PART PRODUCTION PLAN CONTENT

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  - Highlight areas of high structural demand and high AM risk per classification
  - Describe all non-destructive testing and the degree of coverage or any limitations
  - Describe all proof test operations, including role in integrity rationale, method of analysis, and coverage or limitations

Reference Appendix A MSFC-STD-3716

Part Production Plan

PPP, Common Challenges:

- Integrated Structural Integrity Rational (ISIR)
  - Describes, in succinct fashion, how the quality assurance activities imposed on the part, when considered as a whole, form sufficient rationale for structural integrity.
  - Commonly includes
    - Structural margin status
    - L-PBF process controls
    - Defect screening actions: Non-Destructive Evaluations (NDEs), Proof Testing, Leak Testing, etc.
    - Functional acceptance testing

Example:

The XYZ manifold has been classified B3 per MSFC-STD-3716 and is produced with all nominal process controls of the AMCP with no exceptions. All structural margins are positive. The manifold is non-fracture critical; nonetheless, multiple NDE inspections with quality oversight are in place to ensure structural integrity with areas of highest structural demand fully inspectable. The manifold will receive a surface penetrant inspection after final machining and etch followed by full volume NDE via XRCT scanning. The manifold will also be proof tested to 2.5 x MDP followed by a leak check and post-proof test surface penetrant inspection. After installation, a system-level proof test and leak check are performed, followed by confirmation of full functionality. The combination of process controls and workmanship NDE provide a fully adequate ISIR.

Part Production Plan

Part Production Plans force integration of part processing

- Next seven sections describe the build
- All processing
- How its verified by witness specimens
- Pre Production Article requirements

- List of required witness tests, witness articles, and associated acceptance requirements
- Illustration of the complete build with part orientation, location, and witness specimens
- Summary list or table with all production steps in sequence as governed by the Production Engineering Record
  - Include all key operations such as build, powder removal, as-built inspection, support removal, platform removal, heat treating, cleaning, welding, machining, surface treatments, NDE steps, proof test.
- Description of any specific controls required for post-build part processing operations that are process-sensitive, i.e., outcome of the operation is difficult to verify but critical to the part
- Pre-production article requirements, or reference to a separate plan
- List of references supporting the PPP (analysis reports, fracture control reports, etc.)
- Complete list of all required part acceptance certificate-of-compliance information
  - Dimensional inspection report, NDE reports, powder lot, build logs, etc.

Reference Appendix A MSFC-STD-3716

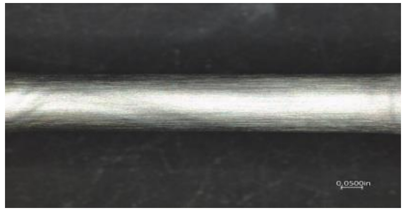
Part Production Plan

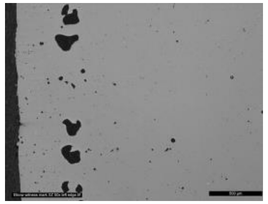
PPP, Common Challenges (Continued)

- Locked build files
- Description of controlled post processes
- NDE Plan
  - Surface finish for Penetrant Inspection
  - Flat enough for UT probe
  - Thin enough for Micro Focus CT

Locked Build Files: Stray vectors Created During Re-slicing

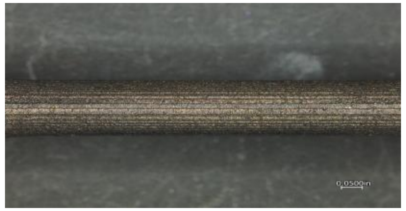
Ground Surface

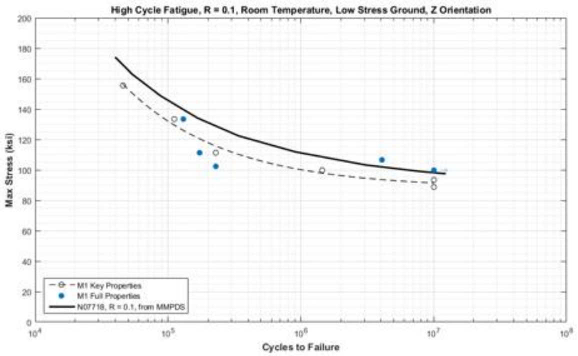


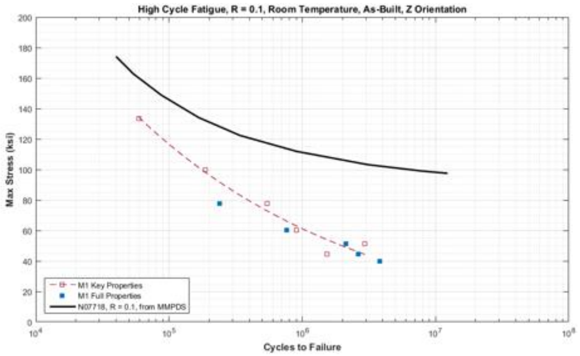


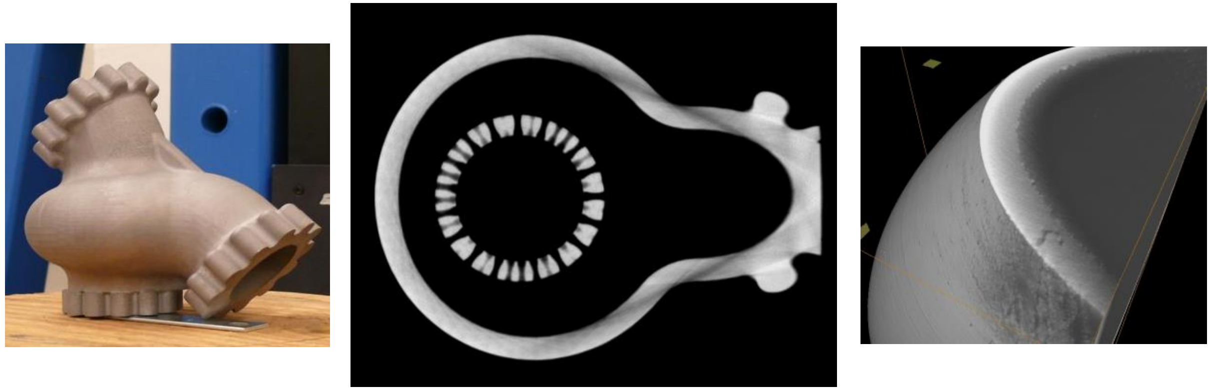
Near Surface Porosity

As-Built Surface







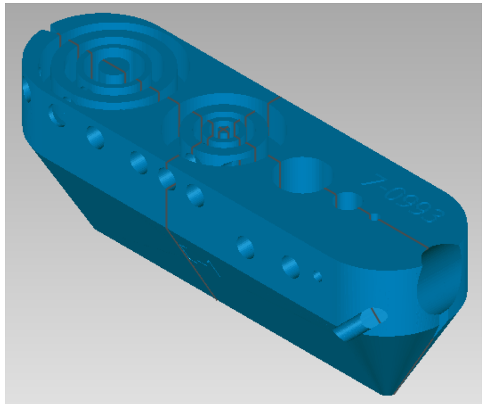


NDE: Powder not cleared, Imbedded Flaw

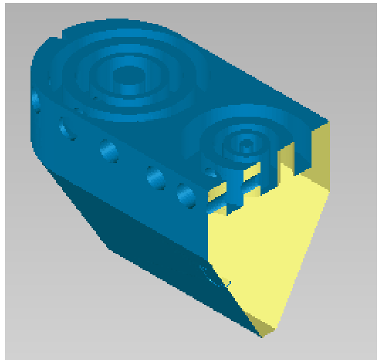
PPP, Common Challenges (Continued)

- Pre-production article evaluation
  - ***Critical step to confirm established foundation successfully produces a part with full integrity and design intent***
  - Dimensional, cut-up material evaluations: microstructure and mechanical
  - Confirmation of inspection procedure and non-destructive evaluation effectivity
  - Evaluate your Critical Areas, Thin Sections, and Thick Sections

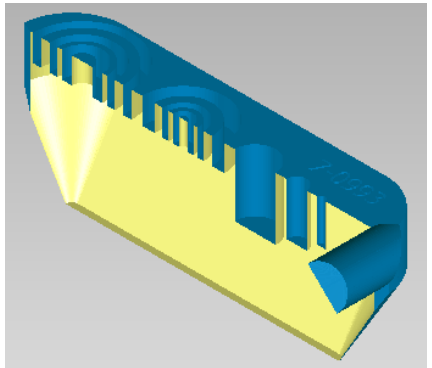
Contour Test Part



Cut Plan



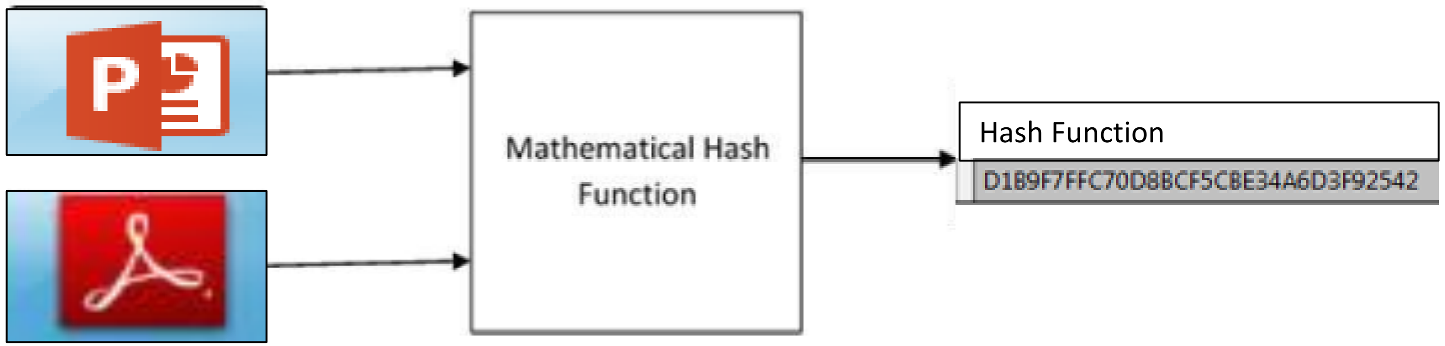
Channels Build Correctly?



Thin Sections Ok? Microstructure Within Acceptance Criteria?

PPP, Common Challenges (Continued)

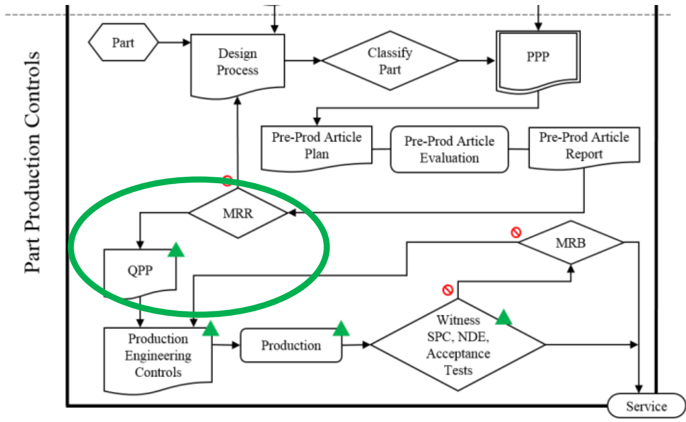
- Understanding cryptographic hash (3716 Appendix D)
  - Cryptographic hash functions can be utilized to store data or determine whether any changes have been made to the data.
  - This guards against corruption, allowing for the program to be used for data integrity and verification.
  - The different hash programs produce the same output and result in a change if any alteration has been made to the data.



This allows for verification that the same, unaltered parameter file is used for AM builds even if they are proprietary!

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

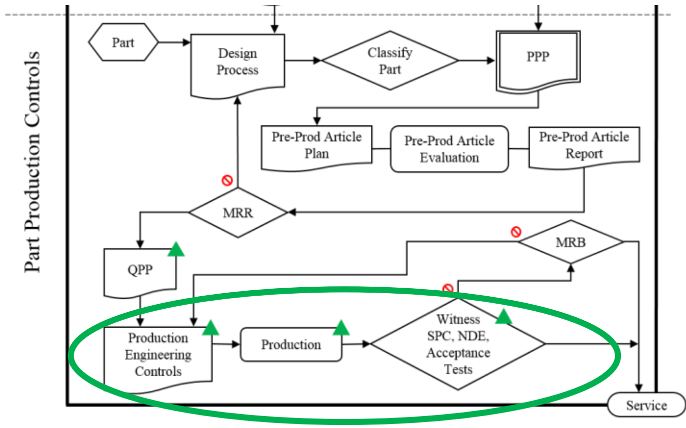


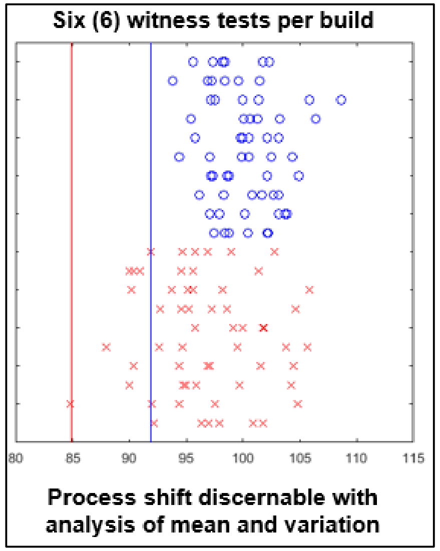
<u>Locked Process Is the QPP! Must be documented in the QMS!</u>

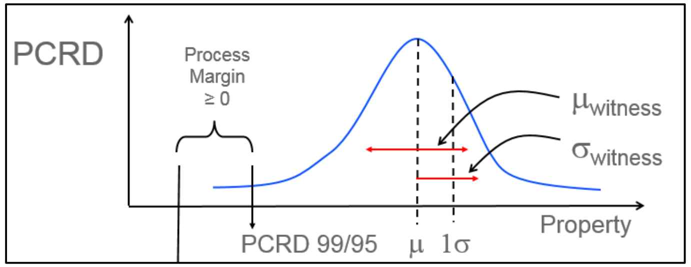
AM Part Production

Part Production – Follow-through on controls

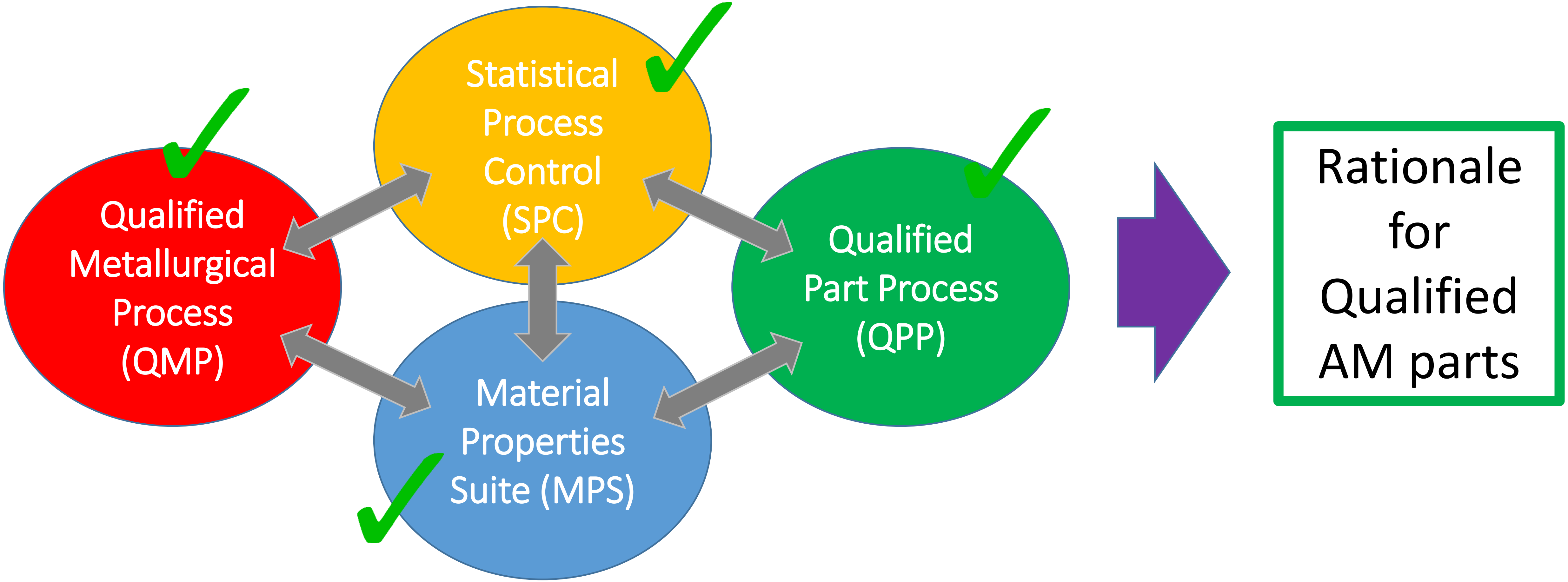
- Statistical Process Control (SPC)
  - Stand Alone acceptance, just making one part (MSFC-STD-3716 Table III)
    - A1: 6 tensile, 2 HCF, 2 Met, 1 Chemistry, 1 Full height Contingency
    - Compare to PCRD
  - Continuous Production (MSFC-STD-3716 Table V)
    - A1: 4 tensile, 1 Met, 1 Chemistry, 1 Full height Contingency
    - Compare to continuous Control Chart
    - Intermittent SPC evolution builds during production
    - SPC Challenges:
      - Do the samples stay with the parts?
      - How to flag a part without the samples tested?
      - Setting limits that identify drift







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

AM Part Production

1. Follow the plan, always, with no short-cuts
2. Do not change a Qualified Part Process without re-qualification
3. 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
4. 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
5. Consider systemic implications for all non-conformances

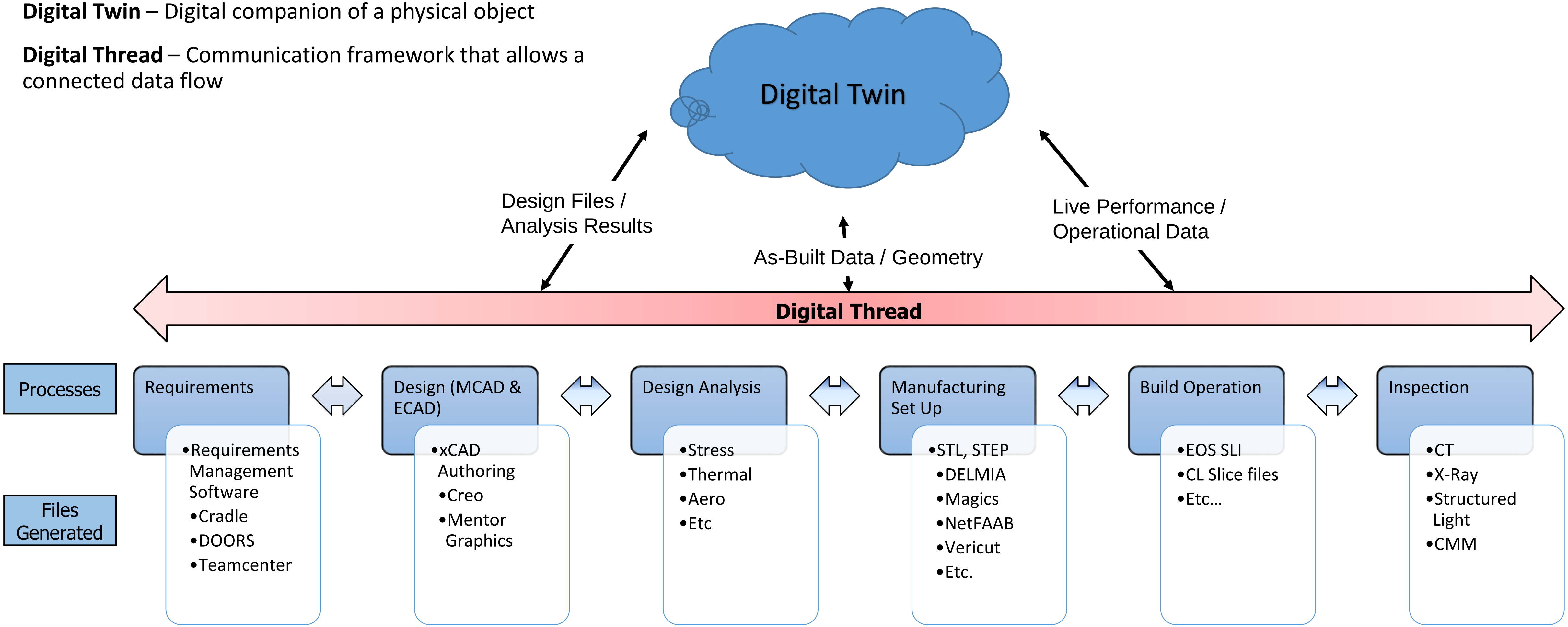
Common Challenges

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

Common Challenges: Digital Thread

Digital Twin – Digital companion of a physical object

Digital Thread – Communication framework that allows a connected data flow



Coming Reliance on In-Situ Monitoring

How to approach in-situ monitoring of AM processes?

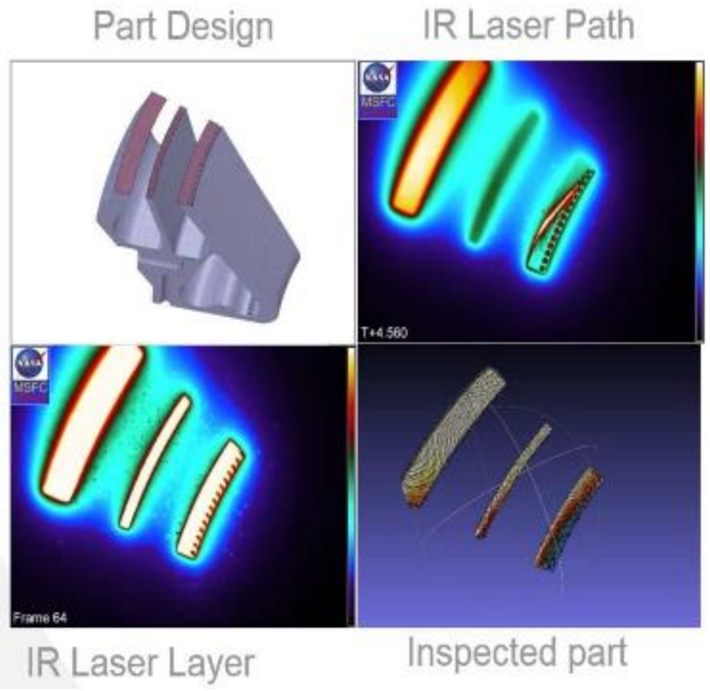
- Harnessing the technology is only half the battle
  - Detectors, data stream, data storage, computations
- Second half of the battle is quantifying in-situ process monitoring ***reliability***

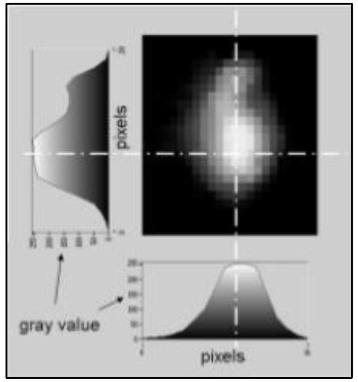
Community must realize that passive in-situ monitoring is an NDE technique

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

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

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

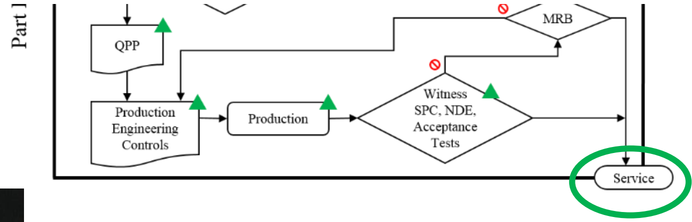


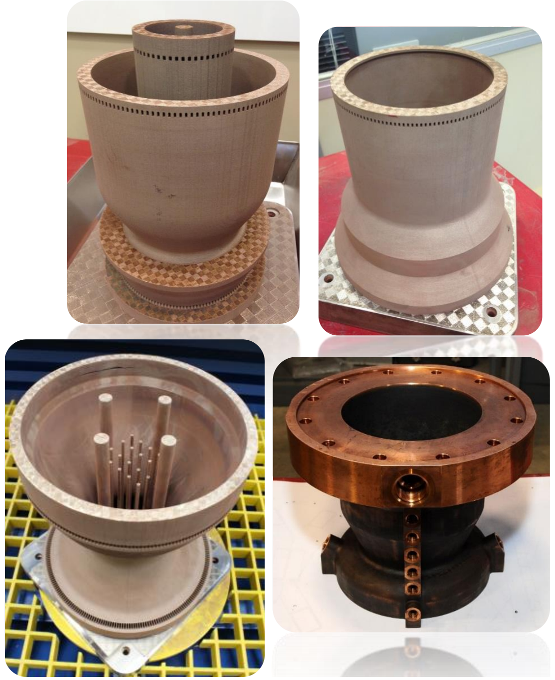


Concept Laser QM Meltpool

Application

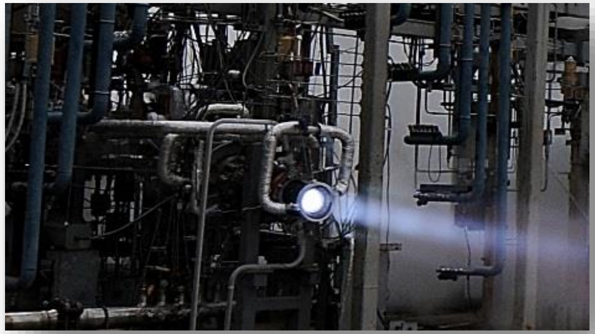
Final Box: *Service!*





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

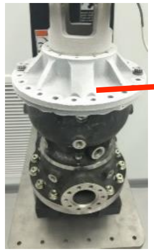
Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate



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

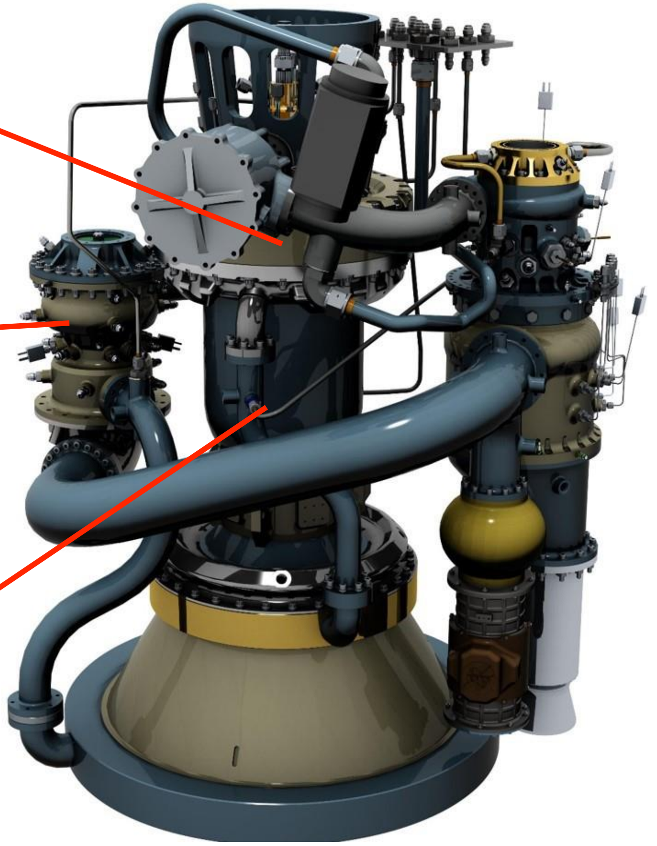
Injector
- Decreased cost by 30%
- Reduced part count: 252 to 6

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



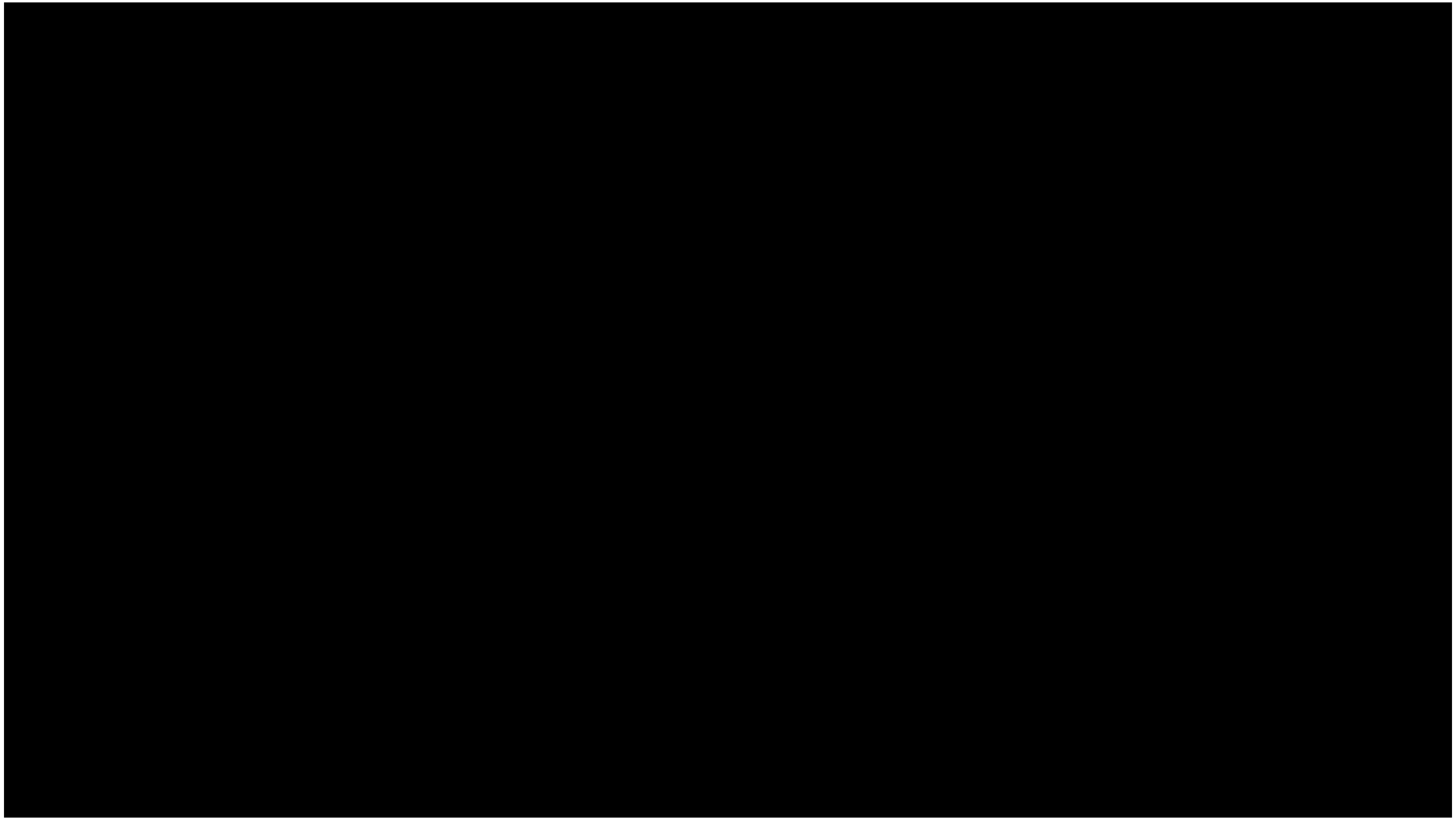
MCC
- Schedule reduction > 50%
- SLM with GRCop-84
- Methane test successful

AM Demonstrator Engine

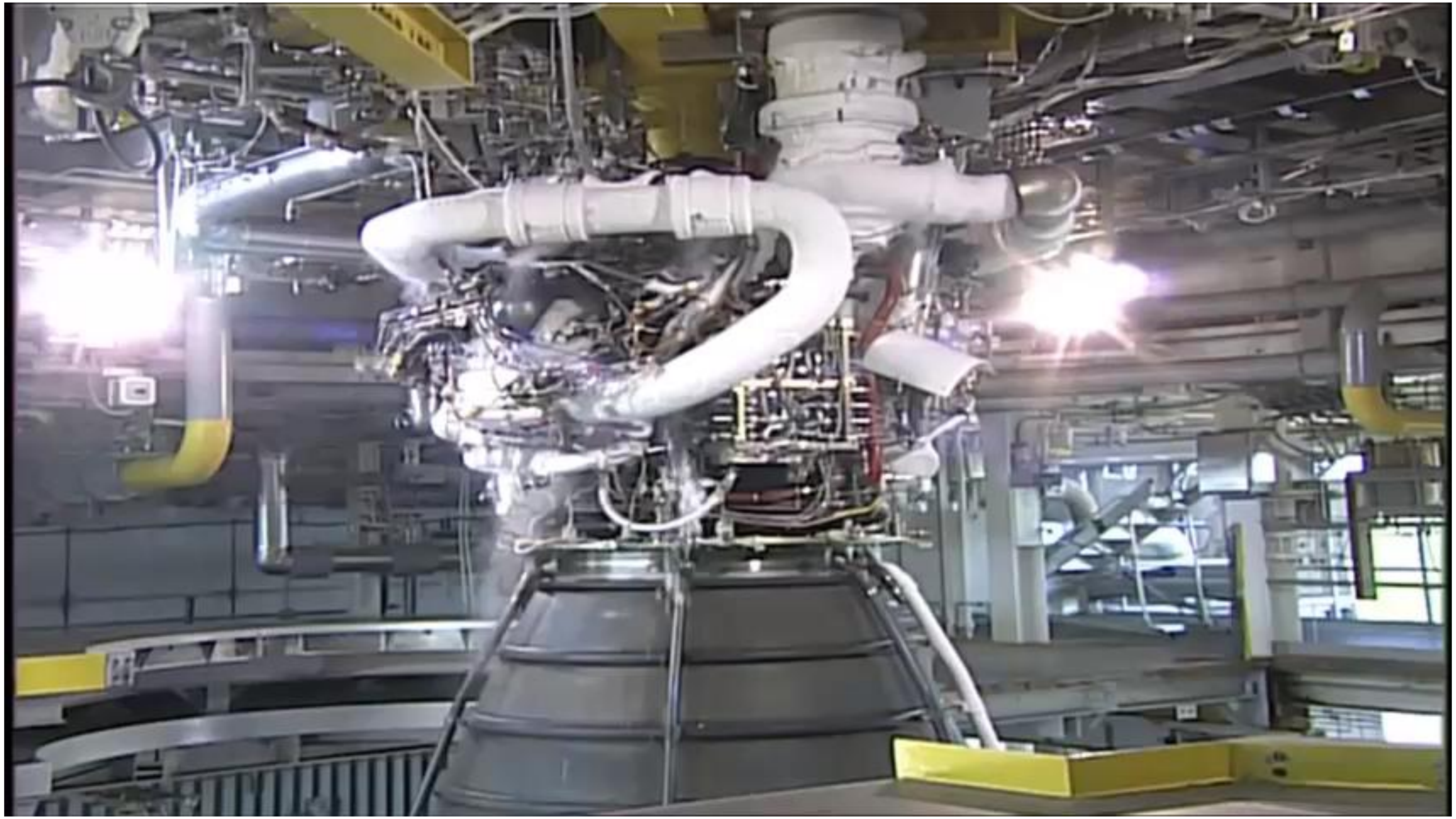


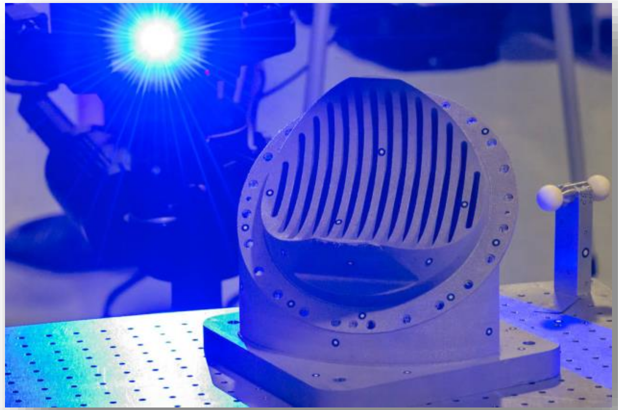
SLM Alloy 718 Injector Testing

Additively Manufactured Injectors Hot-fire Tested at NASA range from 1,200 lbf to 35,000 lbf thrust



Additive Manufacturing is real…





Successful hot-fire testing of full-scale Additive Manufacturing Part to be flown on NASA's Space Launch System (SLS) RS-25 Pogo Z-Baffle – Used existing design with additive manufacturing to reduce complexity from 127 welds to 4 welds

Ref: Andy Hardin, Steve Wofford/ NASA MSFC

Conclusion

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

Control what you do::Evaluate what you get

Summary

This overview was intended to demonstrate, at a fundamental level, the primary aspects of establishing certification rationale for the implementation of AM parts. The concepts covered herein have been agnostic to material. For a detailed example of the requirements to implement this approach in laser powder bed fusion of metals, see the following documents, which may be found at the links below.

- MSFC-STD-3716 "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals"

  https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.pdf
- MSFC-SPEC-3717 "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes"

  https://www.nasa.gov/sites/default/files/atoms/files/msfcspec3717baseline.pdf

Questions?

Thank You!