Methodologies for Qualification of Additively Manufactured Aerospace Hardware

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Welcome and Course Objectives

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

• This course is intended to provide guidance and practical methodologies on how to establish a qualified process and deliver certifiable hardware per the requirements in MSFC-STD-3716 and MSFC-SPEC-3717

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

NASA is not homogeneous

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

Earth

Moon

Mars

**In LEO**
Commercial & International partnerships

**In Cislunar Space**
A return to the moon for long-term exploration

**On Mars**
Research to inform future crewed missions
Additive Manufacturing (at MSFC)

• Extensive experience in Additive Manufacturing (AM) technologies, and have been involved in about 30 different AM systems in the past 26 years.

• Over $11.5M capital investments in metallic powder bed systems in the past 5 years, and have committed significant engineering manpower resources

• NASA AM Objectives
  • Decrease production lead time & costs
  • Develop Flight Certification Standards
  • Process development and characterization
  • Share knowledge and data in pursuit of smart vendor base
  • Design optimized components & test at relevant conditions
  • Appropriate Application
    • High complexity & difficult to manufacture
    • Low production rate
    • Long lead time & high cost
Additive Manufacturing at NASA

For-Space:

In-Space:
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.

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

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

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


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


Motivation: Laser Powder Bed Fusion in near term, human-rated flight projects:
• Space Launch System
• Orion Spacecraft
• 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?”
Additive Manufacturing: Any process for making a three-dimensional object from a 3-D model or other electronic data source primarily through processes in which successive layers of material are deposited under computer control.
• Guidelines documents and standards for additive manufacturing are in development at this time. The requirements of this NASA Technical Standard on M&P controls, materials design values, metallic and nonmetallic materials, and nondestructive inspection apply to hardware manufactured by additive techniques, just as they do for traditional manufacturing techniques.

• For nonstructural, nonmetallic 3-D printed hardware, controlled and verified processes are essential; but other M&P aspects like flammability, toxic offgassing, and vacuum outgassing also apply, just as for any other nonmetallic material.

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

§ guidance (italics) and requirements excerpts from NASA-STD-6016A
Key aspects of producing structural metallic hardware by additive manufacturing techniques, such as direct metal laser sintering (DMLS) and selective laser melting (SLM), include proper development of structural design values and controlled processes, although other requirements, such as stress-corrosion resistance and corrosion control, also apply. Verification of appropriate process control should include first article inspection to verify proper material properties and macro/microstructure and mechanical property testing of integrally manufactured specimens from each hardware unit.

§ guidance (italics) excerpts from NASA-STD-6016A
Active Standards for AM within NASA

**MSFC-STD-3716 & MSFC-SPEC-3717**

*Policy: MSFC-STD-3716*

*Procedure: MSFC-SPEC-3717*

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

https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.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
1. Ingot Making
2. Cutting
3. Heating
4. Forging
5. Heat Treating
6. Machining
7. Inspection
8. Delivery with CoC

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

Production facilities now largely responsible for material integrity
Statistical process controls required in environments unaccustomed to it
What are “Qualification” and “Certification”?

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

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

• Have a plan
• Integrate a Quality Management System (QMS)
• Build a foundation
  • Equipment and Facility
  • Training
  • Process and machine qualification
  • Material Properties / SPC
• Part planning
  • Design, classification, Pre-production articles
  • Qualify and lock the part production process
• Produce to the plan – Stick to the plan
• General requirements in the AMCP govern the engineering and production practice and are paralleled by a Quality Management System (QMS).

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

• Part Production Control requirements are typical of aerospace operations and must be met before placing a part into service.
First Part of Class: Foundational Process Controls provide the basis for reliable part design and production

Second Part of Class: Part Production Controls are typical of aerospace operations and include design, part classification, pre-production and production controls
General Requirements
and
Foundational Process Controls

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

Quality Management System

- Critical to maintain consistent implementation policy
- Ensures you stick to your plan and tailoring
- Ensures consistent training, processes and procedures
Integrate a Quality Management System

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

Source: https://www.orielstat.com/blog/medical-device-qms-overview/
Planning for AM certification does NOT start with a part!

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

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

Foundation

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

Concept Laser/GE

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

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

**EM40-OWI-081**

Basic Concept Laser Operator

11. PERSONNEL TRAINING AND CERTIFICATION

**SHE 102: MSFC SHE PROGRAM REFRESHER TRAINING**

**SHE 238: RADIATION SAFETY - IONIZING RADIATION PRODUCING DEVICES**

**SHE 317: MSFC ENVIRONMENTAL COMPLIANCE TRAINING CONCEPT LASER OPERATOR CERTIFICATION, LEVEL 1, 2**

Based On “On the Job Training”

**EM40-OWI-077**

Structured Light Scanning and Photogrammetry

1. PERSONNEL TRAINING AND CERTIFICATION

1.1. Operator Certification

1. Only certified operators or operators under the supervision of a certified operator shall operate equipment.

   a. If it is determined that data has not been collected by a person not properly certified, a review shall be conducted to determine the capability of the data.

   b. Certifiable Laser Operator, Basic Concept Laser Operator, or Designated Trainee. This review will determine whether the data shall be discarded or used.

2. An operator’s certification shall be revoked when:

   a. The individual no longer employs NASA or one of its contractors.

   b. The review is performed and concluded as follows:

      i. The Team Lead, the Assistant Manufacturing and Digital Systems Team Lead, or the Deputy Chief of Advanced Manufacturing Branch.

      ii. The Director, the Assistant Manufacturing and Advanced Manufacturing Division.

      iii. The Director, Chief of the Manufacturing and Advanced Manufacturing Division.

   c. The certification is valid for two (2) years from the date of certification.

   d. A list of certified operators shall be maintained and stored in accordance with the Records Section of this document.

   e. The person training operators must ensure that certification, if following shall be met and be documented.

   i. Level 1 Certification:

      a. Send for Organizational Training Commission on safety.

      b. Complete training course as prescribed by the manufacturer’s manual or provided by a certified operator. A certification letter will be issued at this time.

      1. Phenomenon two processes and applications.

      2. Measure light using two processes and applications.

      3. Correct up to 4 (four) non-critical measurements, under a certified trainer.

      4. Complete all steps in the following:

         i. The ability to install and set up the equipment.

         ii. The ability to set up and use the equipment.

         iii. The ability to use.”
Qualified Metallurgical Process

Begins as a *Candidate* Met. Process

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

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

Feedstock Controls
• What you are Building with Fusion Process
• How a machine operates

Thermal Process
• Control what Evolves your Material State
Feedstock Controls

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


Typical Roughness

Very Smooth

Fusion Controls

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

*Any Machine Parameter that affects Material Quality must be Controlled!*
Fusion Controls

Tolerance to variation

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

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

Axis: Representative of any parameters, i.e. power, speed
Parameter Influence on Defects

**Lack of Fusion Defect**

**Lack of Fusion Defect after HIP**

**Nominal**

- **Hot**
  - High Energy
  - Keyhole porosity
  - Overheating/burning

- **Cold**
  - Low Energy
  - Lack-of-fusion

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

Thermal Process

Post-build Thermal Processing

- 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**
## L-PBF Metallurgical Process Definition

<table>
<thead>
<tr>
<th>Powder Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse protocol:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fusion Process Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine ID:</td>
</tr>
<tr>
<td>Model/Model:</td>
</tr>
<tr>
<td>Serial Number:</td>
</tr>
<tr>
<td>Configuration Date:</td>
</tr>
<tr>
<td>Software Version:</td>
</tr>
<tr>
<td>Firmware Version:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactor Configuration:</th>
<th>Carbon fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build platform material:</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Preheat temperature:</td>
<td>80°C</td>
</tr>
<tr>
<td>Nominal dosing range:</td>
<td>Variable</td>
</tr>
<tr>
<td>Purge Gas composition:</td>
<td>Argon</td>
</tr>
<tr>
<td>Ventilation flow rate:</td>
<td>TBD</td>
</tr>
<tr>
<td>Ventilation setting:</td>
<td>15%-20%</td>
</tr>
<tr>
<td>Diffuser configuration:</td>
<td>Stock</td>
</tr>
<tr>
<td>Dew point limit:</td>
<td>N/A</td>
</tr>
<tr>
<td>Oxygen limit:</td>
<td>N/A</td>
</tr>
<tr>
<td>Temperature limits:</td>
<td>N/A</td>
</tr>
<tr>
<td>Fusion Parameter File:</td>
<td>2017-0995 M290 QualBuild.losjob</td>
</tr>
<tr>
<td>Hash:</td>
<td>D189F7F7C7D8EC56CBEA34A65F92542</td>
</tr>
</tbody>
</table>

| Layer thickness: | 0.04 mm |
| Other: | N/A |

### Thermal Process
Builds processed per this QMP will receive the following thermal treatments:
1. **Stress Relief**: 1950°F ± 25°F for 1.5 hrs, -5/-15 min. furnace cool with venting to air as soon as allowable. Foil wrapping of parts required.
2. **Hot Isostatic Press (HIP)**: Foil wrapping of parts required.
3. **Solution Treatment (AMS 5664)**: 1950°F ± 25°F for 1 hour (or time commensurate with cross sectional area) in an inert atmosphere, followed by cooling at a rate of air cooling or faster.
4. **Precipitation Treatment (AMS 5664)**: 1400°F ± 15°F for 10 hrs = 5.0 hrs, furnace cool to 1200°F ± 15°F, hold at 1200°F ± 15°F until a total aging heat treatment time of 20 hours has been reached, cool.
Qualification of the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process
Step 1: Metallurgical Qualification

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

Foundation

Qualification of the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

Step 2: Surface texture and detail resolution

- Reference Parts
- Mix of qualitative and quantitative measures
Qualification of the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

Step 3: Mechanical properties

• Tensile, fatigue, toughness...

• Registration through Equivalence

  • Material Property Suite (MPS): Actively maintained, alloy and condition specific material property information that includes material test data, design values, and SPC criteria

  • “In-family” performance

QMP “Registration” is the process of demonstrating properties of the qualified process are equivalent to those in the applicable MPS
What do I need to build to produce a QMP?

Master QMP

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM Standard</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>E8/E8M</td>
<td>15</td>
</tr>
<tr>
<td>Tensile, With process restart</td>
<td>E8/E8M</td>
<td>5</td>
</tr>
<tr>
<td>High Cycle Fatigue</td>
<td>E466</td>
<td>10</td>
</tr>
<tr>
<td>Fatigue, With process restart</td>
<td>E466, E606E06</td>
<td>5</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td>E132, E369</td>
<td>3</td>
</tr>
<tr>
<td>Tensile (at Temperature)</td>
<td>E21, E450</td>
<td>6</td>
</tr>
<tr>
<td>Customized QMP</td>
<td>As specified</td>
<td>2</td>
</tr>
</tbody>
</table>

*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 Metallurgical Process
Foundation

• Reference QMP for Example Only

Microsoft Word Document
The **Material Property Suite (MPS)** consists of four inter-related entities:

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

- Material properties and design values in additive manufacturing require modifications to the approach typical of traditional metallic materials, with requirements more similar to that used in composites CMH-17.
- Important distinctions arise due to the sensitive nature of the process and individualistic aspect of AM machines. Each machine is a foundry!
- Traditional supplier roles and responsibilities shift with the AM machine making the final material product form and part. (Casting analogy)
  - AM Process Vendor responsible for material integrity
Material Properties
Foundation

• When design and production are not within the same entity, agreements must be reached regarding design value assumptions and associated qualification and monitoring requirements of the AM hardware.

• Design values must be continuously substantiated through process qualification and witness requirements.

• Material property evaluations are complicated by the AM process, leading to new considerations:
  – Feedstock lot variability
  – Build-to-build and machine-to-machine variability
  – Coupon to part transferability of properties
  – AM process-specific influence factors
    • Anisotropy, Surface finish effects, Thin walls, Build history effects on material structure, etc.
Material Property Suite
Foundation

Data Repository
Includes data from
• Qualification testing
• Material Characterization
• Pre-production Article Evaluations

Grouping of data
Group data by
• QMP = Material/process/heat treat
• “Combinable” conditions for design
Data Repository, continued

Contains all data needed for

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

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

- Statistically describes nominal witness behavior of a machine
- Utilizes all appropriate sources of *witness coupon data* in Repository
- Used to set acceptance criteria for witness tests
Statistical process controls are important in sustaining certification rationale

- **Statistical equivalency evaluations** substantiate design values and process stability build-to-build
  a) Process qualification
  b) Witness testing
  c) Integration to existing material data sets
  d) Pre-production article evaluations

- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts

The dark and scary place most manufacturers are NOT used to operating....
Statistical Process Control
Acceptance Criteria

• Derived from PCRD
• Acceptance criteria for witness tests
PCRD and SPC Criteria

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

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

- **MPS, Lot-Provisional:**
  An MPS that contains data from fewer than five (5) unique powder feedstock lots and ten (10) build and heat treat lots
  - Only applicable to parts of Class B
A basis to begin designing AM parts with certification intent is feasible once the foundation is laid.

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

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

Produce to the plan!
Stick to the plan!
Overview of Current Requirements

General Requirements

Additive Manufacturing Control Plan

Quality Management System

Foundational Process Control Requirements

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

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

Environment Control

Equipment Control

 Personnel Training

Part Production Control Requirements

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

Foundational Process Controls

Candidate Part

Part Production Controls

Part Production Controls

Service
Part Planning

AM Part Design

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

Example AM Part Classification Scheme
Design Process

Design For Additive Manufacturing Paradigm Shift

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

Topology Optimization FDM Tool Rack

Build Simulation

Hybrid crown & perforated block support

Self-Supporting Angles

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

Powder Removal Features
Part Classification

Classification System

Classification Questions

1. Catastrophic Failure?

2. Heavily Loaded?

3. Does the build have challenging aspects or areas that cannot be inspected?
The first division among L-PBF parts is based upon the consequence of failure for the part: if failure of the part creates a catastrophic hazard, then consequence of failure is assigned high (Class A); otherwise, consequence of failure is assigned low (Class B).
Part Classification

• Part Classification system is a *risk communication* tool
  • What happens if the part fails?
  • How severe is the stress in the part?
  • How challenging is the part to design, build, and *inspect*?

• Established criteria at each step for consistency

• The higher a part’s classification, the more stringent the downstream requirements become
  • B4 parts should need less scrutiny than an A1 part
  • Non-destructive evaluation needs also likely to differ

• Part-specific tailoring starts with classification
Part Classification

Challenges to the classification system encountered early

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

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

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

Reference Appendix A MSFC-STD-3716
Part Production Plans force integration of part processing

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

APPENDIX A. PART PRODUCTION PLAN CONTENT

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

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

- Drawing number and part name
- Part synopsis, providing a brief summary of
  - The purpose of the part in context to the system
  - The operational environments (temperatures, fluids)
  - CAD model views to illustrate the part and key features
- Material
  - Identification of the QMP specified for production
  - Identification of MPS used for assessment
- Part classification with summary rationale for consequence of failure, structural demand, and AM risk
- Integrated Structural Integrity Rationale for the part
  - Describe limiting factors in strength and fracture analyses
  - Highlight areas of high structural demand and high AM risk per classification
  - Describe all non-destructive testing and the degree of coverage or any limitations
  - Describe all proof test operations, including role in integrity rationale, method of analysis, and coverage or limitations

Reference Appendix A MSFC-STD-3716
PPP, Common Challenges:

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

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

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

Reference Appendix A MSFC-STD-3716
Part Production Plan

PPP, Common Challenges (Continued)

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

Locked Build Files: Stray vectors Created During Re-slicing

NDE: Powder not cleared, Imbedded Flaw

Ground Surface

Near Surface Porosity

As-Built Surface

NDE: Powder not cleared, Imbedded Flaw
Part Production Plan

PPP, Common Challenges (Continued)

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

Contour Test Part
Cut Plan
Channels Build Correctly?
Thin Sections Ok? Microstructure Within Acceptance Criteria?
PPP, Common Challenges (Continued)

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

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

1. Agreed upon and approved AM Part Production Plan
2. Pre-production article evaluation
3. AM Manufacturing Readiness Review (Do we have our ducks in a row?..)
   - All stakeholders agree AM part development is successful and complete for qualification or production articles to be produced
   - Demarcates the point in time when changes to AM part definition (digital files, engineering instructions, etc) are locked. NO MORE CHANGES
   - Qualified Part Process (QPP) state is documented in the Quality Management System
4. Produce to the Plan and STICK TO THE PLAN

*Locked Process Is the QPP! Must be documented in the QMS!*
Part Production – Follow-through on controls

- Statistical Process Control (SPC)
  - Stand Alone acceptance, just making one part (MSFC-STD-3716 Table III)
    - A1: 6 tensile, 2 HCF, 2 Met, 1 Chemistry, 1 Full height Contingency
    - Compare to PCRD
  - Continuous Production (MSFC-STD-3716 Table V)
    - A1: 4 tensile, 1 Met, 1 Chemistry, 1 Full height Contingency
    - Compare to continuous Control Chart
    - Intermittent SPC evolution builds during production
  - SPC Challenges:
    - Do the samples stay with the parts?
    - How to flag a part without the samples tested?
    - Setting limits that identify drift
Part reliability rationale comes from the sum of both in-process and post-process controls, weakness in one must be compensated in the other.
1. Follow the plan, always, with no short-cuts

2. Do not change a Qualified Part Process without re-qualification

3. Efficiency in process monitoring is critical to minimize the inevitable disruption
   - Witness tests can take considerable time to complete
   - Track the performance of each machine using all available metrics by control chart
   - In-process monitoring may provide early warning of changes in machine performance

4. Emphasize the importance of inspection for every part
   - Not just NDE, but visual inspection of as-built conditions
   - Watch for changes in part appearance – colors, support structure issues, witness lines/shifts

5. Consider systemic implications for all non-conformances
Common Challenges

• Turn around of samples used to monitor builds
  • Often three or more months from build to fully heat treated test data
  • Delay is a risk!

• Conventional manufacturing facilities and vendors are not used to the required level of process control
  • Much more difficult when working with vendors
  • Switching Alloys
  • Powder Reuse

• Cleaning of AM parts for contamination-sensitive applications
• Understanding “Influence Factors” in mechanical properties
• Implementing fracture control
• Maintaining the Digital Thread
Common Challenges: Digital Thread

**Digital Twin** – Digital companion of a physical object

**Digital Thread** – Communication framework that allows a connected data flow

**Digital Twin**

- Design Files / Analysis Results
- As-Built Data / Geometry
- Live Performance / Operational Data

**Digital Thread**

- Processes
  - Requirements
    - Requirements Management Software
      - Cradle
      - DOORS
      - Teamcenter
  - Design (MCAD & ECAD)
    - xCAD Authoring
      - Creo
      - Mentor Graphics
  - Design Analysis
    - Stress
    - Thermal
    - Aero
    - Etc
  - Manufacturing Set Up
    - STL, STEP
    - DELMIA
    - Magics
    - NetFAAB
    - Vericut
    - Etc
  - Build Operation
    - EOS SLI
    - CL Slice files
    - Etc...
  - Inspection
    - CT
    - X-Ray
    - Structured Light
    - CMM

**Files Generated**
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 – may not be non-destructive
- Establishing the reliability of the algorithm used to interact and intervene in the AM process adds considerable complexity over passive systems
Final Box: Service!

AM Demonstrator Engine

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

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

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

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

1/25/2018
SLM Alloy 718 Injector Testing
Additively Manufactured Injectors Hot-fire Tested at NASA
range from 1,200 lbf to 35,000 lbf thrust
Additive Manufacturing is real...

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

Ref: Andy Hardin, Steve Wofford/ NASA MSFC
1. Certification rationale is most heavily rooted in the foundational controls
   - Having a Plan
   - Fully involved QMS
   - Equipment and Facility Controls
   - Training
   - Process/machine qualifications
   - Material properties
   - SPC

2. Part Planning must confirm the foundation produces a good part consistently

3. Part production follows a fixed process with statistical process controls

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

- MSFC-STD-3716 “Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals”
  https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.pdf
  https://www.nasa.gov/sites/default/files/atoms/files/msfcspec3717baseline.pdf
Questions?

Thank You!