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

There are currently no NASA standards providing specific design and construction requirements for certification of additively manufactured parts. Several international standards organizations are developing standards for additive manufacturing; however, NASA mission schedules preclude the Agency from relying on these organizations to develop standards that are both timely and applicable. NASA and its program partners in manned spaceflight (the Commercial Crew Program, the Space Launch System and the Orion Multi-purpose Crew Vehicle) are actively developing additively manufactured parts for flight as early as 2018. To bridge this gap, NASA Marshall Space Flight Center (MSFC) has authored a center-level standard (MSFC-STD-3716)[1] to establish standard practices for the Laser Powder Bed Fusion (L-PBF) process. In its draft form, the MSFC standard has been used as a basis for L-PBF process implementation for each of the manned space flight programs. The development of an Agency-level standard is proposed, which based upon the principles of MSFC-STD-3716, would have application to multiple additive manufacturing processes and be readily adaptable to all NASA programs.

Based on the principles of MSFC-STD-3716 the development of Agency-level standards is underway. A team with representatives from nine NASA centers with consultants from other government agencies has been formed. The goal of this team is to develop standards which will be application to multiple additive manufacturing processes and be readily adaptable to all NASA Centers, Programs, and projects. Three standards are currently under development: one each for 1) crewed space flight, 2) non-crewed space flight, and 3) aeronautics. As part of this effort, several specifications may be required to address raw materials, parts procurement, and processes to supplement the standards. These standards will create requirements with guidance which can then be used to develop manufacturing plans and provide product specifications for both general and specific applications. The standards will not specifically state how to manufacture or certify a component but the requirements will identify factors that need to be addressed for all phases of design, manufacture, and qualification.

The NASA standards will be applicable to mature technologies. Specific technologies will be listed in the documents but the document will not be limited to these technologies to allow for growth. It was also determined that the standards will concentrate specifically on metals (powder and wire fed), polymers, composites and ceramics. Materials determined to be out of scope are regolith and printed circuits.

Influence of Mission Classification

For NASA science missions and payloads a risk based Mission Classification is assigned per NPR 8705.4[3]. To capture all the missions that would be covered by the three NASA standards a total of six mission classes could be considered:

1. Manned Space Flight
2. Class A (per NPR 8705.0004)
3. Class B (per NPR 8705.0004)
4. Class C (per NPR 8705.0004)
5. Class D (per NPR 8705.0004)
6. Associated GSE and test hardware

The NASA team considered three possible approaches to how Part Classification and Mission Classification could interact. These three cases are:

1. Part Class determined independent of Mission Class
2. Mission Class influences Part Class through Consequence of Failure or other criteria
3. Part Class and Mission Class Independent

The team consensus and recommended approach was that Part Classification and Mission Classification should be considered independently. This decision lead to the recommendation to develop the three NASA standards.

Proposed Document Structure

As previously stated, the new NASA standards will be based on the principles of MSFC-STD-3716. The standard lists 65 unique Additive Manufacturing Requirements (AMRs) which are listed in Appendix F, Table VIII. Each AMR will be reviewed and tailored as appropriate for each standard. These AMR cover topics such as foundational controls, material property requirements, design and assessment, fundamentals of part production controls, post-build operations and part inspection and acceptance.

Portions of MSFC-SPEC-3717 will also be pulled into the NASA standards and generalized to include all applicable additive manufacturing technologies. This specification list 45 unique Process Control and Qualification Requirements (PCQRs) covering metallurgical process definitions, qualification of metallurgical processes and equipment and facility process control. Similar to the AMRs, the PCQRs will be generalized to make them applicable to all appropriate materials and technologies. A separate NASA specification will be written for equipment and facility process control leaving, so these PCQRs will not be included in the new NASA specifications. Figure 1 pictorially outlines the merging of requirements.

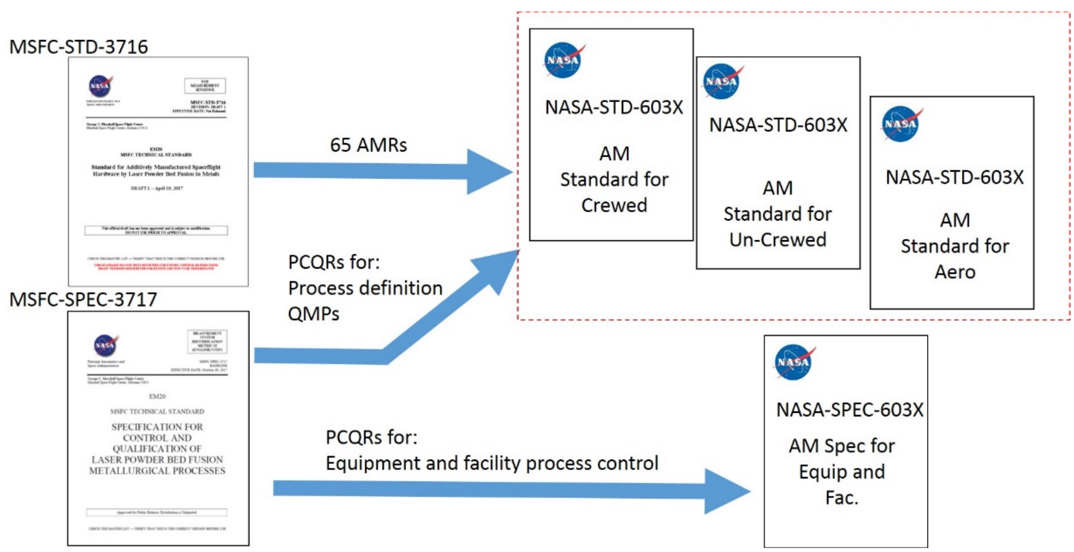

Figure 1. Merging of requirements

Rearranging of requirements and additions

In order to improve document flow, a decision was made to rearrange the order of the AMRs and PCQRs to create a document that is more product oriented. The standards will be geared more towards the Materials or Quality Engineer whose goal is AM part certification instead of a product designer. Also, additional requirements not in MSFC documents were identified as additional including sub-contractors and partner requirements, part drawing requirements and non-metallic material properties. The new document outline will be as follows:

- AM Control Plan (AMCP)
- Quality Management System (QMS)
- Equipment and Facility Control Plan (EFCP)
- Qualified Material Process (QMP)
- Material Property Suite (MPS)
- Part Drawing
- Part Production Plan (PPP)
- Qualified Part Process (QPP)
- AM Manufacturing Readiness Review (AMRR)
- Production Engineering Board
- Part Acceptance Data Package

Classification

In order to allow for the tailoring of requirements for a particular applications a classification system is needed. MSFC-SPEC-3716 uses a classification system, Figure 1, based on three key decisions: consequence of failure, structural demand and additive manufacturing risk. This decision tree leads to 8 distinct classifications as shown in Figure 2.

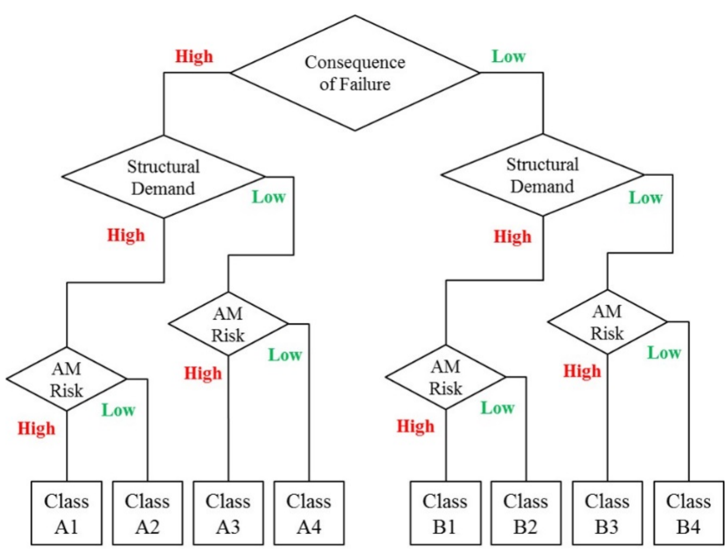

Figure 2. MSFC-SPEC-3716 classification system

To aid in tailoring for the three proposed NASA standards a slightly different approached was developed, as shown in Figure 3. The new classification system will have three levels of primary classification (A, B and C) and allows for secondary classification for certain cases for Class A and Class B parts. The primary classification directly inform and drive the tailoring of requirements for each parts and the secondary classification will act as a communication tool allowing for effective risk management when deemed necessary.

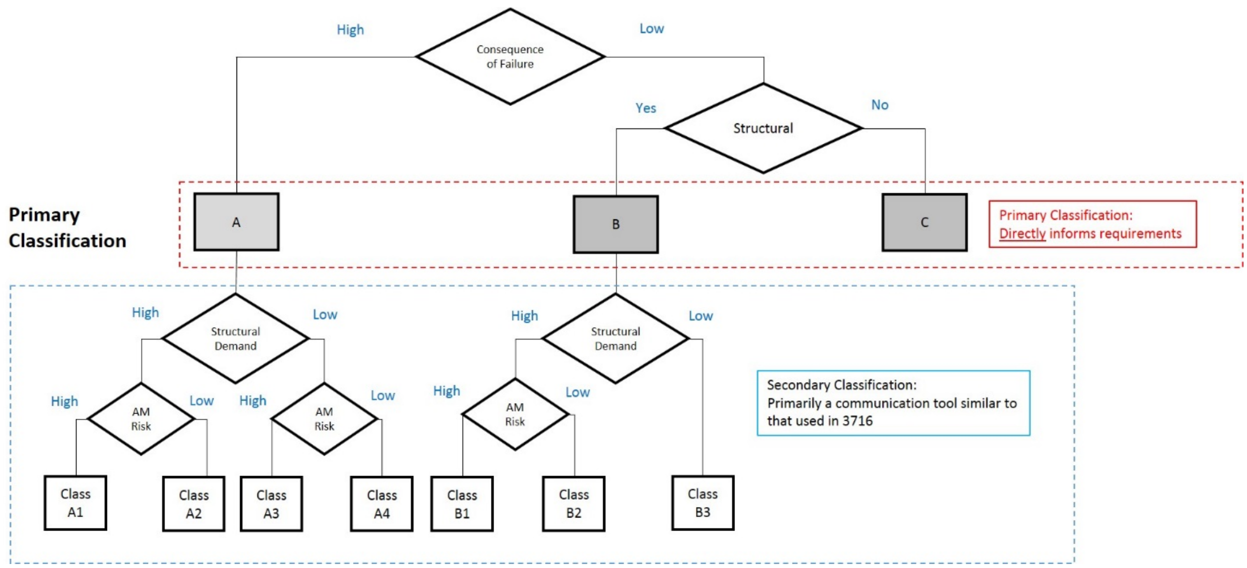

Figure 3. Proposed classification system for new NASA standards

For the crewed and non-crewed standards, the first decision gate was the same as for MSFC-SPEC-3716 but the criteria will be modified to address all NASA applications. The initial assessment is that a part will designated as Class A (High Consequence of Failure) if one or more of these criteria are applicable:

- Fracture Critical per NASA-STD-5019A[4]
- If failure would lead to a catastrophic hazard (loss of life, disabling injury or loss of a major national asset)
- If failure would lead to the loss of one or more primary/minimum mission objectives

Note: in the event of part redundancy, Class A may still be applicable if the project decides that the risk of a common mode failure is credible.

For the aeronautics standard the consequence of failure criteria will be alternated, mainly because NASA-STD-5019A will never be levied. For this standard the fracture control requirement will be replaced with a fatigue critical criteria. Also, the third criteria will be rewritten to allow for aircraft with a high risk tolerance.

Unlike the MSFC standard the new classification created a second decision gate to determine if a part with a low consequence of failure is structural. Parts to be designated as structural and Class B is one or more of the following criteria are applicable:

- Are part of primary or secondary load path
- A structural analysis is required
- Is proto-flight
- Is a fastener
- Can create a debris hazard

This second decision gate therefore creates a new “do no harm” Class C.

The second classification also has two decision gates. The first is the evaluation of structural demand using the assessment criteria listed in Table 1. If all structural assessment requirements meet or exceed those listed in Table 1, then the part is classified as having low structural demand (Subclass 3 or 4). If any of the listed requirements are exceeded, then the component is assigned a high structural demand (Subclass 1 or 2).

Material Property	Criteria for High Structural Margin
Loads Environment	Well-defined or bounded loads environment
Environmental Degradation	Temperature only
Ultimate Strength	30% margin over factor of safety
Yield Strength	20% margin over factor of safety
Point Strain	Local plastic strain < 0.005
High Cycle Fatigue, Improved Surfaces	4x additional life factor or 20% below required fatigue limit cyclic stress range
High Cycle Fatigue, As-built Surfaces	10x additional life factor or 40% below required fatigue limit cyclic stress range
Low Cycle Fatigue	No predicted cyclic plastic strain
Fracture Mechanics Life	10x additional life factor
Creep Strain	No predicted creep strain

Table 1. Assessment Criteria to Determine Structural Demand

The second leg of secondary part classification is based on the risk scoring criteria given in Table 2. If the summed risk score is greater than or equal to 5, then the part is assigned a high risk (Subclass 1 or 3). A score of 4 or lower generates a low risk assignment and a Subclass rating of 2 or 4.

Additive Manufacturing Risk	Yes	No	Score
All critical surface and volumes **can be reliably inspected**, or the design permits **adequate proof testing** based on stress state?	0	5	
As-built surface **can** be fully removed on all fatigue-critical surfaces?	0	3	
Surfaces interfacing with sacrificial supports **are fully accessible** and improved?	0	3	
Structural walls or protrusions are ≥ 1mm in cross-section?	0	2	
Critical regions of the part **do not** require sacrificial supports?	0	2	
		Total	

Table 2. Assessment Criteria for AM Risk

<u>Tailoring approach</u>

For each of the NASA standards, AMRs or PCQRs, a requirement matrix has been created. These matrixes will first modify each requirement to make it less specific and applicable to the new standard. Then the matrix will designate each requirement based on part classification to be used as-written, optional or tailorable. Tailoring guidelines will be written and provided in either the body of the specification or in an appendix. As example of a line from a requirements matrix is shown in Figure 4.

Requirement	Requirement Description	MSFC-STD-3716	NASA-STD (proposed language)	A	B	C	Notes
AMR-3	Additive Manufacturing Control Plan	[AMR-3] The CEO responsible for the design and manufacture of L-PBF hardware shall provide an AMCP that accomplishes each of the following: a. Documents the implementation of each of the requirements of this MSFC Technical Standard. b. Documents and provides rationale for any tailoring of the requirements of this MSFC Technical Standard. c. Documents the methods used to control compliance with these requirements by subcontractors and vendors. d. Provides for complete governance for the implementation of L-PBF such that, once approved by the procuring authority, the AMCP becomes the document used for verification of L-PBF requirements.	[AMR-3] The CEO responsible for the design and manufacture of AM hardware shall provide an AMCP that accomplishes each of the following: a. Documents the implementation of each of the requirements of this NASA Technical Standard. b. Documents and provides rationale for any tailoring of the requirements of this NASA Technical Standard. c. Documents the methods used to control compliance with these requirements by subcontractors and vendors. d. Provides for complete governance for the implementation of AM such that, once approved by the procuring authority, the AMCP becomes the document used for verification of AM requirements.	AW	T	O	See Appendix for Tailoring Guidelines

Figure 4. Requirements Matrix Example.

Industry standards

The NASA standard will be written to utilized industry developed AM standard when appropriate. Since industry standards are being developed and changed at a rapid pace, a separate NASA specification will be created to list these standards and provide revision level configuration control. This will allow the NASA AM community to make adjustments without revising the standards themselves.

Process Specifications

The use of process specifications will be defined in the requirements matrix. In cases where no industry standard exist or is considerable substandard NASA may decide to author a unique specification. For areas covered by MSFC-STD-3717 tailoring guidance will be provided either in the body of the text or in an appendix.

Procurement Specifications

Either in the body of the standards or in a separate appendix guidance will be provided as to how to write a procurement specification. Certain Procurement Specification may be written to make it as easy as possible to buy a "good" part from a "proven" manufacturer. These may not be appropriate for Class A1 Parts on Class A missions. Industry standards will be leveraged as much as possible. These procurements will focus primarily on raw material requirements, vendor quality/process controls, historical material property trends, and limited part-specific requirements. When appropriate, Procurement specification will intentionally be written non-specific to allow a vendor to control proprietary processes.

Appendixes

In addition to tailoring and procurement specification guidelines additional appendixes maybe be required to cover topics such as:

- Guidance in writing an AMCP
- Part Production Plan (PPP) authorship
    - Guidance on what should be in a process qualification or feedstock specification.

1. "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals," NASA Marshall Space Flight Center MSFC-STD-3716, October 18, 2017.
2. "Specification for Control and Qualification of Laser Power Bed Fusion Metallurgical Processes," NASA Marshall Space Flight Center MSFC-STD-3717, October 18, 2017.
3. NPR 8705.4, "Risk Classification for NASA Payloads," June 12, 2012.
4. NASA-STD-5019A, "Fracture Control Requirements for Spaceflight Hardware," February 26, 2016.