NASA's Approach to Additive Manufacturing Certification: Methodologies for Qualification of Additively Manufactured Aerospace Hardware

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Course Description

The implementation of additive manufacturing techniques to produce critical spaceflight systems is well underway. These technologies will be a key contributor to developing both launch vehicles and spacecraft that will play a crucial role in delivering the first woman and first person of color to the surface of the moon in 2025. To assist in the assurance of flight readiness, NASA has created comprehensive certification-based standards for mature technologies for both metallic and non-metallic materials.

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 NASA-STD-6030 and NASA-STD-6033
- Course Objectives
  - Reinforce a basic understanding of AM processes
  - Become familiar with NASA-STD-6030 and NASA-STD-6033 requirements for spaceflight hardware
  - Appreciate integrated path to Qualification and Certification
  - Understand products necessary to get you to Qualification and Certification

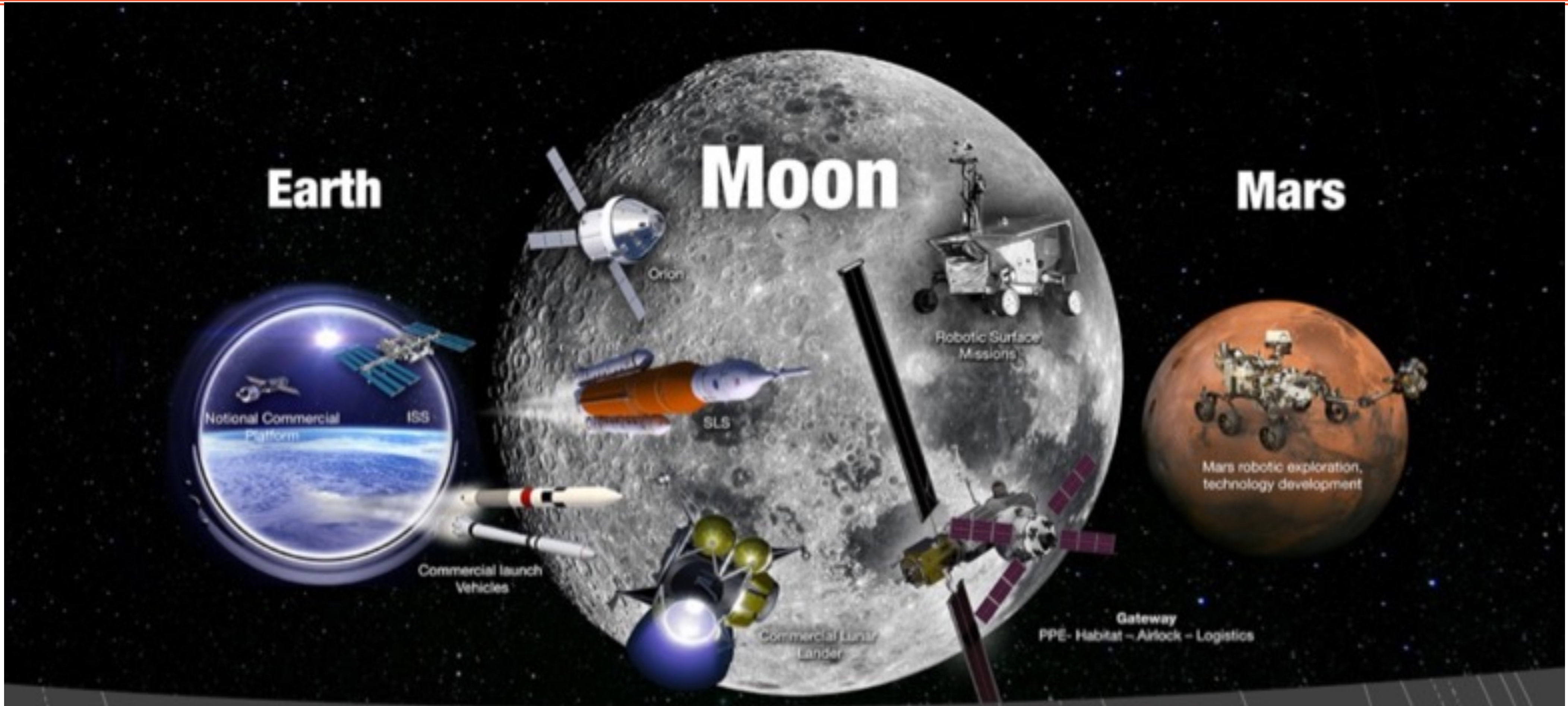
Raise your hand if…

- You’ve worked with additive manufacturing before?
- You’re in a primarily certification role?
- You’re familiar with NASA-STD-6030?
- You’re just happy to be here?

Agenda

- Intro of NASA’s roles in AM; examples (A)
- Overview of NASA AM Qual and Cert framework (A)
- General Requirements (M)
- Foundational Process Controls
  - QMP (M)
  - MPS (A)
- Part Production Controls (M)
- Putting them all together (M)

Exciting Activities at NASA

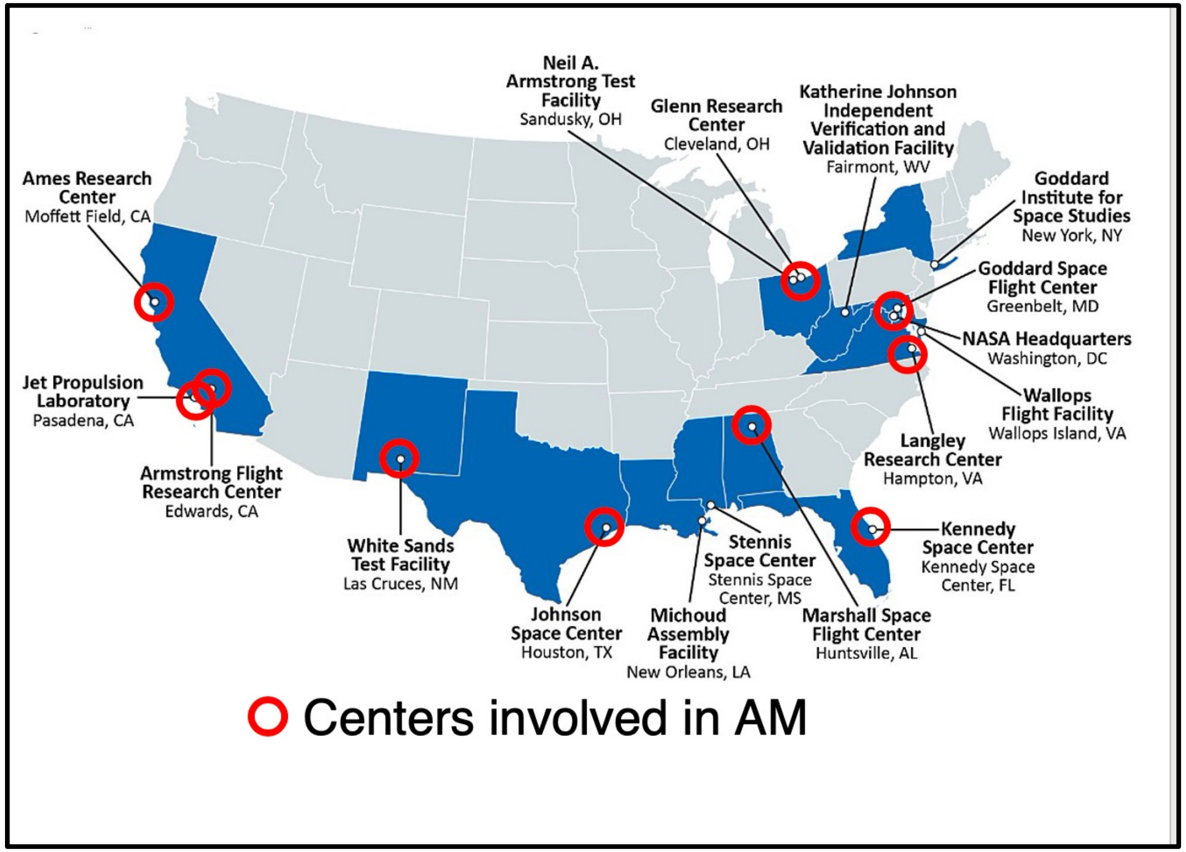


Exciting time at NASA with a lot of activities around Earth Orbit, getting ready to go to the Moon with eyes on Mars

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



NASA's Roles in AM

- Drive AM technology innovations – more affordable access to space and advanced aeronautics applications

- Provide framework for Spaceflight AM hardware certification
  - Enable NASA's tech authority to conduct meaningful and efficient evaluations of AM implementation
  - Advise NASA flight programs on potential risks – meeting objectives according to levied (and agreed upon) requirements and approved exceptions

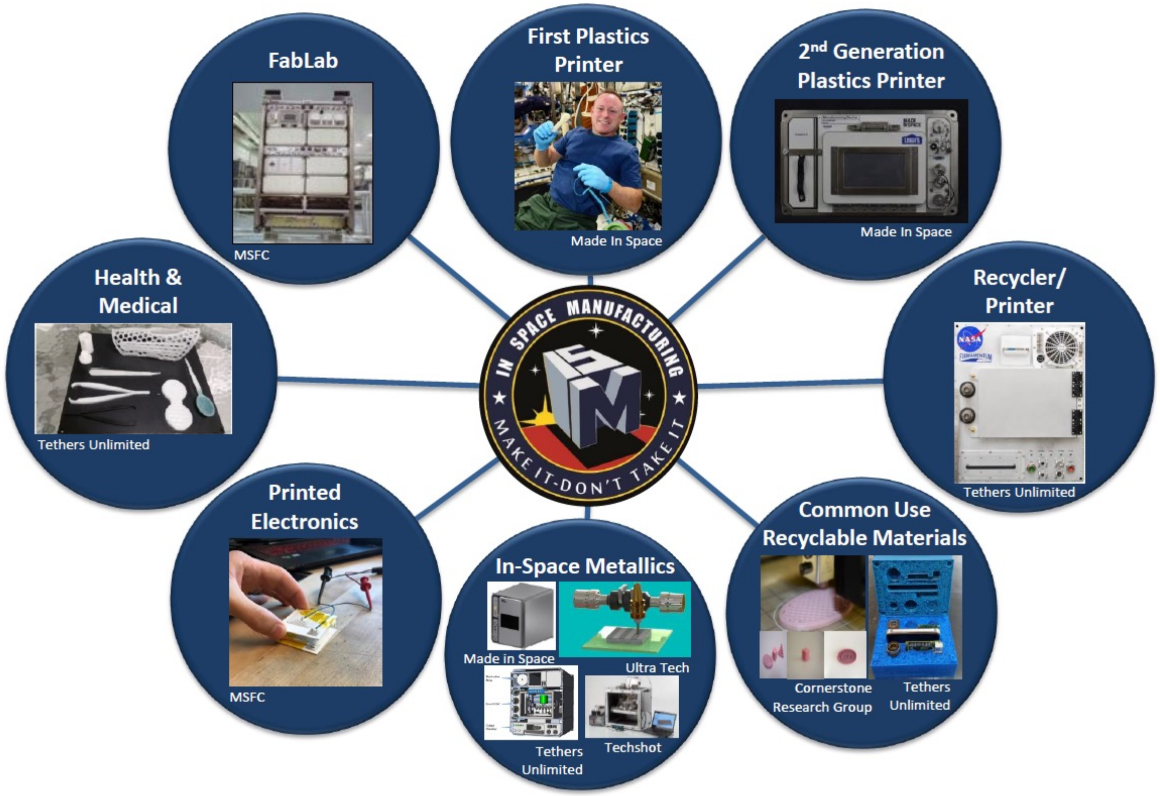
Additive Manufacturing (at MSFC)

- Extensive experience in Additive Manufacturing (AM) technologies and have been involved in about 30 different AM systems in the past 30 years.
- Over $12.5M capital investments in metallic powder bed systems in the past 8 years, and have committed significant engineering manpower resources
- Embracing 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:



Additive Manufacturing at NASA

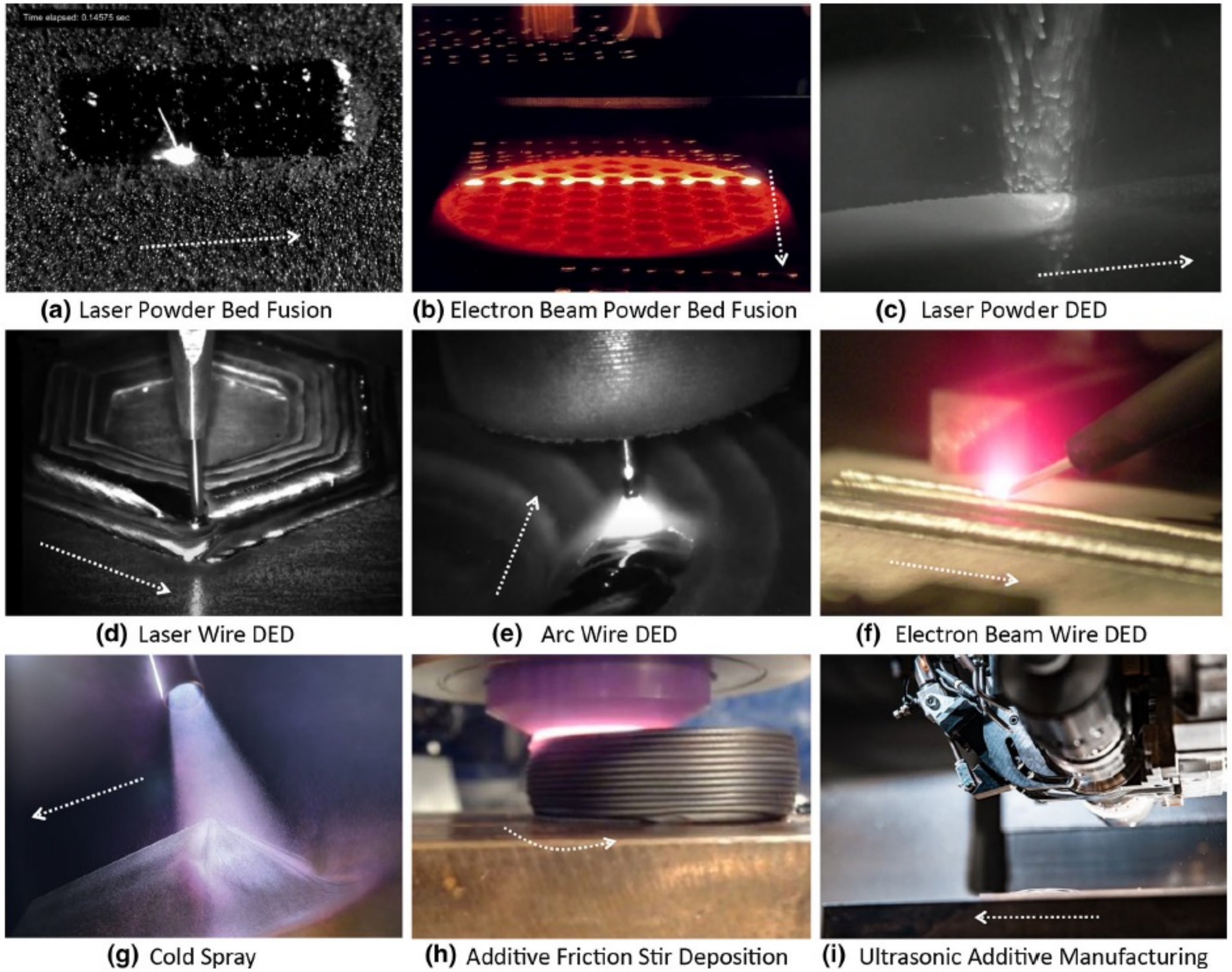
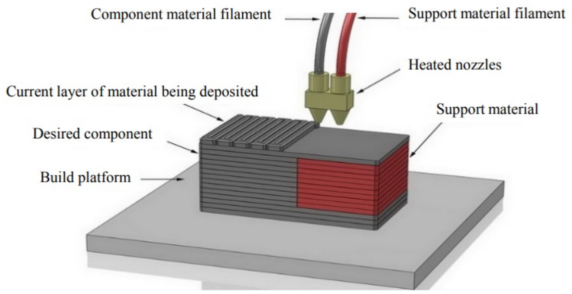
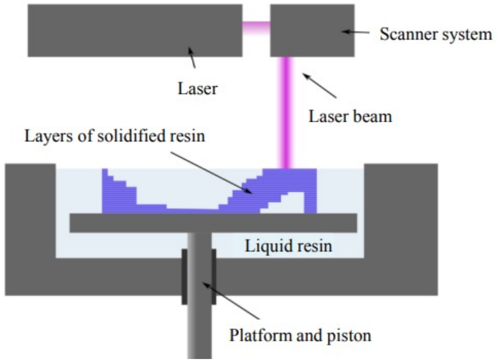


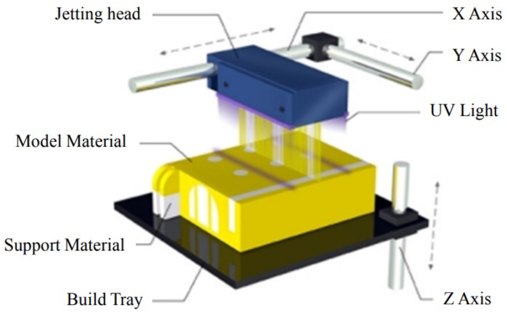
Fig. 3 Closeup images of the various metal AM processes along with deposition/build direction. (a) Laser powder bed fusion (Ref 29), (b) Electron beam powder bed fusion [Credit: Courtesy of Freemelt AB, Sweden, www.freemelt.com], (c) Laser powder DED [Credit: Formalloy], (d) Laser wire DED [Credit: Ramlab and Cavitar], (e) Arc wire DED [Credit: Institut Maupertuis and Cavitar], (f) Electron beam DED [Credit: NASA], (g) Cold spray [Credit: LLNL], (h) Additive friction stir deposition (Ref 30), (i) Ultrasonic AM [Credit: Fabrisonic]



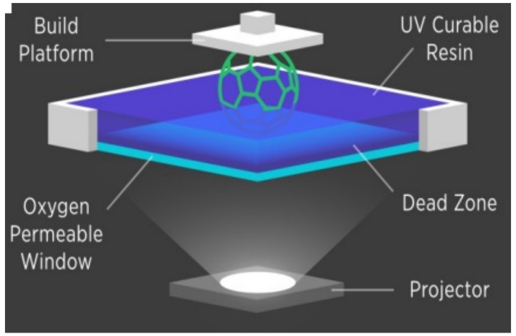
(j) Fused Deposition Modeling



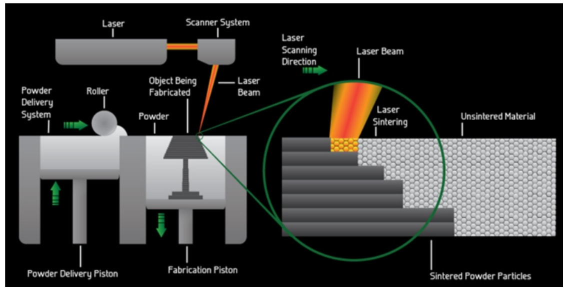
(k) Stereolithography



(l) Direct-write



(m) Continuous Liquid Interface Production



(n) Selective Laser Sintering

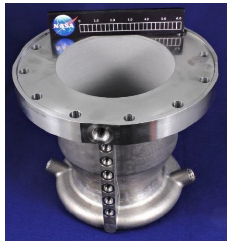
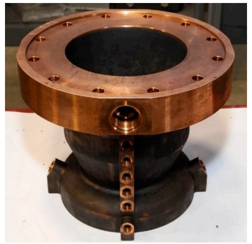
Metals Images Credit: Gradl, P., Tinker, D.C., Park, A. *et al.* Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. *J. of Materi Eng and Perform* (2022). https://doi.org/10.1007/s11665-022-06850-0

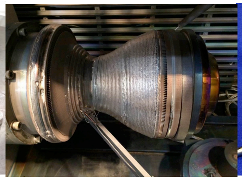
Polymers Images Credit: Black, H.T., Celina, M.C., McElhanon, J.R. Additive Manufacturing of Polymers: Materials Opportunities and Emerging Applications. *Sandia Report* (2016). https://www.osti.gov/servlets/purl/1561754

Examples of AM implementation

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.

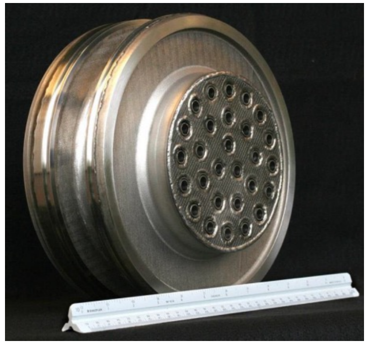





https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625

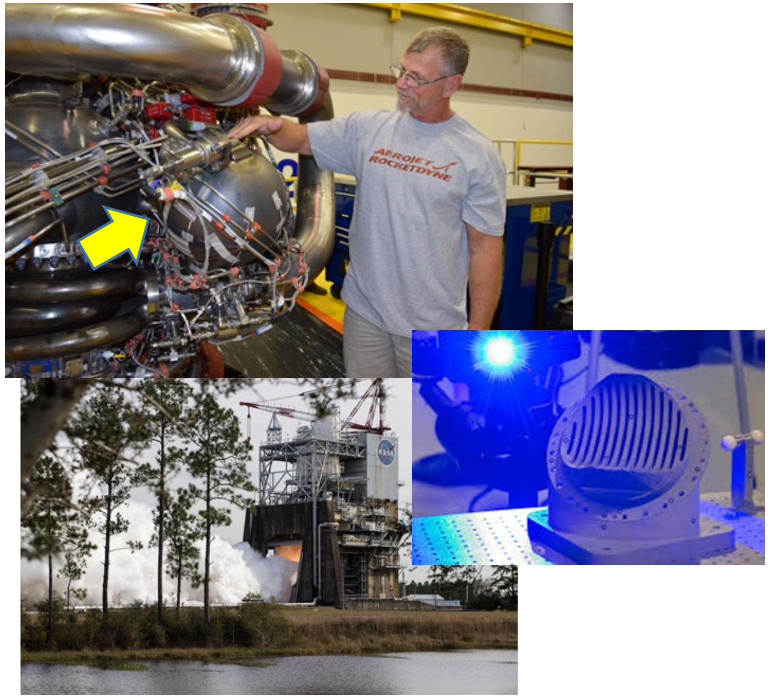
NASA MSFC rocket injectors made by AM resulting in a 70% reduction in cost.

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

28-element Inconel® 625 fuel injector built using a 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)

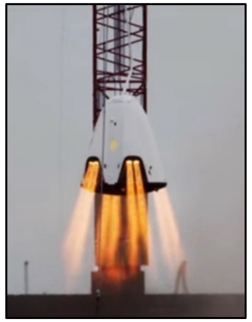
- Over 100 Weld Eliminated
- Nearly 35% Cost Reduction

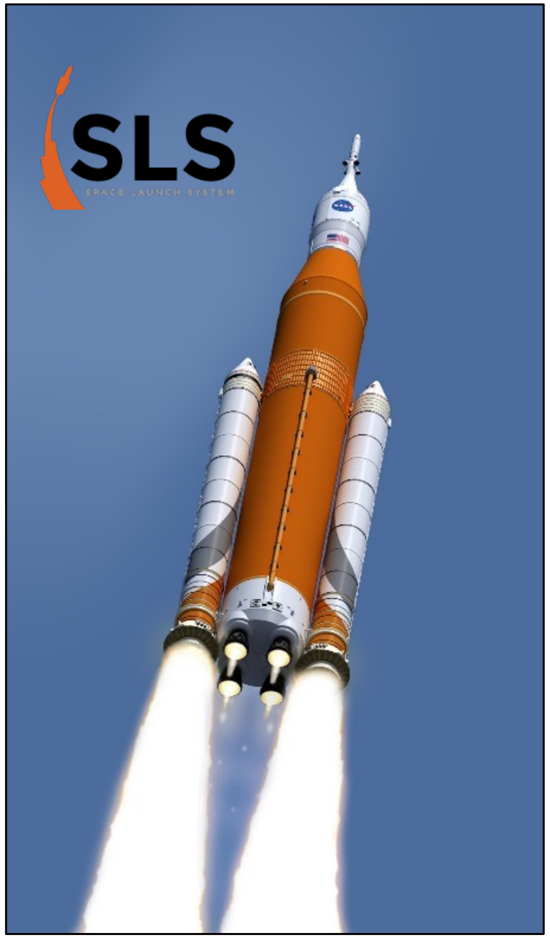
https://www.nasa.gov/exploration/systems/sls/nasa-tests-3-d-printed-rocket-part-to-reduce-future-sls-engine-costs

NASA AM Standards

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

- Space Launch System
- Human Landing System
- Commercial Crew Program





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

Why NASA AM Standard?

- AM being inserted to produce critical spaceflight systems – rapidly
- NASA needed to create certification and qualification strategies as well as consistent governing policy
- Understanding that the metallic AM parts are a unique metallurgical product form with no true precedent and no benefit of many years of incremental refinement by third-party practitioners which typically provides the experiential and scientific foundation for the more traditional processes
- For this reason, undiscovered failure modes remain in the metallic AM process. NASA-STD-6030 is supposed to provide the AM implementation approach that is heavily rooted in metallurgical understanding and respecting the evolving and meticulous metallic AM process

- Emphasis on Integration across disciplines and throughout the process
- Some roles and responsibilities are transitioned (i.e. Production facilities now largely responsible for material integrity)
- Requires 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
- Statistical process controls required in environments unaccustomed to it

Definition of Additive Manufacturing

NASA-STD-6016C Standard Materials and Processes Requirements For Spacecraft

Additive Manufacturing: Process of joining materials to make parts from three-dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies. Adj., additively manufactured. (Source: NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems)

Revision	C		2021-09-30	Limited Revision: • Modified hazardous fluid compatibility requirement [MPR 47] to require MUA for compatibility verification. • Revised section 4.2.4.11 requirement [MPR 174] and guidance on additive manufacturing to cite NASA-STD-6030. • Added new guideline and requirement [MPR 213] on composite NDE to section 4.2.5.1 • Revised guidance on sandwich assemblies in section 4.2.6.2. • Changed requirement [MPR 188] on sandwich assemblies in section 4.2.6.2 to call out the requirements of CMH-17 Volume 6: Structural Sandwich

METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD Office of the NASA Chief Engineer	NASA-STD-6016C Approved: 2021-09-30 Superseding NASA-STD-6016B

STANDARD MATERIALS AND PROCESSES

REQUIREMENTS FOR SPACECRAFT

NASA-STD-6016C

Standard Materials and Processes Requirements For Spacecraft

NASA-STD-6016C

4.2.4.11 Additive Manufacturing

[MPR 174] Spaceflight hardware manufactured by additive manufacturing techniques shall be designed, produced, and documented in compliance with NASA-STD-6030.

NOTE: The requirements of NASA-STD-6030 do not encompass all requirements for an AM part (flammability, toxic offgassing, vacuum outgassing, etc. also apply).

Additive Manufacturing Control Plans are reviewed and approved by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization per section 4.2 of NASA-STD-6030.

An Equipment and Facilities Control Plan per NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facility Control, is developed by the AM part producer and approved by the cognizant engineering organization per section 4.5 of NASA-STD-6030.

Material Property Suites used to design Class A and B additively manufactured parts are reviewed and approved by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization per section 6 of NASA-STD-6030.

Part Production Plans are reviewed and approved by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization per section 7 of NASA-STD-6030.

MSFC-STD-3716 & MSFC-SPEC-3717

For Laser Powder Bed Fusion

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

Written for SLS RS-25 Restart Program

Only covered metallic LPBF

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

Policy: MSFC-STD-3716

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

Active Standards for AM within NASA

MSFC ENGINEERING

NASA-STD-6030 & NASA-STD-6033

METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6030

Approved: 2021-04-21

ADDITIVE MANUFACTURING REQUIREMENTS

FOR SPACEFLIGHT SYSTEMS

APPROVED FOR PUBLIC RELEASE—DISTRIBUTION IS UNLIMITED

What's New?

- Expanded part classification
- Covers a multitude of metallic and now polymer processes beyond just LPBF
- Effort underway for development of a handbook to supplement 6030 and 6033

Category	Technology	Materials Form
Metals	Laser Powder Bed Fusion (L-PBF)	Metal Powder
	Directed Energy Deposition (DED), Any Energy Source	Metal Wire
	DED, Any Energy Source	Metal Blown Powder
Polymers	L-PBF	Thermoplastic Powder
	Vat Photopolymerization	Photopolymeric Thermoset Resin
	Material Extrusion	Thermoplastic Filament

METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6033

Approved: 2021-04-21

ADDITIVE MANUFACTURING REQUIREMENTS

FOR EQUIPMENT AND FACILITY CONTROL

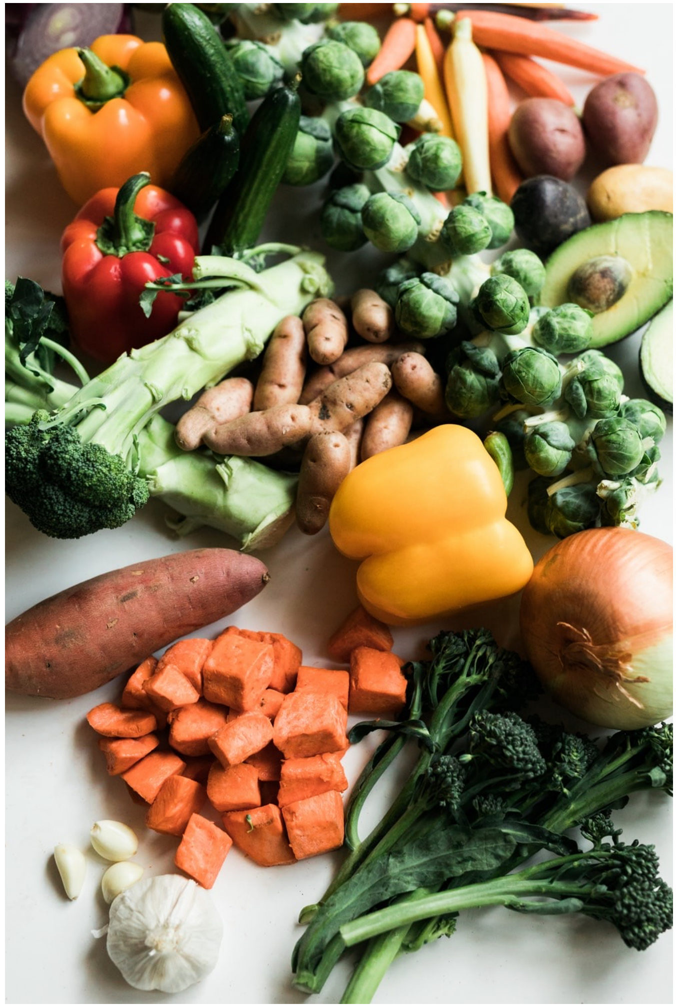
APPROVED FOR PUBLIC RELEASE—DISTRIBUTION IS UNLIMITED

https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-04-21_nasa-std-6030-approveddocx.pdf

https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-04-21_nasa-std-6033_-_approveddocx.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

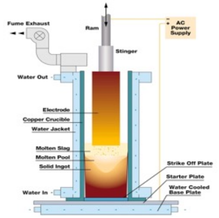


What are the key ingredients?

Some roles and responsibilities are transitioned

Subtractive Forging Process

CoC



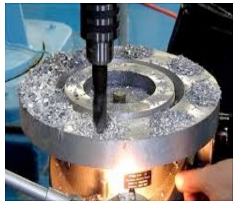
1. Ingot Making

2. Cutting

3. Heating

4. Forging

5. Heat Treating

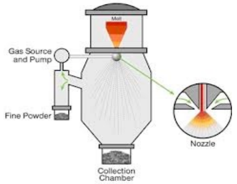


6. Machining

7. Inspection

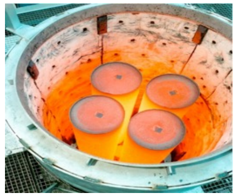
8. Delivery with CoC

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 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.

A Note on Terminology

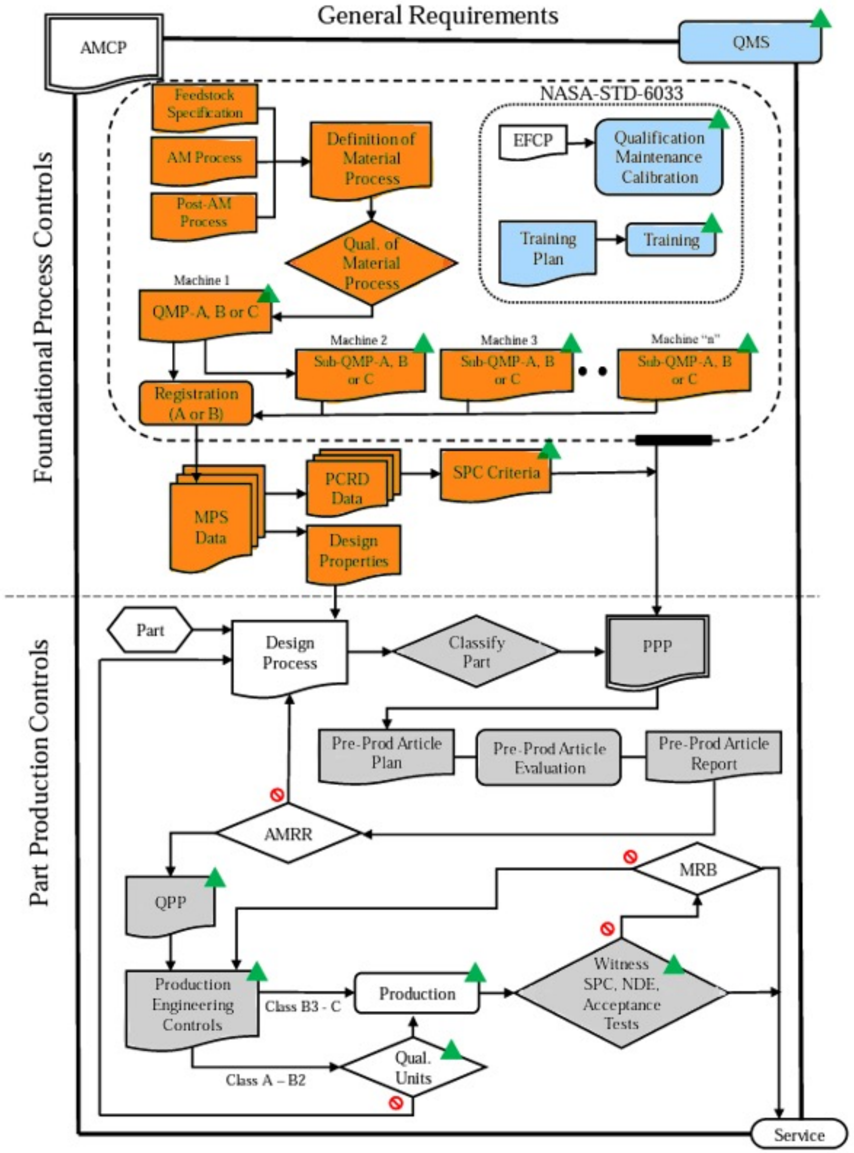
Definition of IQ, OQ, PQ

Per ASTM 52930:2021 Additive Manufacturing – Qualification principles – Installation, operation, and performance (IQ/OQ/PQ) of PBF-LB equipment

IQ (Installation Qualification): Establishment by objective evidence that all key aspects of the process equipment and ancillary system installation adhere to OEM approved specification and that recommendations of the supplier of the equipment are suitably considered.

OQ (Operation Qualification): Establishment by objective evidence that the process control limits and action levels which results in product that meets all predetermined requirements.

PQ (Performance Qualification): Establishment by objective evidence that a process consistently produces result of product meeting its predetermined requirements



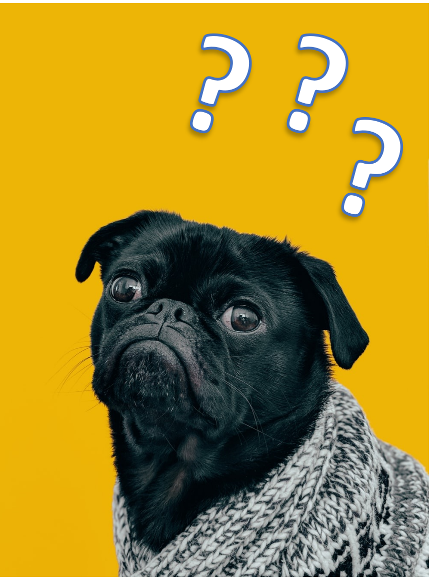
Overview of Certification Framework

- 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

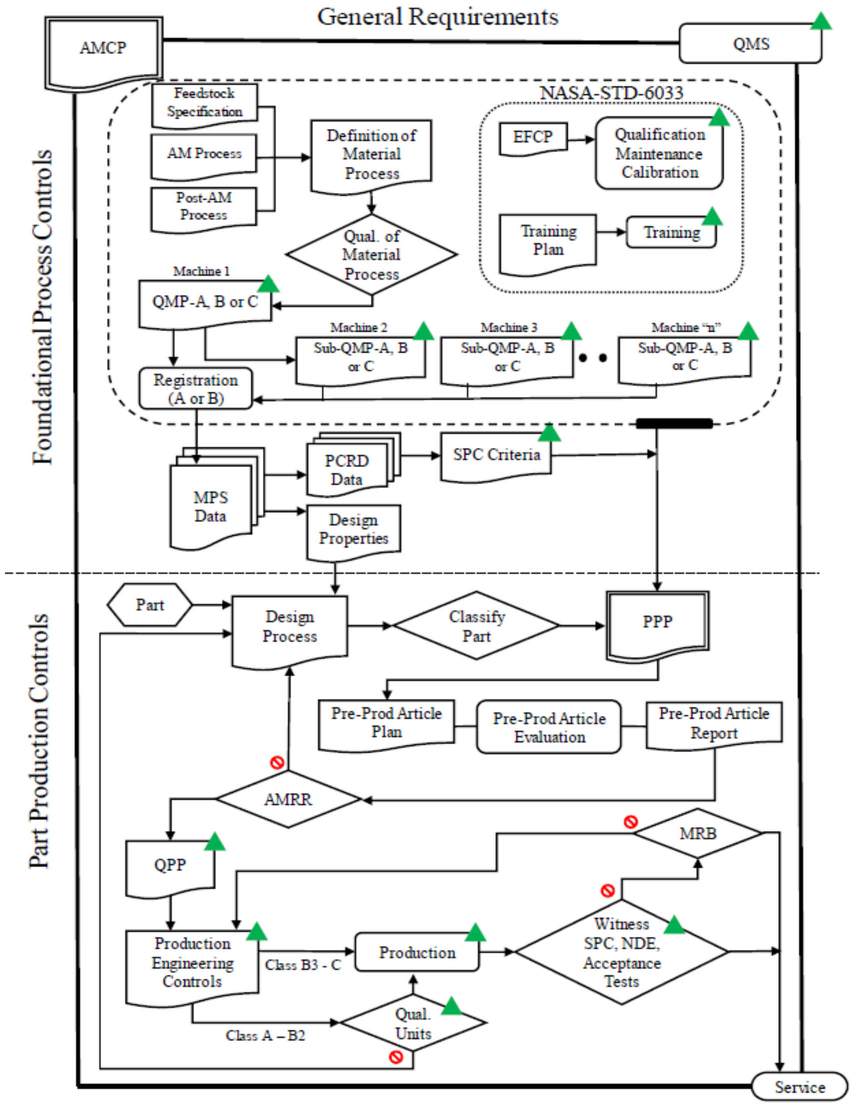
A Note on Tailoring

- NASA standards are meant to be tailored. It's difficult to define a best practice for every imaginable space application, so generally the standard prescribes the most stringent requirements to address the most critical applications.
- Programs can work with their cognizant engineering organization (CEO) to determine what makes sense for their specific program and unique risk posture.
- The 6030 and 6033 Compliance Matrices are meant to be a tool to help document the tailoring approach agreed to by your stakeholders.
- See Section 4.1 Tailoring of NASA-STD-6030 for more details.

Where do I start?

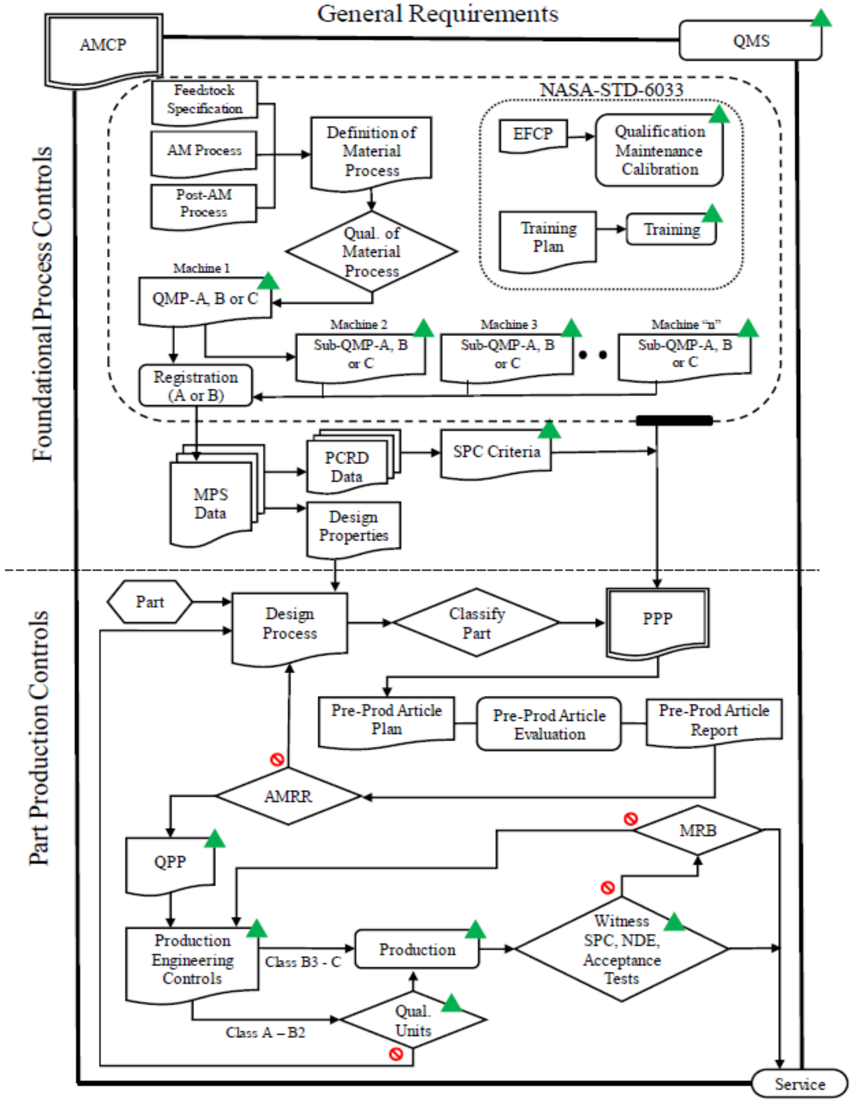


- NASA-STD-6030 starts with Foundational Process Controls and then discusses Part Production Controls
- If you already have a part identified that you want to print, it can be challenging to know where to start your compliance efforts with 6030
- For training purposes, we'll start with the foundation, but depending on the vendors and facilities involved, some of this foundation may already be established
  - As with any type of certification activity, trust but verify!



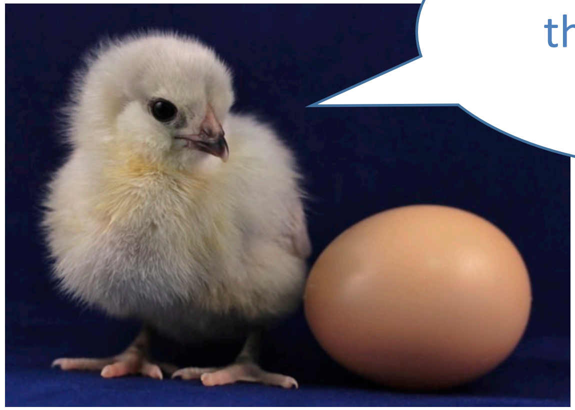
NASA-STD-6030 Outline

- 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 Material Processes (QMPs)
  - Equipment Controls (covered by NASA-STD-6033)
  - Personnel Training (covered by NASA-STD-6033)
  - Material Property development
- Part Production Control requirements are typical of aerospace operations and must be met before placing a part into service.

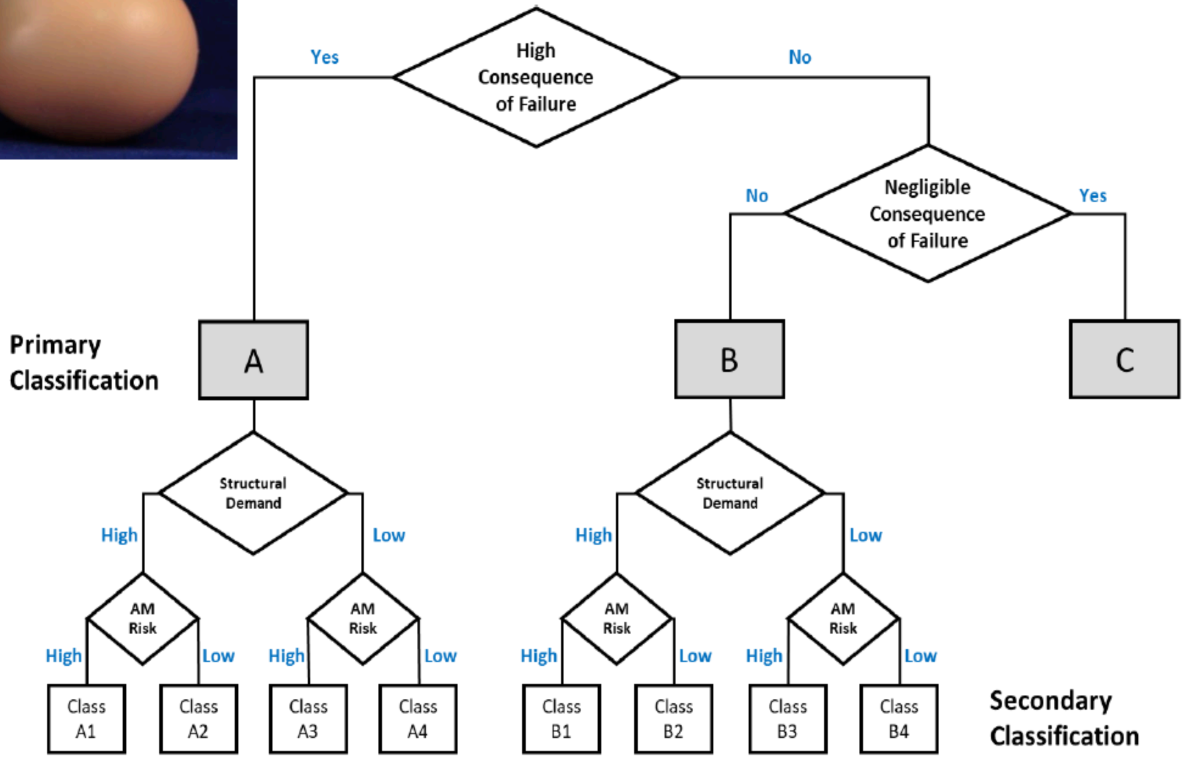


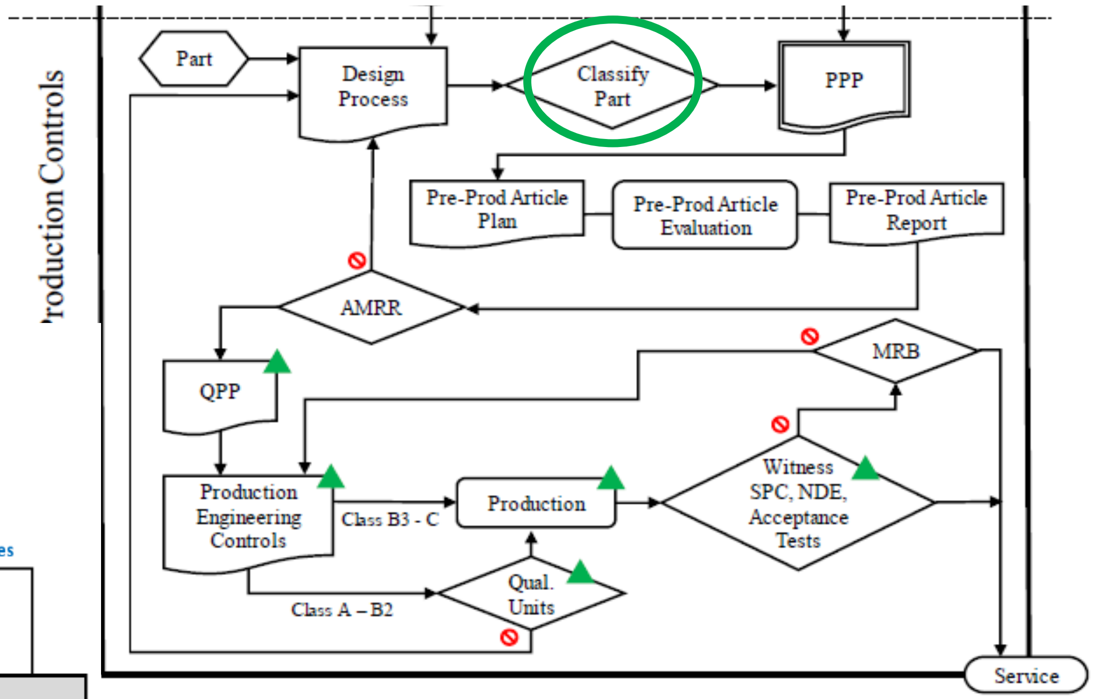
Part Classification

Overview



Which came first, the part or the process?





1. *Catastrophic Failure?*
2. *Heavily Loaded?*
3. *Does the build have challenging aspects or areas that cannot be inspected?*

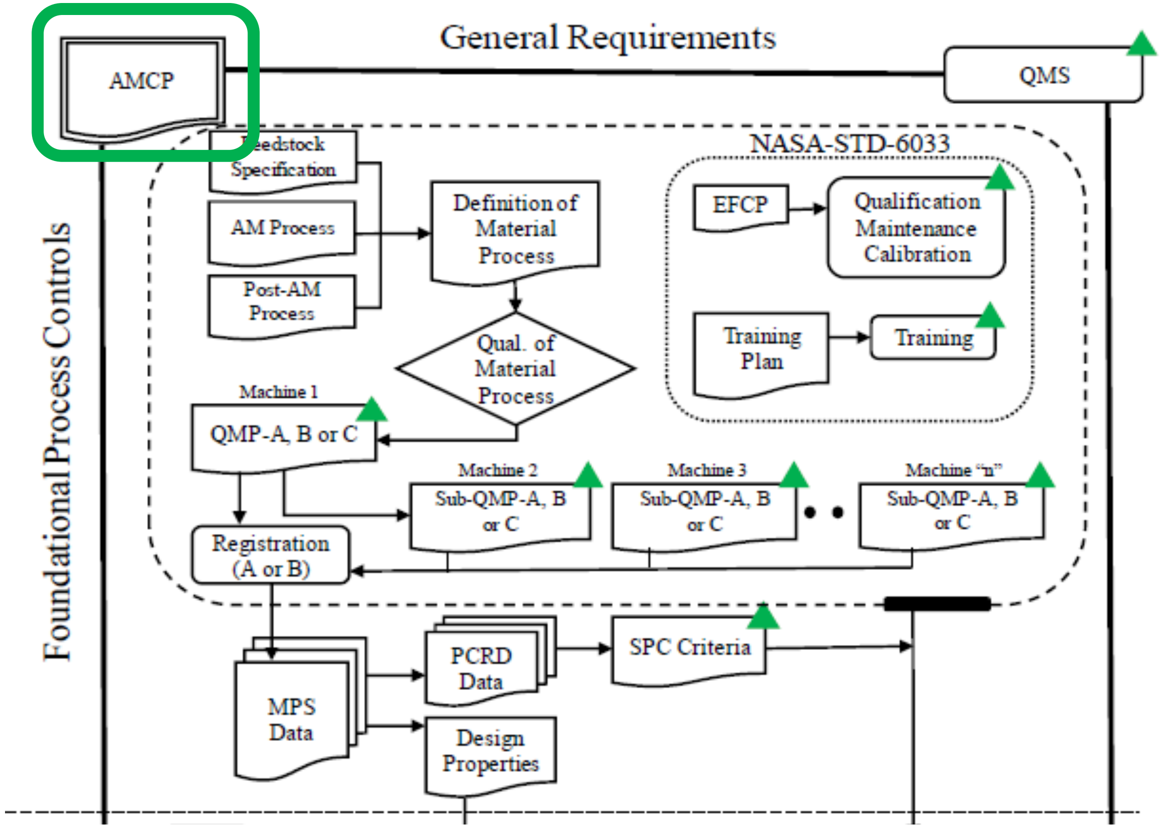
General Requirements
and
Foundational Process Controls

Have A Plan!

Overarching and Foundational Controls

Additive Manufacturing Control Plan

- 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



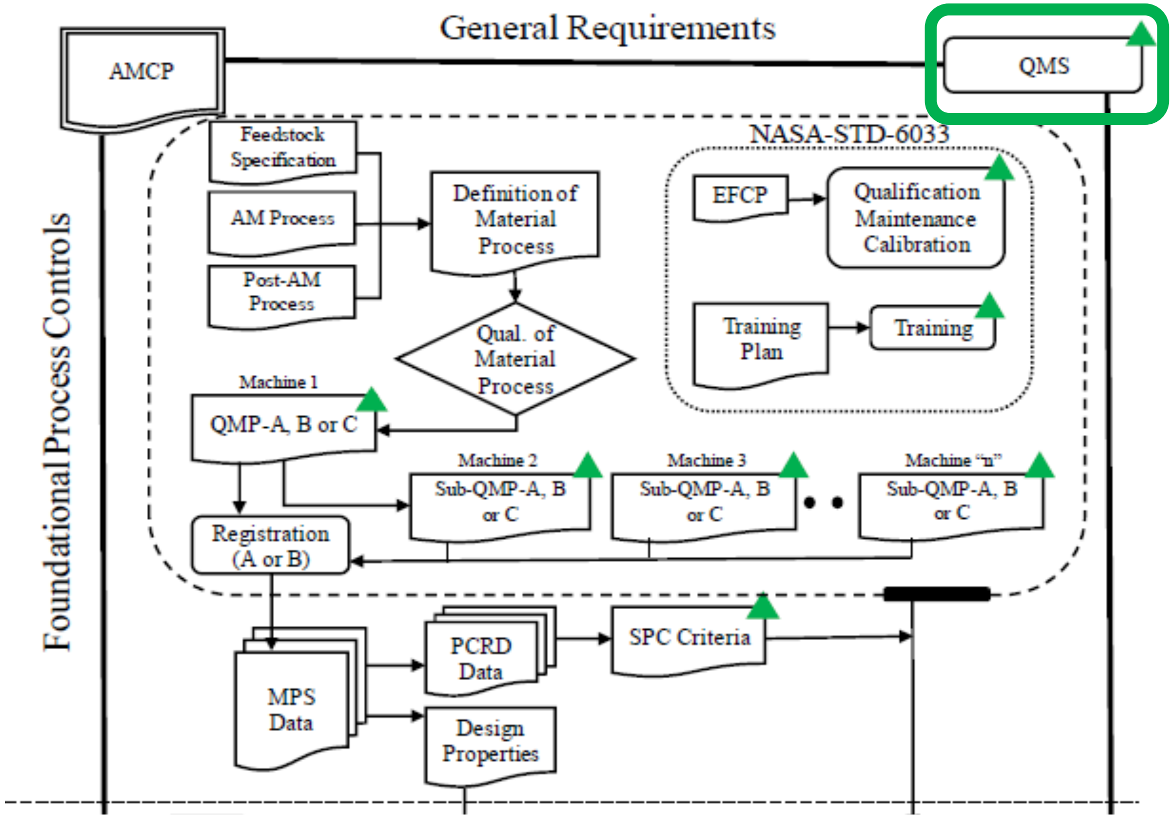
Have a Plan

- 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 ubiquitous
- Long, perilous chain of controls needed
  - Design documentation
  - Feedstock
  - Facility control
  - Machine calibration
  - Digital Thread
  - Inspection
  - Statistical process controls…

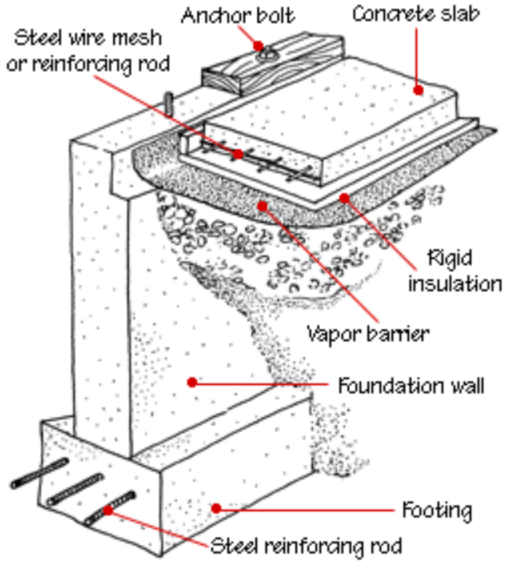
Source: https://www.orielstat.com/blog/medical-device-qms-overview/

- 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



But I already have a part I want to print!

AM is hot! We get it. A lot of people start here, but because you already have a part in mind, you need to be careful to not skip any steps relative to your foundational additive process maturity. Again, this will vary based on your vendor, facilities, and the specific application you're considering.

Technology Readiness Levels

TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
- System prototype demonstration in a space environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported

It's easy to think you're up here…

…but really be down here

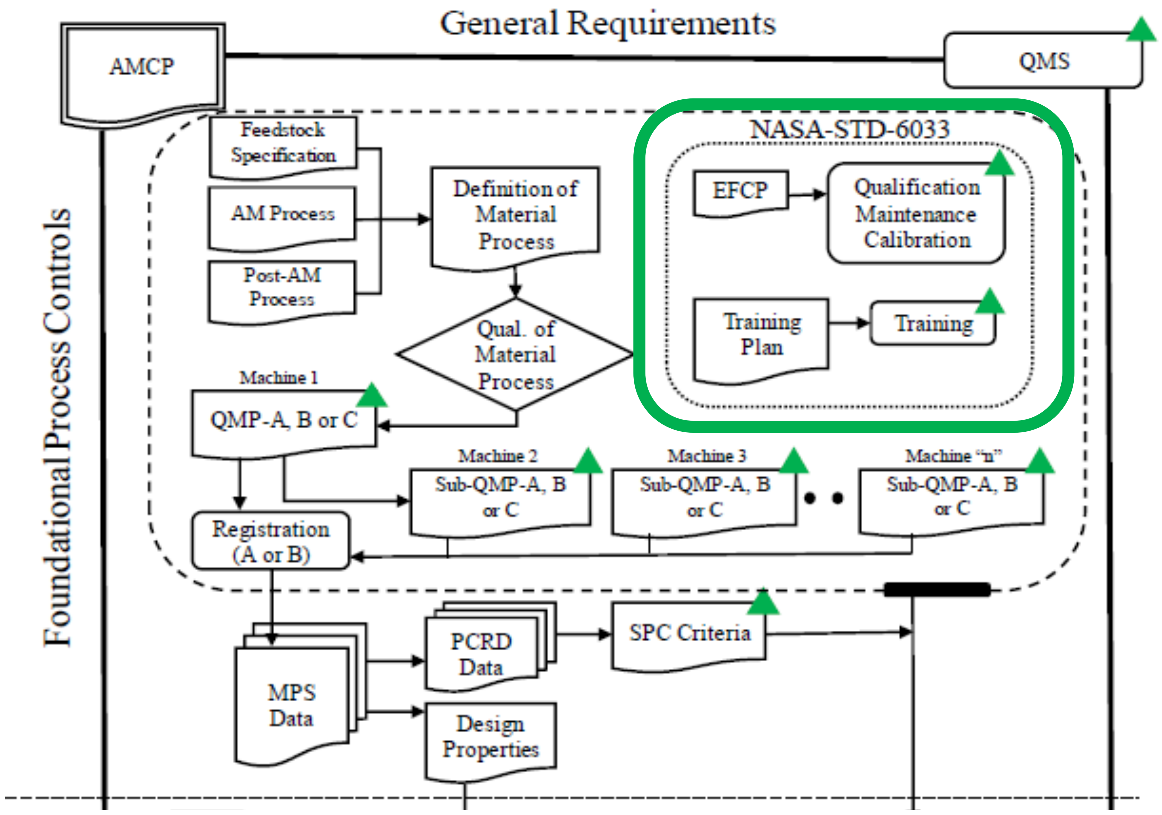
Manufacturing Readiness Levels

MRL	Definition
10	Full Rate Production demonstrated and lean production practices in place.
9	Low Rate Production demonstrated. Capability in place to begin Full Rate Production.
8	Pilot line capability demonstrated. Ready to begin low rate production.
7	Capability to produce systems, subsystems or components in a production representative environment.
6	Capability to produce a prototype system or subsystem in a production relevant environment.
5	Capability to produce prototype components in a production relevant environment.
4	Capability to produce the technology in a laboratory environment.
3	Manufacturing proof of concept developed
2	Manufacturing concepts identified
1	Basic manufacturing implications identified

Overarching and Foundational Controls

Equipment and Facility Control Plan

- Flexibility in implementation
- Governs AM equipment and facility
    - Qualification
    - Maintenance
    - Calibration
- Personnel Training Program
    - 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



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

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 Example

Directed Energy Deposition

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

EM40-OWI-116
Baseline
Document Date: 02/24/22

ORGANIZATIONAL WORK INSTRUCTION

EM40 – NONMETALLIC MATERIALS & ADVANCED MANUFACTURING DIVISION

DIRECTED ENERGY DEPOSITION

5. INSTRUCTIONS

5.1. Pre-operational Checks

5.1.1. Turn on chillers, laser generator, robot controller, and ventilation units. If the vacuum sieve will be used, ensure that this unit is also on and no errors are present.

5.1.2. Verify that all units are operational and that no alarms are present.

5.1.2.1. "Chain 1 abnormal 40, 40" error code will appear in the error list at the robot controller regularly upon restart and can cleared by

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

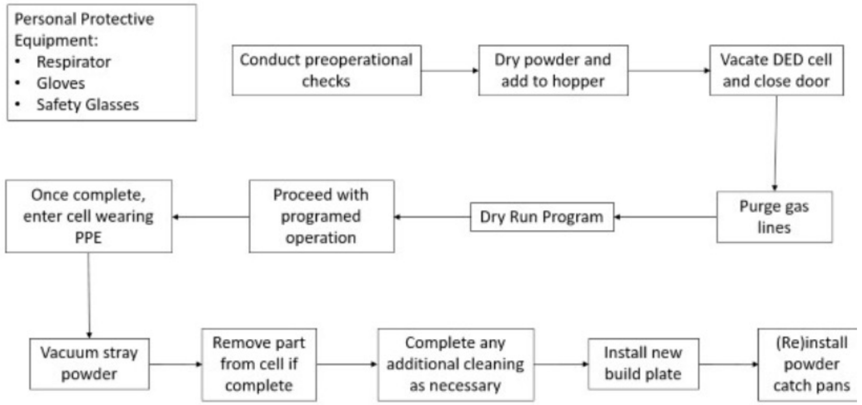
11. PERSONNEL TRAINING AND CERTIFICATION

The machine operator is to be familiar with the operator manual provided by DM3D, "DMD Robotic System." This document is found on the EM42 Directed Energy Deposition SharePoint site. A list of qualified operators will be kept in the operators' booth and will be updated as required.

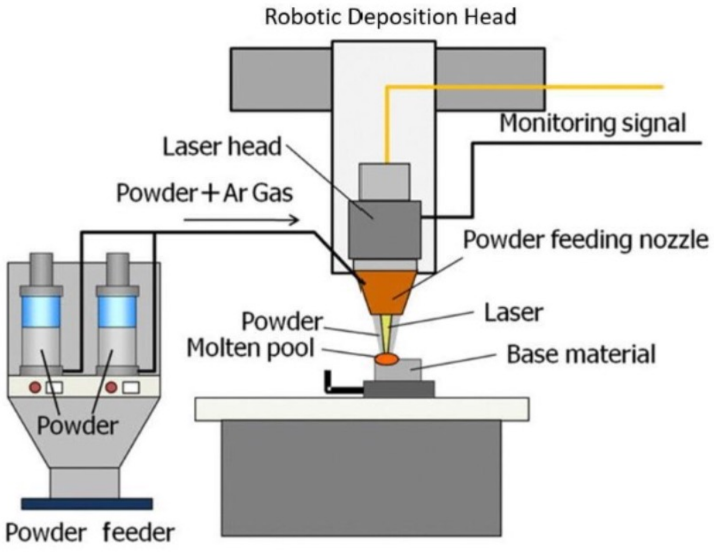
11.1. Training

SHE 102: MSFC SHE PROGRAM REFRESHER TRAINING
SHE 228: RADIATION SAFETY - IONIZING RADIATION PRODUCING DEVICES
SHE 216: LASER SAFETY
SHE 302: CHEMICAL MANAGEMENT TRAINING
SHE 317: MSFC ENVIRONMENTAL COMPLIANCE TRAINING
Reference MWI 3410.1 PERSONNEL CERTIFICATION PROGRAM

12. FLOW DIAGRAM



Appendix A – General DED Operation



Appendix B – DED Cell Layout

Break 1

Qualified Material Process

Foundation

Qualified Material Process

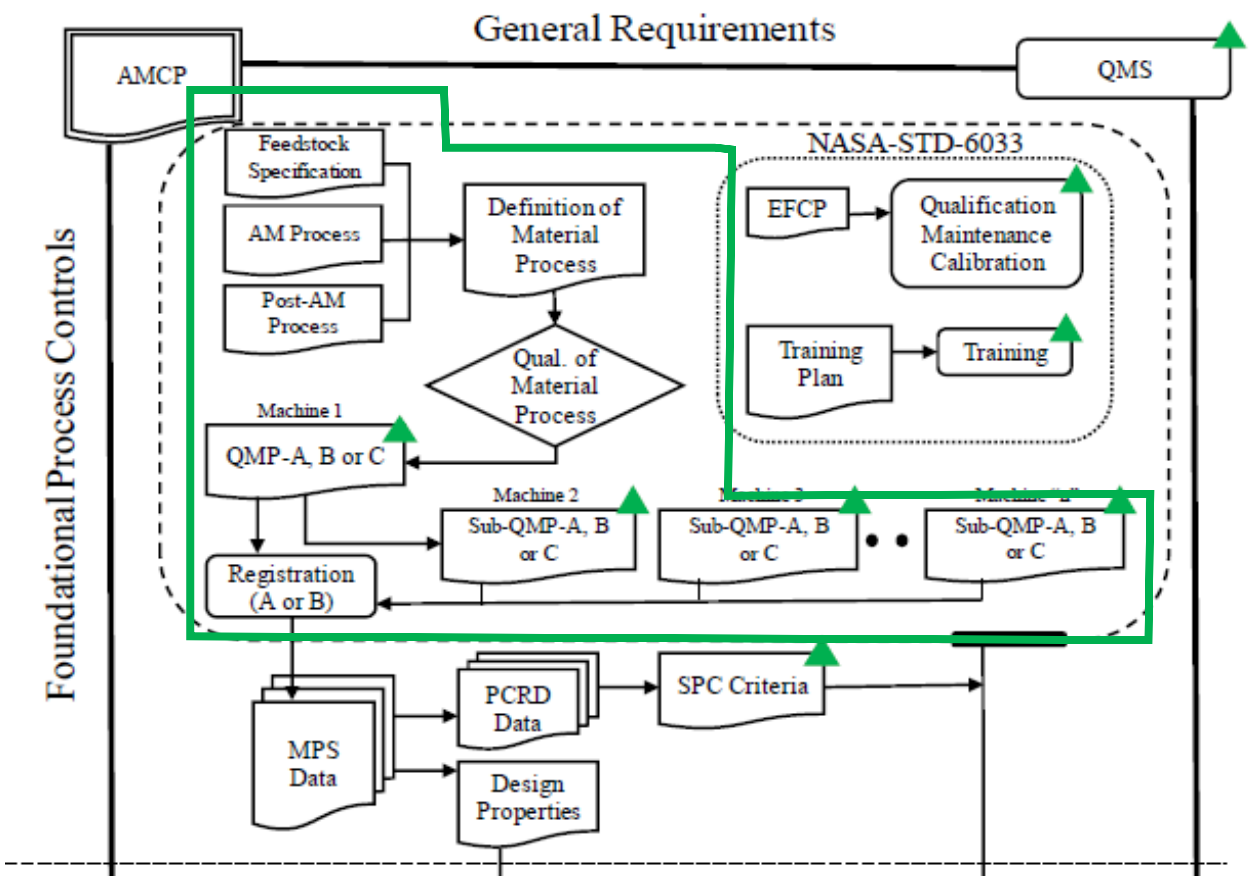
Begins as a ***Candidate*** Material Process

Defines aspects of the basic, ***part agnostic***, fixed AM process:

- Feedstock
- Fusion Process
- Thermal Process

Enabling Concept

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



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
- f) Locked process parameters, no dynamic feedback loops*

**More and more systems are leveraging dynamic, closed-loop process control schema. NASA's AM Team is in the process of getting smarter on these technologies to incorporate qualification guidance into the next revision of NASA-STD-6030.*

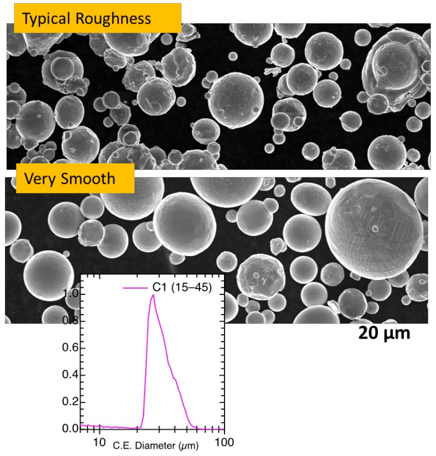
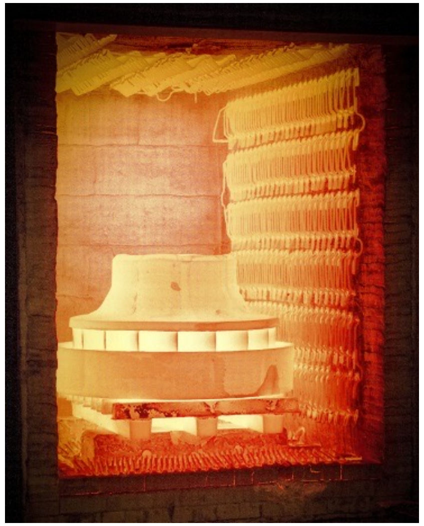


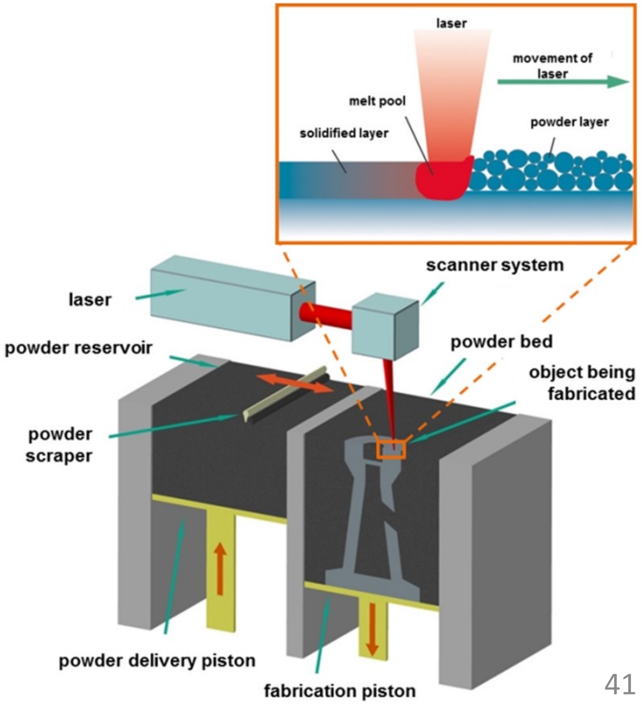
Table 1. GRCop-42 Powder Composition (weight %)

Element	Minimum	Maximum	Target
Cr	3.1	3.40	3.27
Nb	2.7	3.00	2.92
Fe	—	250 PPM	Target <50 ppm
O	—	500 PPM	Target <250 ppm
Al	—	600 PPM	Target <400 ppm
Si	—	350 PPM	Target <100 ppm
Cu	Balance		
Cr/Nb*	2.02 (atomic) 1.13 (weight)	2.12 (atomic) 1.18 (weight)	2.07 (Atomic) 1.14 (weight)

* Atomic ratio is based on percentage of Cr and Nb in atomic percent.
Weight ratio is based on percentage of Cr and Nb in weight percent.

From: MSFC GRCop-42 Alloy Gas Atomized Powder Specification





Candidate Material Process

Foundation

Definition of Material Process

Feedstock Specification

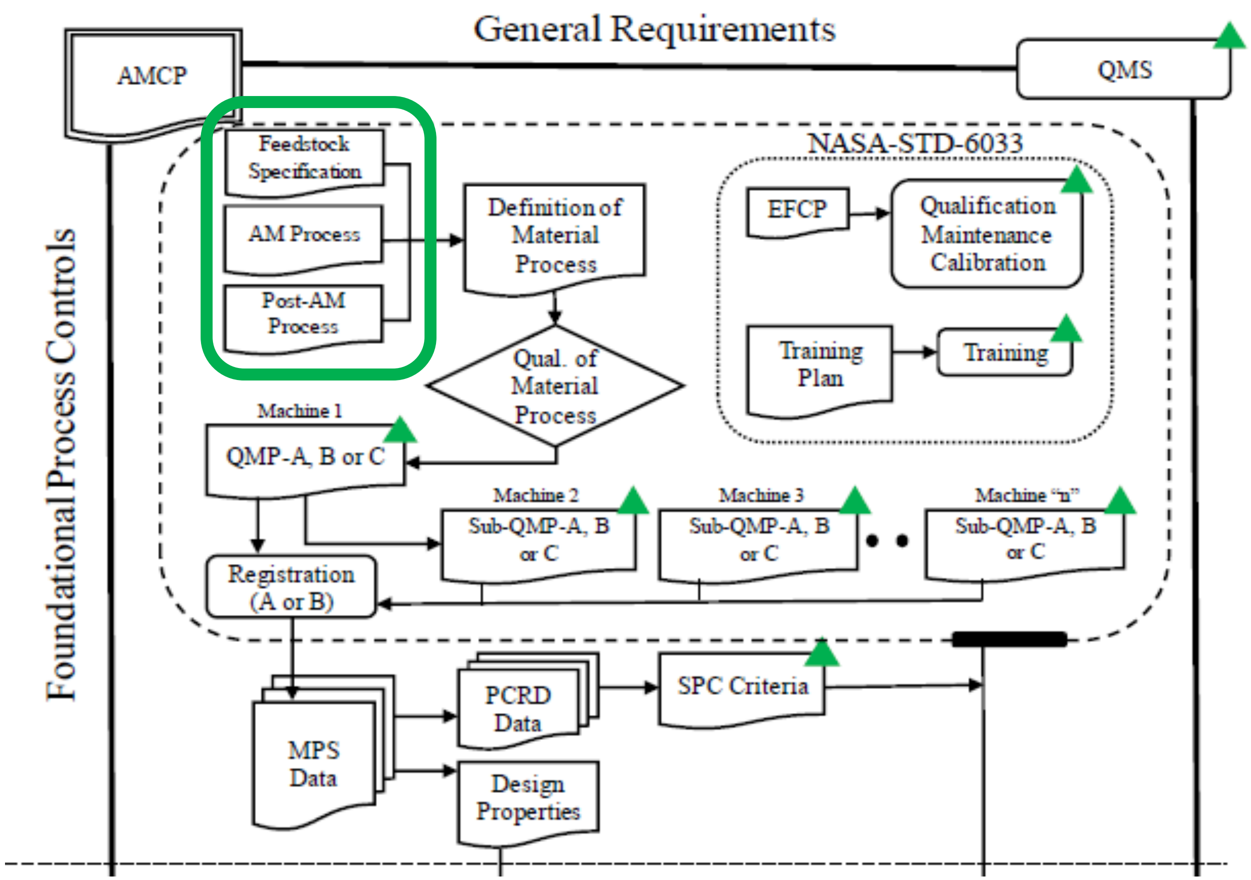
- What you are building with

AM Process

- How a machine operates

Post-AM 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

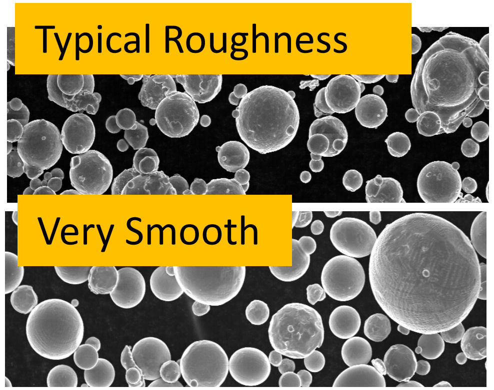
Powder Specification:
Inconel 718
for Laser Powder Bed Fusion
Additive Manufacturing

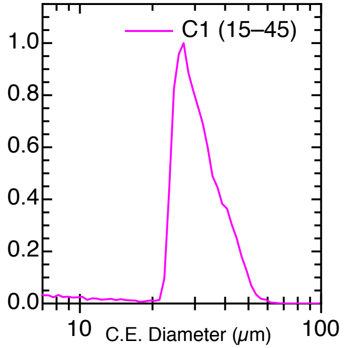
DRAFT – March, 2017

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

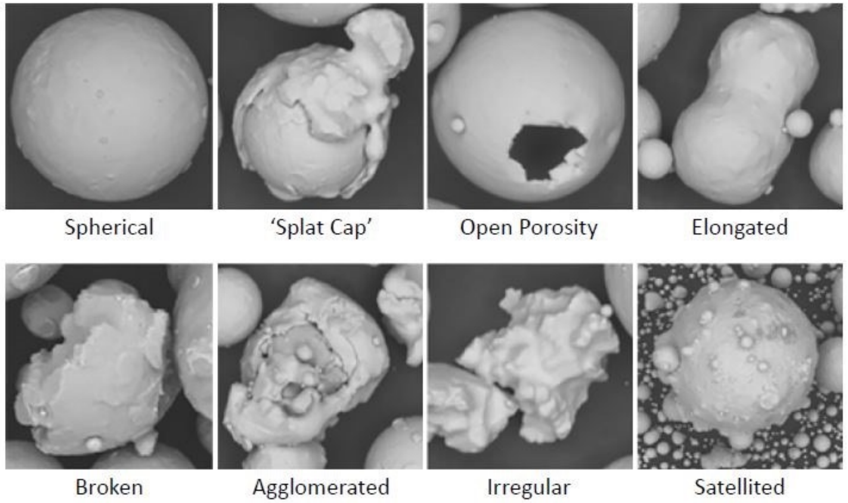
CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED





20 μm



Powder Morphology. Courtesy Metal AM, Winter 2017.

Ref AMS Specifications:
AMS7001: *Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni - 21.5Cr - 9.0Mo - 3.65 Cb (Nb) Annealed*
AMS7002: *Process Requirements for Production of Metal Powder Feedstock for use in Additive Manufacturing of Aerospace parts*

Feedstock Evaluation: NASA Feedstock Requirements vs. SAE Metal Powder Feedstock Spec Example

NASA-STD-6030

Table 9—Virgin Powder Feedstock Controls

	Powders
a	Requiring powder producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, Quality Management Systems – Requirements for Aviation, Space, and Defense Distributors, or an equivalent approved by the CEO.
b	Specifying unambiguously the method of powder manufacture.
c	Specifying powder chemistry requirements, including acceptable methods of measurement and tolerance.
d	Specifying particle size distribution (PSD) requirements and the acceptable methods for powder sampling and determining the PSD, including explicit limits in weight percent on the quantity of coarse and fine particles outside the PSD range.
e	Specifying, at least qualitatively, the mean particle shape (powder morphology) and limits on satellite/agglomerated particles using standardized terminology/methodology.*
f	Controlling the blending of virgin powder heats/batches into powder lots by requiring that each blended powder heat/batch individually meets all requirements of the feedstock specification.
g	Prohibiting post-production additions to the powder lot for control of PSD or chemistry (doping).
h	Providing requirements for powder cleanliness and contamination control, including moisture content for sensitive materials.
i	Providing requirements for powder packaging, labeling, and environmental controls.
j	Specifying rheological (flow and spreading) behavior of the powder and associated method of verification.
k	Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each powder heat and blended lot and the date(s) and location(s) of powder production.
l	Specifying powder crystallinity morphology control, such as solvent processing procedures and heat treatments, if applicable.

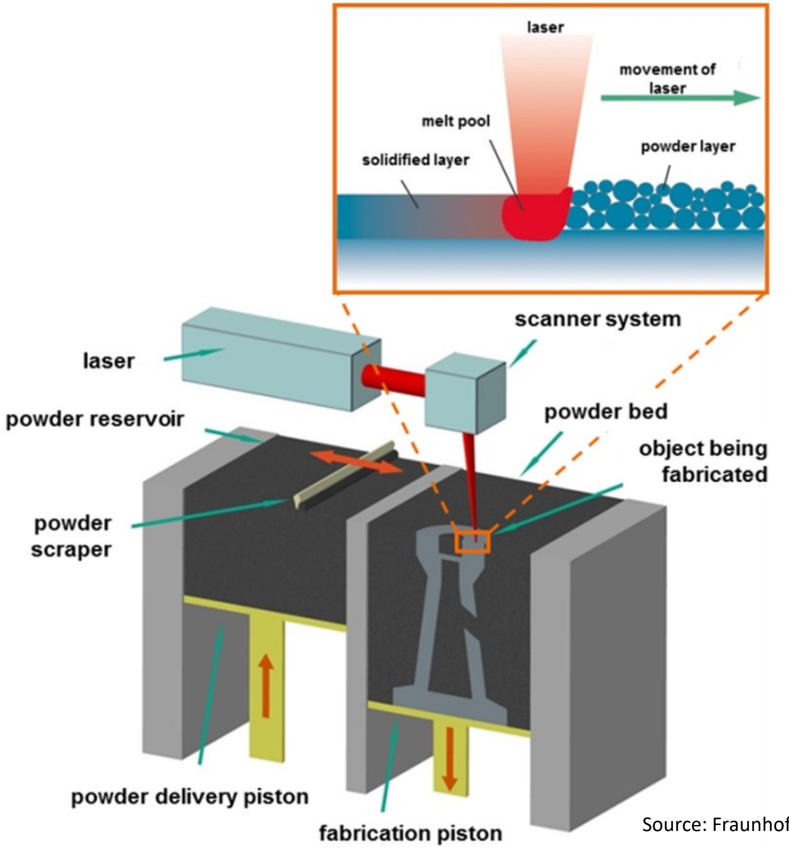
** Description of powder morphology requirements should use standardized terminology to the greatest extent possible by following powder standards such as ASTM F1877, Standard Practice for Characterization of Particles, and ASTM B243, Standard Terminology of Powder Metallurgy.*

SAE AMS 7002 Feedstock Specification

- ✔ a) Requires AS9100 quality management system.
- ✔ b) Includes well defined requirements of powder manufacturing method and specifies some requirements.
- ✔ c) Composition uniformity requirements are specified for raw and manufactured feedstock materials.
- ✔ d) PSD specifics are also requested, not stated. Sampling is discussed and must conform to ASTM B215 – Standard Practices for Sampling Metal Powders.
- ✘ **e) Adjacently calls out morphology but does not specify any requirements for shape or satellite/agglomerates.**
- ✔ f) Blending of powder heats into powder lots is fully addressed with several requirements for the feedstock.
- ✔ g) Additives and doping is not-permitted for chemistry uniformity.
- ✔ h) Cleanliness and contamination are directly addressed.
- ✔ i) Adjacently addresses all packaging, labelling, and environment control requirements. Specific documentation will be needed
- ✘ **j) Requires physical property characterization, but doesn’t specify rheological requirements (specified in separate SAE standard)**
- ✔ k) Material certification and compliance is directly addressed. Additionally, traceability requirements covers the identifiers.
- ✘ **l) Crystallinity is not addressed within the specification.**

Fusion Controls

- Equipment:
  - Make, Model, *Serial Number*
  - Software/Firmware versions
  - Settings (dosing, recoater speed & material)
- Atmosphere Controls
  - Oxygen limits
  - Ventilation flow rate
  - Gas quality (purity, dew point)
- Fusion Parameters
  - Layer thickness
  - Area fill schemes
  - Power, speed, hatch, contours…



Source: Fraunhofer IWU

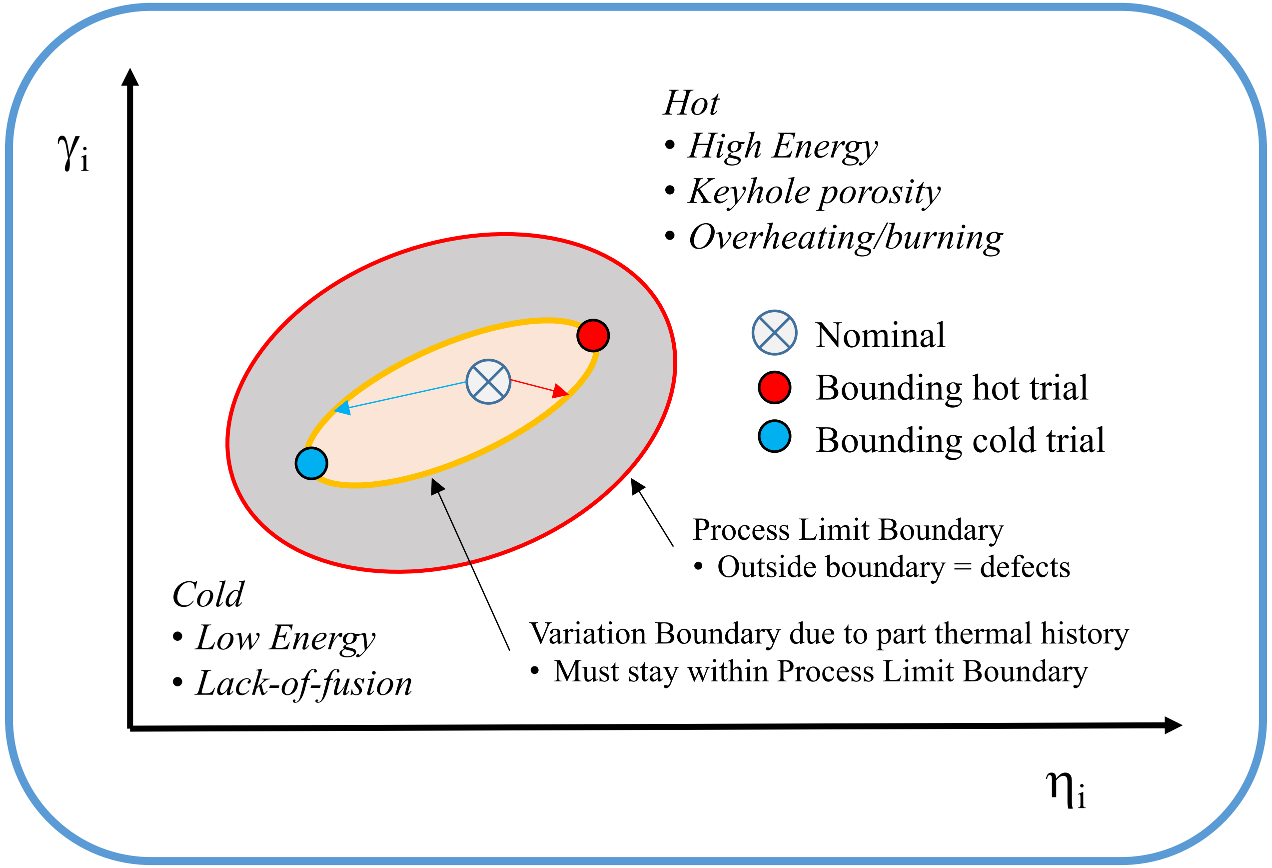
Note: The values of the parameters may remain undisclosed and proprietary. To establish the QMP using the build control parameter file, the file name and its cryptographic hash are referenced in the QMP record.

Any Machine Parameter that affects Material Quality must be Controlled!

Fusion Controls

<u>Tolerance to variation</u>

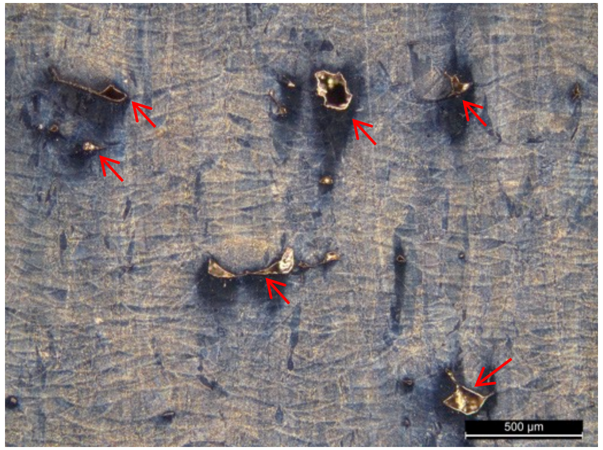
- Part build scenarios create variation in process conditions
  - Thermal history effects
  - Scan patterns
- “Process Box” evaluation for qualification
- QMP needs to be “centered” in the process box to allow robust part build capability
- Process Restarts



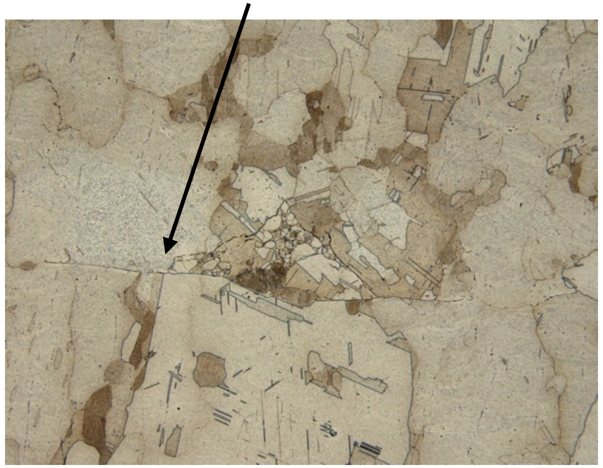
Process Box: Resulting variations in nominal commanded process due to part geometry, scan pattern and thermal history
Axes: Representative of any parameters, i.e., power, speed

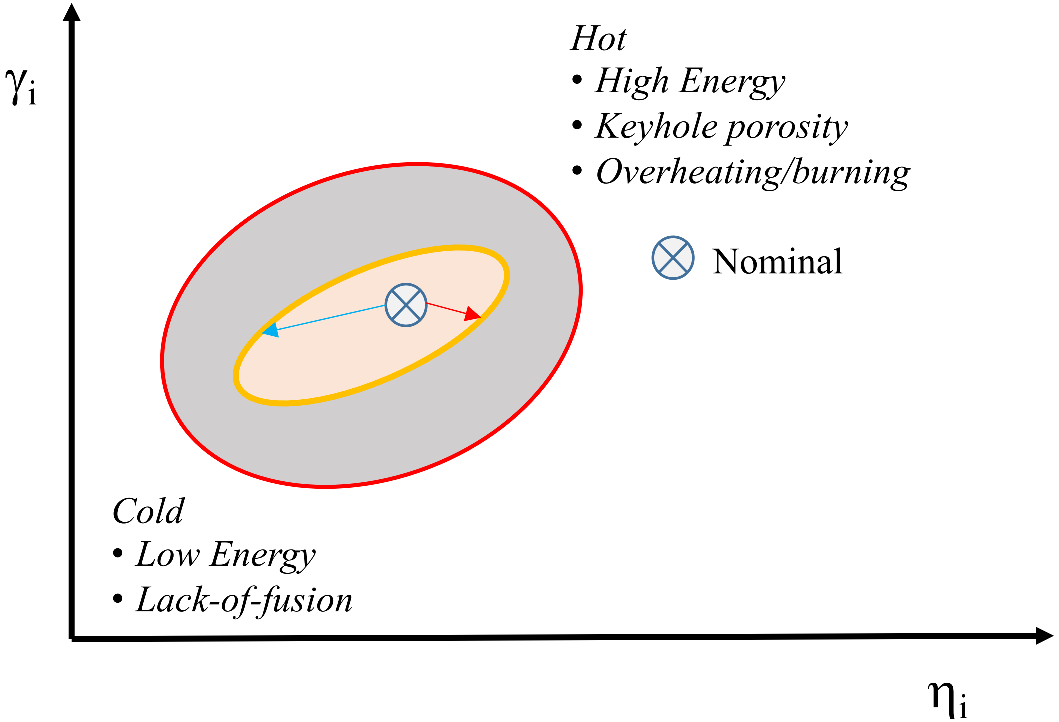
Parameter Influence on Defects

Lack of Fusion Defect

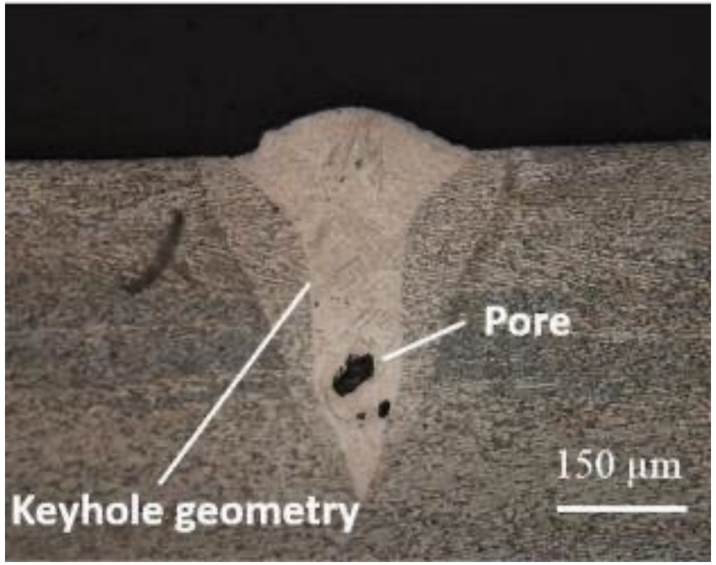


Lack of Fusion Defect after HIP

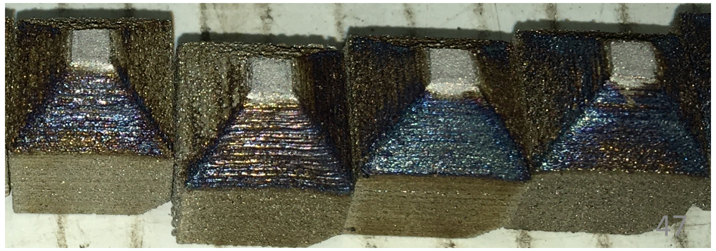




Process Box: Resulting variations in nominal commanded process due to part geometry, scan pattern and thermal history
Axis: Representative of any parameters, i.e., power, speed



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



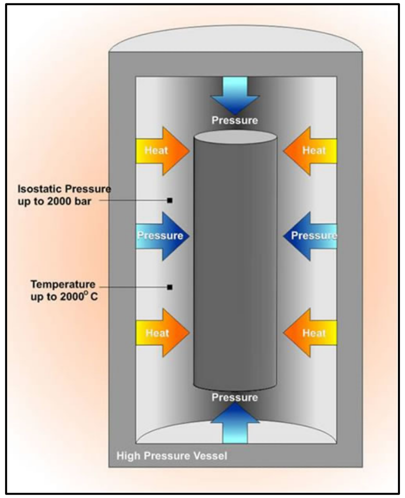
Candidate Material Process

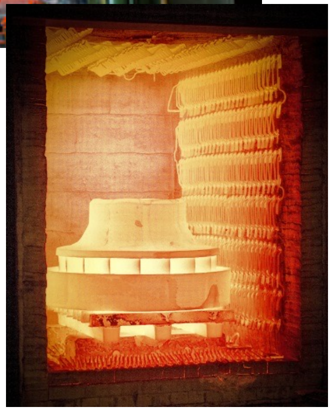
Foundation

Thermal Process

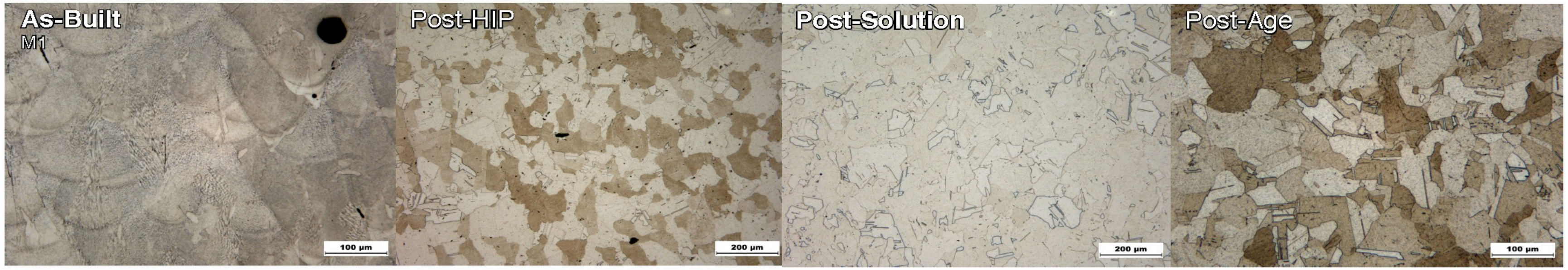
<u>Post-build Thermal Processing</u>

- 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



Qualified Material Process

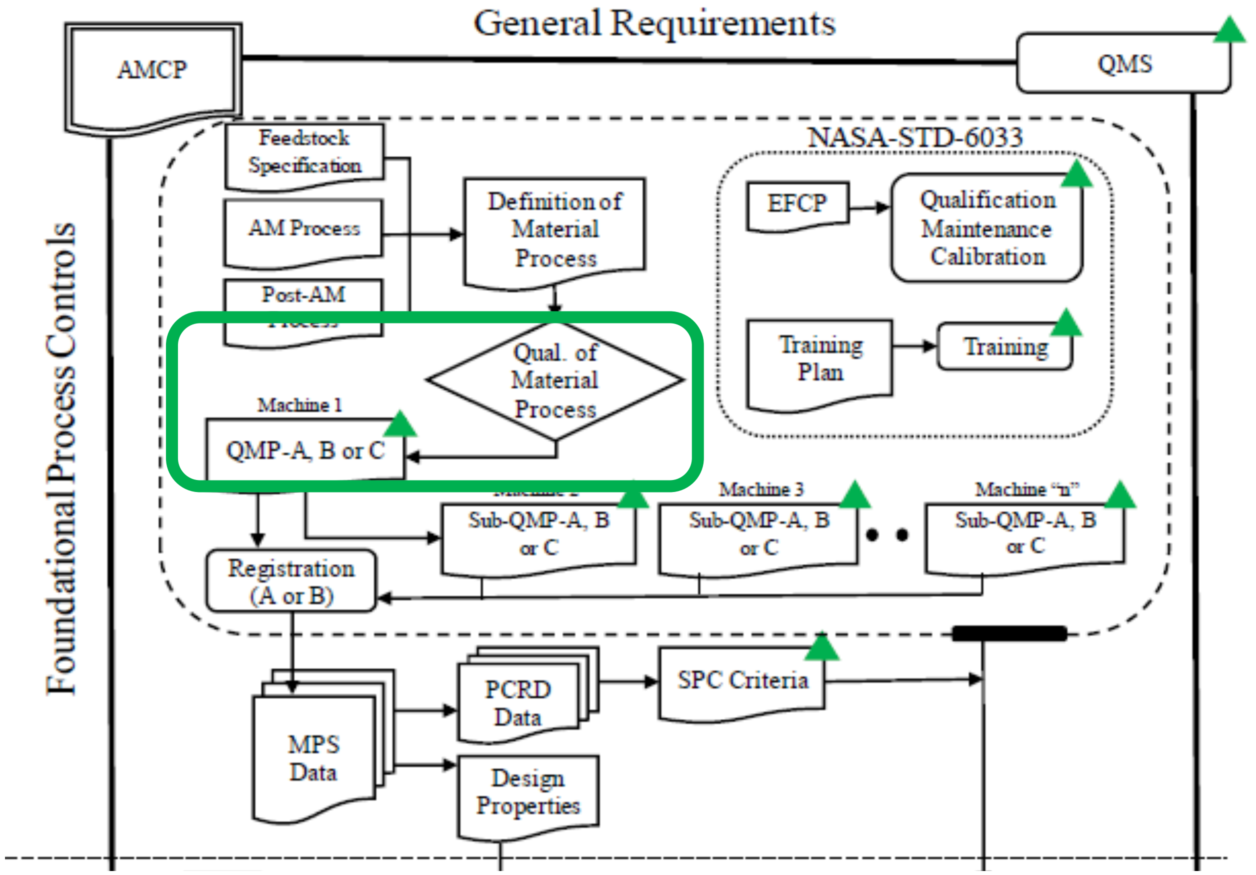
Foundation

Qualification of the Candidate Material Process

Establishing a QMP: Qualified Material Process

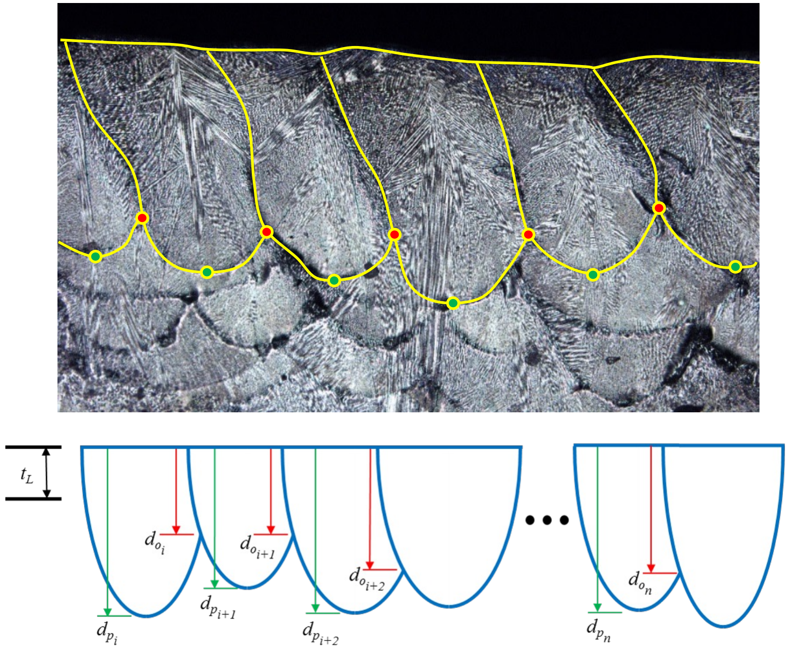
Four Step Process

- Material Qualification
- Surface Texture and Detail Resolution
- Flaw Population
- Mechanical Properties

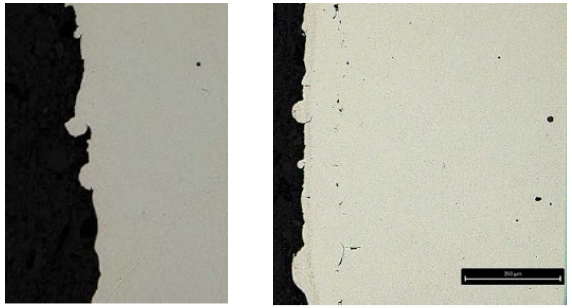


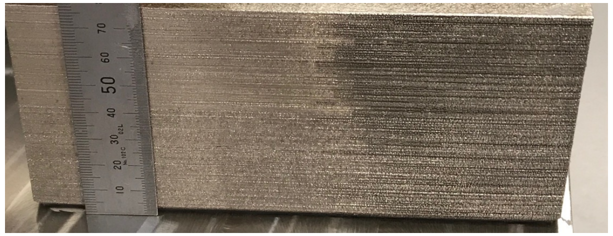
Step 1: Material Qualification

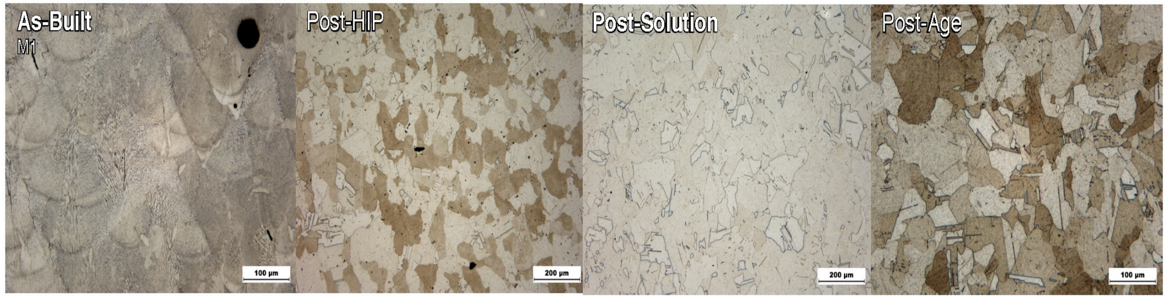
- Influence Factors
- Consistency throughout build area
- Tolerance to variation
- Interface quality (restart, contour passes, striping, islands, multi-laser zones)
- Top layer melt pools
- Microstructural evolution
  - Final state free of strong texture
  - Acceptance criteria for As Built and Final



Melt Pool Evaluation


Contour Evaluation


Transition Zone



Microstructure Evolution

Qualified Material Process

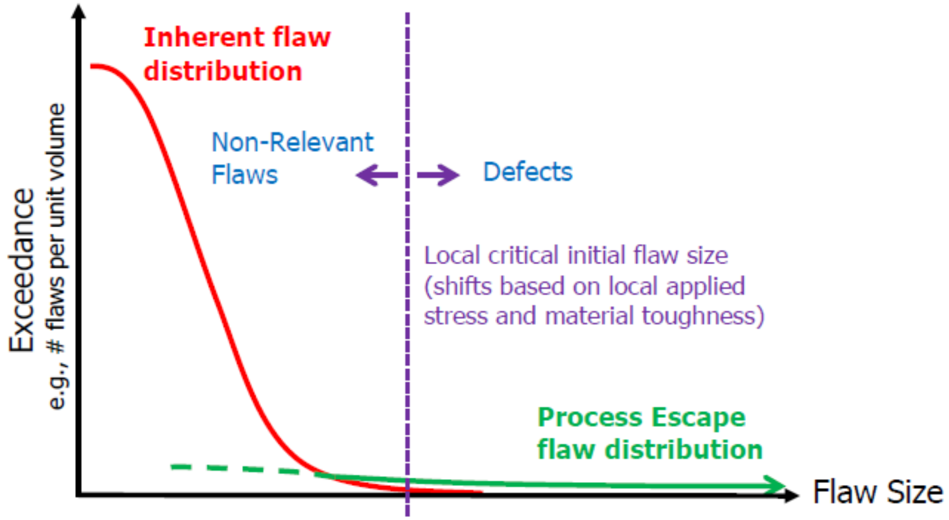
Foundation

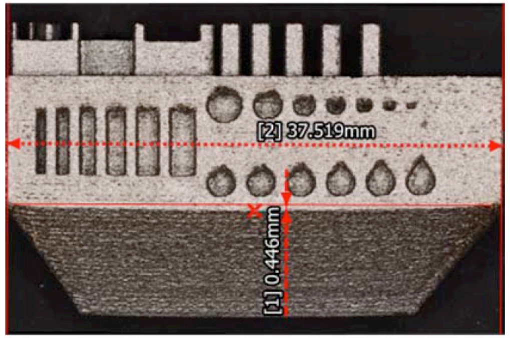
Step 2: Surface texture and detail resolution

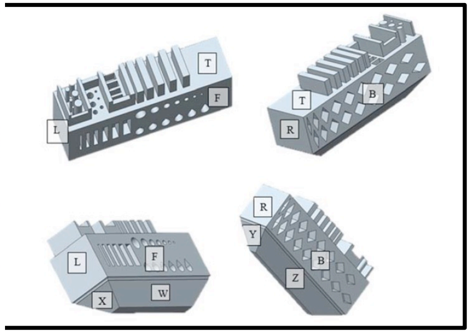
- Reference Parts
- Mix of qualitative and quantitative measures

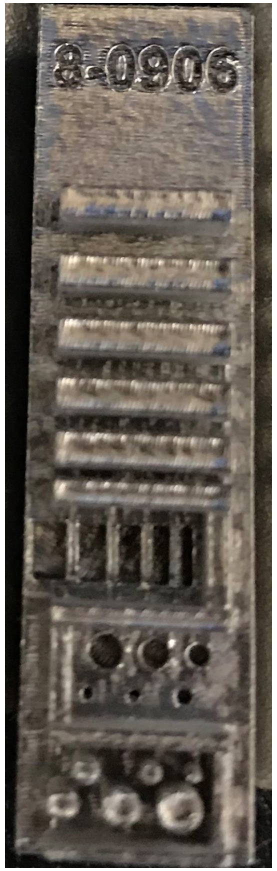
Step 3: Flaw Population

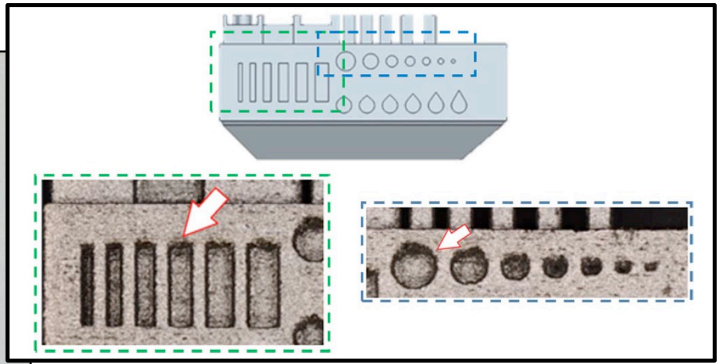
- Quantifiable metrics to aid equivalency judgements for common inherent flaws (things we expect)
  - Types, sizes, frequency of occurrence
  - Process escape flaws are not the focus here

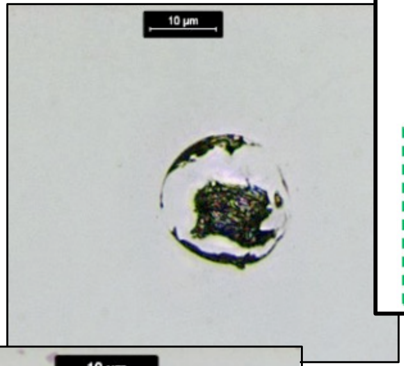


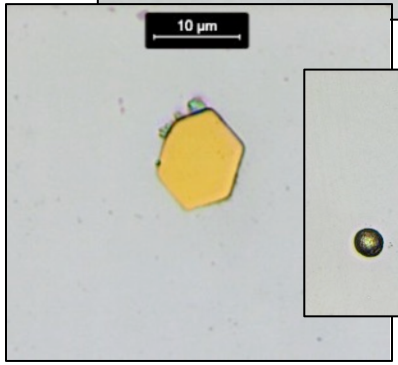


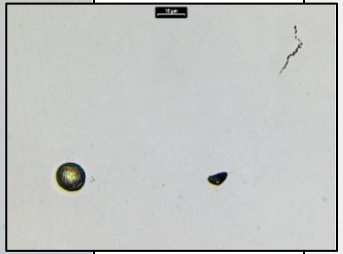


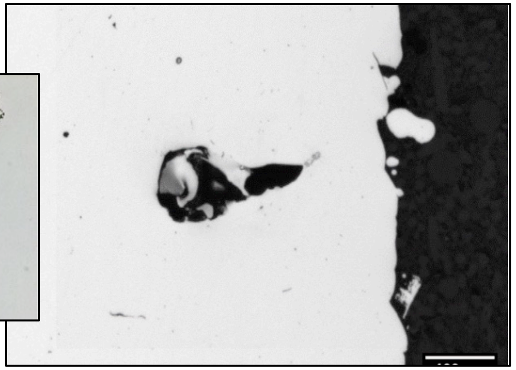


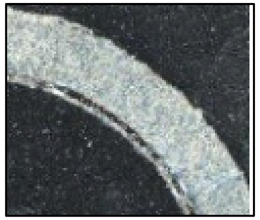






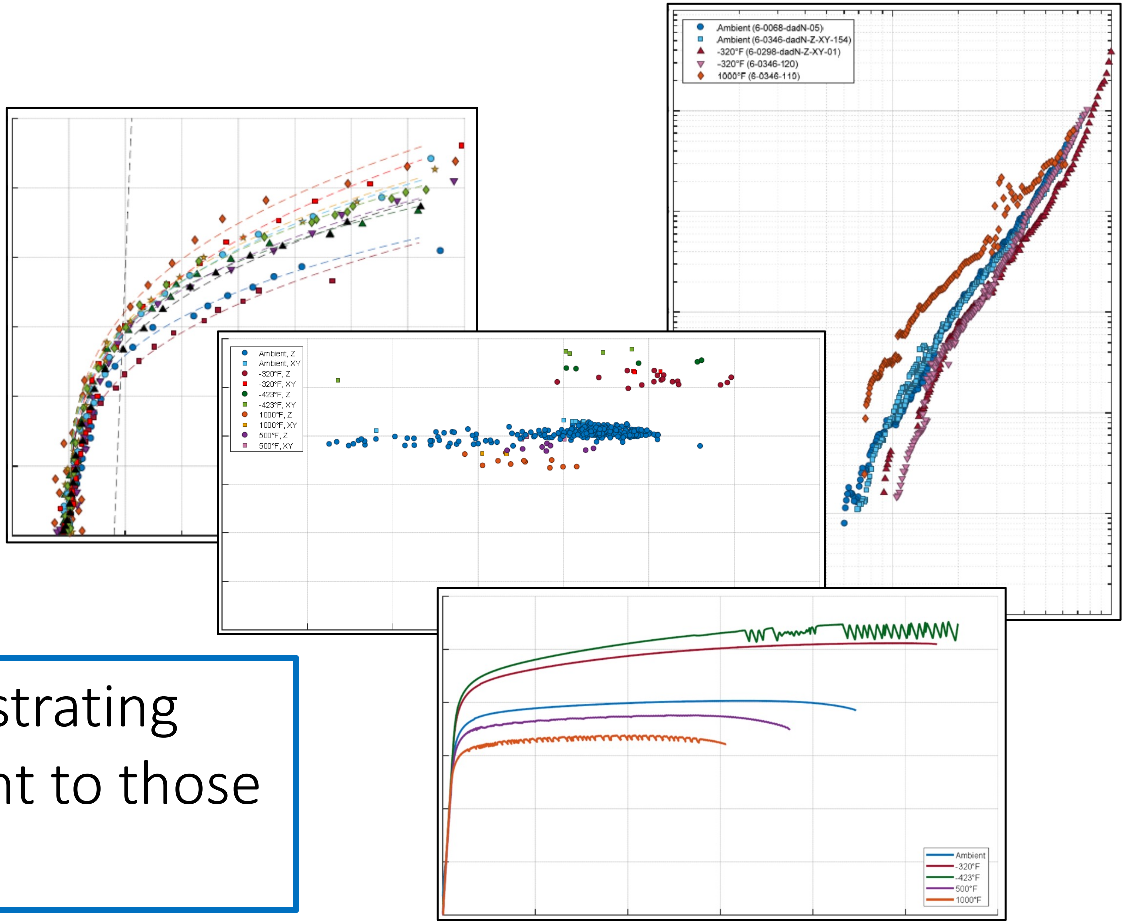






Step 4: Mechanical properties

- 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 Material Process

Foundation

What do I need to build to produce a QMP?

Metallic Master QMP

Table 13—Minimum Mechanical Property Tests for Metal QMP Builds

QMP Item	Property	ASTM Standard*	Quantity			Notes
			QMP-A	QMP-B	QMP-C	
1	Tensile	E8/E8M	15	15	6	Survey of build area and materials using machine tensile specimens meeting requirements of sections 5.5.3.1.a and 5.5.3.1.b of this NASA Technical Standard.
2	Tensile, with Process Restart	E8/E8M	5	5	-	Required if process restart is allowed. Tensile testing of process restart interface characterized by restarting in sample gauge section of machined specimen. Item 2 tests not required if restart is included in testing for Item 1.
3	High Cycle Fatigue (HCF)	E466	10	5	-	For QMP-A, 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. For QMP-B, five (5) tests to MPS PCRD fatigue condition.
4	Low Cycle Fatigue (LCF)	E606/E606M	5	5	-	Five (5) tests at a cyclic strain range represented in MPS data.
5	Fatigue, with Process Restart	E466, E606/E606M	5	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 Items 3 and/or 4.
6	Fracture Toughness	E1820, E399	3	0	-	Tests with crack in worst-case orientation relative to build plane.
7	Tensile (at Temperature)	E21, E1450	6	3	-	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	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 material process is identical

Note: NASA-STD-6030 Tables 15 and 16 list Polymeric QMP Requirements

Metallic Sub QMP and Requalification

Table 14—Minimum Mechanical Property Tests for Metal Sub-QMP and SPC Evaluation Builds

Sub-QMP and SPC Item	Property	ASTM Standard*	Quantity			Notes
			QMP-A	QMP-B	QMP-C	
1	Tensile	E8/E8M	10	10	4	Survey of build area locations using machined tensile specimens.
2	Tensile, with Process Restart	E8/E8M	5	5	-	Required if process restart is allowed. Tensile testing of process restart interface characterized by restarting in sample gauge section of machined specimens. Item 2 tests not required if restart is included in testing for Item 1.
3	High Cycle Fatigue (HCF)	E466	5	5	-	Five (5) tests to MPS PCRD fatigue condition.
4	Low Cycle Fatigue (LCF)	E606/E606M	-	-	-	Not required for sub-QMP (only QMP).
5	Fatigue, with Process Restart	E466, E606/E606M	5	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 in worst-case orientation relative to build plane.
7	Tensile (at temperature)	E21, E1450	-	-	-	Not required for sub-QMP (only QMP).
8	Customized QMP	As specified	2	2	-	Test at conditions defined by the candidate metallurgical process required for acceptance; minimum of two (2) tests at condition.

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

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 Material Process

Foundation

- Excerpts from Reference QMPs to follow
- Developed in MSFC Lab
- ***For Example Only***

Stratasys Fortus 900 Ultem 9085 QMP-C

FDM Qualified Material Process Record

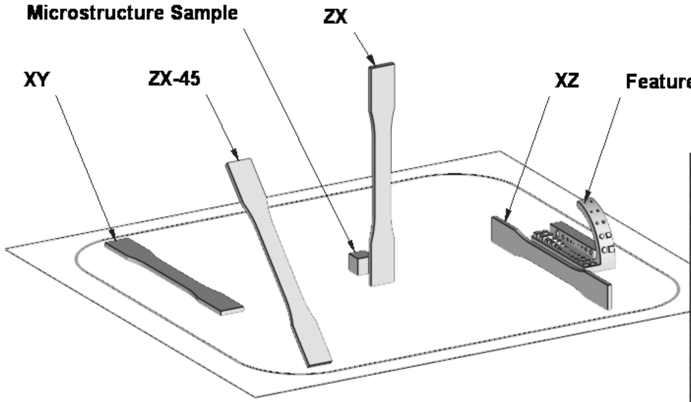
QMP Title: QMP-MSFC-900mc-ULTEM (PEI) 9085	
QMP Record Number: QMP-MSFC-900mc-ULTEM (PEI) 9085_REV0	
Check as applicable: x Master QMP □ QMP, based upon Master QMP: □ Customized QMP (Customized FDM Visual Inspection Typical Acceptable Anomalies & Unacceptable Defects Section)	
General Description: Fused Deposition Modeling (FDM) ULTEM (PEI) 9085	
RESTRICTIONS ON USE: QMP-C applicable only to parts classified as Class-C or Exempt per NASA-STD-6030	
QMP Approval Statement: All necessary data for qualification of this material and traceability to the requirements of NASA-STD-6030 Class C has been reviewed, judged acceptable, and archived.	
CEO Approval: Brian West	Date:

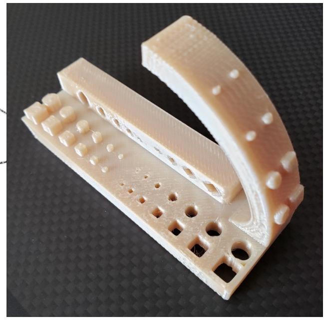
FDM Material Process Definition

Filament Feedstock			
Feedstock Specification:	STRATASYS ULTEM™ 9085 Certified Grade (CG) MDS_FDM_ULTEM9085_0921a.pdf		
Material traceability:	ULTEM™ 9085 CG MFR Certificates of Analysis for both raw material and filament are supplied, documenting test results and identification to match filament manufacturing lot number to raw material lot numbers providing traceability from printed part per MSFC-SPEC-555 requirements		
FDM Process Controls			
Machine ID:	900mc	Model/Model:	FORTUS 900mc
Serial Number:	L0444	Configuration Date:	5/3/2022
Slicer Software:	Insight 14.11	System Software:	3.32.3700.0
System/Slicer software updates shall be evaluated by the MSFC Additive Manufacturing team in order to fully understand the changes and impacts to the FDM process. If changes are deemed to be significant or not fully understood, a new Qualification Build shall be required to confirm test data remains in family and the FDM process performs as expected. For changes deemed insignificant, written justification shall be provided in order to document that a thorough review and impact assessment has been performed. This activity shall be logged and archived in a software revision log as a companion file to the approved QMP.			
Extruder Tip & Life:	T16 392 in^3 Maximum model material volume consumption		
Dew point limit:	N/A		
Build Plan/Toolpath File	.CMB		
Part Interior Style	Solid		
Contour Style	Single Contour		
Contour width	0.020 inch		

Other Topics

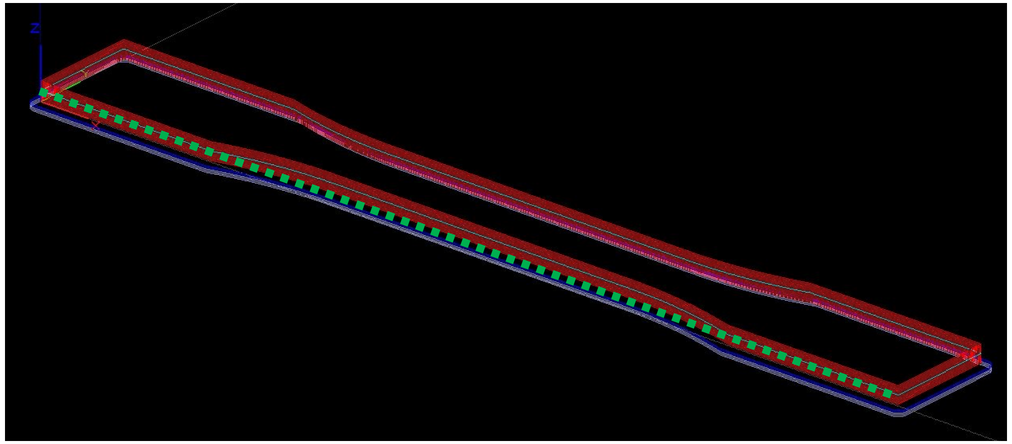
- Inspection Guide
- Tensile Data for Nominal and Thin Wall Parameters
- Comparison to NCAMP Reference Tensile Data

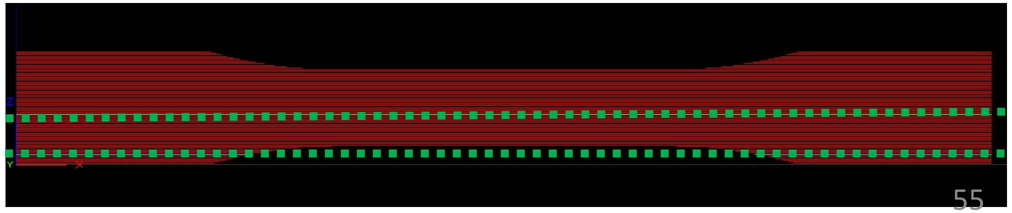




Qualifying Process Restarts

Short pause:
Ten minutes
Medium pause:
One hour
Long pause:
24 hours





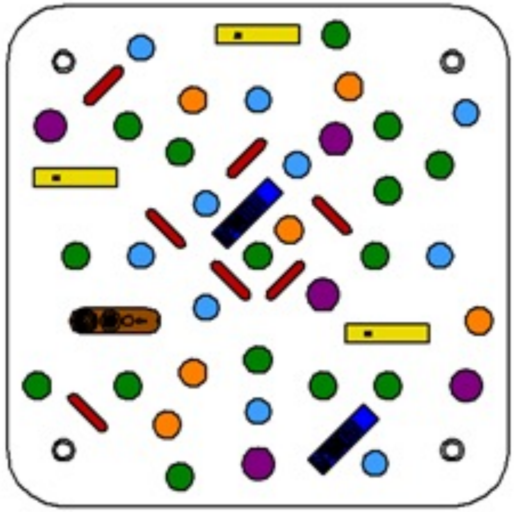
M290 IN 718 QMP – Plan & Build

L-PBF Qualified Metallurgical Process Record

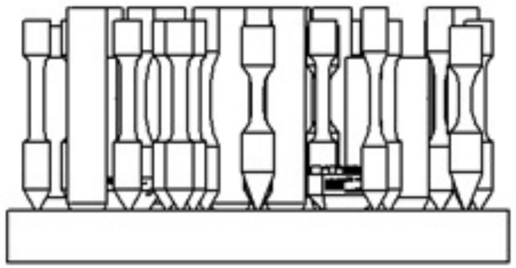
QMP Title: QMP-MSFC-M290-INC718-SR-HIP-5664-0	
QMP Record Number: QMP-MSFC-M290-INC718-SR-HIP-5664-0	
Check as applicable: □ Master QMP □ QMP, based upon Master QMP: □ Customized QMP (Complete Customized L-PBF Metallurgical Process Definition Section)	
General Description: Powder bed fusion Inconel 718	
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:	Date:

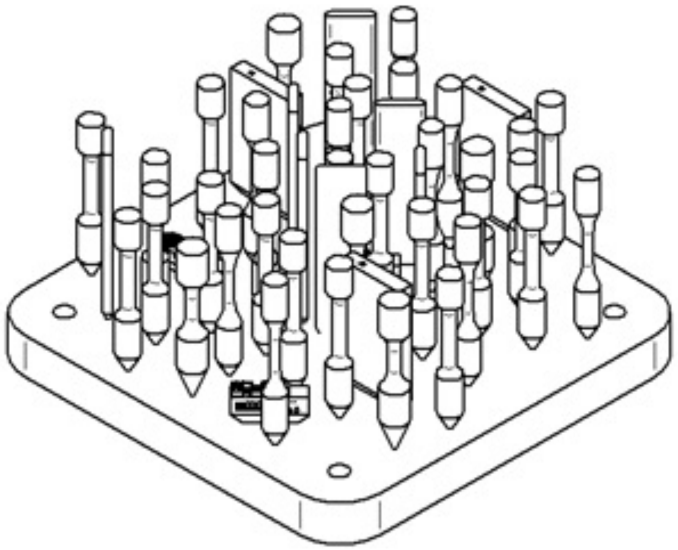
L-PBF Metallurgical Process Definition

Powder Feedstock			
Feedstock Specification:	EM-42 Additive Manufactured Inconel 718 Powder Specification		
Reuse protocol:	State reuse protocol or reference specification/policy for reuse protocol.		
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:	N/A
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.		



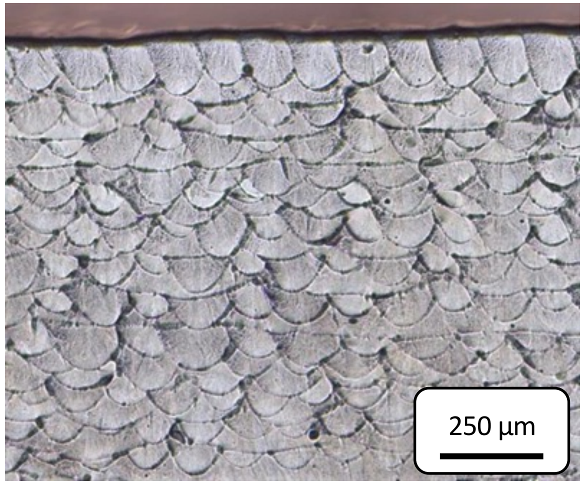
Specimen Type	Qty	Name	Key
High Cycle Fatigue	10	HCF-1 thru HCF-10	
Low Cycle Fatigue	5	LCF-1 thru LCF-5	
Tensile (RT)	15	TN-1 thru TN-15	
Tensile (Cryo, ET)	6	TN-16 thru TN-21	
Fracture Toughness	3	FT-1 thru FT-3	
Metallographic Samples	7	MET-1 thru MET-7	
Dimensional Samples	2	D-1 thru D-2	
Contour Analysis Samples	1	C-1	



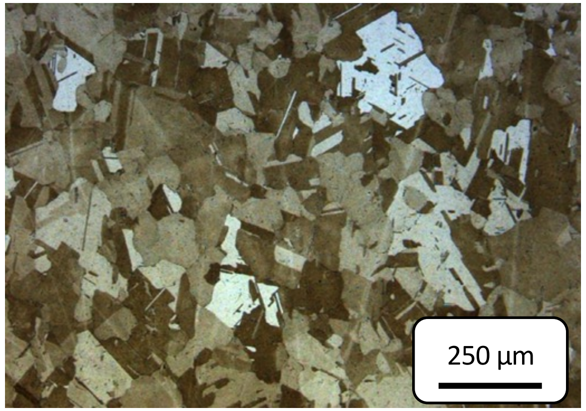


QMP M290 Build Layout

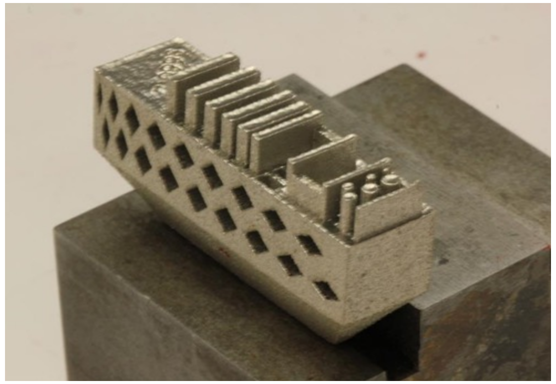
M290 IN 718 QMP – Results



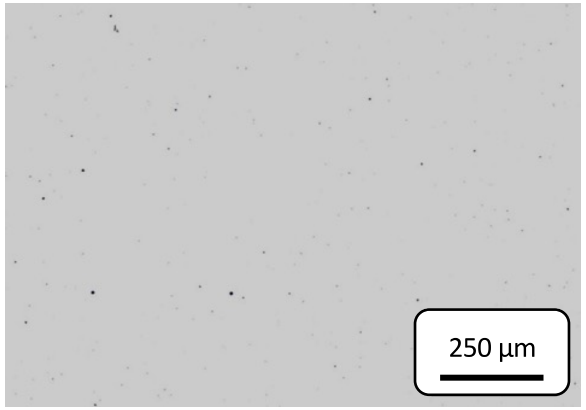
As-Built Microstructure



Fully Heat-Treated Microstructure

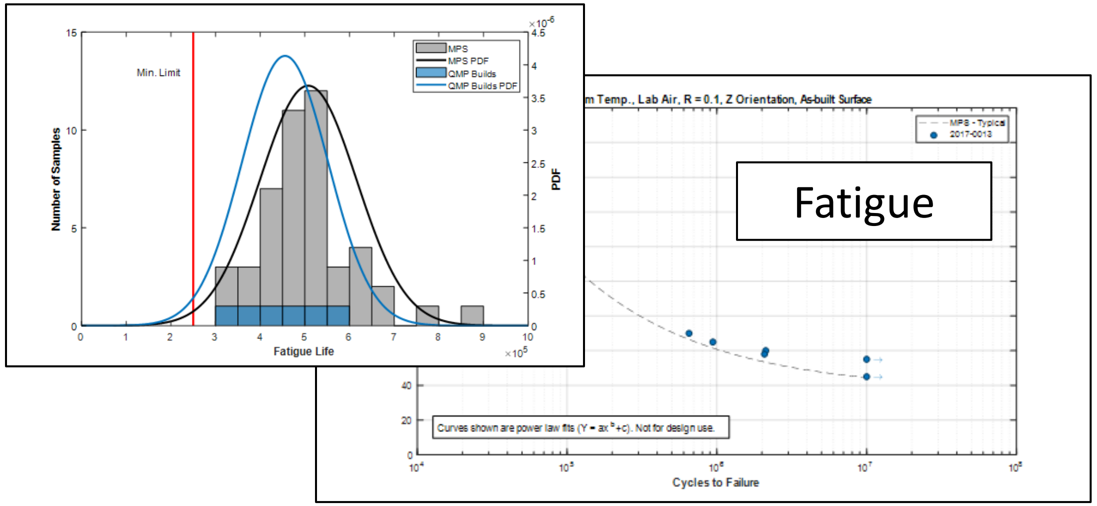


Achievable Features & Dimensional Accuracy

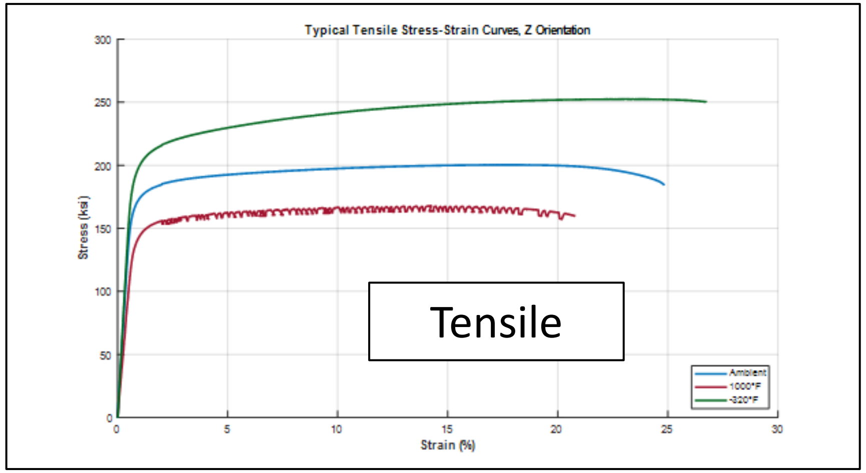


2-D Micrograph

Verdict: No detrimental defects observed (*detailed in MSFC-SPEC-3717*). Randomly dispersed and less than 1% of area.



Mechanical Properties to Establish Design Values



Concept Laser M2 GRCop-42 QMP

L-PBF Material Process Record

Title: MP_BlueOrigin_ACO_M2_GRCop42	
Record Number: MP_BlueOrigin_ACO_M2_GRCop42	
General Description: Powder bed fusion GRCop42	
Approval Statement: This document was developed as part of an Advanced Collaboration Opportunity between NASA Marshall Space Flight Center (MSFC) and Blue Origin. It draws comparisons to MSFC GRCop-42 data and NASA-STD-6030 requirements. It should not, however, be interpreted as a complete qualification to NASA-STD-6030 requirements.	
CEO Review: Brian West	Date: 5/18/2022

L-PBF Metallurgical Process Definition

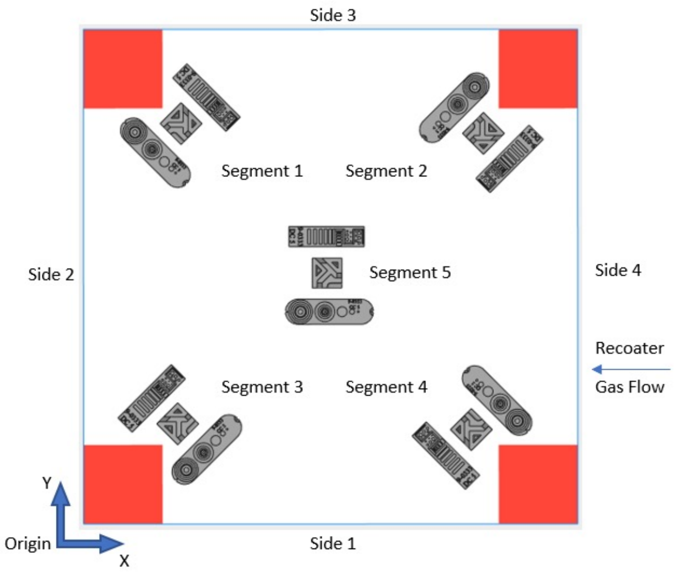
Powder Feedstock	
Feedstock Specification:	PAC GRCop42 Lot#: AMPGR42NASAAM21030
Reuse protocol:	No Reuse

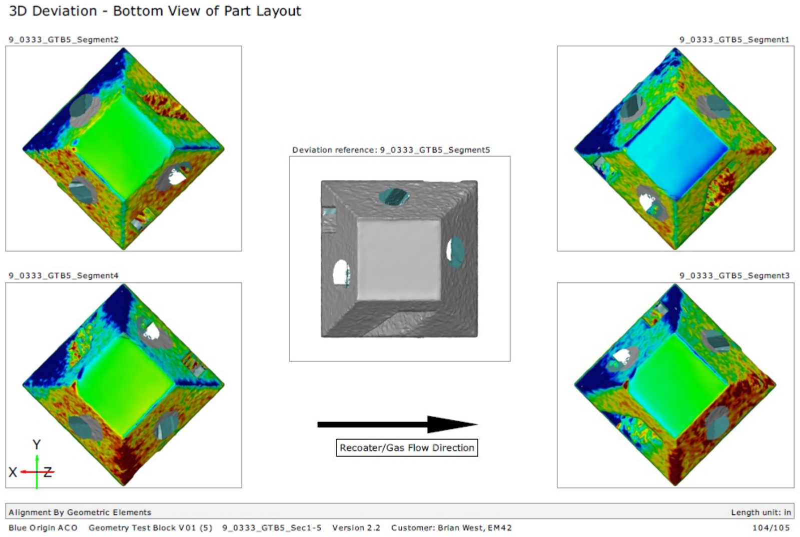
Powder Specification and Certifications

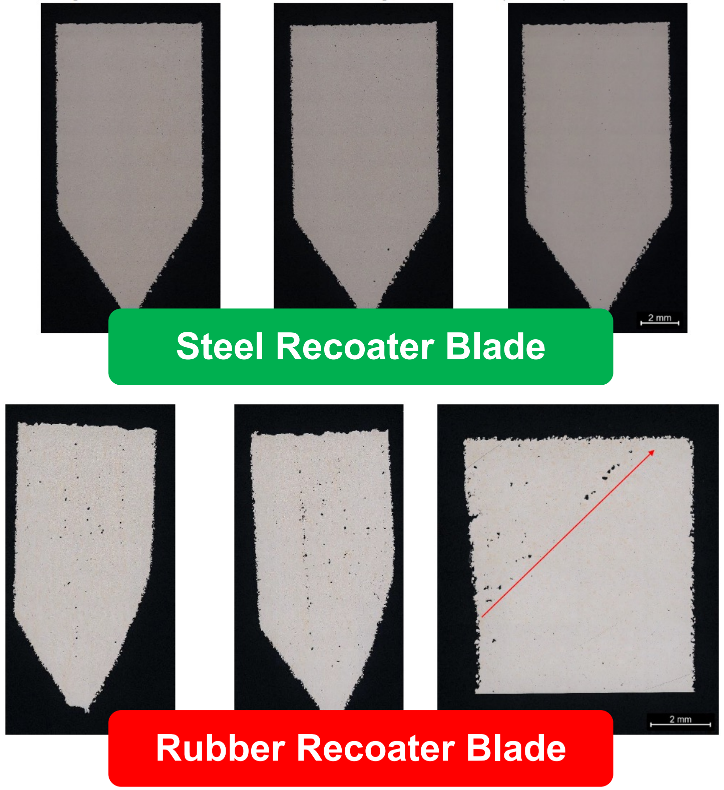
Powder procured IAW *GRCop-42 Alloy Gas Atomized Powder Specification, Rev 1-29, issued 7/22/2020*

Powder CoC available upon request.

Fusion Process Controls			
Machine ID:	Concept Laser	Model/Model:	M2
Serial Number:	M2-2021-02-02	Configuration Date:	5/20/21 - 9/9/21
Slicer Software:	Materialize Magics	Software Version:	25.02
Recoater Configuration:	Steel Blade		
Build platform material:	Stainless steel, In 718 coating		
Preheat temperature:	None		
Nominal dosing range:	Variable		
Purge Gas composition:	Argon		
Argon gas flow:	60mm/s		
Oxygen limit:	Not directly controlled, but typically in ~0.01-0.05% range		
Humidity and Temperature controls:	Not measured/controlled		
Parameter File:	GRCop42_Material_Parameter	Hash:	N/A
Layer thickness:	30µm		
Other:	N/A		





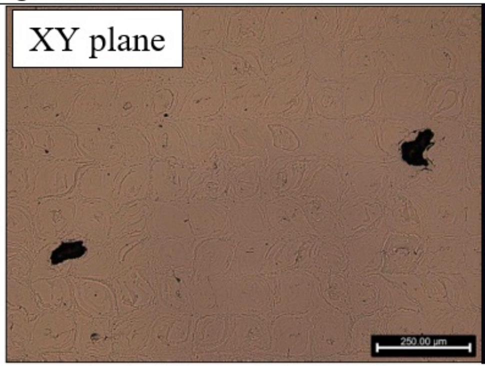


Mechanical Testing

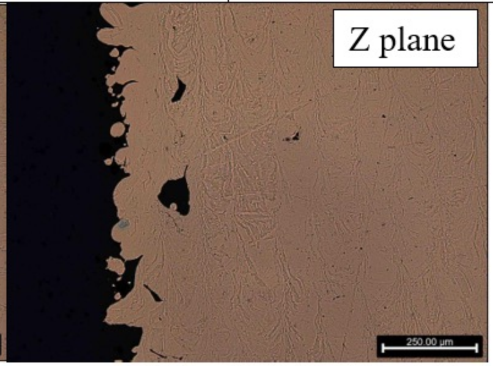
1. Tensile
2. Tensile, Thin Walls
3. High Cycle Fatigue
4. Low Cycle Fatigue
5. Fracture Toughness
6. Fatigue Crack Growth Rate

Concept Laser M2 GRCop-42 QMP

As-built Microstructure Evaluation:	
Plane	Z and XY Planes
Magnification	100x

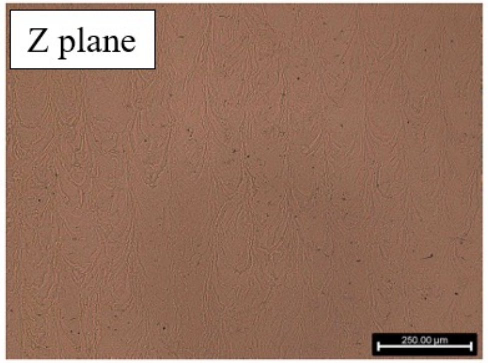


Lack of Fusion Defects in Core

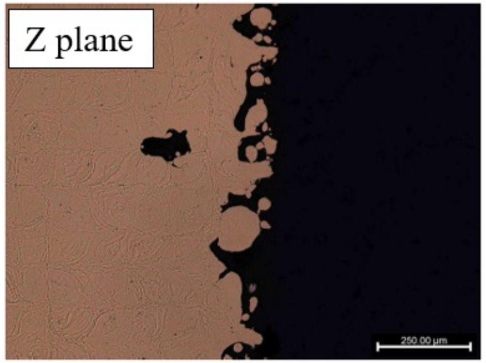


Contour Defects at Edges

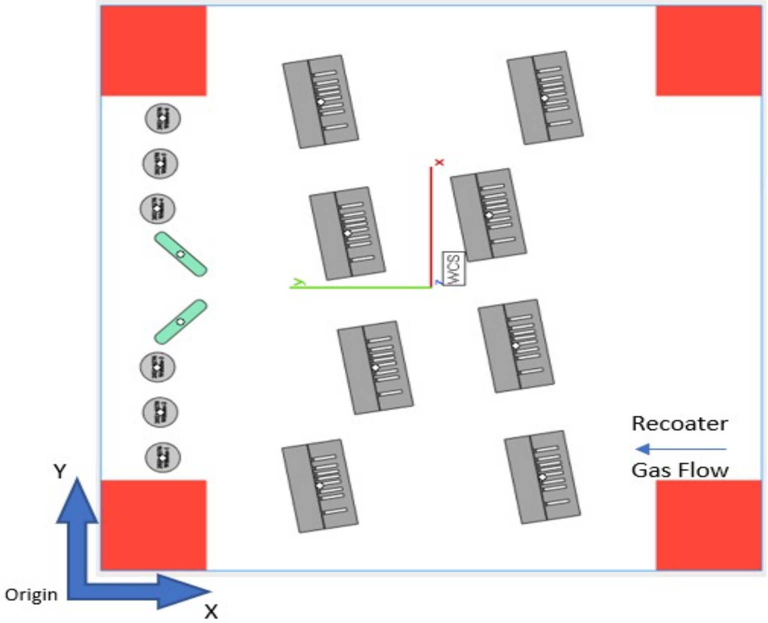
Heat-treated Microstructure Evaluation:	
Plane	Z Plane
Magnification	100x



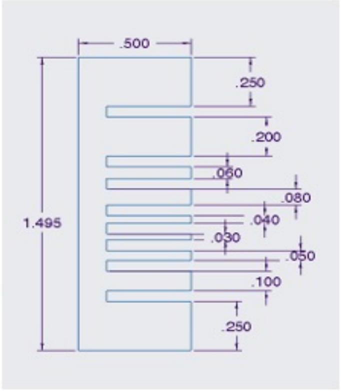
No core defects noted

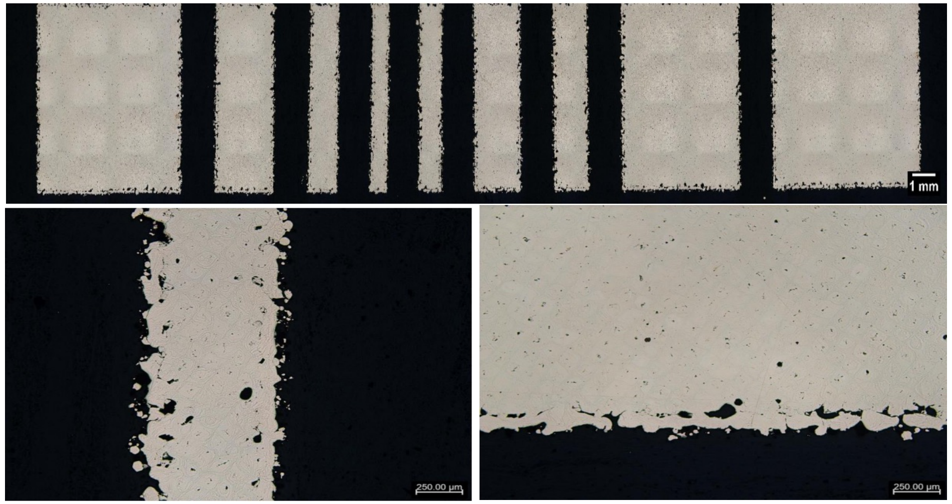


Contour Defects at Edges



Top View of Thin Specimens



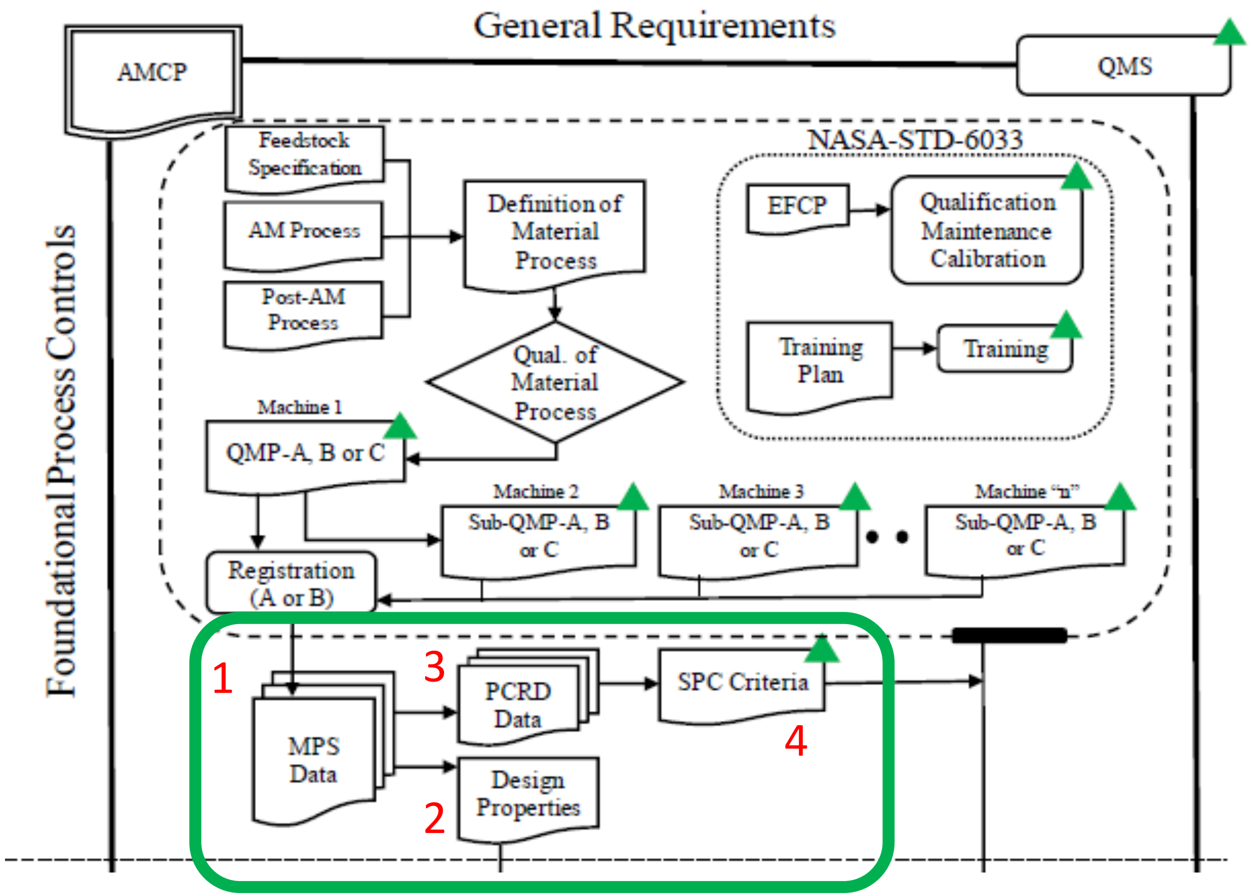


Material Properties

Foundation

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

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

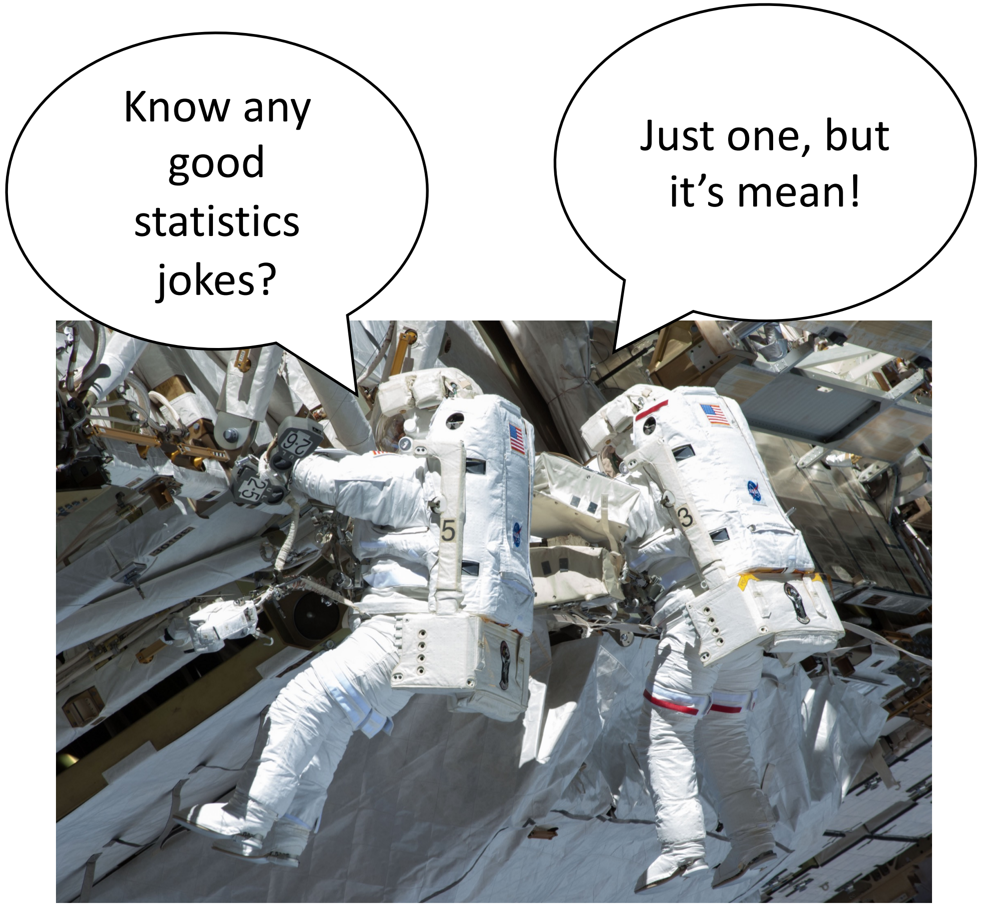


Engineering Equivalence

- Methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet all its expectations
- Differs from the determination of statistical equivalence for a material characteristic (such as ultimate strength) in that we determine equivalence holistically through engineering judgement by considering many interrelated and causal material characteristics as they contribute to the overall performance of the material
  - Often equivalence determinations must be made in the absence of statistically significant pools of data
- Enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
- Engineering equivalence is not an easy task – it requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

Engineering Equivalence

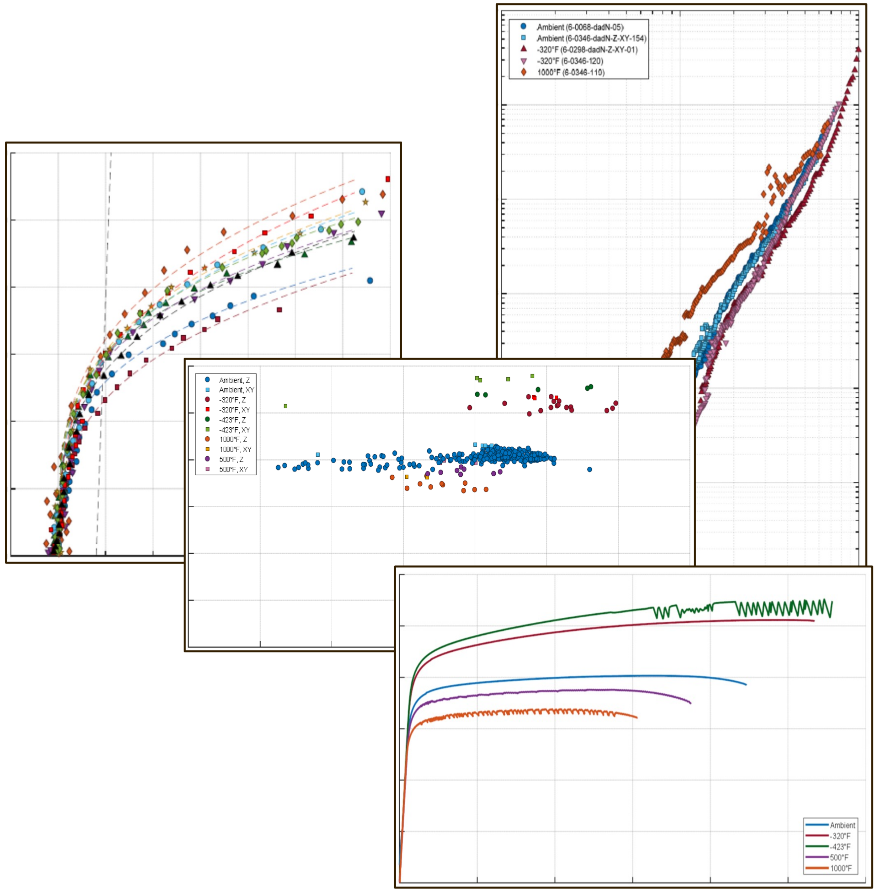
- Required to enable the material allowable and design value concepts in AM
- Avoid fixating on strength alone
- Leverage concept that material performance is derived from process → structure → property → performance relationship
- Does **not** generally mean "better than or equal to"
- Implies whether process is "in-family" with a baseline set of data
- Engineering judgement is needed to keep the "false-call" rate and associated engineering review in balance
- A lot of equivalence tools are statistical, but several are anchored in engineering judgement



Material Properties

Foundation

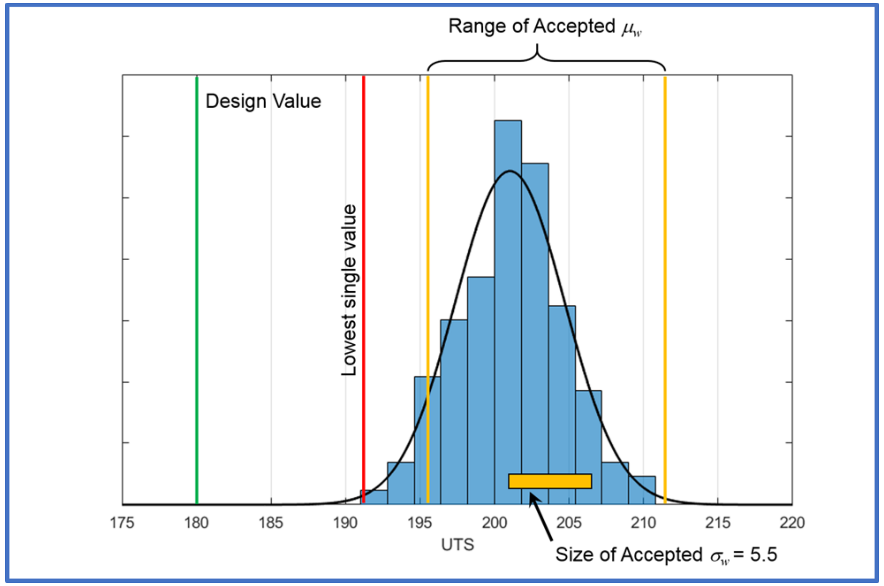
- Material properties and design values in additive manufacturing require modifications to the approach typical of traditional metallic materials, with requirements more like that used in composites CMH-17
- Important distinctions arise due to the <u>sensitive nature</u> of the process and <u>individualistic aspect</u> 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

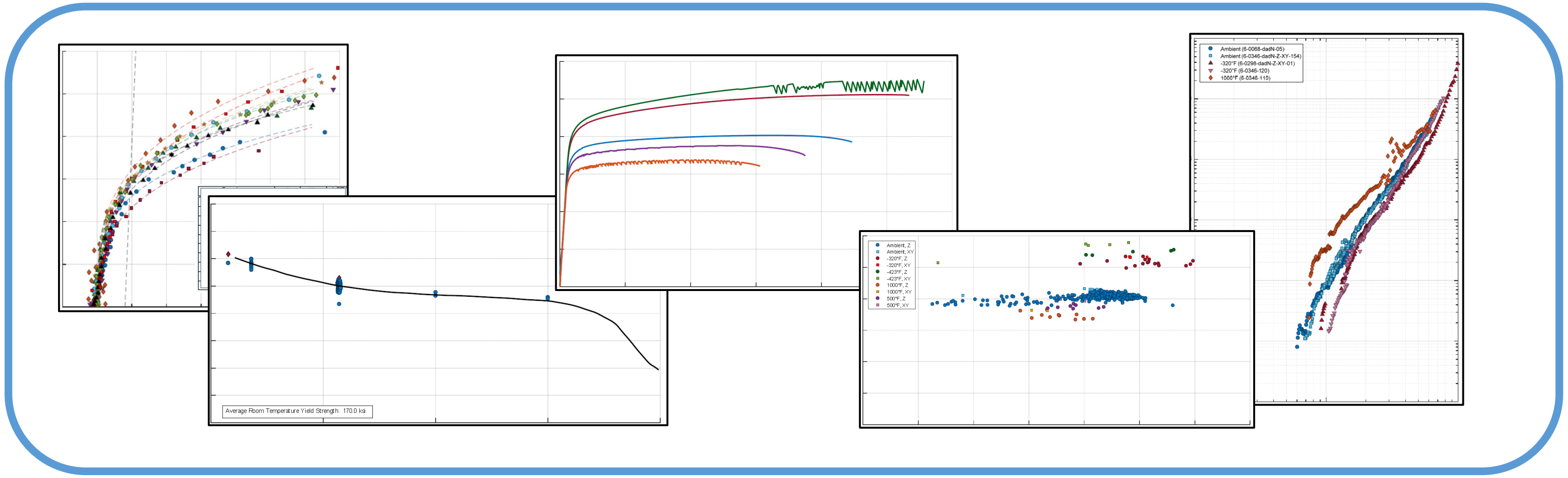
Foundation

- 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 and reuse
  - 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

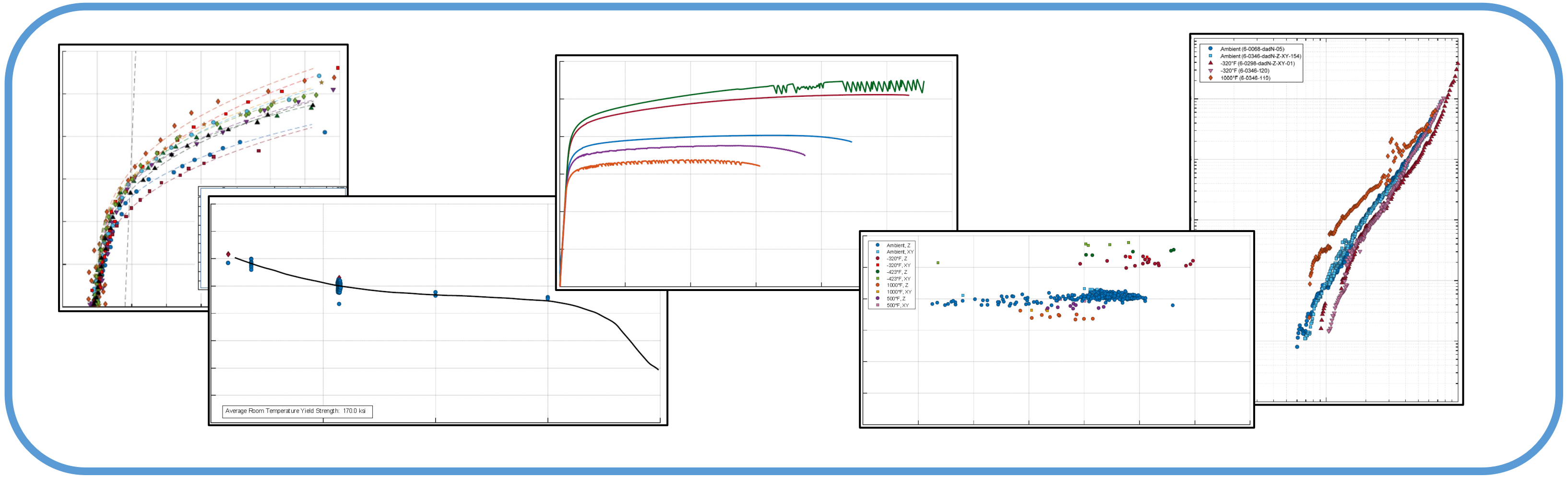
Includes data from

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

Grouping of data

Group data by

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



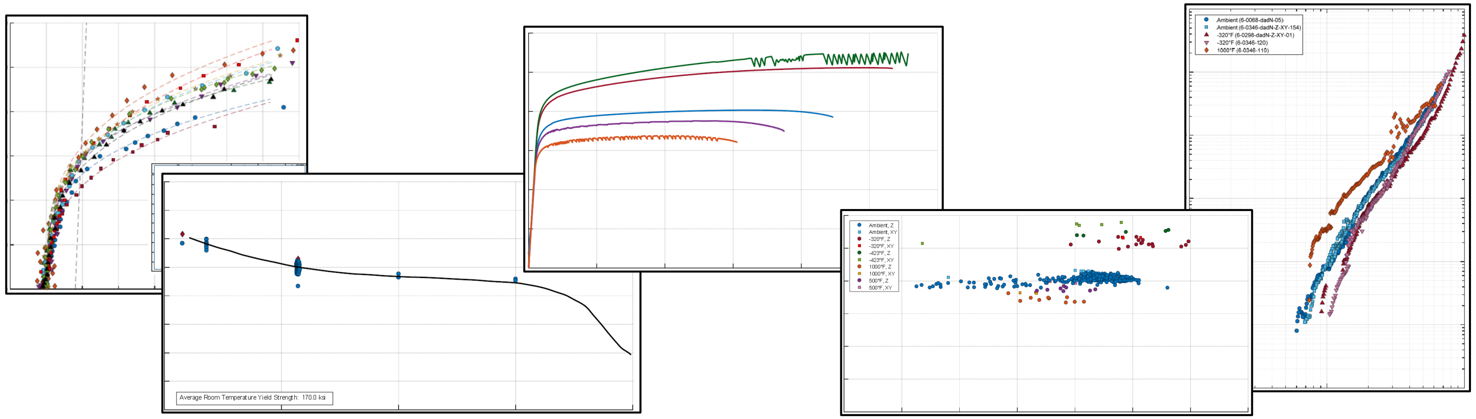
Data Repository, continued

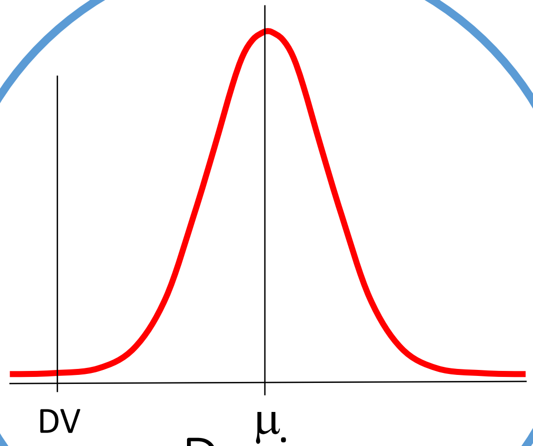
Contains all data needed for

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

Material Property Suite

Foundation





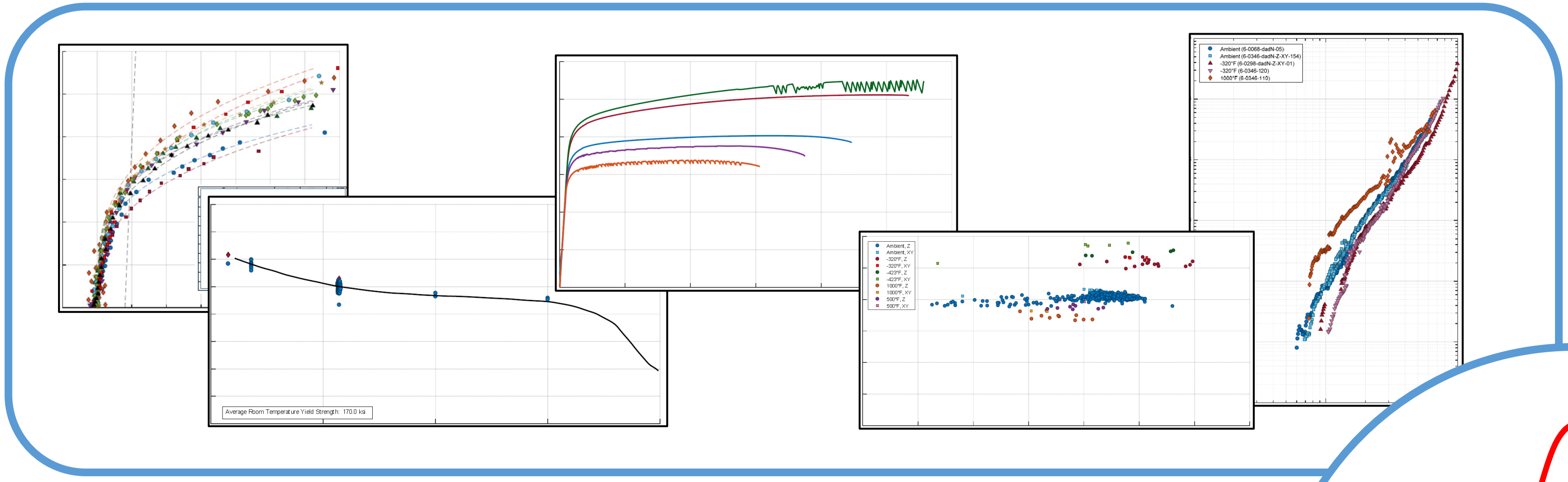
Design Values

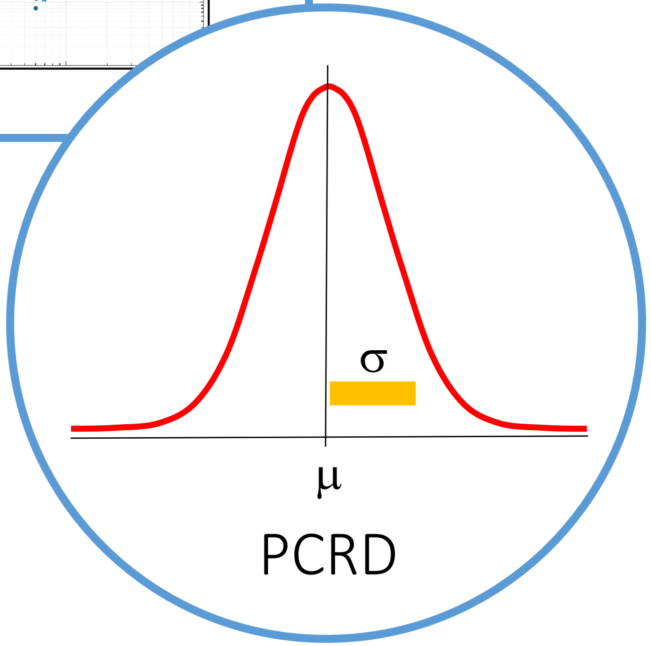
Design Values

- 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

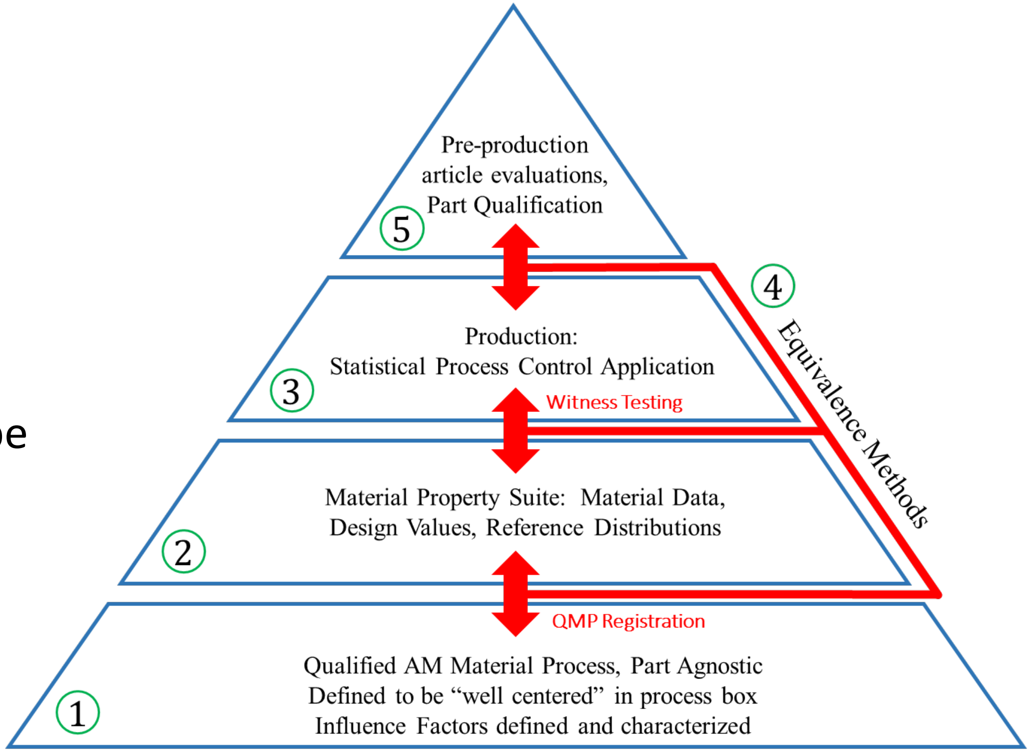
- Statistically describes nominal witness behavior of a specific machine
- Utilizes all appropriate sources of *witness coupon data* in Repository
- Used to set acceptance criteria for witness tests

Statistical Process Controls

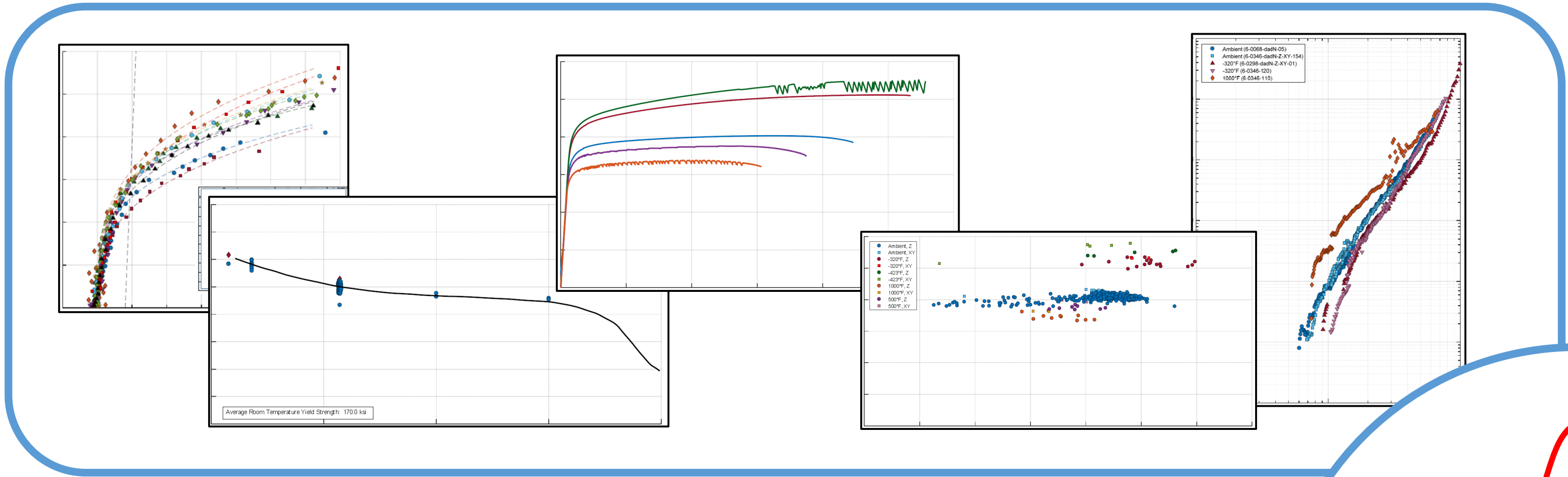
Foundation

Statistical process controls are important in sustaining certification rationale

- *Engineering 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
- A lot of equivalency tools are statistical, but several are anchored in engineering judgement
  – E.g., Microstructural acceptance criteria that may not always be discrete,
  – Flaw Population/Defect states
- 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….

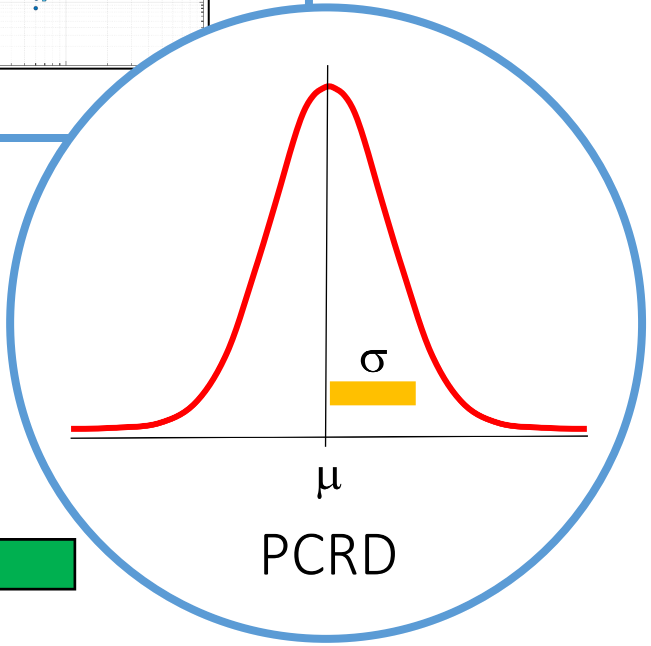


Statistical Process Control

Acceptance Criteria

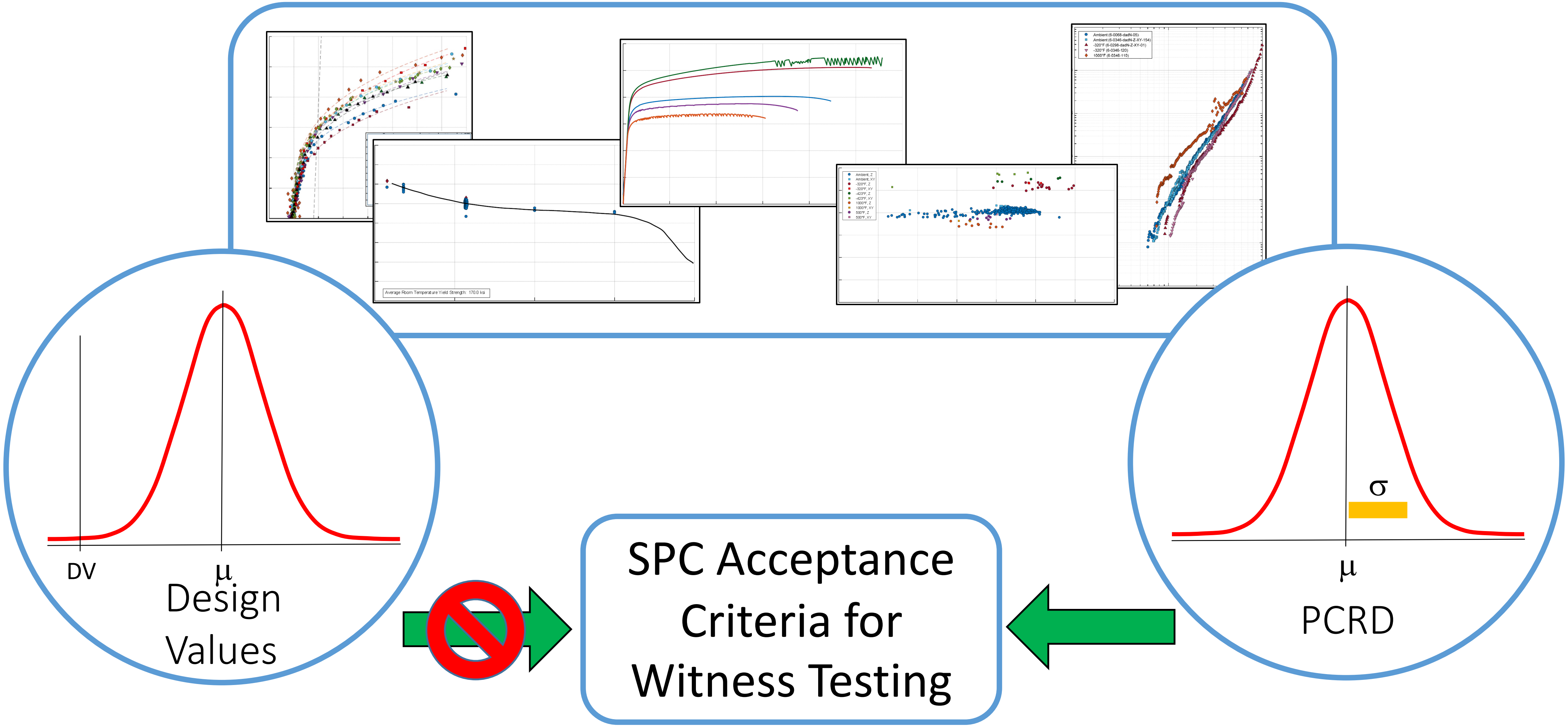
- Derived from PCRD
- Acceptance criteria for witness tests

SPC Acceptance Criteria for Witness Testing



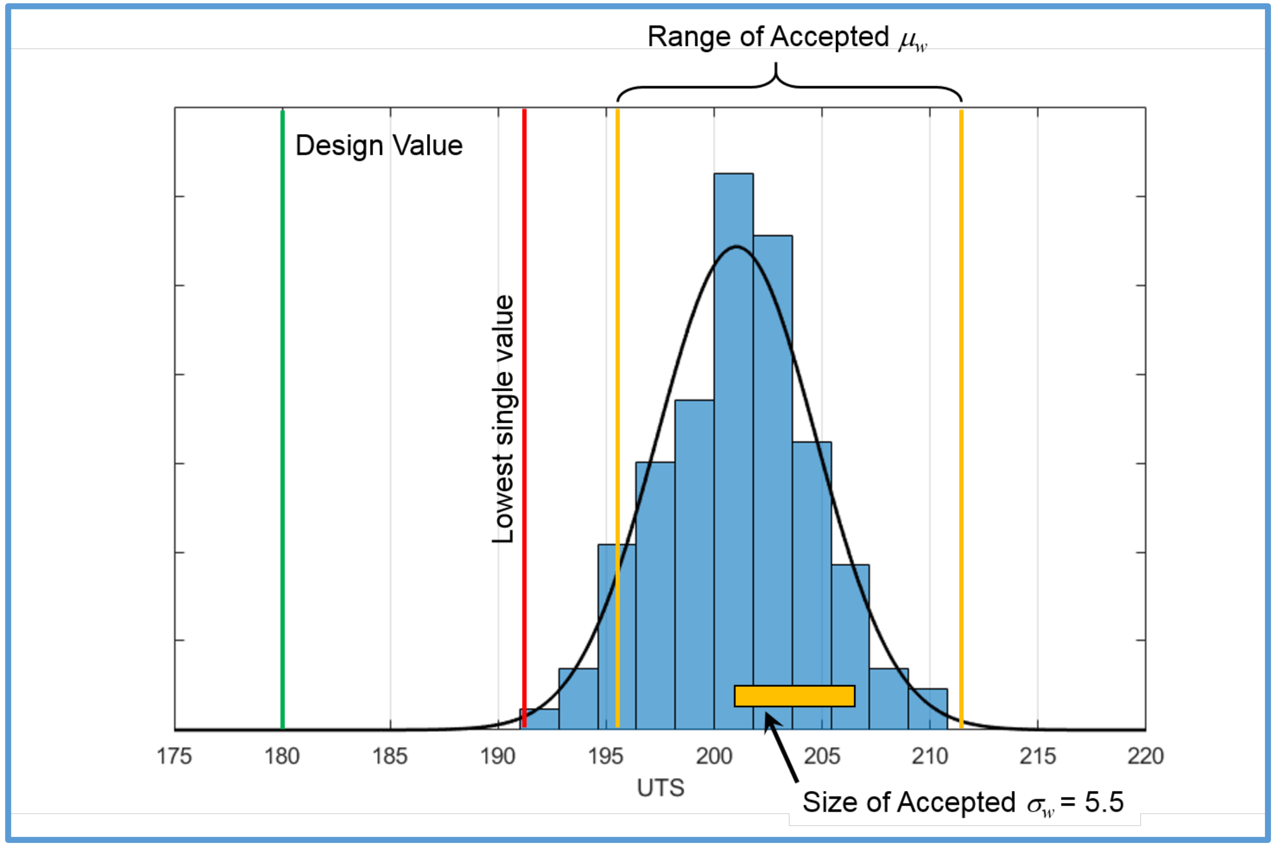
Material Property Suite

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*:

Table 18—Required Lot Quantities for Lot-Mature Metal MPS Properties

Properties	Feedstock Lots (nominally balanced*)	Build/Heat Treat Lots (nominally balanced*)
Physical and constitutive	3	5
Tensile	5	10
Secondary	3	5
Fatigue	5	10
Fracture mechanics	3	5
Stress rupture/creep	3	5

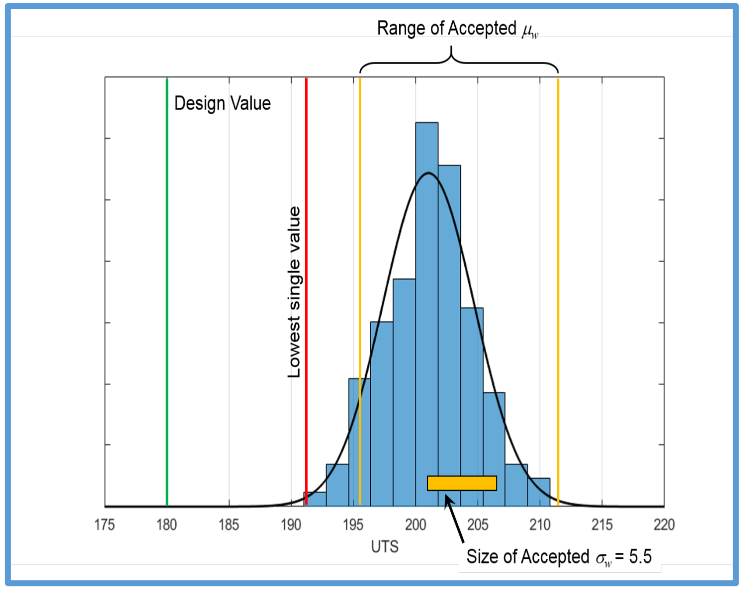
* Nominally balanced lot contributions as described in commentary.

Table 19—Required Lot Quantities for Lot-Mature Polymeric MPS Properties

Properties	Feedstock Lots	Build Lots
Physical and constitutive	3	5
Tensile/compression†	5	10
Shear	5	10
Flexural	5	10
Fatigue	5	10
Creep/sustained load	5	10

† Including notch testing, if required

  - Nominally balanced distribution across lot data used for all design values
  - Sufficient variability incorporated to be applied to parts of all classes



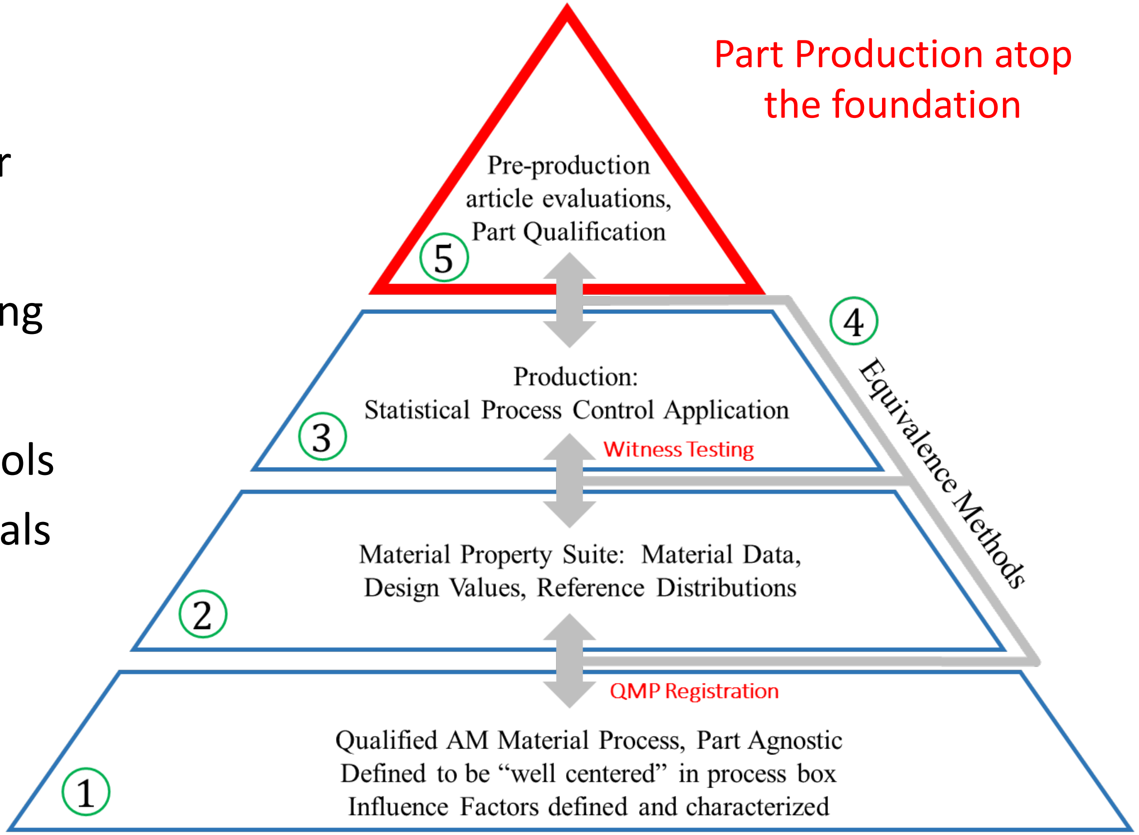
- *MPS, Lot-Provisional*:
  - Less than the required quantities listed in Tables 18 and 19
  - Only applicable to parts of Class B and C
    - Class B requires part-specific Material Usage Agreement

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.



Break 2

Part Production Controls

Produce to the plan!
Stick to the plan!

Overview of Part Requirements

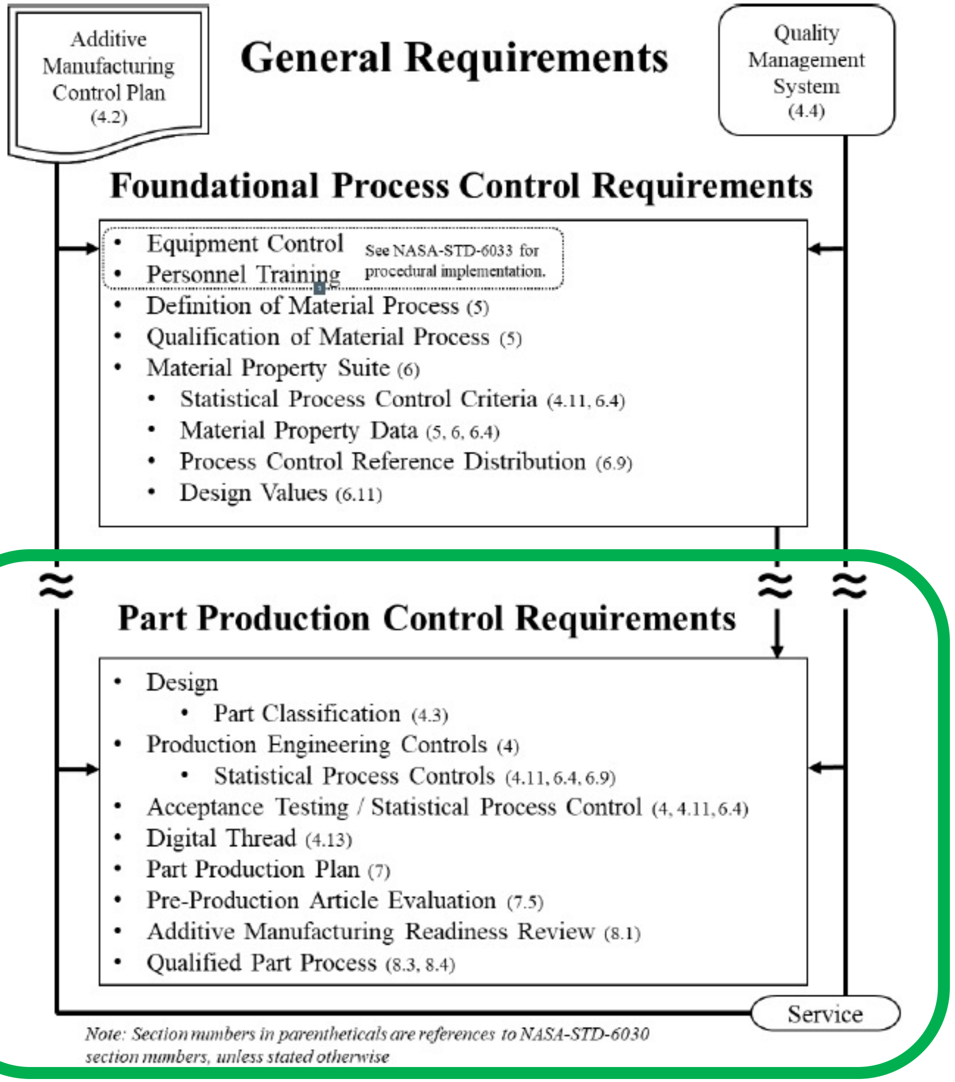
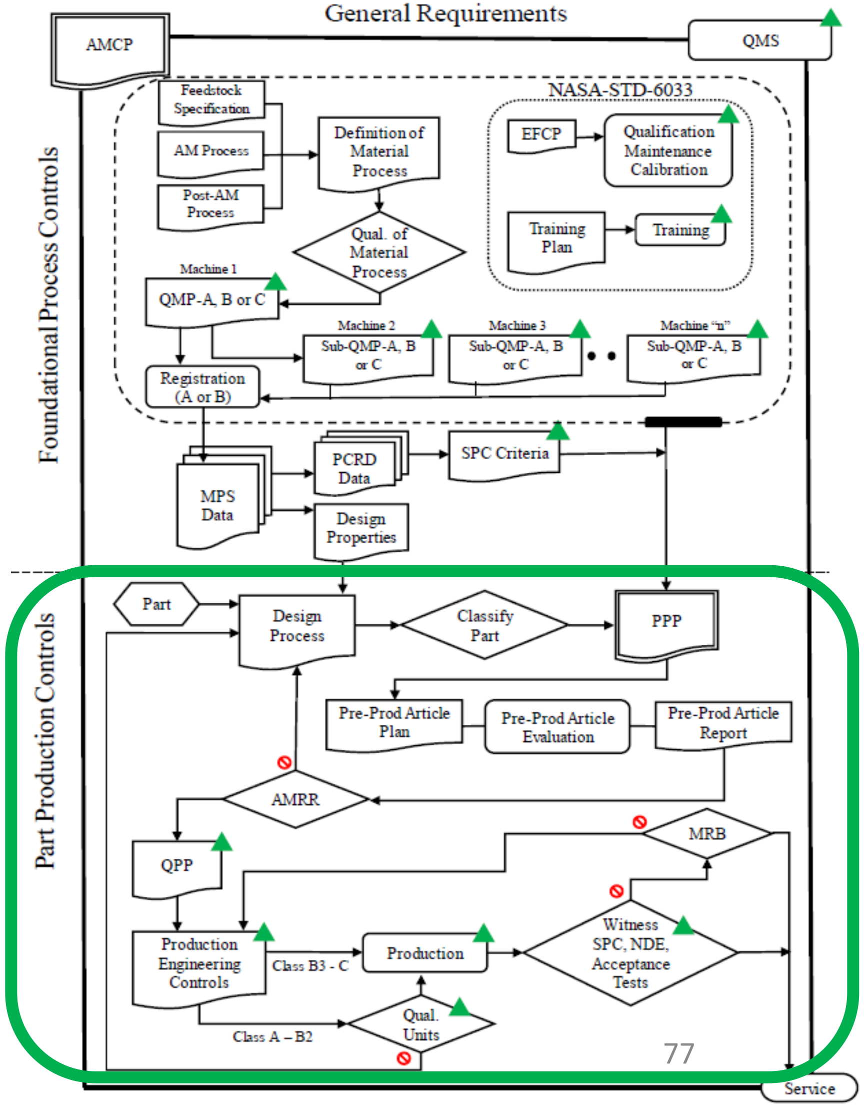


Figure 1—Topical Outline for NASA-STD-6030

Candidate Part

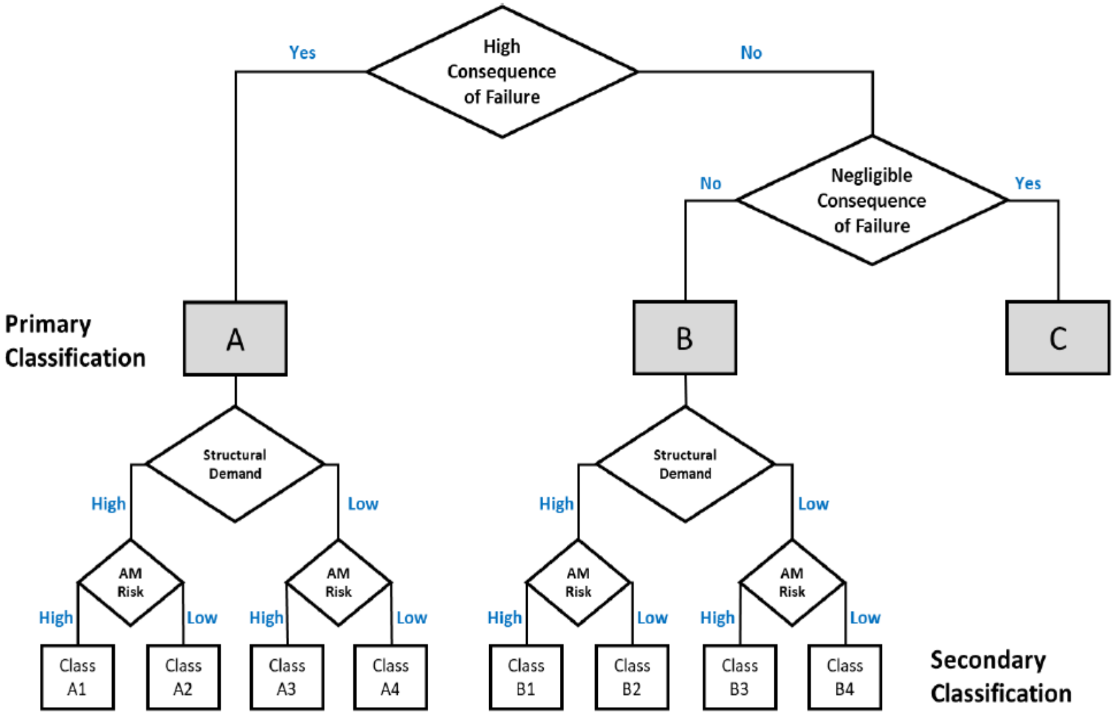
Part Production Controls



Part Planning

AM Part Design

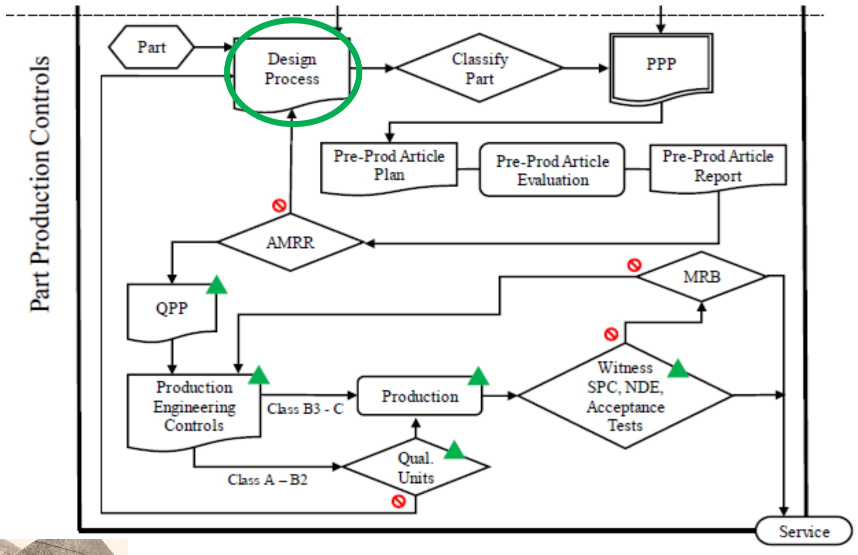
- *Requires integration* across disciplines
  - Manufacturing, Materials Engineers, Quality Assurance
- AM design for manufacturability
  - Ease of build, self supporting, cost effective
  - For certification, NO awards given for most complicated, suave-looking part
  - Prized certification characteristics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

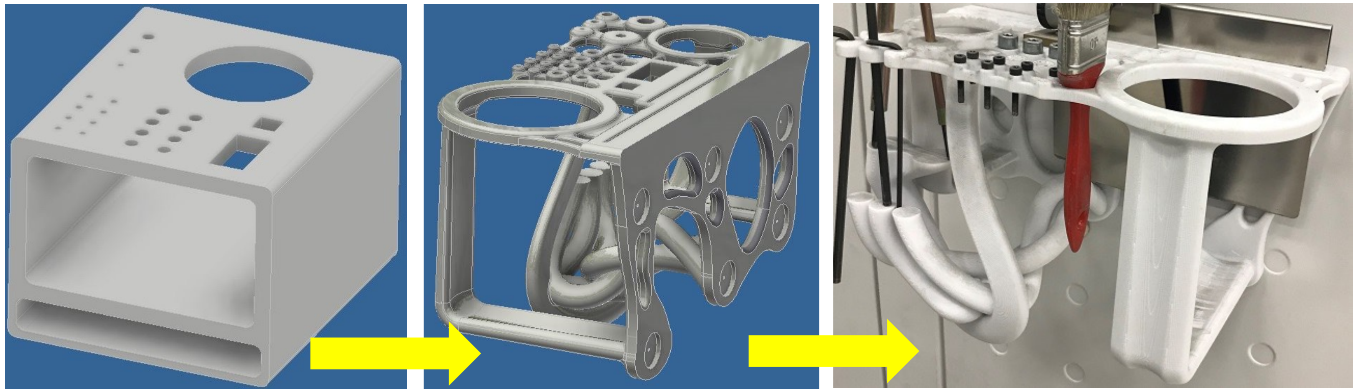


Design Process

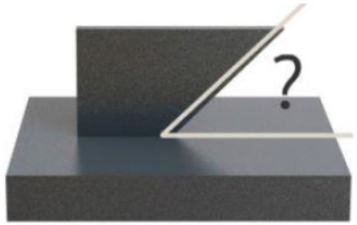
Design For Additive Manufacturing Paradigm Shift

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





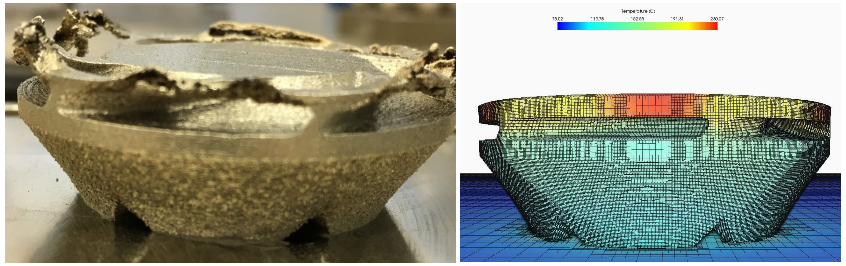
Topology Optimization FDM Tool Rack



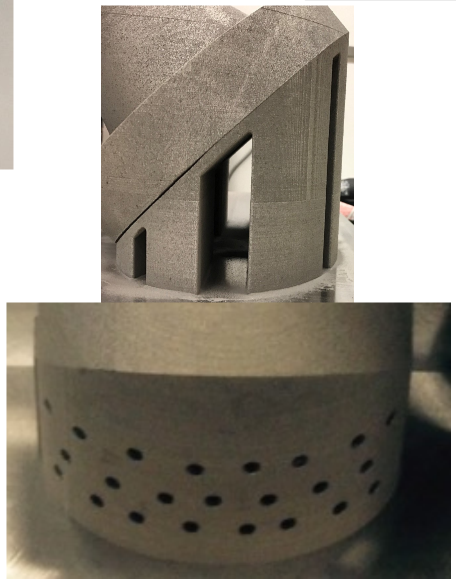
The minimum angles that will be self supporting are approximately:

- Stainless steels: 30 degrees
- Inconels: 45 degrees
- Titanium: 20-30 degrees
- Aluminium: 45 degrees
- Cobalt Chrome: 30 degrees

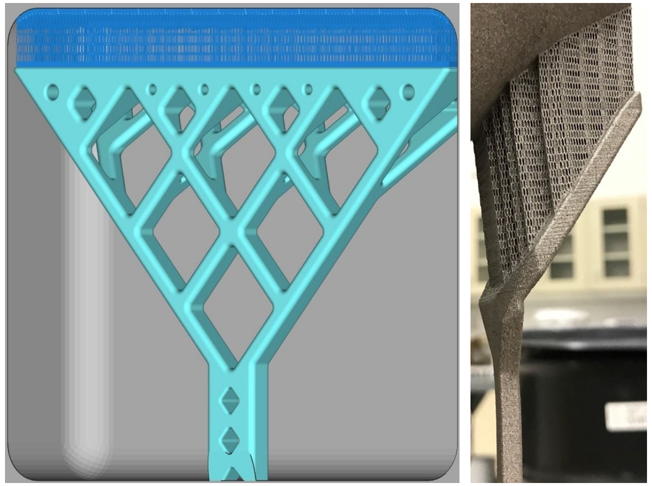
Self-Supporting Angles



Build Simulation

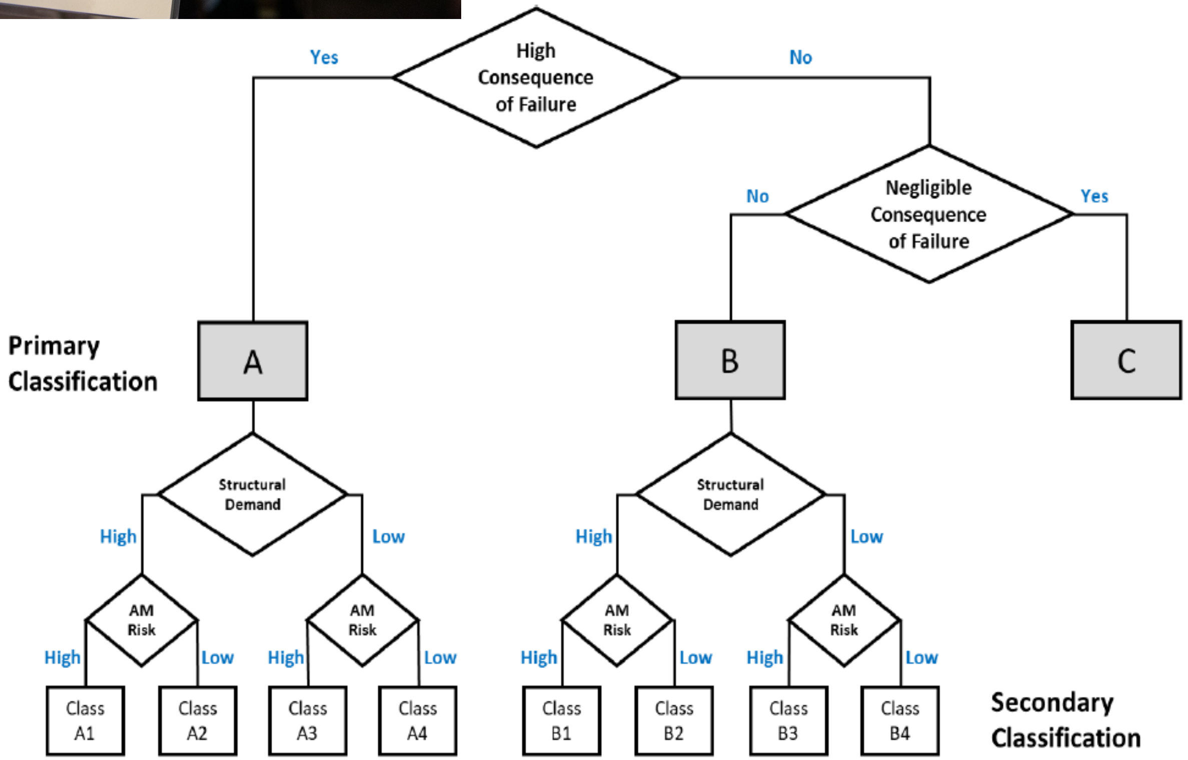


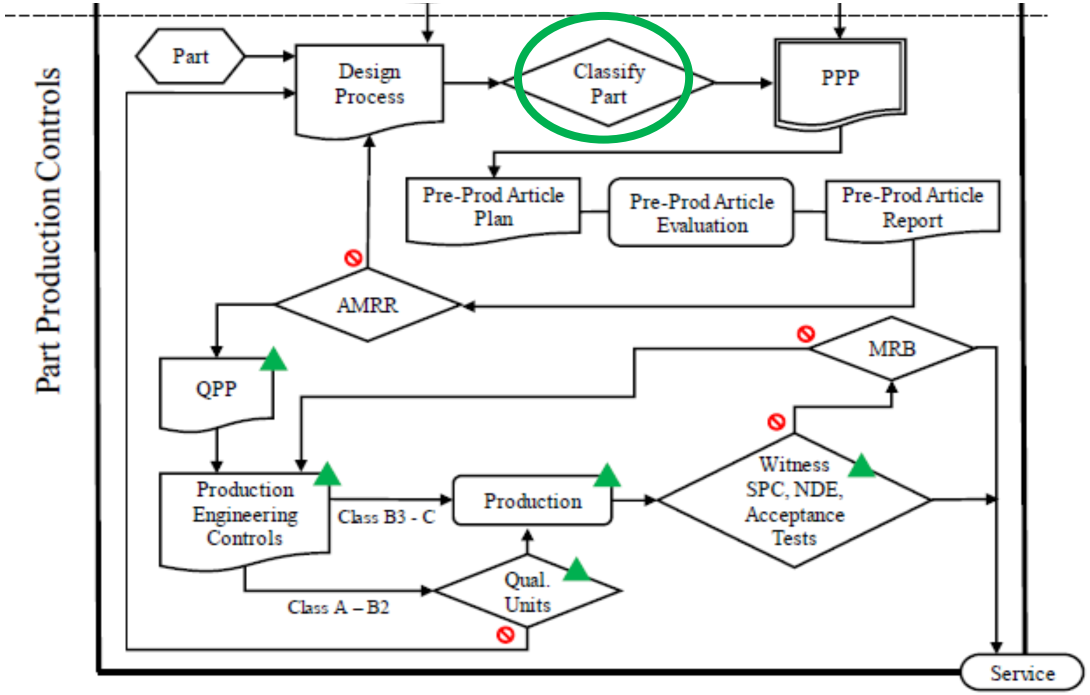
Powder Removal Features



Hybrid crown & perforated block support

Part Classification system is a *risk communication* tool





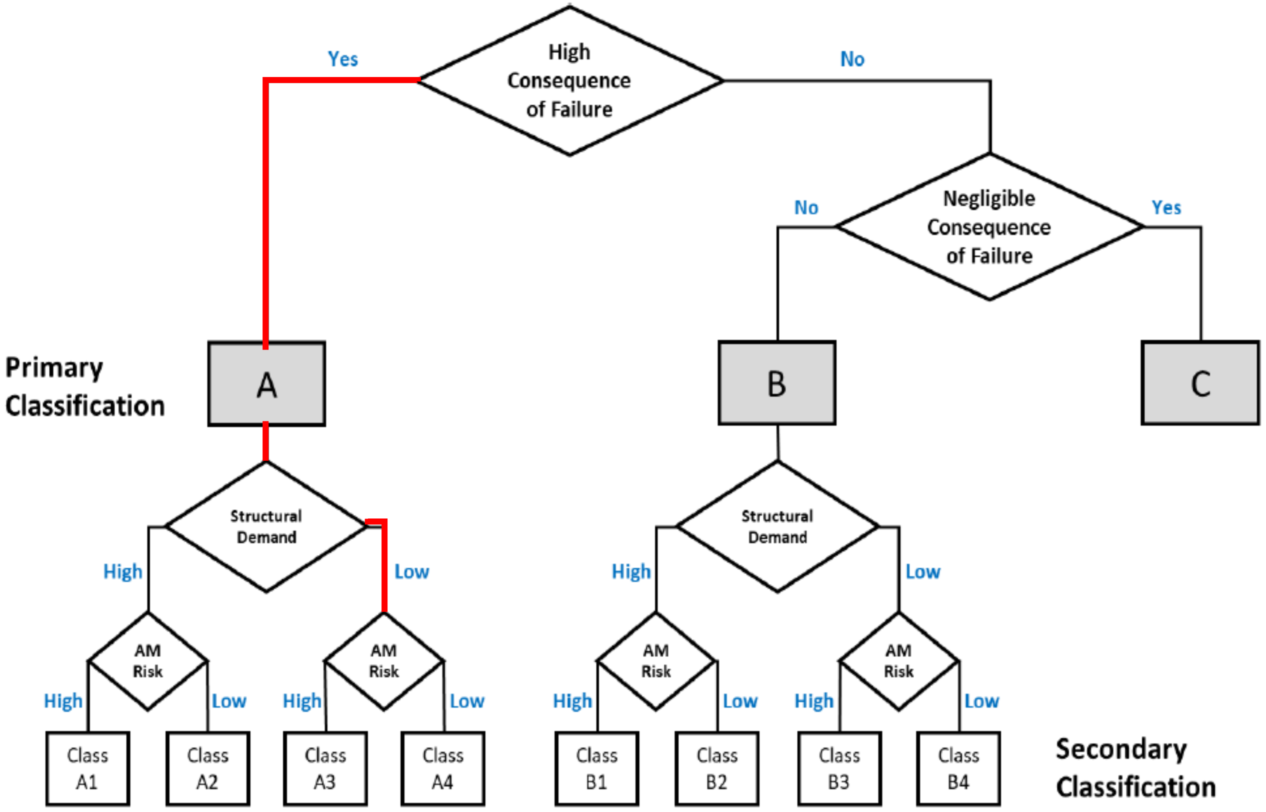
1. *Catastrophic Failure?*
2. *Heavily Loaded?*
3. *Does the build have challenging aspects or areas that cannot be inspected?*

Part Classification Example

- Main Oxidizer Line
- Inconel 718 printed on EOS M290
- Due to limitations in the build height for the ideal AM build orientation of the part, it’s manufactured as two separate pieces which are then welded together
- Component was part of an AM demonstrator engine
- Component aids in routing oxidizer to flow from a high-pressure turbo pump to a valve
- Exposed to liquid oxygen with applied temperature of -281°F and applied pressure of 1676 psi
- Failures would cause leakage of liquid oxygen resulting in engine damage and loss of vehicle (catastrophic)

Part Classification

Secondary Part Classification – Structural Demand

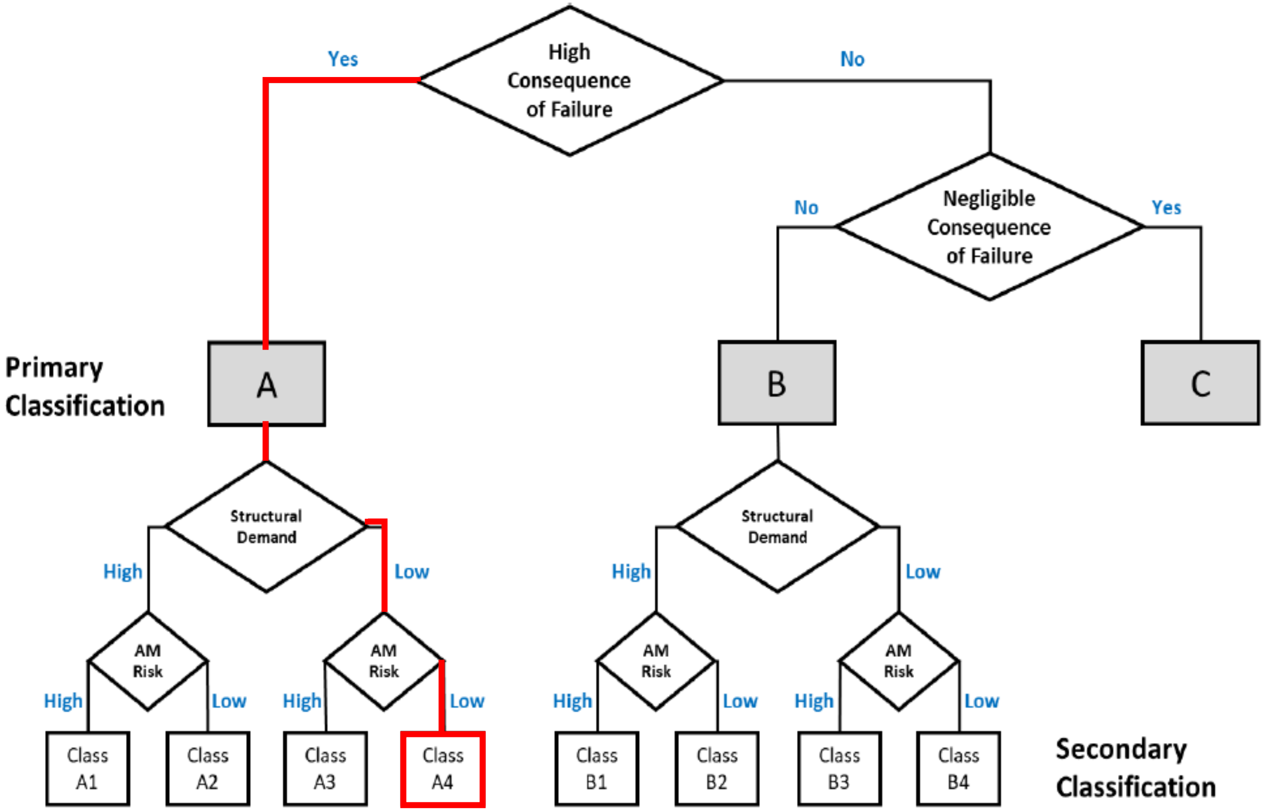


1. Catastrophic Failure?
2. Heavily Loaded?
3. Does the build have challenging aspects or areas that cannot be inspected?

Analysis Input/Material Property	Criteria for Low Structural Demand
Load cases	Well-defined or bounded loads environment ✓
Environmental degradation	Only due to temperature ✓
Ultimate strength	Minimum margin* $\geq$0.3 ✓
Yield strength	Minimum margin* $\geq$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 ✓

Part Classification

Secondary Part Classification – AM Risk



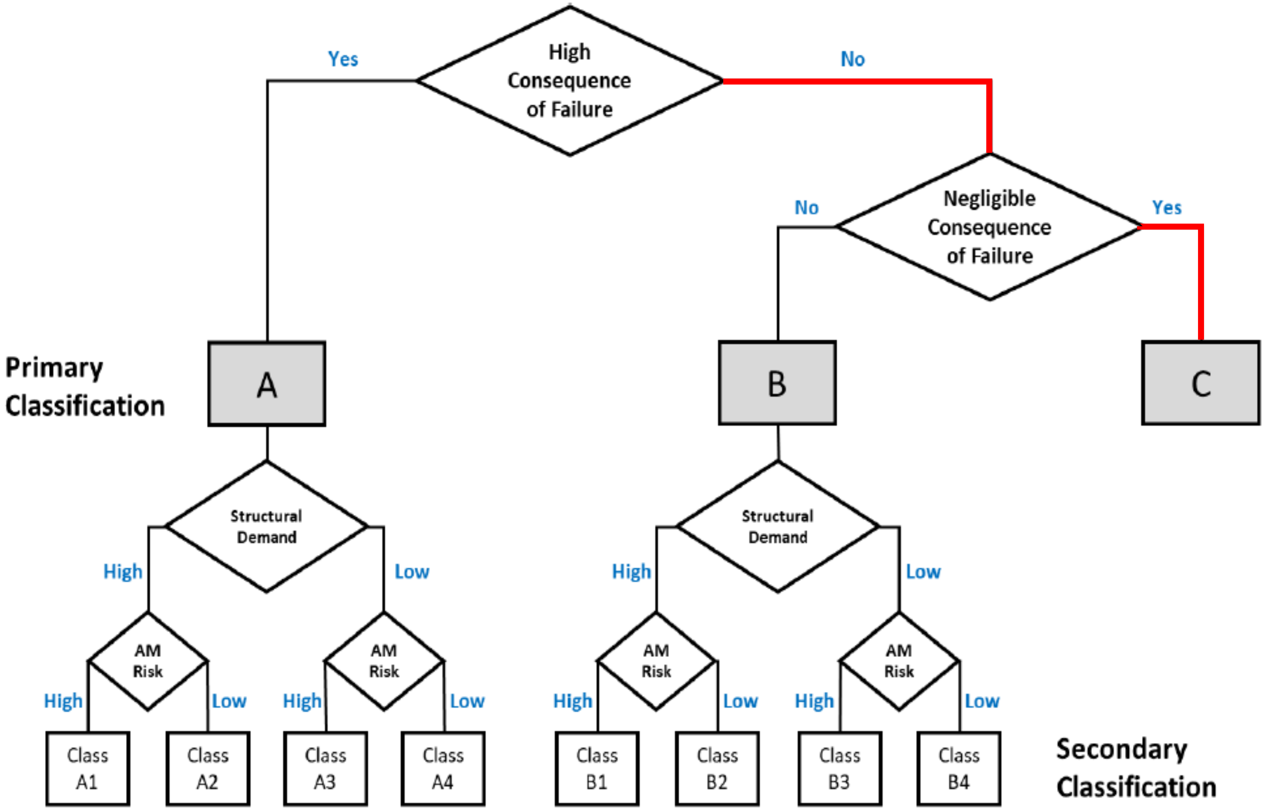
	Metallic		Polymer			
	L-PBF	DED	L-PBF	Score For		
Additive Manufacturing Risk				Yes	No	Score
All surfaces and volumes can be reliably inspected, or the design permits adequate proof testing based on stress state?	X	X	X	0	5	0
As-built surface can be fully removed on all fatigue-critical surfaces?	X	X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

If the summed AM risk scores < 5, the part will be assigned Low AM Risk and placed into subclass 2 or 4

If the summed AM risk scores ≥ 5, the part will be assigned High AM Risk and placed into subclass 1 or 3

Part Classification Example

Part Classification



1. Catastrophic Failure?
2. Heavily Loaded?
3. Does the build have challenging aspects or areas that cannot be inspected?

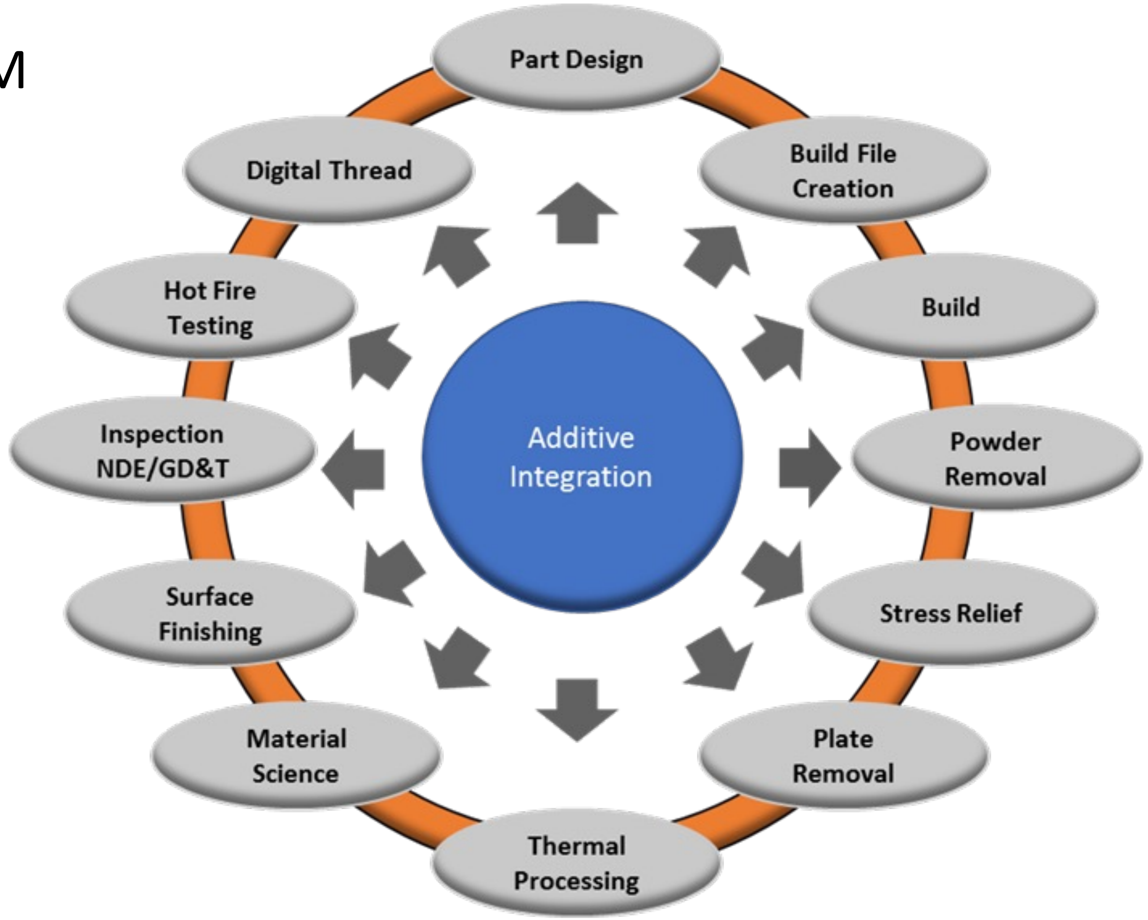
NASA-STD-6030 Section 4.3.1.3 Requirements
a. Failure of part does not lead to any form of hazardous condition. ✓
b. Failure of part does not eliminate a critical redundancy. ✓
c. Part does not serve as primary or secondary containment. ✓
d. Part does not serve as redundant structures for fail-safe criteria per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware. ✓
e. Part is not designated "Non-Hazardous Leak Before Burst" per NASA-STD-5019. ✓
f. Failure of part does not cause debris or contamination concerns, as defined by the Non-Fracture Critical Low-Release Mass classification per NASA-STD-5019, NASA-STD-6016, and/or other project/program requirements. ✓
g. Failure of part causes only minor inconvenience to crew or operations. ✓
h. Failure of part does not alter structural margins or related evaluations on other hardware. ✓
i. Failure of part does not adversely affect other systems or operations. ✓
j. Failure of part does not affect minimum mission operations. ✓

See Table 22 of 6030 for more details

Part Planning

AM Part Production Plans

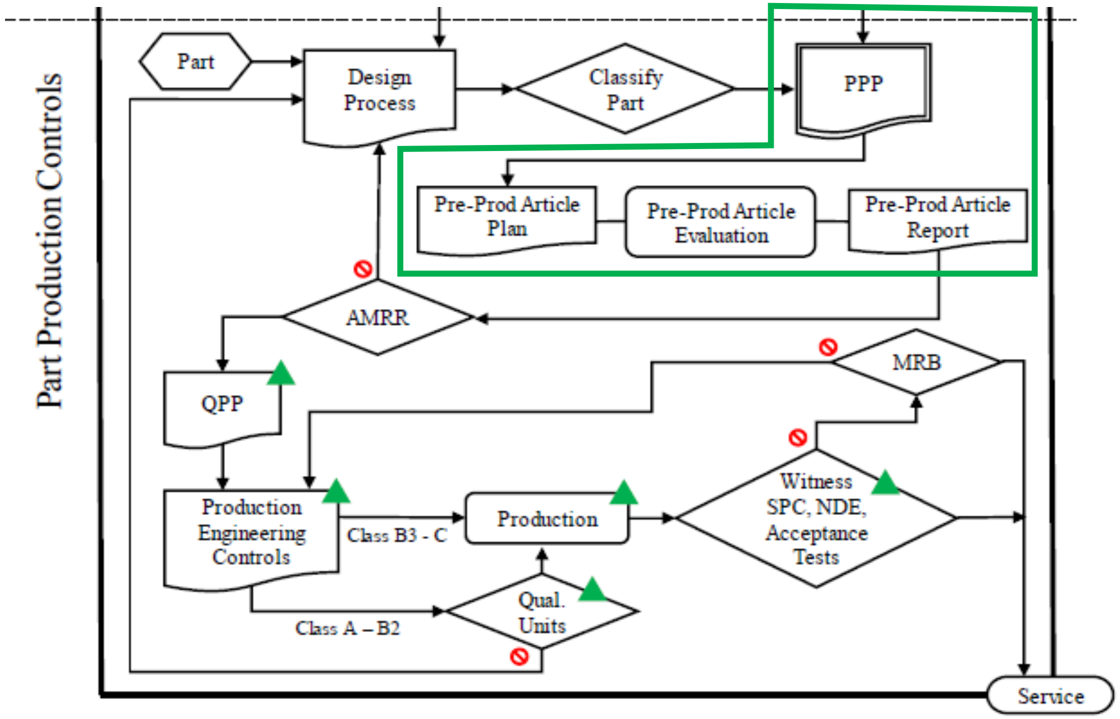
- Challenging to integrate all required aspects of AM design requirements through drawing content
- Requires many aspects to be integrated
  - Build layout
  - Specification of qualified process ID
  - Witness test and acceptance
  - Post processing details
  - ***<u>Inspection requirements and limitations</u>***
- NASA requires an AM Part Production Plan as a drawing companion



Part Production Plan

Part Production Plans force integration of part processing

- Mechanism to define process controls unique to a particular part design/build
  - Capture process criteria that's not on the drawing
- Primary means of documenting and communicating the part production intent and level of risk associated with the part
- *For Class C parts, the PPP need only include the part classification rationale and witness testing*



Part Production Plan

Part Production Plan

- Six main sections
- **First** section covers Part-Specific Information
- **Second** section covers Part Classification and detailed rationale

7.1 Part-Specific Information

[AMR-98] For Class A and Class B parts, the PPP **shall** list the following minimum general information, or may reference other configuration-controlled documentation that is available to NASA on request:

a. Drawing number and part name.

b. Illustrations and/or CAD model views (with scale).

c. The purpose of the part in context to the system.

d. The operational environments (e.g., temperatures, fluids, radiation, etc.).

e. Referenced build file name contained in the digital thread.

f. Material (including material specifications, if applicable):

(1) Feedstock material specification.
(2) Part material specification (or equivalent).

g. Identification of the QMP specified for production.

h. Identification of a specific MPS for the associated material used for part assessment, including influence factors, if applicable.

i. Serialization, part marking, and methodology for tracking individual parts, if applicable.

j. Cleanliness, if special considerations or requirements apply (e.g., oxygen service, optical surfaces, delicate electronics, etc.).

k. Qualification plan, when applicable.

Part Production Plan

Part Production Plan

- **Third** section covers Integrated Structural Integrity Rationale
    - 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
- **Fourth** section covers the AM Part Production Summary
    - Can be a list, table, or flow chart of the primary production steps, in sequence, that are critical to successful production of the part

7.3 Integrated Structural Integrity Rationale

[AMR-100] For Class A and B parts, the PPP **shall** have an integrated structural integrity rationale that provides justification of part integrity commensurate with its consequences of failure and associated requirements, and addresses or describes, at a minimum, the following:

a. Key results and any limitations identified in the strength and fracture analyses.

b. Areas of high structural demand and high AM risk per section 4.3.2 of this NASA Technical Standard.

c. Application of influence factor data in the assessment.

d. Rationale for the mitigation of residual stresses or how they are accounted for in the part assessment.

e. NDE, acceptance criteria, degree of coverage, and limitations.

f. Proof test operations, including the role in integrity rationale, method of analysis, and coverage or limitations.

g. Residual risks identified to date.

h. Reference to all supporting analysis and documents.

i. Summary of fracture control implementation, if applicable.

Part Production Plan

Integrated Structural Integrity Rationale (ISIR) Example

Main Oxidizer Line

- Pressurized, structural and fracture critical
- AM classification: A4
- Stress Analysis Summary and Conclusions
  - Satisfaction of the Margin of Safety Requirements on both Yield and Ultimate Strength
- Proof Pressure Test with factor of 2.0x Maximum Design Pressure
- Detailed NDE Plan listing Critical features, coverage, and probability of detection
  - Inner radii where the channel transitions directions
  - Visual and Volumetric inspections
  - Outside surface will be machined and inspected with dye penetrant
  - Ultrasonic, X-ray, and X-Ray CT Plans
- If full NDE inspection was not achievable, then rationale would be required, and the associated risks identified

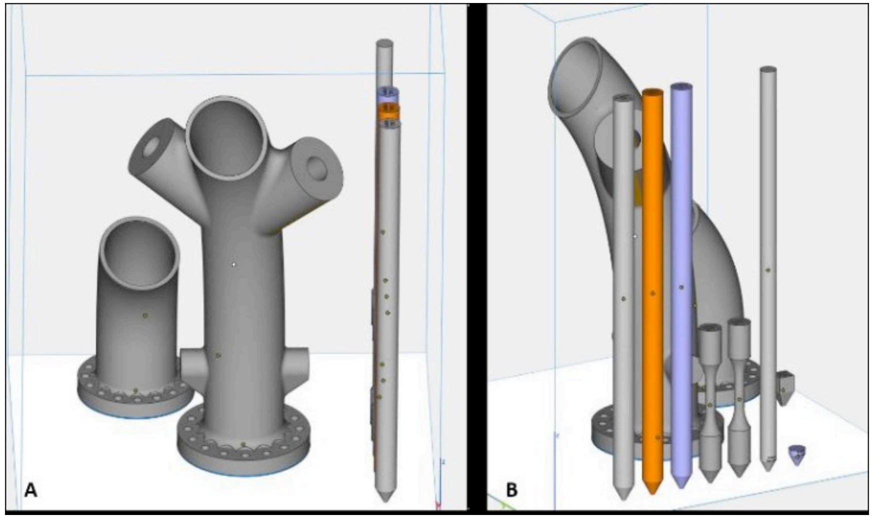
See these additional documents for guidance on ISIR:
NASA-STD-5019A, Fracture Control Requirements for Spaceflight Hardware
NASA-STD-5001B, Structural Design and Test Factors of Safety for Spaceflight Hardware

Part Production Plan

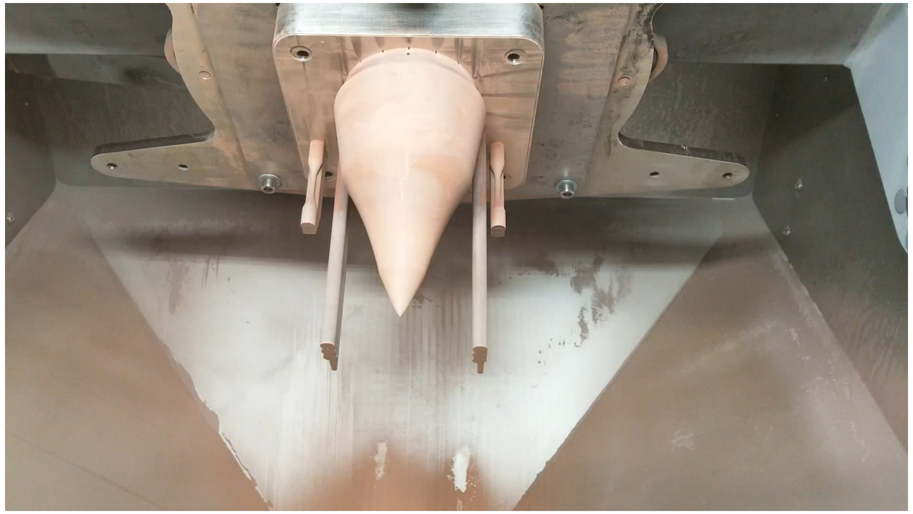
Part Production Plan

Also, within the **fourth** section:

- Witness Testing
  - Quantities
  - Types
  - Layout in the build volume
  - Acceptance Criteria
- Planned Interruptions (e.g., for powder refilling)
  - Allowable height ranges, any inspections required at interruption
- Post-Build Operations Requiring Specific Controls (examples follow, but not all-inclusive list)
  - Support structure remove requiring unique methods
  - Thermal treatments
  - Photo processing
  - Cleaning, potentially including non-line-of-sight feedstock removal
  - Joining, etc.



MAIN OXIDIZER LINE AM PART BUILD LAYOUT INCLUDING WITNESS SPECIMENS



Part Production Plan

Part Production Plan

- **Fifth** section covers the Preproduction Article Requirements
  - Generally, correlates to traditional First Article requirements
  - NDE, potential testing, destructive cut-up, metallography, etc.
  - Qualifies part and material quality
- **Last** section is the End Item Data Package (EIDP) Information
  - All the relevant documents in the engineering record for the part

7.6 End Item Data Package (EIDP) Information

[AMR-106] For Class A and B parts, the PPP **shall** include a complete list of all items that will be required for the part acceptance as part of the EIDP, including, but not limited to:

a. Build designation.

b. Post-build processing records (e.g., thermal treatment).

c. Witness testing report.

d. Cleaning verification.

e. Dimensional inspection report.

f. NDE report.

g. Feedstock certification.

h. Proof testing report.

i. List of all nonconformances and records of their disposition (including unplanned build interruptions and repairs; see sections 4.7 and 4.10 of this NASA Technical Standard).

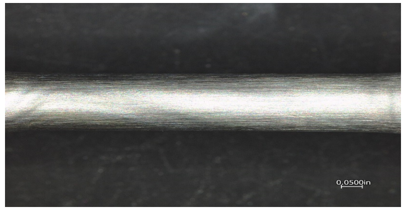
Part Production Plan

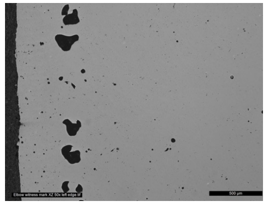
Common Challenges

- Build files not locked
- Insufficient description and control of post processes
- Maturity of 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

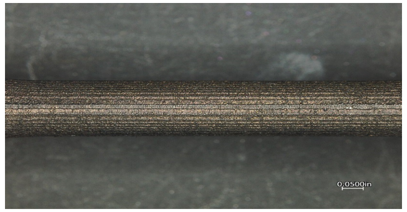
Ground Surface

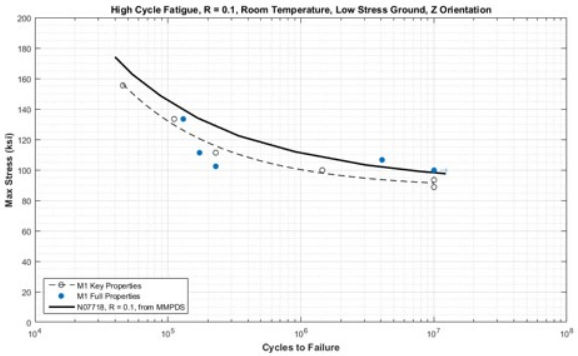


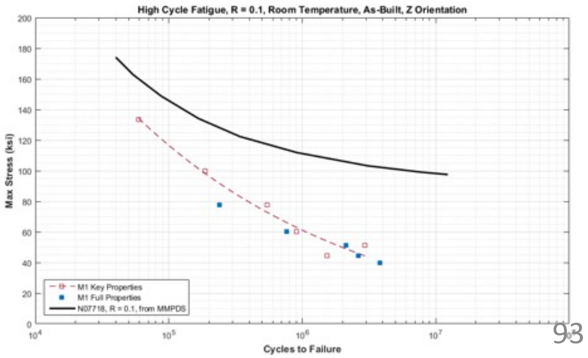


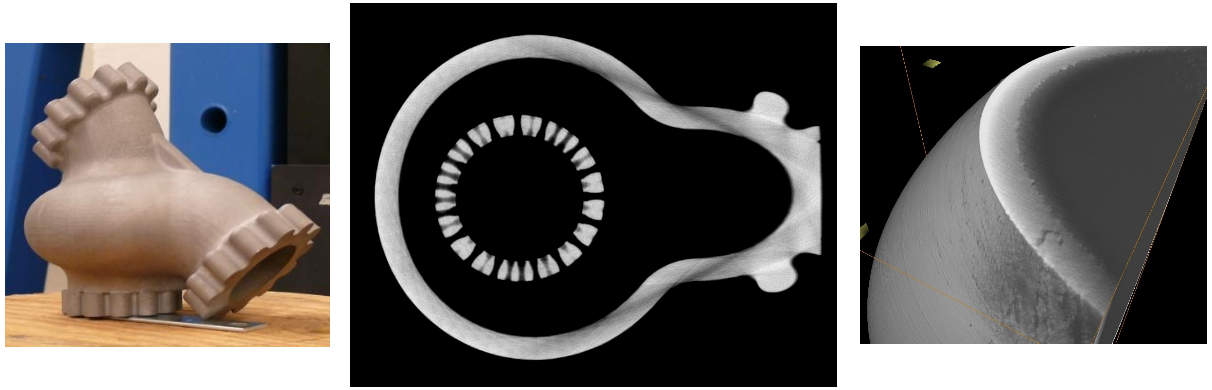
Near Surface Porosity

As-Built Surface









NDE: Powder not cleared, Imbedded Flaw

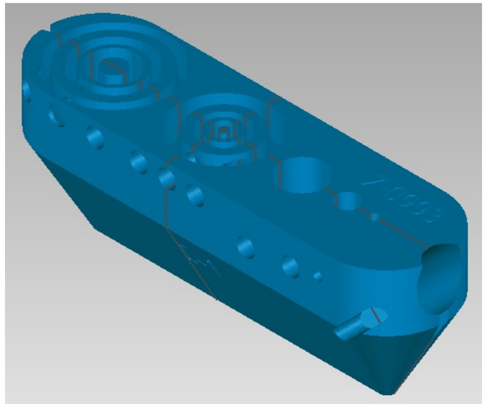
Part Production Plan

Common Challenges (Continued)

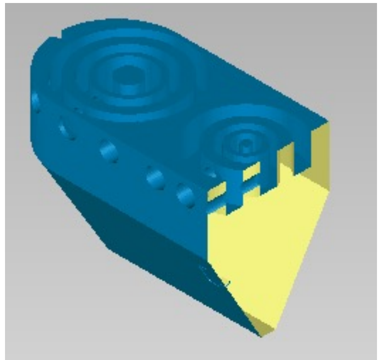
Pre-production article evaluation

- *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

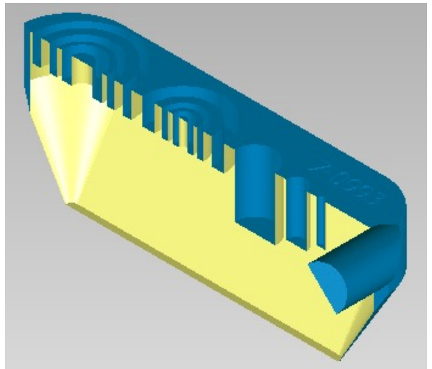
Contour Test Part



Cut Plan



Channels Build Correctly?



Thin Sections Ok? Microstructure Within Acceptance Criteria?

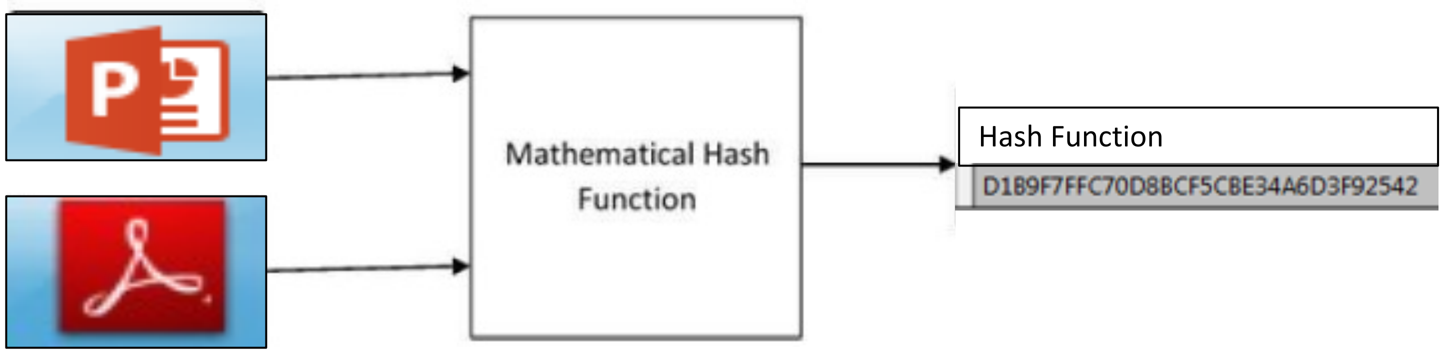
Part Production Plan

Common Challenges (Continued)

Understanding cryptographic hash

(*see NASA-STD-6030, 4.13.1 Maintaining File Identity and Integrity in the Digital Thread*)

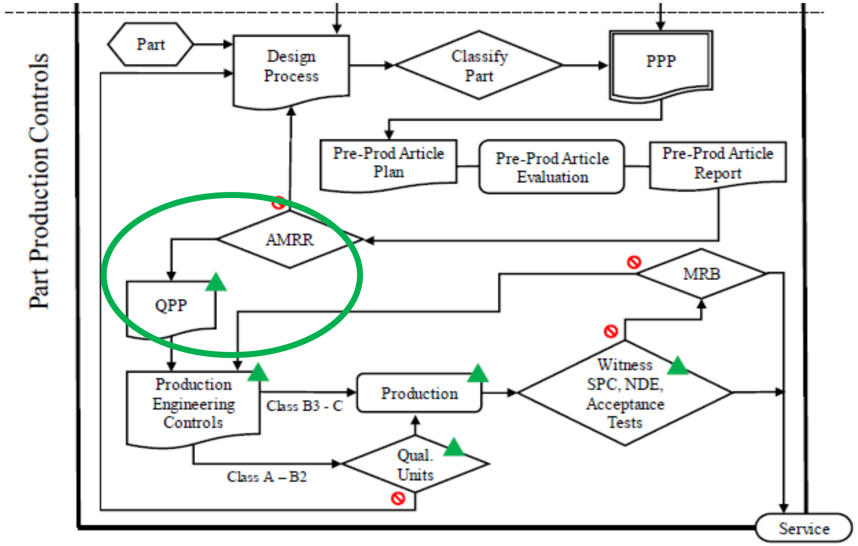
- Cryptographic hash functions can be utilized to store data or determine whether any changes have been made to the data.
- This guards against corruption, allowing for the program to be used for data integrity and verification.
- The different hash programs produce the same output and result in a change 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 Readiness Review
   (Do we have our ducks in a row? *Note: Not required for Class C parts, but highly encouraged.*)
   – 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



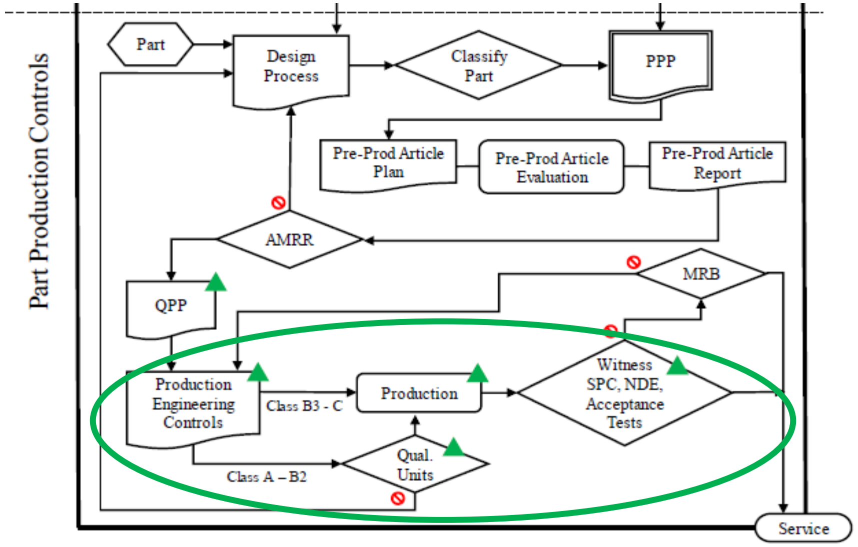
<u>Locked Process Is the QPP! Must be documented in the QMS!</u>

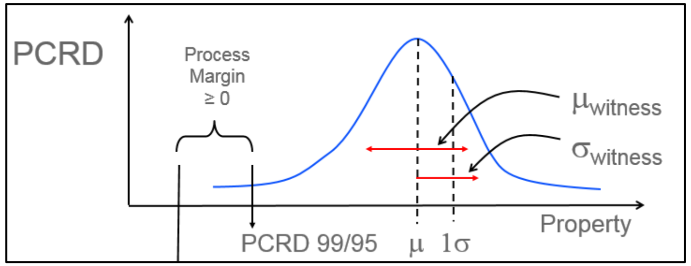
AM Part Production

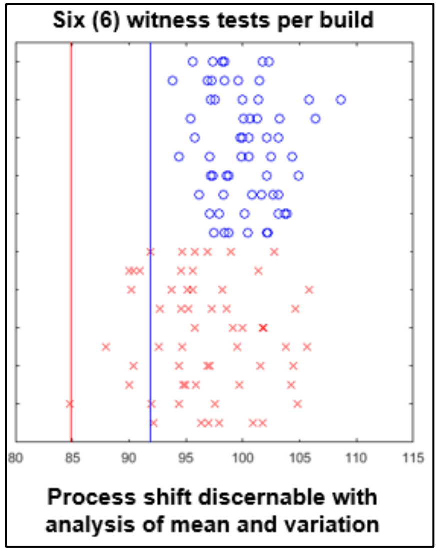
Follow through on controls

Statistical Process Control (SPC)

- Independent Builds (just one or a handful of parts)
  - Class A1: 6 tensile, 2 HCF, 2 Met, 1 Chemistry, 1 Full height Contingency
  - See NASA-STD-6030, Tables 5 and 6 for other part classes
  - Compare to PCRD
- Continuous Production
  - Class A1: 4 tensile, 1 Met, 1 Chemistry, 1 Full height Contingency
  - See NASA-STD-6030, Tables 7 and 8 for other part classes
  - Compare to continuous Control Chart
    - Established for Ultimate Strength, Yield Strength, and Elongation according to ASTM E2587 and controlled by the QMS
  - Intermittent SPC evaluation 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

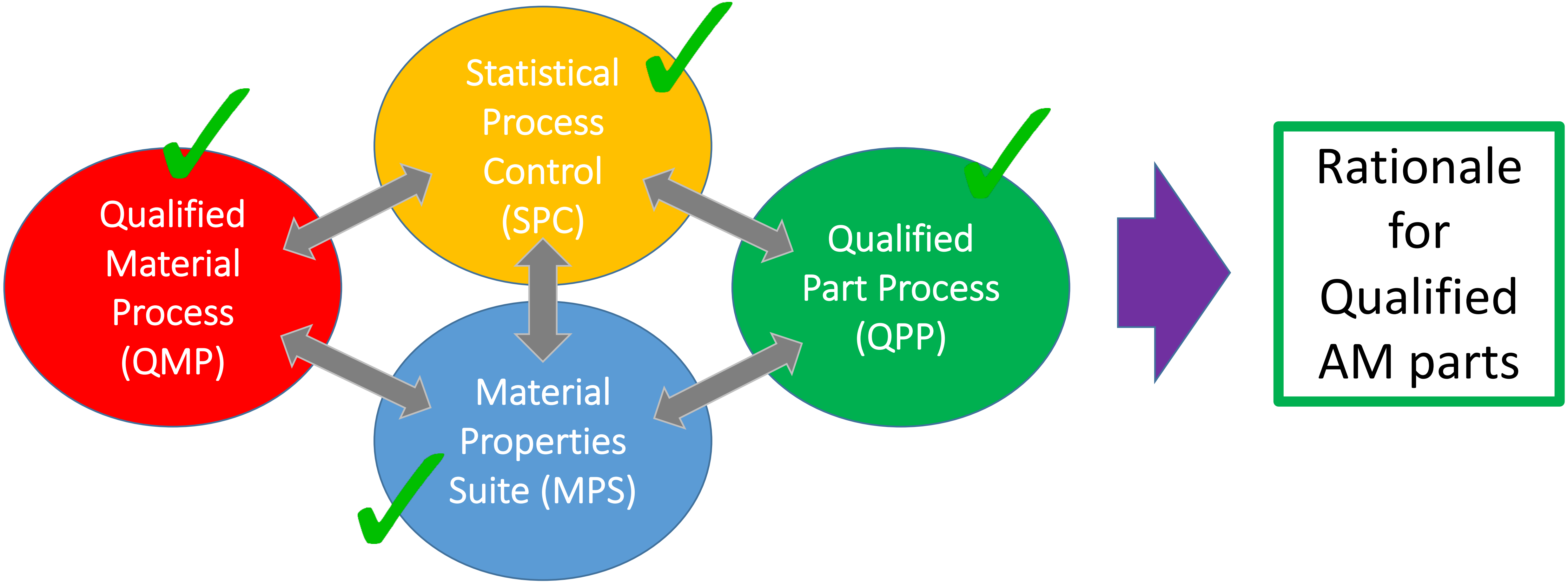






Builds with witness test results that violate control chart acceptance criteria are assigned a non-conformance, initiating a root cause and corrective action in accordance with the QMS.

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

Break 3

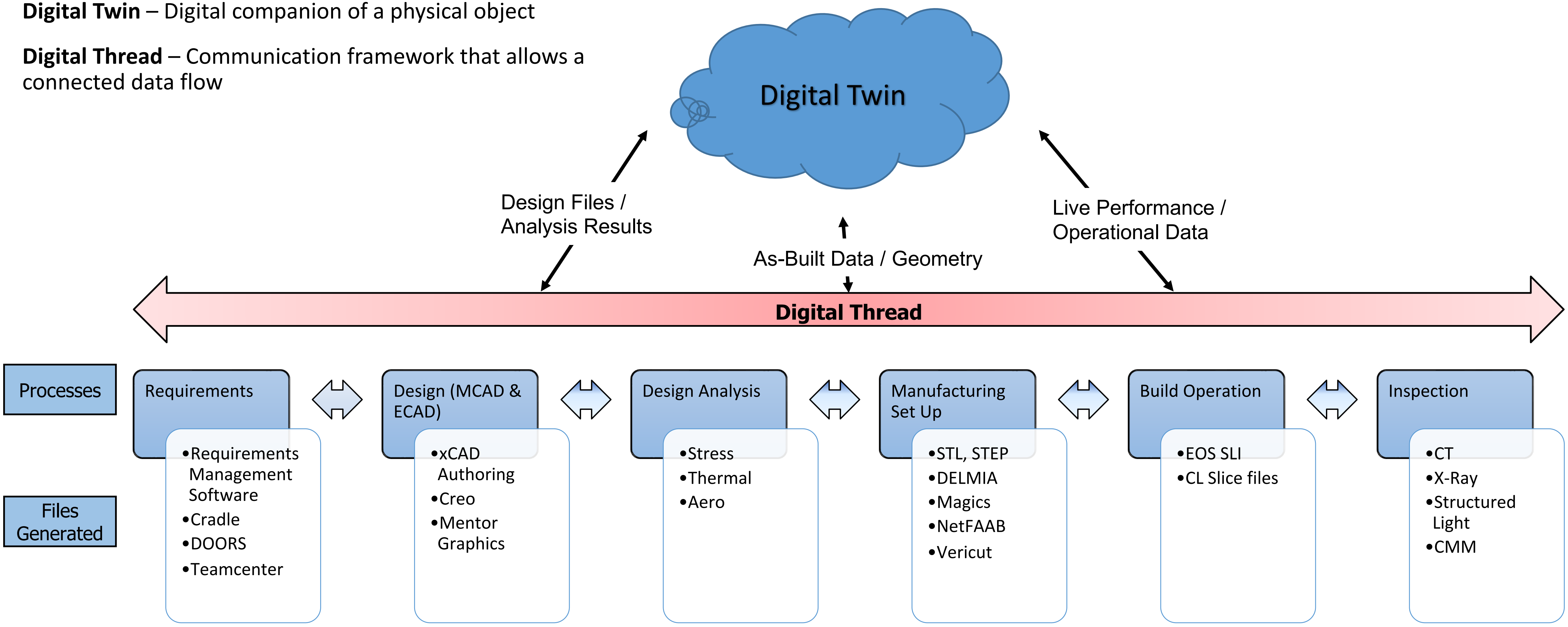
Common Challenges

- 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
  - As the technology evolves so do the influence factors (e.g., multi-laser stitching!)
- 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?

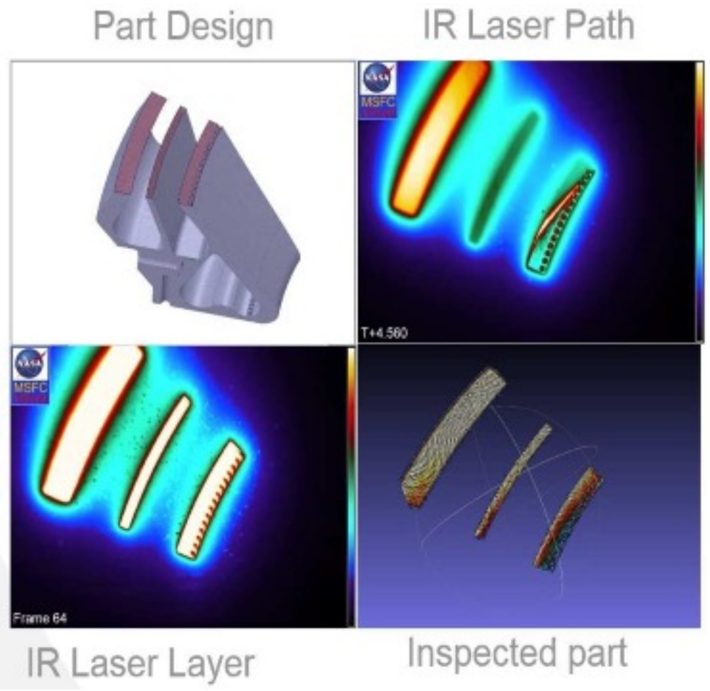
- Harnessing the technology is only half the battle
  - Detectors, data stream, data storage, computations
- Second half of the battle is quantifying in-situ process monitoring ***reliability***

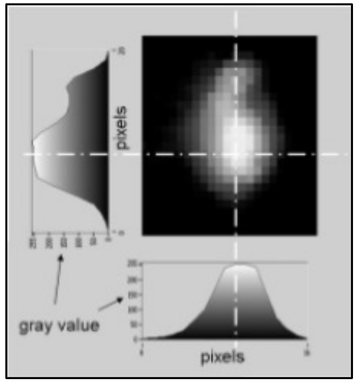
Community must realize that passive in-situ monitoring is an NDE technique

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

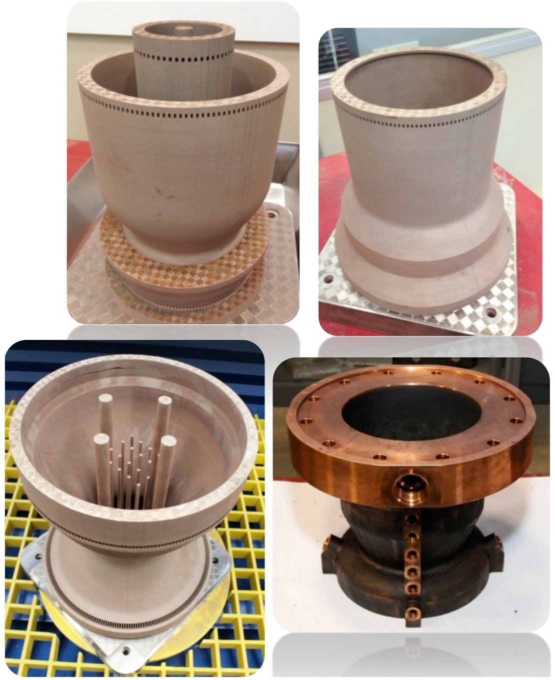




Concept Laser QM Meltpool

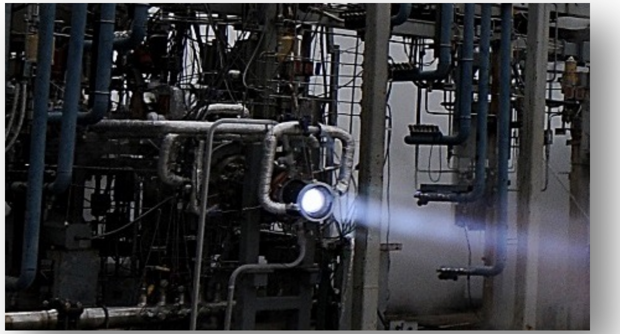
Application

Final Box: *Service!*

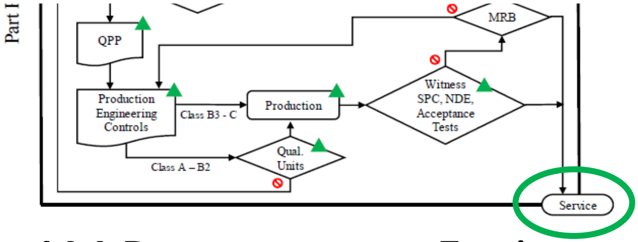


GRCop-84 3D printing process developed at NASA and infused into industry

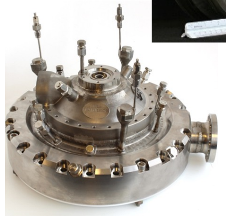
Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate



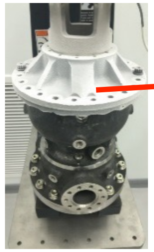
LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power



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

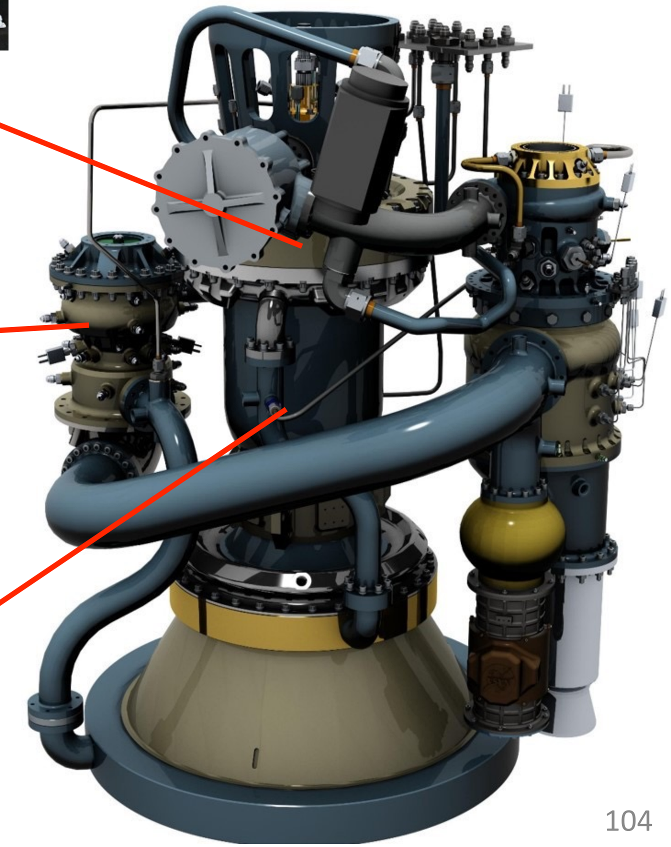


FTP
- Schedule reduced by 45%
- Reduced part count: 40 to 22
- Successful tests in both Methane and Hydrogen



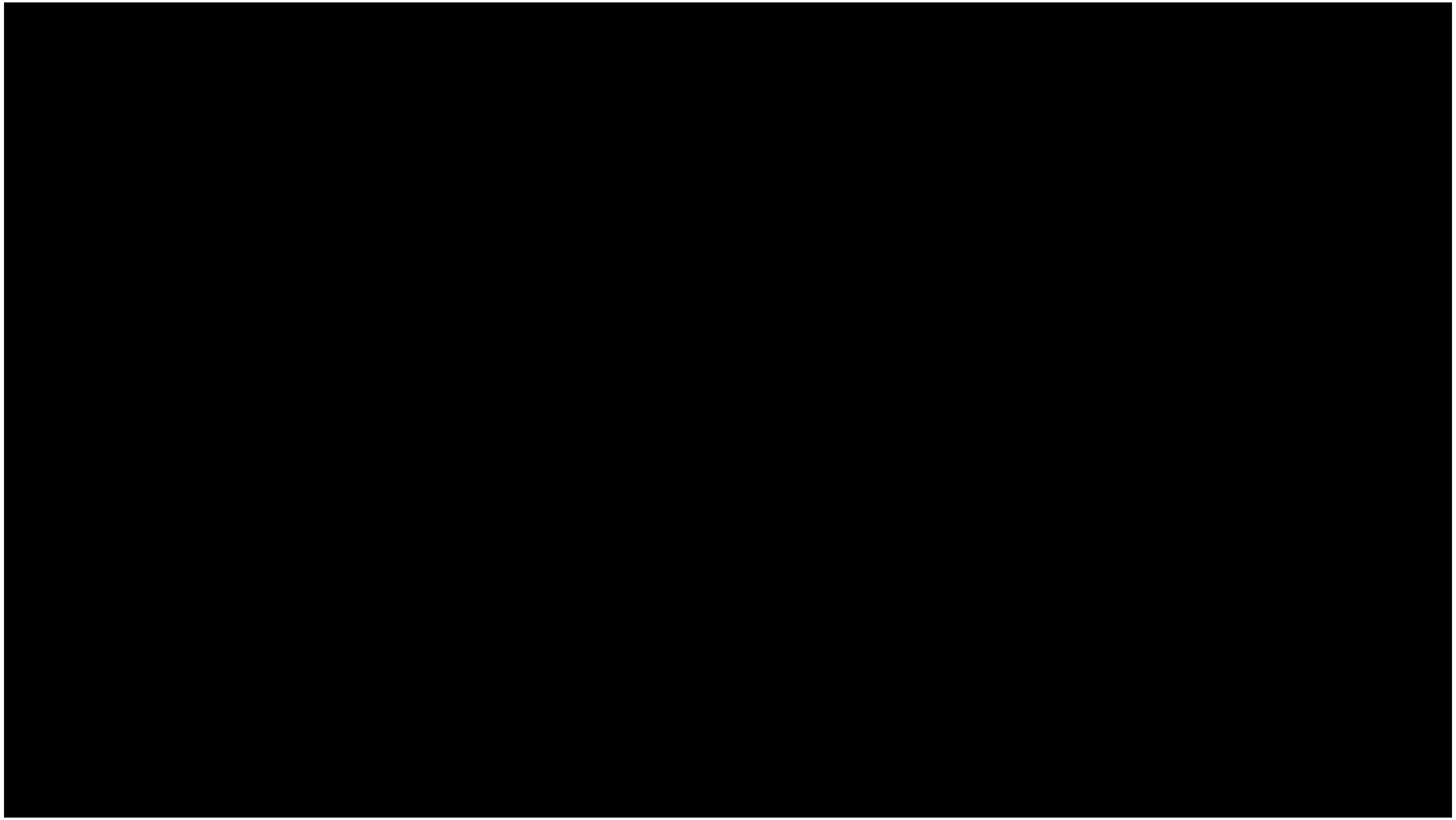
MCC
- Schedule reduction > 50%
- SLM with GRCop-84
- Methane test successful

AM Demonstrator Engine

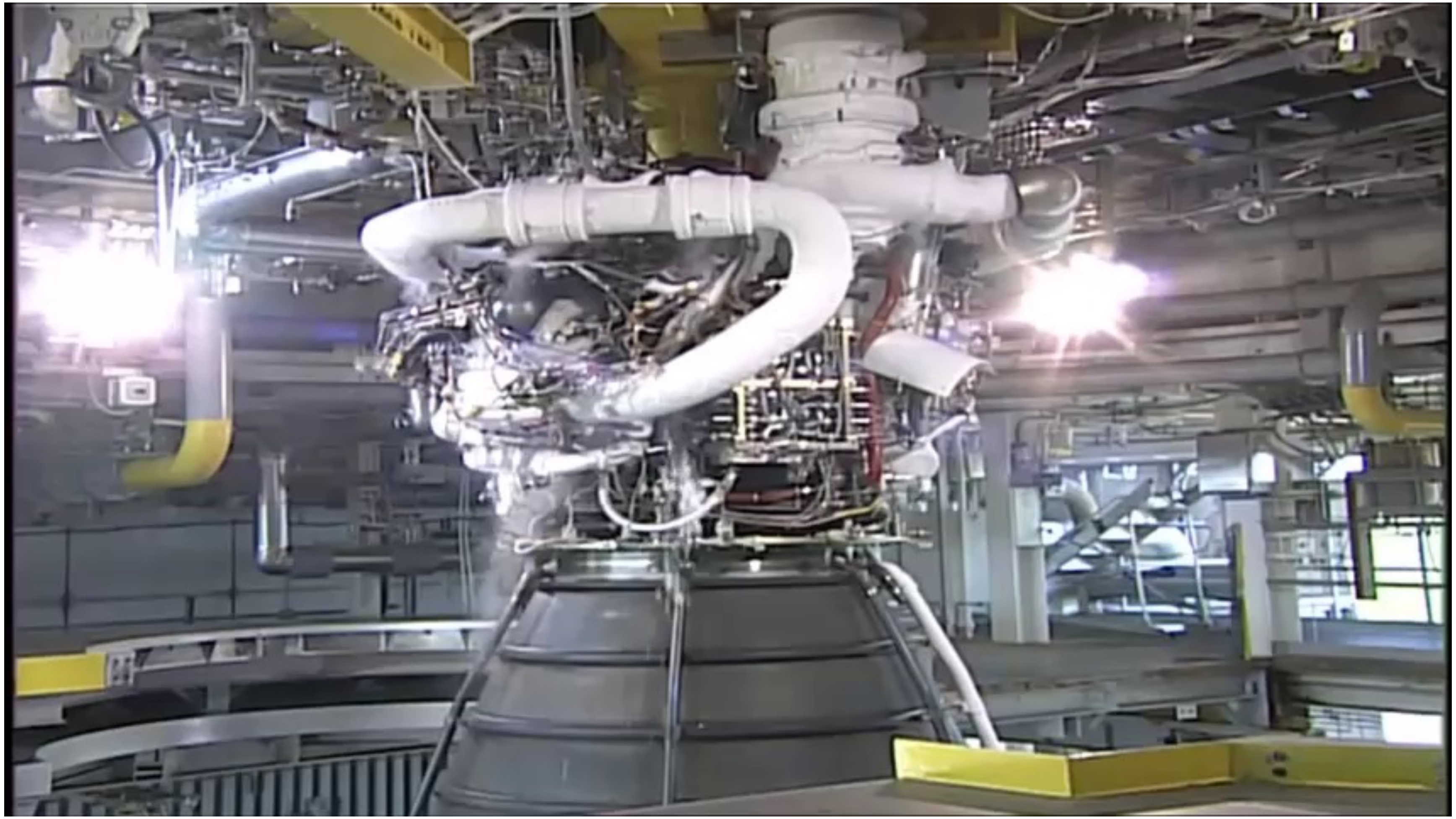


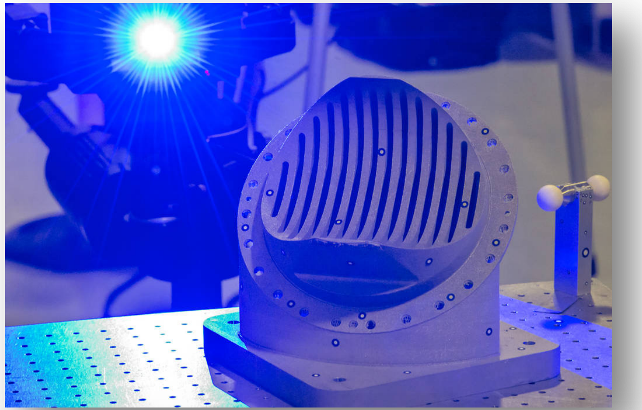
SLM Alloy 718 Injector Testing

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 <u>127 welds to 4 welds</u>

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Ref: Andy Hardin, Steve Wofford/ NASA MSFC

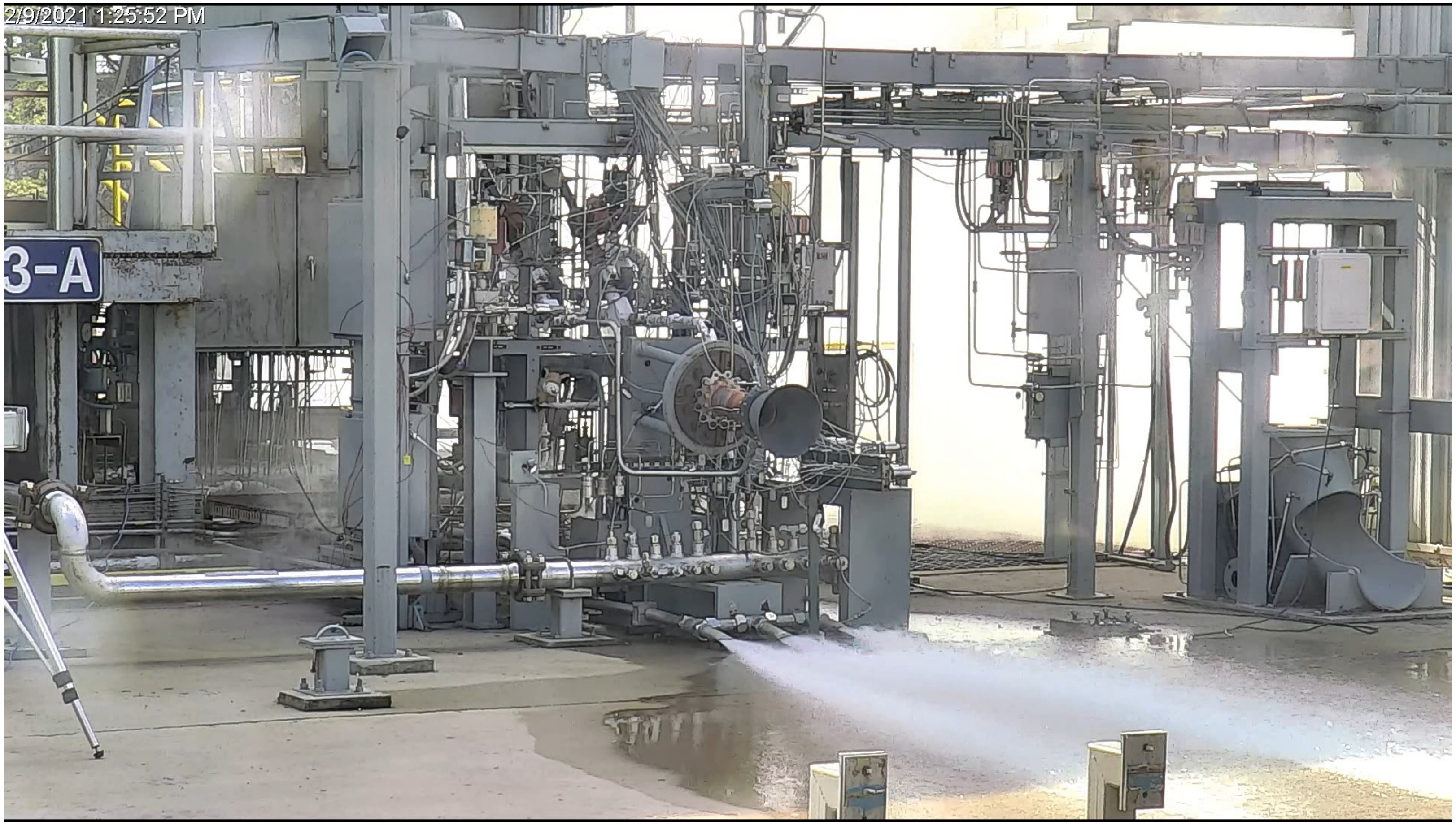
LLAMA Program

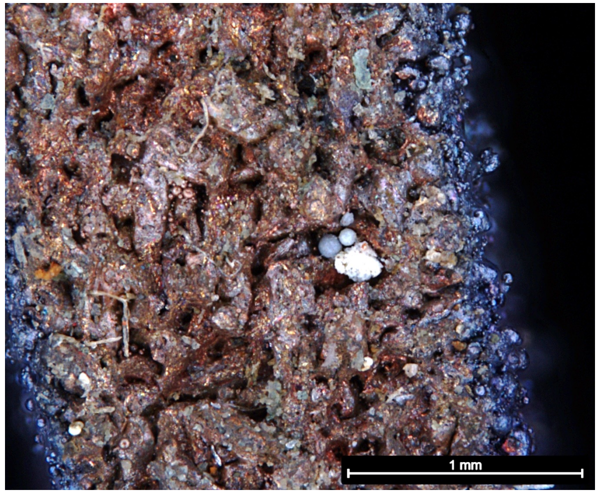
Why we don't just rely on tensile tests

- Hot-fire test demonstration of high duty cycle lander concept rocket thrust chamber (reusable cryogenic propulsion; minimum 50 starts)
- LPBF GRCop-42 Chambers & DED Nozzle
- Chamber separated during hot-fire testing mainstage ~11 seconds into testing (even though chamber had multiple successful starts prior to)
- Extensive Investigation followed
  - X-ray CT
  - LPBF Restart Procedures
  - Metallography evaluations, Tensile and Fatigue Testing, Chemistry, etc.
- Found granular surfaces, unmelted particles, and irregular pores in microtensile specimens sectioned from the chambers
  - Defects congregated more at the build interruptions
- Areas affected by build interruptions must be properly evaluated and dispositioned. AM machine restarts represent a risk, and appropriate restart procedures should be developed and followed to maintain material quality.
  - Witness specimens using different types of restarts showed similar tensile strengths and LCF results
  - HIP didn't fully close voids
- Build logs didn't indicate any issues. ***Demonstrates process-sensitivity of AM!***

LLAMA Program

Why we don't just rely on tensile tests





Conclusion

1. Certification rationale is most heavily rooted in the foundational controls
   - Having a Plan
   - Fully involved QMS
   - Equipment and Facility Controls
   - Training
   - Process and 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. For the complete requirements to implement NASA's approach see the following documents, which may be found at the links below.

NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems:
https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-04-21_nasa-std-6030-approveddocx.pdf
NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facility Control:
https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021-04-21_nasa-std-6033_-_approveddocx.pdf

For more information, you can also check out ***Metal Additive Manufacturing for Propulsion Applications***. Chapter 9 covers Certification of Metal Additive Manufacturing.

https://arc.aiaa.org/doi/book/10.2514/4.106279

https://www.amazon.com/Metal-Additive-Manufacturing-Propulsion-Applications/dp/1624106269

Questions?

Thank You!