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ADDITIVE MANUFACTURING REQUIREMENTS FOR SPACEFLIGHT SYSTEMS

DOCUMENT HISTORY LOG

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FOREWORD

This NASA Technical Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. It may also apply to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center [FFRDC]), other contractors, recipients of grants and cooperative agreements, and parties to other agreements only to the extent specified or referenced in applicable contracts, grants, or agreements.

This NASA Technical Standard defines the minimum set of requirements for additive manufactured (AM) parts used for NASA crewed spaceflight systems, provides guidance and recommendations for tailoring this NASA Technical Standard for NASA non-crewed missions, and covers in-space AM operations.

Requests for information should be submitted via "Feedback" at https://standards.nasa.gov. Requests for changes to this NASA Technical Standard should be submitted via MSFC Form 4657, Change Request for a NASA Engineering Standard.

Original Signed By	April 21, 2021
Ralph R. Roe, Jr. NASA Chief Engineer	Approval Date

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NASA-STD-6030

ADDITIVE MANUFACTURING REQUIREMENTS FOR SPACEFLIGHT SYSTEMS

1. SCOPE

This NASA Technical Standard is directed toward additive manufacturing (AM) processes used in the design, fabrication, and testing of space program flight hardware for NASA, including, but not limited to, crewed, non-crewed, robotic, launch vehicle, lander, and spacecraft program/project hardware elements. All crewed spaceflight hardware is covered by the requirements of this document, including vendor-designed, off-the-shelf, and vendor-furnished items. Guidance and recommendations for tailoring this NASA Technical Standard for NASA non-crewed missions, such as robotic missions (spacecraft and launch vehicles), are provided in Appendix B. This NASA Technical Standard is also intended to cover in-space AM operations; however, significant tailoring of these requirements is expected.

AM parts used in interfacing ground support equipment (GSE) or test equipment are covered by the requirements of this NASA Technical Standard only to the extent required to prevent damage to or contamination of spaceflight hardware.

1.1 Purpose

The purpose of this NASA Technical Standard is to define the minimum requirements for AM processes used for spaceflight systems, provide guidance and recommendations for tailoring this NASA Technical Standard for NASA non-crewed missions, and cover in-space AM operations.

1.2 Applicability

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. It may also apply to the Jet Propulsion Laboratory (a Federally Funded Research And Development Center [FFRDC]), other contractors, recipients of grants and cooperative agreements, and parties to other agreements only to the extent specified or referenced in applicable contracts, grants, or agreements.

Verifiable requirement statements are designated by the acronym “AMR” (Additive Manufacturing Requirement), numbered, and indicated by the word “shall”; this NASA Technical Standard contains 115 requirements. Explanatory or guidance text and rationales for requirements are indicated in italics beginning in section 4 of this NASA Technical Standard. To facilitate requirements selection by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A.

1.3 Tailoring

Refer to section 4.1 in this NASA Technical Standard.

1.4 Summary of Methodology

This NASA Technical Standard provides the policy framework for the development and production of hardware produced using AM processes. It accommodates requirements from NASA's governing design and safety standards and provides necessary controls for the safe implementation of the technology. It does not dictate other structural design or structural certification criteria. Figure 1, Topical Outline for NASA-STD-6030; Figure 2, Key Products and Processes, NASA-STD-6030; and Figure 3, Symbol Legend for Key Products and Processes, outline and illustrate the key products and processes controlled by this NASA Technical Standard and, figuratively, how each is related.

Figure 1 summarizes the organization of this NASA Technical Standard. It begins with the general requirements for an Additive Manufacturing Control Plan (AMCP) to govern the engineering and production practice. The AMCP always works in parallel with a Quality Management System (QMS), which provides quality assurance from establishing the foundational processes through placing the part into service. Under the umbrella of the AMCP and the QMS, Figure 1 outlines how the requirements of this NASA Technical Standard fit into two categories: foundational process control and part production control. The foundational process control requirements for AM processes provide the basis for reliable part design and production. They include qualification of manufacturing processes, equipment controls, personnel training, and material property development. The part production control requirements are typical of aerospace operations and include design and assessment controls, part production plans (PPPs), preproduction article processes, and relevant production controls.

Figure 2 provides a more detailed view of this outline by illustrating the key products and processes of this NASA Technical Standard. The symbols used in the figure indicate the type of product or action (e.g., internal documents, documents requiring approval, databases, or decisional actions). The legend for these symbols is given in Figure 3. Structured similarly to the outline in Figure 1, Figure 2 further illustrates the flow of the products and processes through the general, foundational, and part-production controls. While showing the figurative relationships of the key products and processes, Figure 2 cannot be read as a serial flow chart, particularly for the prerequisite foundational controls.

Beginning at the top of Figure 2 with the general requirements, the implementation of the requirements of this NASA Technical Standard, and any tailoring that may be required, is documented by the AMCP prepared by the cognizant engineering organization (CEO) responsible for development and implementation of the AM parts. The AMCP also defines how the QMS(s) is(are) integrated throughout the process. Key points of QMS integration are illustrated with a green triangle symbol in Figure 2. The AMCP and the QMS govern the engineering and quality assurance disciplines, respectively, from start to finish.

The foundational process control requirements include methodologies for AM process qualification, control and operation of equipment, personnel training, and the characterization of AM material performance for material allowables, design values, and statistical process control (SPC) monitoring. For material process control, the key steps include establishing a Qualified Material Process (QMP) to ensure a consistent process definition, using a specification to control the raw material feedstock, evaluating the process capability, and, finally, documenting the process capability in a configuration-controlled QMP record for each AM machine. The scope contained in the QMP can scale depending on the classification of the parts (A, B, or C) the CEO wishes to produce using the QMP, resulting in the hierarchy of QMP-A, QMP-B, or QMP-C. It is important to note that a QMP record does not contain all aspects of the process development effort that led to the QMP. The QMP record contains the definition of the final process and supporting data.

Qualified machines and trained operators are key foundational controls required by this NASA Technical Standard and are implemented through NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facility Control. Although represented independently in Figure 2, they are essential to any successful AM operation; and plans are required to define how controls are implemented. An Equipment and Facility Control Plan (EFCP), the basic contents of which are covered in NASA-STD-6033, is developed and maintained by any facility producing AM parts. The EFCP sets and enforces the requirements for qualification, maintenance, and calibration activities on AM machines and associated equipment. Associated equipment may include, but is not limited to, sieve equipment, measuring or calibration instruments, cleaning tools, and other such apparatus that are influential to continued successful operation of the AM process. Equipment controls are only as good as the training of the operators. NASA-STD-6033 defines acceptable personnel training protocols to be implemented and tracked through QMS records.

The requirements governing the development of AM material properties and related guidance are specified herein and are controlled in the context of a Material Property Suite (MPS). The MPS concept includes three entities: first, a material property database; second, a subset of that database used to derive and implement a Process Control Reference Distribution (PCRD) that provides SPC criteria for witness test evaluation; and third, a maintained set of material allowables and design values for part design. Integrating simple SPC concepts to monitor the process and substantiate the integrity of material allowables is a unique aspect of this NASA Technical Standard required to accommodate the process-sensitive nature of AM.

Once the foundational process controls are established, the process of design and production of AM parts can occur. The flow of operations required for AM part production, shown in the lower half of Figure 2, is typical of most aerospace hardware production. Aspects of the process flow that are unique to AM are described as follows.

When a part is identified as a candidate for AM production, the part design has to be made compatible with the AM process. This can be non-trivial, and this NASA Technical Standard does not prescribe AM design practice—it provides only high-level guidance to caution against common pitfalls. This NASA Technical Standard influences the design process through policies regarding fracture control, part qualification, and the use of the MPS for design properties specific to the AM material product form.

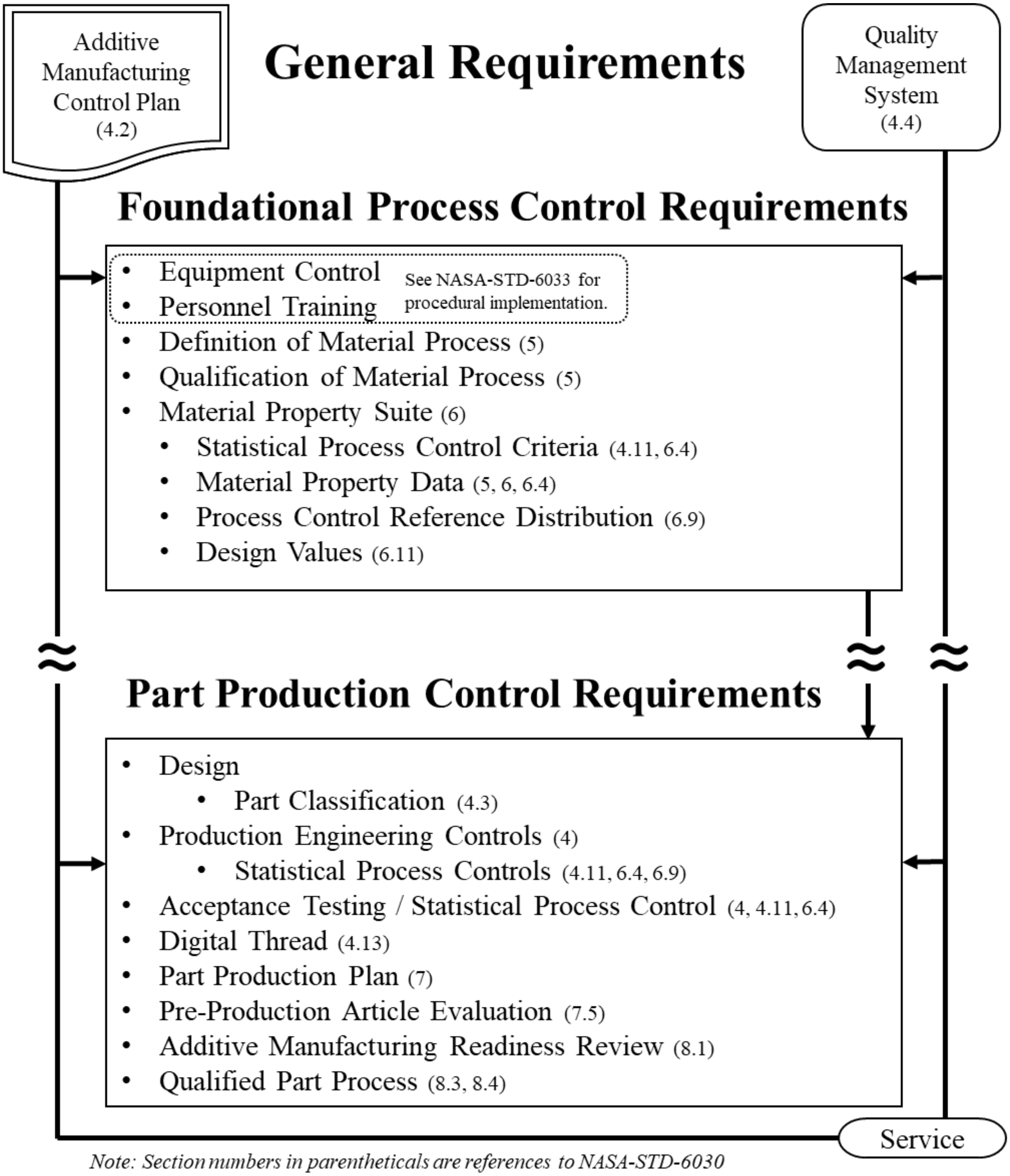
Once a part design and assessment nears maturity, a classification system is used to assess the risk associated with the part. Parts are classified on their consequence of failure, structural demand, and AM risk, which accounts for part inspection feasibility and AM build sensitivities. The part classification is used to communicate part risk consistently and to set commensurate levels of control. A uniform, standardized classification system is important to enable NASA to maintain consistent requirements and mitigations for risk both within and across programs using AM parts.

The requirement to develop a PPP is one aspect of this production flow that may be considered unique due to the AM process. The PPP documents the rationale for, and the implementation of, the production methodology, including such items as part build orientation, appropriate QMP, witness test requirements, inspection methods and limitations, and proof-testing methodology. The PPP is a deliverable product requiring NASA approval prior to proceeding into production; the PPP needs to convey succinctly the full design and production intent of the part. Once approved, the combination of drawing and PPP serve as the basis for establishing the complete engineering production controls.

The PPP may specify the preproduction article process or delegate that to a standalone preproduction article plan. The preproduction article process is executed strictly and, once complete, leads to an Additive Manufacturing Readiness Review (AMRR) of the preproduction article report, the drawing, the QMP, and all preliminary engineering production controls used to obtain the preproduction article. If the AMRR is deemed successful, then the entire candidate process for part production, including drawings, electronic files, and production engineering steps and sequences become fixed, version controlled, and prohibited from changes not approved by the CEO. This fixed process state defines a Qualified Part Process (QPP), which is then used to control part production.

A number of process verifications are required following, or concurrent with, the final stages of part production. These verifications form the evidence for part acceptance to the defined design state. At a minimum, these verifications typically include a review of available build logs and related content used to substantiate process control, dimensional inspections, nondestructive evaluations (NDEs) of surface and volumetric integrity, proof testing, and testing of witness specimens produced during the build process. Evaluation of witness specimens provides evidence of systemic process control through statistical comparison with defined performance metrics developed as part of the MPS. This NASA Technical Standard allows for witness testing schemes based on individual part acceptance or as an ongoing SPC methodology for continuous operations. Although the use of SPC part acceptance methods is commonplace, this may represent a new paradigm for many NASA hardware producers.

Requirements and commentary using subjective terms (e.g., appropriate, worst-case, or fully accessible) appear occasionally in this NASA Technical Standard to purposefully allow flexibility in meeting the intent of the requirements in a manner commensurate with the needs and risk posture of the program or project. The CEO has the responsibility to remove the subjectivity by unambiguously describing in the AMCP how the intent of the requirement will be met. It is the responsibility of NASA to review all responses in the AMCP to determine their acceptability.



Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

Figure 1—Topical Outline for NASA-STD-6030

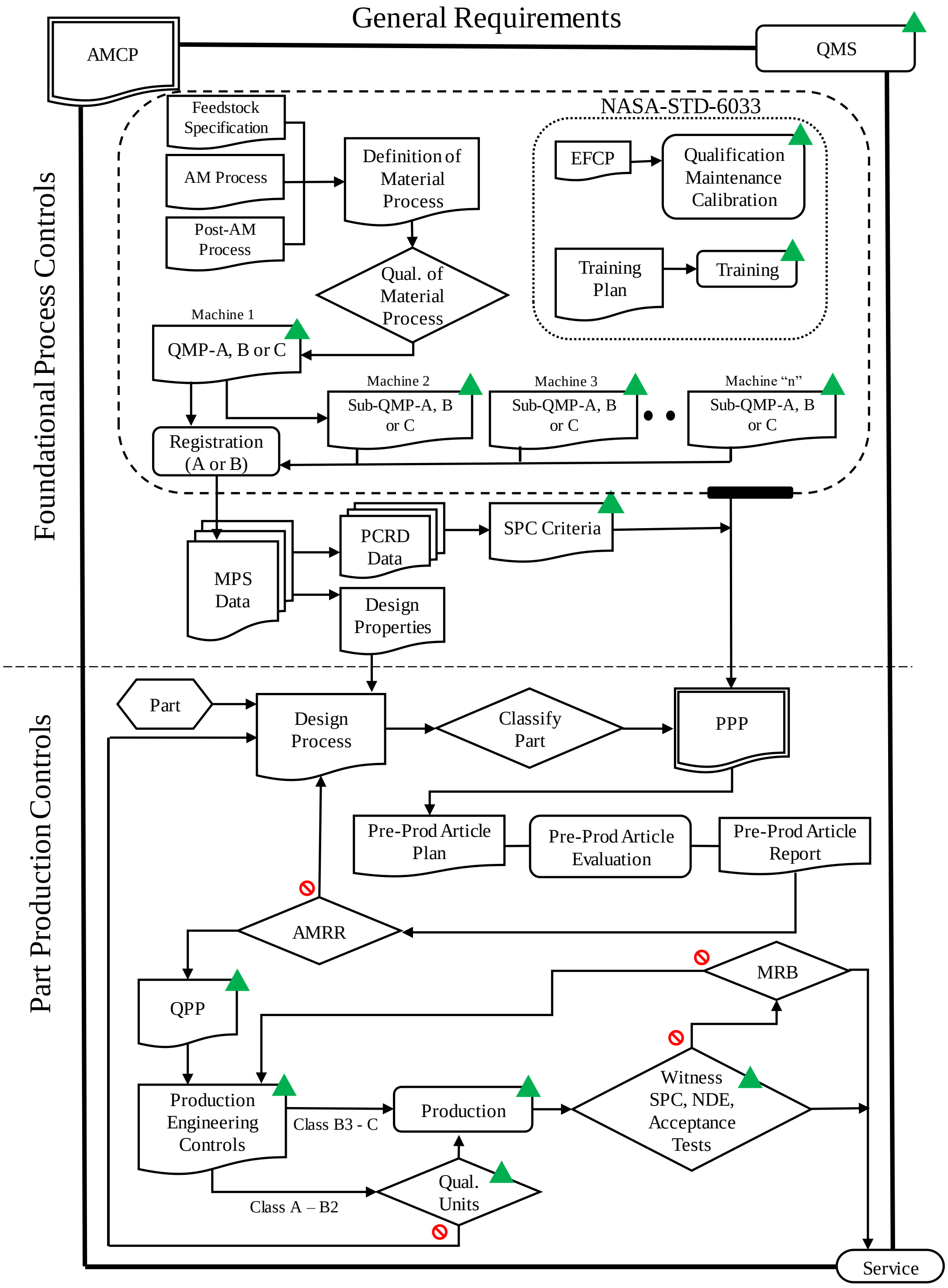


Figure 2—Key Products and Processes for NASA-STD-6030

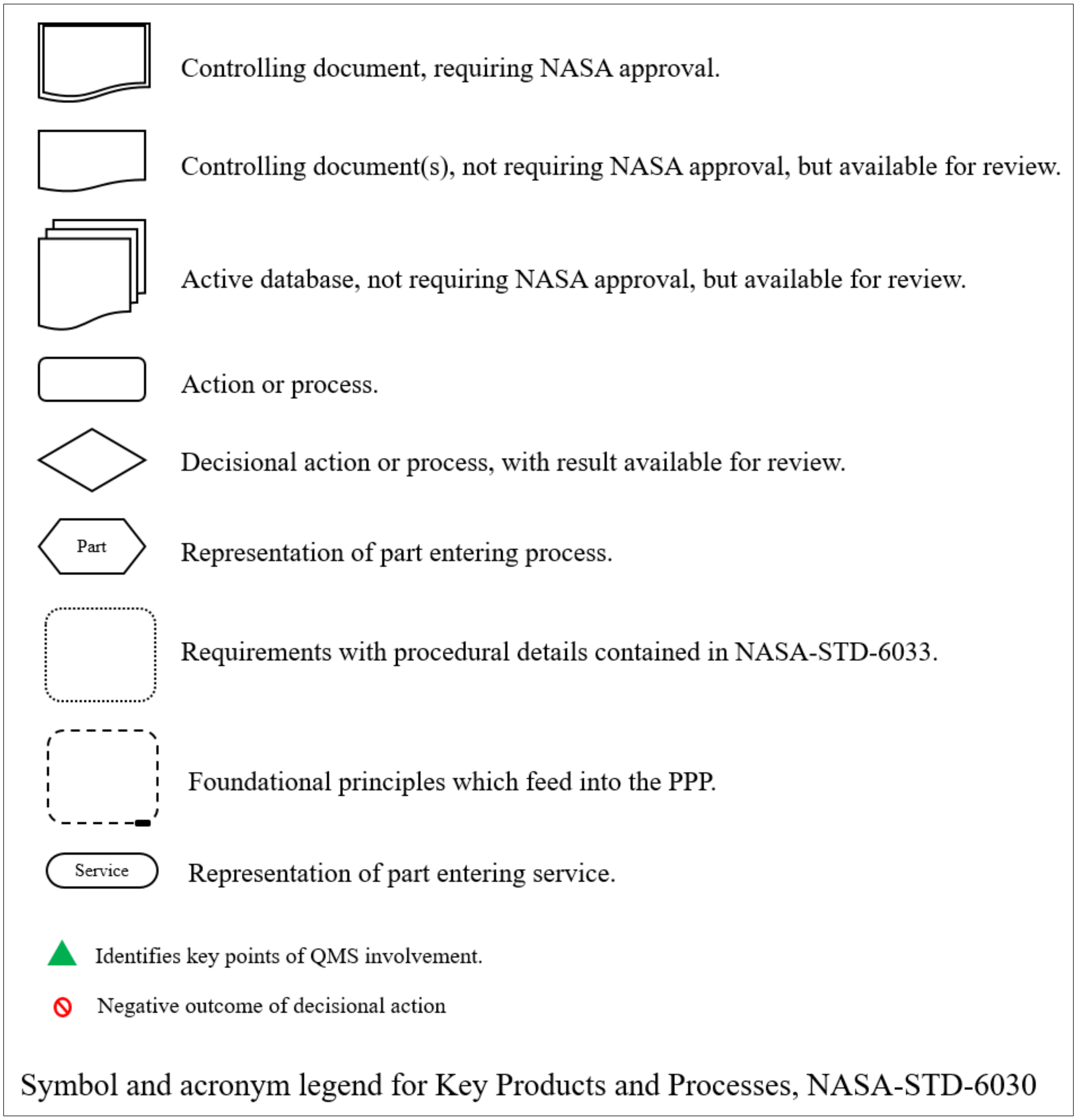


Figure 3—Symbol Legend for Key Products and Processes

1.4.1 Deliverables

This NASA Technical Standard outlines the following discrete deliverables to be created by the CEO and/or part producer for delivery to NASA for review and, in most cases, approval:

a. AMCP.

b. Part-agnostic Material Usage Agreement (MUA) (section 6.3 of this NASA Technical Standard).

c. Part-specific MUA (section 6.3 of this NASA Technical Standard).

d. PPP (section 7 of this NASA Technical Standard).

See section 6.5 of this NASA Technical Standard for exceptions to MUA requirements for Class B part production.

1.4.2 Applicable Technologies

This NASA Technical Standard is applicable to mature AM materials and processing technologies that have demonstrated through test and statistical analysis to be capable of producing parts with predictable and repeatable material properties and performance capabilities. Table 1, Applicable Technologies and Materials Types, lists the applicable technologies and material types covered by this NASA Technical Standard. Table 1 also indicates which primary classification (i.e., A, B, or C, as described in section 4.3 of this NASA Technical Standard) can be applied to each process technology and material type combination. Closed-loop controls using active, adaptive, *in situ* feedback technologies (e.g., commonly used in electron beam powder bed fusion [EB-PBF]) that dynamically alter process parameters are not applicable technologies under this NASA Technical Standard. Use of AM technologies and materials not explicitly described in Table 1 requires documentation and approval in the AMCP and accompanying MUAs. Use of technologies and materials not explicitly described in Table 1 requires approval by the CEO and the responsible NASA Materials and Processes (M&P) organization. Note that there are part classification restrictions on the use of polymeric materials (see Table 1).

Table 1—Applicable Technologies and Material Types

			Class		
Category	**Technology**	**Materials Form**	**A**	**B**	**C**
Metals	Laser Powder Bed Fusion (L-PBF)	Metal Powder	Yes	Yes	Yes
	Directed Energy Deposition (DED), Any Energy Source	Metal Wire	Yes	Yes	Yes
	DED, Any Energy Source	Metal Blown Powder	Yes	Yes	Yes
Polymers	L-PBF	Thermoplastic Powder	No	Yes	Yes
	Vat Photopolymerization	Photopolymeric Thermoset Resin	No	No	Yes
	Material Extrusion	Thermoplastic Filament	No	No	Yes

2. APPLICABLE DOCUMENTS

2.1 General

2.1.1 The documents listed in this section contain provisions that constitute requirements of this NASA Technical Standard as cited in the text.

2.1.2 The latest issuances of cited documents apply unless specific versions are designated.

2.1.3 Non-use of a specifically designated version is approved by the delegated Technical Authority.

2.1.4 Applicable documents may be accessed at https://standards.nasa.gov, obtained directly from the Standards Developing Body or other document distributors, or obtained from information provided or linked.

2.1.5 References are provided in Appendix C.

2.2 Government Documents

NASA

NPR 7120.5	NASA Space Flight Program and Project Management Requirements

NPR 7120.8	NASA Research and Technology Program and Project Management Requirements
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-STD-5009	Nondestructive Evaluation Requirements for Fracture Critical Metallic Components
NASA-STD-5017	Design and Development Requirements for Mechanisms
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft
NASA-STD-6033	Additive Manufacturing Requirements for Equipment and Facility Control
JSC 65828	Structural Design Requirements and Factors of Safety for Spaceflight Hardware

2.3 Non-Government Documents

ASTM International

ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM D2990	Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics
ASTM D5766/D5766M	Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite
ASTM D6484	Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite
ASTM D6742	Standard Practice for Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates

ASTM D7028	Standard Test Method for Glass Transition Temperature (DMA T_g) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA)
ASTM E8/E8M	Standard Test Methods for Tension Testing of Metallic Materials
ASTM E21	Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials
ASTM E399	Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic
ASTM E466	Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
ASTM E606/E606M	Standard Test Method for Strain-Controlled Fatigue Testing
ASTM E1450	Standard Test Method for Tension Testing of Structural Alloys in Liquid Helium
ASTM E1820	Standard Test Method for Measurement of Fracture Toughness
ASTM E2587	Standard Practice for Use of Control Charts in Statistical Process Control

Battelle Memorial Institute

MMPDS	Metallic Materials Properties Development and Standardization (MMPDS)

Composite Materials Handbook

CMH-17	Composites Materials Handbook-17

SAE International

SAE AMS2750	Pyrometry
SAE AS9100	Quality Management Systems – Requirements for Aviation, Space and Defense Organizations
SAE AS9120	Quality Management Systems – Requirements for Aviation, Space, and Defense Distributors

2.4 Order of Precedence

2.4.1 The requirements and standard practices established in this NASA Technical Standard do not supersede or waive existing requirements and standard practices found in other Agency documentation, or in applicable laws and regulations unless a specific exemption has been obtained by the Office of the NASA Chief Engineer.

2.4.2 Conflicts between this NASA Technical Standard and other requirements documents are resolved by the delegated Technical Authority.

3. ACRONYMS, ABBREVIATIONS, SYMBOLS, AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

≥	Greater than or equal to
≤	Less than or equal to
>	Greater than
<	Less than
%	Percent
µm	Micrometer
A/N	As Needed
A/R	As Required
A/S	Acceptance as Specified
A2LA	American Association for Laboratory Accreditation
AM	Additive Manufacturing/Additively Manufactured
AMCP	Additive Manufacturing Control Plan
AMR	Additive Manufacturing Requirement
AMRR	Additive Manufacturing Readiness Review
AR	Aircraft Registration
CAD	Computer-Aided Design
CC	Control Chart
CEO	Cognizant Engineering Organization
CFD	computational fluid dynamics
CH	Cryptographic Hash
cm	Centimeter(s)
CNC	Computerized Numerical Control
CoC	Certificate of Conformance
Comp	Comparative
CoV	Coefficient of Variation
DED	Directed Energy Deposition
DMA	Dynamic Mechanical Analysis
DOE	Design of Experiment
DOT	Department of Transportation
DPD	Digital Product Definition

DV	Design Value
EB-PBF	Electron Beam Powder Bed Fusion
EFCP	Equipment and Facility Control Plan
EIDP	End Item Data Package
FAA	Federal Aviation Administration
FEA	finite element analysis
FFRDC	Federally Funded Research and Development Center
FH	Full Height
FMEA	Failure Modes and Effects Analysis
GSE	Ground Support Equipment
HCF	High Cycle Fatigue
HDT	Heat Deflection Temperature
HIP	Hot Isostatic Pressing
in	Inch(es)
ISS	International Space Station
JSC	Johnson Space Center
L-PBF	Laser Powder Bed Fusion
LCF	Low Cycle Fatigue
M&P	Materials and Processes
MIUL	Material Identification and Usage List
MMPDS	Metallic Materials Properties Development and Standardization
MPS	Material Property Suite
MRB	Material Review Board
MSFC	Marshall Space Flight Center
MUA	Material Usage Agreement
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
NRRS	NASA Records Retention Schedules
NURBS	Non-uniform Rational Basis Spline
Opt	Optimization
PBF	Powder Bed Fusion
PCRD	Process Control Reference Distribution
PEEK	polyether ether ketone
PPP	Part Production Plan
Prod	Production
PSD	Particle Size Distribution
QMP	Qualified Material Process
QMS	Quality Management System
QPP	Qualified Part Process
Qual	Qualification
RFCB	Responsible Fracture Control Board
SI	Système Internationale or metric system of measurement

SLA	Stereolithography
SPC	Statistical Process Control
SPEC	Specification
STD	Standard
STL	Standard Tessellation Language
Sub	Subsequent
T_g	glass transition temperature
UTS	Ultimate Tensile Strength
UV	Ultraviolet
YS	Yield Strength

3.2 Definitions

Additive Manufacturing (AM): 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.

Additive Manufacturing Control Plan (AMCP): Document describing the means of conformance, the method of implementation, and the tailoring rationale for each requirement in this NASA Technical Standard.

Additive Manufacturing Part/Preform: Any part using an AM process to produce some or all of the part material volume. For the purposes of this NASA Technical Standard, “part” and “preform” can be used interchangeably. Note: A qualified part process may include multiple parts in a build.

Additive Manufacturing Part Producer: The entity using the AM process to produce a part.

Additive Manufacturing Readiness Review (AMRR): An integrated engineering review of the maturity of all manufacturing controls for an AM part to confirm that all necessary process controls and production engineering are in place to produce a part that fully and reliably meets the certified design state. At a minimum, the AMRR team includes individuals cognizant of the part from the disciplines of design, structural assessment, materials and processes, AM production, and safety and mission assurance. A successful, documented AMRR demarcates the production process of the part becoming a QPP.

Batch: Feedstock that can be composed of used material, virgin material, or a mixture of the two.

Build/Build Cycle: A single, complete operation of the AM process to create objects. Multiple objects are commonly created consecutively or concurrently during a build.

Build Area: The area in the build plane where the build process is controlled and qualified to a QMP per this NASA Technical Standard. The build area may be defined smaller than the full reach of the energy source or print head if needed to maintain the quality level of the build process.

Build File: A machine-readable file that requires no further changes to execute the AM fabrication process.

Build Interruption: An interruption of the programmed build sequence that deviates from the approved fixed process used to produce AM builds layer by layer. Build interruptions may be planned or unplanned.

Build Lot: All objects created during a single build operation. This can include multiple objects created consecutively or concurrently during the build.

Build Plane: Plane in which the build process takes place (i.e., the plane normal to the direction of material addition). For L-PBF, vat polymerization, and fused deposition modeling, the build plane is commonly fixed and the build platform is incrementally lowered to create the build.

Build Platform: Solid material base upon which parts are built.

Build Record: Any record of the outcome of a production process, including but not limited to those listed in the production engineering record, shop traveler, work authorization order, etc.

Candidate Material Process: A set of machine parameters, feedstock, and post-processing specifications that constitutes a material process prior to its being registered to an MPS, at which point it becomes a QMP.

Candidate Part Process: A collection of all necessary content required to consistently and reliably produce an AM part compliant with the certified design state. This content includes but is not limited to an approved PPP, a QMP, preproduction article evaluation results, as well as all drawings, models, production engineering controls, parameter settings, etc., that are involved in the definition and production of the part.

Catastrophic Hazard: (1) A condition that could result in a mishap causing fatal injury to personnel and/or loss of one or more major elements of the flight vehicle or ground facility, or (2) a condition that may cause death or permanently disabling injury, major system or facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission. (See NPR 8715.3D, NASA General Safety Program Requirements.)

Certified Design State: A complete, stable design state that has been reviewed and verified as meeting all levied requirements to safely and reliably complete the intended mission.

Certificate of Conformance (CoC): A document signed by the supplier to affirm the product has met the requirements of the relevant specification(s), contract(s), and any other applicable regulations.

Configuration Management: Process for establishing and maintaining consistency of a product's functional and physical characteristics, evaluating and authorizing any changes to those characteristics, and recording and documenting the characteristics and any changes to them to verify compliance with the product's configuration requirements throughout its life.

Critical Hazard: A condition that may cause severe injury or occupational illness, or major property damage to facilities, systems, or flight hardware. (See NPR 8715.3D, NASA General Safety Program Requirements..

Cognizant Engineering Organization: The organization responsible for establishing/maintaining the certified design state of the AM hardware and delivering AM hardware compliant with all levied requirements. The CEO will typically be a supplier to NASA, a subcontractor, or NASA.

Containment, Primary: An impermeable, chemically compatible tank, vessel, pipe, transport vessel, or equipment intended to serve as the primary container for, or for the transfer of, a material.

Containment, Secondary: An impermeable, chemically compatible tank, vessel, pipe, transport vessel, or equipment intended to serve as containment in the event of failure of the primary containment.

Continuous Production Build: Any build cycle within a continuous series, on the same machine, to the same or equivalent QMP, where each build and the AM machine is monitored and tracked in accordance with all SPC requirements of section 4.11 in this NASA Technical Standard. Continuous production builds have reduced witness sampling requirements; they rely on an integrated performance history of prior and subsequent builds and periodic SPC evaluation builds (same sample set as a subsequent [Sub]-QMP), to substantiate process control rationale. A series of continuous production builds may include a variety of builds for different parts.

Customized Material Process: Any candidate material process requiring specific controls or unique witness testing to achieve and/or demonstrate particular material performance characteristics.

Design Value: Material properties that are established from test data on a statistical basis and represent the finished part properties. These values are typically based on material allowables and adjusted, using building block tests as necessary, to account for the range of part-specific features and actual conditions. Design values are used in analysis to compute structural design margin (e.g., margin of safety). (See also Material Allowable.)

Digital Product Definition: The finalized digital model encompassing all relevant drawings and process-specific information to generate a build file.

Digital Thread: The virtual medium in which data are stored and subsequently referenced through a part's life cycle. This configuration-managed infrastructure contains and fingerprints the digital references for a part from foundational process controls through part production controls.

Directed Energy Deposition: AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

Equipment and Facility Control Plan: Document that controls the AM equipment, associated facilities, and training of personnel involved with producing AM hardware.

Equivalent QMP: QMPs are considered equivalent if they meet the Subsequent-QMP commonality criteria as stated in section 5.5.1 of this NASA Technical Standard.

Fatigue Limit: A cyclic stress or strain range below which fatigue initiation failures are unlikely at a defined number of cycles based on fatigue testing. The fatigue limit is commonly defined at a pragmatic cycle count appropriate for the hardware, often 10^7 or 10^8 cycles. For the context of this NASA Technical Standard, a fatigue limit is defined to be $\geq 10^7$ cycles. At this time, AM materials are not considered to have an endurance limit (a cyclic stress level below which fatigue life is infinite).

Heat: A material that, in the case of batch melting, is cast at the same time from the same furnace and is identified with the same heat number.

Independent Build: Any AM build cycle that is not part of a continuous production build series. Independent builds have additional witness specimen requirements that improve the ability to evaluate the quality of the build independent of the results of prior or subsequent builds from the AM machine.

Influence Factors: Any factor that has the capacity to alter the baseline performance of the material (i.e., the material allowable). For AM materials, influence factors may be fundamentally unique to the AM process (e.g., the unique impact of down-facing surfaces, local feature-driven anisotropy, or even part-specific geometric features). Other influence factors include environment (e.g., temperature, humidity) and surface conditions.

Key Process Variables: Elements of the AM process (e.g., build plate configuration, build layout, energy level, layer thickness, interpass temperature, melt pool environment, etc.) that, if changed, could affect physical, mechanical, metallurgical, dimensional, chemical, or performance characteristics.

Material Allowable: Material values that are determined from test data of the bulk material on a statistical basis. Allowable development approaches are established via industry standards (e.g., Metallic Materials Properties Development and Standardization (MMPDS) or company-specific methodology) and are based on testing conducted using accepted industry or company standards. Material allowables form the basis of design values. See also Design Value.)

Material Property Suite (MPS): A maintained collection of AM material property information specific to a material and condition that includes material test data, material allowables and associated design values, and criteria needed to implement and maintain SPC for the AM process.

Material Property Suite, Lot-Mature: An MPS that contains data from a minimum of five (5) unique feedstock lots and ten (10) build cycles and heat treat lots with a nominally balanced distribution across lot data used for all material allowables or design values that require bounding with statistical significance. Properties using a typical basis may be considered lot-mature with fewer lots. A lot-mature MPS has sufficient variability incorporated to allow the use of design values to be applied to parts of all classes built with feedstock lots equivalently controlled by an applicable, registered QMP. See section 6.5 and the definition for lot-provisional MPS in this NASA Technical Standard.

Material Property Suite, Lot-Provisional: An MPS that contains data from fewer than five (5) unique feedstock lots and ten (10) build and heat treat lots and/or does not demonstrate the nominally balanced distribution across a sufficient number of lots of data to be considered a lot-mature MPS. A provisional MPS has restrictions on use as required in section 6.5. See the definition for lot-mature MPS in this NASA Technical Standard.

Material Usage Agreement: The MUA process is NASA M&P best practice described by NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, that enables acceptance of materials and material processes that do not meet the requirements of NASA-STD-6016 and this NASA Technical Standard but, through the MUA review process, are determined to be acceptable. The MUA process also provides the benefit of satisfactorily resolving design nonconformances at the engineering level as opposed to the program level. The purpose of the MUA process is to justify the acceptance of specific material or material process design nonconformances, not the acceptance of a nonconforming product.

Mission: A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution.

Mission Critical: Item or function that must retain its operational capability to assure no mission failure (i.e., for mission success. Mission-critical items or processes may be identified using system design and reliability analyses (e.g., failure modes and effects analysis [FMEA]).

Nonconformance: The state or situation of not fulfilling a requirement. A nonconforming product, process, software, or material does not meet manufacturing specifications/design, composition, or contractual requirements. Examples include but are not limited to failures, discrepancies, defects, anomalies, and malfunctions.

Post-Build Microstructure: Microstructure specimens built after the part is complete, required for DED only.

Post-Build Tensile: Tensile specimens built after the part is complete, required for DED only.

Part Agnostic: A description of documentation, processes, data, etc., that is not specific to a single part and/or configuration.

Part Design: A collection of attributes that describe the fit, form, and function of a part, including its environmental context.

Part Material Specifications: A defined set of characteristics and requirements for the final material condition of a finished part (material requirements, including chemistry, may be different from the feedstock to finished part).

Part Production Plan: Document that defines the full intent for the design, production, and use of the AM part, including unique controls. The purpose of the PPP is to ensure engineering integration across disciplines and provide insight into risks associated with the part and its manufacture.

Powder Bed Fusion (PBF): An AM process that uses a high-energy source to selectively fuse, layer by layer, portions of a powder bed.

Powder Lot (also blended powder lot): A quantity of powder supplied by a certified powder producer that was manufactured by the same process and equipment and blended simultaneously. The blended powder lot may contain multiple heats of powder when all heats independently meet the powder specification.

Process Control Reference Distribution (PCRD): A statistical model representing the nominal performance of a material property used for monitoring process control. A PCRD is developed for material produced to an approved QMP and tested with a consistent specimen geometry, size, orientation, and test procedure. A PCRD is used to define the acceptance criteria applied to selected witness tests for an AM build cycle; the data used to develop the statistical PCRD model are typically the result of nominal witness tests and other data generated with the same consistent specimen geometry and test procedure.

Production Engineering Record: A revision-controlled document or electronic record that defines and records the sequence of all major operations and their outcomes when producing a part.

Protoflight: The protoflight unit is intended for flight on which a partial or complete protoflight qualification test campaign is performed before flight (as opposed to an acceptance test campaign). See also NPR 8705.4, Risk Classification for NASA Payloads.

Quality Management System: A formalized enterprise-wide system of controls used to consistently realize processes and products that meet requirements, generate evidence of process and product conformance, preserve the integrity of conforming product through delivery to the customer, and provide for design and process corrections and improvements.

Qualified Material Process (QMP): The foundational AM process control of feedstock, machine process controls, and post-processes that enable parts to be built with a consistent process of verified material quality. The use of a QMP provides the rationale for the assumed material capability of a part and provides quantifiable metrics to monitor the quality of the material process over time.

Qualified Material Process, Subsequent (Sub-QMP): A qualified material process that has the same feedstock specification and controls, AM build processes (e.g., the same key process variables), and post-processing as an existing QMP. The commonality to the existing process allows for reduced testing to establish a qualified process.

Qualified Part Process (QPP): The full content of the candidate part process following completion of the AMRR process and approval by the CEO. The entirety of the QPP content is configuration controlled by the QMS such that any changes to the contents of the QPP require adjudication as defined in the AMCP. (See section 8.4 of this NASA Technical Standard.

Reference Part: A part, typically small, that pushes the limits of an AM process and is used to provide feedback on the rendering capability and quality of an AM build.

Repair: An action performed on a nonconforming part to make it acceptable for the intended use, but changes the material condition and/or results in the part not meeting all requirements, requiring a waiver or similar.

Rework: An action performed on a nonconforming part to meet all requirements and make it acceptable for the intended use. Rework may still require formal approval.

Safety Hazard: A condition, event, operation, process, equipment, or system that could cause or lead to severe injury, major damage, or mission failure if performed or built improperly or allowed to remain uncorrected. (See NPR 8715.3D, NASA General Safety Program Requirements.)

Self-supporting Structure (unsupported limit): Part features that may be built in an overhanging condition without the need for support structure below it. The maximum angle at which overhanging part features may be reliably built without supporting structure is the unsupported limit.

Steady State: A condition where variables that define the behavior of the system or the process are unchanging over time.

Structure: All components and assemblies designed to sustain loads or pressures, provide stiffness and stability, or provide support or containment.

Structure, Primary: That part of a flight vehicle or element that sustains the significant applied loads and provides main load paths for distributing reactions to applied loads. Also, the main structure that is required to sustain the significant applied loads, including pressure and thermal loads, and upon failure creates a catastrophic hazard. If a component is in an environment where no serious threat is imposed if it breaks, then it is not primary structure.

Support Structure: Supplementary, sacrificial material built along with a part used to anchor overhanging geometry, provide dimensional stability, and/or promote proper thermal management during an AM build.

Surface Treatment: A broad range of industrial processes that alter the surface of a manufactured item to achieve a certain property.

T99: Designation for the lower tolerance bound of a statistical distribution fit to material property data indicating at least 99 percent (%) of the population equals or exceeds this value with a confidence of 95%. See the MMPDS for further information.

Trace Width: The width of material produced during a single vector of the build process that is determined by key process inputs (e.g., energy source power, wire diameter, and/or filament diameter).

Typical Basis: An average value with no statistical assurance associated with it.

Unique Build/Heat Treat Lots (material property lot requirements): Material that does not have either build or heat treat lot commonality.

Witness Line: A visual demarcation along build layer planes indicating a change in steady-state operation of the AM process. The demarcation may be a geometry shift, a change in surface texture or coloration, or any other distinct nonuniformity.

Witness Testing: Tests conducted on a specimen built during the same build cycle as a part. These specimens will be used for SPC, process development, and building mechanical test databases.

4. GENERAL REQUIREMENTS

4.1 Tailoring of this NASA Technical Standard's Requirements

[AMR-1] Program and/or project managers **shall** formally document and approve all tailoring of requirements in this NASA Technical Standard with the concurrence of the responsible NASA Materials and Processes (M&P) organization and the delegated Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements, or NPR 7120.8, NASA Research and Technology Program and Project Management Requirements.

Tailoring may occur at two stages: (1) prior to being levied, where the program or project tailors the requirements to suit its needs, and (2) prior to implementation, where the CEO tailors the as-levied requirements to provide a customized approach to implementation that meets the intent of the requirements. The following are the expected roles and responsibilities during the tailoring process. The program or project (i.e., entity responsible for defining the mission objectives, levying design and construction standards, accepting risks, and controlling cost and schedule resources) has an obligation to define and document any project-specific tailoring of these requirements prior to levying them. The responsible NASA M&P organization and the delegated Technical Authority have an obligation to review and concur (or not) with the intended project-specific tailoring and identify and assess any associated risks. Once levied, the requirements may be further tailored for implementation by the CEO through the AMCP. Tailoring for implementation proposed by the CEO is approved through formal acceptance of the AMCP by the responsible program or project, with the responsible NASA M&P organization and delegated Technical Authority providing concurrence (or not) along with identification and assessment of associated risks.

4.2 Additive Manufacturing Control Plan (AMCP)

[AMR-2] The CEO responsible for the design, acquisition, and conformance of AM hardware **shall** submit a consolidated AMCP addressing all applicable AM processes for review and approval by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization, that does the following:

a. Documents the means of conformance and method of implementation for each of the requirements of this NASA Technical Standard and NASA-STD-6033 (see section 4.5 of this NASA Technical Standard).

b. Documents and provides rationale for any tailoring of the requirements of this NASA Technical Standard.

c. Provides for complete governance for the implementation of AM on the program or project such that, once approved, the AMCP becomes the controlling document for implementation and verification of AM requirements of this NASA Technical Standard.

[Rationale: The AMCP is necessary to document the decisions made in the implementation of this NASA Technical Standard and becomes the governing document for the CEO regarding AM requirements.]

Tailoring includes using existing or previously developed contractor processes and standards when identified and submitted as part of the AMCP.

Projects that are only using Class C parts may choose to write a simple AMCP. Such an AMCP may only directly respond to requirements that apply to Class C parts. Most of the requirements for the QMP, MPS, qualification, and witness testing do not apply or are greatly reduced. While the AMCP is intended to be part agnostic, projects that are using a small number of similar or related Class C parts could choose to combine an AMCP with the limited PPP requirements given in section 7 of this NASA Technical Standard.

Note: The requirements of this NASA Technical Standard do not encompass all requirements for an AM part (e.g., fracture control).

4.2.1 Applicable Documents, AMCP

[AMR-3] All applicable documents cited in the AMCP **shall** be controlled by the QMS, subject to configuration control, and made available for review when requested by NASA, the CEO, or any designated representatives.

[Rationale: Sufficient oversight of AM operations can only be conducted when NASA, the CEO, and any of their designated representatives has access to the controlling documents.]

The majority of the technical details and controls necessary for the production of reliable AM parts will not typically be contained directly in the AMCP, but in documents cited as applicable in the AMCP. NASA, the CEO, or a designated representative will be provided access to these documents upon request.

4.2.2 Supplier Compliance with the AMCP

[AMR-4] The CEO **shall** ensure flow-down of the requirements of this NASA Technical Standard, as tailored per the AMCP, through all relevant tiers of the supply chain and ensure that the relevant documents controlled by subtier suppliers are made available to NASA upon request.

[Rationale: The CEO is expected to rely on suppliers for aspects of producing AM parts. The quality of parts may be compromised at any stage of the process. This requirement precludes the use of suppliers whose products or services are not compliant with the controls of this NASA Technical Standard.]

This supplier requirement is not limited to the AM part producer but extends to all potential suppliers and sub-tier suppliers involved in the process of designing and producing AM parts. For example, suppliers providing part processing or witness testing (e.g., heat treating, mechanical testing, or chemical analysis) are expected to be approved by the CEO and accredited through Nadcap™, the American Association for Laboratory Accreditation (A2LA), or other nationally accepted accreditation body.

The CEO may require suppliers and sub-tier suppliers to develop a tailored plan to comply with this NASA Technical Standard or a tailored plan to comply with the CEO's plan. Alternatively, the CEO may flow down a limited subset of (or even no) requirements, with the CEO making up the difference between the subset and the AMCP. Regardless of which approach is selected, the CEO is responsible for ensuring that hardware designed and fabricated by subcontractors and/or suppliers meets the approved AMCP or this NASA Technical Standard.

4.3 Additive Manufacturing Part Classification

4.3.1 Primary Classification

[AMR-5] The CEO **shall** assign a primary classification (i.e., Class A, B, or C) to all AM parts in accordance with the content of Figure 4.

[Rationale: Part classification is required to enable a consistent evaluation of part risk through defined metrics for consequence of failure, structural demand, and AM-associated risks.]

See Figure 4 of this NASA Technical Standard for a graphical representation of the primary and secondary classification system.

The classification system establishes a consistent methodology to define and communicate the risk associated with AM part designs. Throughout this NASA Technical Standard, these classifications determine appropriate levels of process control, qualification, and inspection.

The part classification system uses a two-tier system to designate AM parts based on relative risk. The alphabetical class is determined by consequence of failure, with Class A being the highest and Class C being the lowest. An additional exempt designation is defined in section 4.3.1.4 of this NASA Technical Standard. The numerical subclasses for Class A and B parts are determined by a combination of structural demand on the part and the risk associated with the AM implementation for the part.

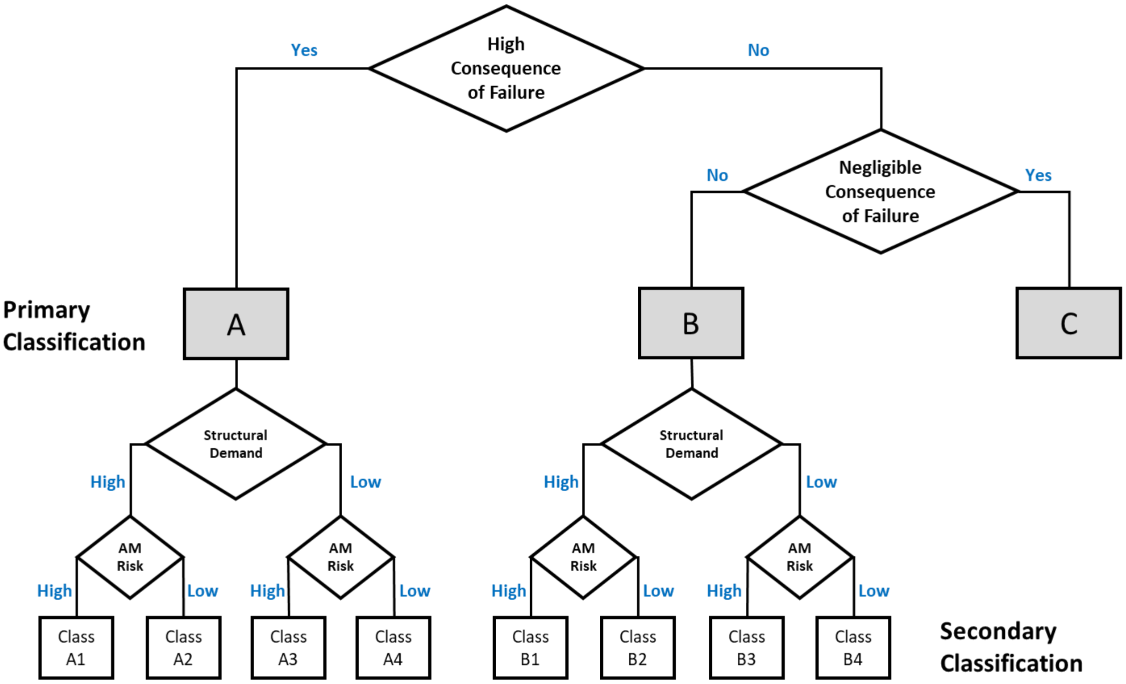


Figure 4—AM Part Classification

4.3.1.1 Class A Parts

[AMR-6] A part **shall** be designated as Class A, High Consequence of Failure, if failure of the part leads to a catastrophic, critical, or safety hazard and/or the part is defined as mission critical by the program or project.

[Rationale: Parts with a high consequence of failure require more stringent controls on the AM process to manage risks associated with their use.]

Note: See Section 3.2 of this NASA Technical Standard for definitions of catastrophic, critical, and safety hazard, which are taken from NPR 8715.3D, NASA General Safety Program Requirements. Other NASA NPRs, NPDs, standards, specifications, and contracts may define these terms differently. In instances of conflict, the AMCP will need to clarify any deviations to the definitions provided herein.

The consequence of failure for any human-rated hardware should be determined via FMEA or may follow from assessments done for fracture control classification. Considerations for high consequence of failure may also include the loss of mission objectives or the loss of a "national asset" or similar high-cost hardware or facility that warrants the added controls for Class A parts. Range safety requirements may also govern consequence of failure evaluations.

4.3.1.1.1 Class A Part Restrictions

[AMR-7] Class A parts **shall** not:

a. Be made from polymeric materials
b. Be fasteners.
c. Contain printed threads.

[Rationale: The current state of the art for AM is not yet mature enough for these categories of parts.]

Non-metallic AM parts are intended for use only in Class B and Class C applications.

4.3.1.2 Class B Parts

[AMR-8] Parts not designated Class A or Class C **shall** be designated as Class B.

[Rationale: Class B parts are not synonymous with benign failures—Class B parts are to be aerospace-quality parts of high reliability. Many failures falling short of catastrophic can produce major programmatic delays/impact. The consequence of failure for parts in non-flight development hardware should be based on collateral damage assessments and chosen at the discretion of the project. A higher class designation may always be chosen for a part.]

4.3.1.2.1 Class B Part Restrictions

[AMR-9] Class B parts **shall** not:

a. Be fasteners.
b. Contain printed threads.

[Rationale: The current state of the art for AM is not yet mature enough for these designs.

Threads for Class B parts may still be machined or formed after AM printing.

4.3.1.3 Class C Parts

[AMR-10] A part **shall** be designated as Class C, Negligible Consequence of Failure, provided that ALL of the following criteria are satisfied:

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.

Contamination requirements are commonly defined in interface control drawings.

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.

[Rationale: Class C designs have the lowest performance requirements and the fewest controls for realizing the performance specifications and process repeatability.]

This class of parts allows tailored quality assurance and material performance controls due to negligible consequences of failure. Consideration of consequence have to include all possible end uses of the part, including protoflight scenarios or development hardware that may transition to actual flight hardware.

For the above checklist, failure can be defined as any failure condition (including, but not limited to, yielding, buckling, cracking, fracture, leak, wear/galling, or corrosion) where the part does not achieve every aspect of its design intent.

NASA-STD-6030 imposes a large number of process AMRs for Class A and Class B parts. Although Class C parts have a negligible consequence of failure, a minimum set of requirements is kept to ensure that flight parts still meet their intended function. A large number of AMRs are eliminated, and the remaining set of AMRs is selected to ensure that the AM process produces sound material.

Many of the remaining AMRs were simplified to reduce cost, schedule, and complexity. The following are examples of simplified process controls for Class C parts:

- *For process qualification, only six tensile coupons are to be made and tested using the machine setup (see section 5.4 of this NASA Technical Standard).*
- *For process control, the production parts are built using the identical machine setup as the qualification coupons.*
- *For process verification, only two tensile coupons are to be included in the production build (see section 4.11 of this NASA Technical Standard).*

AMRs for NDE and preproduction articles are removed. AMRs for statistical methods are also removed (e.g., MPS, PCRD, materials allowables, and design values).

The AMCP and PPP are required for Class C parts, although these plans are simplified since the majority of AMRs are waived. The remaining AMRs required document the process controls, part usage, and justification for part classification to ensure all concerned understand what will be done and what is further tailored.

Choosing to tailor out process controls and process verifications intended to ensure functionality of Class C parts is not encouraged, but it may be acceptable for the risk posture of some projects provided those projects meet any higher-level platform requirements (e.g., a CubeSat transitioning through the International Space Station [ISS] habitat).

Note that all parts still need to meet NASA-STD-6016 requirements necessary to ensure safety of flight (e.g., flammability, toxic offgassing) and vehicle compatibility (e.g., vacuum outgassing).

4.3.1.4 Exempt Parts

[AMR-11] A part **shall** be designated as Exempt provided that all of the following criteria are satisfied and it meets all criteria for Class C (see section 4.3.1.3), which exempts it from all other requirements in this NASA Technical Standard:

a. The part does not require any form of structural assessment.

b. The part does not permanently interface to, or attach to, the launch vehicle, spacecraft, habitable module, or any subsystems thereof.

c. Except for use in habitable crew spaces, the part does not provide any functionality or serve any purpose to the launch vehicle, spacecraft, or any subsystems thereof.

[Rationale: Every AM part requires evaluation for classification, and documentation thereof, even if that classification results in no further requirements.]

Parts that meet the criteria for Exempt are still recommended for Class C, if practical.

Documentation of rationale and approval of an Exempt part designation may take place in a number of different ways, including, but not limited to, a Materials Identification and Usage List (MIUL), MUA, contract memorandum, material certification, or safety review hazard report. A detailed rationale addressing the criteria of sections 4.3.1.3 and 4.3.1.4 of this NASA Technical Standard is recommended. A specific mechanism for documentation and approval is intentionally omitted from this requirement since many programs using this designation may have greatly reduced numbers of requirements or deliverables. As such, it is important that projects and programs that allow Exempt parts define requirements for documentation and approval.

Note that all parts must still meet NASA-STD-6016 requirements necessary to ensure safety of flight (e.g., flammability, offgassing, and compatibility) and vehicle compatibility (e.g., vacuum outgassing).

4.3.2 Secondary Classification

[AMR-12] For Class A and B parts, a secondary classification **shall** be assigned based on structural demand and AM risk, according to Table 2, Structural Demand, Metallic AM Parts, Table 3, Structural Demand, Polymeric AM Parts, and Table 4, Assessment Criteria for Additive Manufacturing Risk (also see Figure 4).

4.3.2.1 Structural Demand

The purpose of the structural demand assessment is to identify the relative structural performance demands on the part. Parts with high structural margin are less sensitive to variations and uncertainty in material performance. The use of structural demand in classification of parts is not uncommon (e.g., see the classification system in SAE AMS2175, Castings, Classification and Inspection of); however, past use of such structural criteria has typically been simplistic and non-specific. The criteria herein are intended to be sufficiently comprehensive of common structural failure modes to allow the margin required in each assessment to be specific to its property. For example, the strength margin requirements are set to cover potential variability in strengths, not to bound fatigue or fracture behavior, as these properties are addressed directly. The requirements of the above tables may be tailored to account for significant conservatisms present in analysis methods or material properties; however, the intent of the criteria must be maintained, and rigorous substantiation of the tailoring request will be required.

The assessment of structural demand does not levy or alter any of the structural requirements, factors of safety, or required structural margins for any hardware. The criteria for low structural demand in the tables are used only as a consistent indicator for the level of demand (e.g., stress) on the part to inform the amount of structural risk associated with the part.

For each AM part, the results of the structural assessment conducted in accordance with the levied structural requirements are compared against the appropriate table for material type: metals (Table 2) or polymers (Table 3). The criteria in the table are only applicable when that criteria is required by the structural requirements. For example, the fracture mechanics life criteria is not applicable to non-fracture critical hardware that do not require this evaluation. There is not an expectation for any structural evaluations beyond those required by the structural requirements to be conducted solely for purposes of classification.

If all structural assessment requirements for a given part meet or exceed those in Table 2 for metals and Table 3 for polymers, then the part is considered to have a low structural demand and is assigned a subclass of 3 or 4 pending evaluation of AM risk (see Tables 2 and 3). Otherwise, the part is considered to be high structural demand.

Table 2—Structural Demand, Metallic AM Parts

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* ≥0.3
Yield strength	Minimum margin* ≥0.2
Point strain	Local plastic strain <0.005
High cycle fatigue, improved surfaces	Cyclic stress range (including any required factors) ≤80% of applicable fatigue limit
High cycle fatigue, as-built surfaces	Cyclic stress range (including any required factors) ≤60% of applicable fatigue limit
Low cycle fatigue	No predicted cyclic plastic strain
Fracture mechanics life	20x life factor
Creep strain	No predicted creep strain

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

The following notes are provided for some of the above criteria for metallic AM systems:

Loads Cases — The loads environment for spaceflight systems and structures is rarely comprehensively understood. Examples of loads that are not well defined or bounded include parts passing through or operating near resonance, or parts requiring forced response and coupled dynamic loads analysis to predict fluid-structure interaction. Commonplace uncertainties (e.g., the precise magnitude of a random vibration or loads due to quasi-static pressure or thrust loads) are considered sufficiently defined and do not violate the intent of this criterion.

Environmental Degradation — To meet the low structural demand criterion, temperature is the only allowed source of environmental material degradation. Exposure to a hydrogen embrittling environment would be an example failing this criterion.

Ultimate and Yield Strength — These assessments are performed as defined by the governing structural requirements. Methodologies for yield and ultimate evaluations often differ by analysis organization. The requirements to demonstrate low structural demand are expressed as the margin needed in excess of the required factor of safety, per standard NASA notation (see Table 2 and discussion of "Margin" here).

Margin — Margin refers to the common definition of the margin of safety, as defined in structural requirements such as NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware, or NASA-STD-5012, Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines. It is the fraction by which the allowable capability (σ_{design}) exceeds the applied load ($\sigma_{operation}$) as multiplied by the factor of safety. The margins used in the structural demand assessment criteria are those defined by the method of *margin calculation from the levied structural requirements and should come directly from the structural assessment. Margins should not have to be recalculated for evaluation of part classification. Appropriate tailoring to equivalent metrics may be used in cases where the structural requirements use other means of calculating margin (also applies to Table 3).*

Point Strain — This evaluation is required for all parts and is intended to limit the dependence on ductility for low structural demand parts. Linear elastic evaluation where peak, local von Mises stress remains below yield is sufficient. Proper modeling practice for converged mesh discretization dependence within stress models is assumed. For cases where peak, local von Mises stress is greater than yield, any approved method of calculating plastic strain is acceptable (e.g., elastic-plastic finite element analysis or Neuber notch analysis).

High Cycle Fatigue — For low structural demand, the cyclic stress must be below the defined fatigue limit cyclic stress by the percentage indicated. Fatigue initiation life evaluation includes the influence of the surface condition. The factors provided for "improved surfaces" intend that such surfaces have been altered through machining or other chemical or mechanical processes to eradicate or mitigate the effects of the as-built L-PBF surface on fatigue life as substantiated experimentally. Part surfaces that remain in the as-built condition are to be evaluated against fatigue data developed with a representative as-built surface.

Low Cycle Fatigue — Plastic point strains are not intended to occur cyclically for parts with low structural demand.

Fracture Mechanics Life — This evaluation is only intended for parts subject to damage tolerance analysis. For low structural demand, the damage tolerance assessment demonstrates life ≥20 missions, based on a starting defect applicable to the inspection method.

Creep — Confirmation of no-creep deformation is intended only in cases where creep-inducing environments are present.

Table 3—Structural Demand, Polymeric AM Parts

Analysis Input/Material Property	Criteria for Low Structural Demand
All materials	
Load cases	Well-defined or bounded loads environment
Environmental Degradation	Only allowed due to temperature and moisture, if specific environmental performance data exist. Design environment temperature does not cross the *Tg*.
Fatigue	Cyclic stress range (including any required factors) ≤50% of applicable fatigue limit
Sustained stress/creep strain	No sustained stress[†] and no predicted creep strain
Material with elongation at failure ≥3% in application environment	
Ultimate strength	Minimum margin[*] ≥0.5
Yield strength[‡]	Minimum margin[*] ≥0.3
Material with elongation at failure <3% in application environment	
Ultimate strength[#]	Minimum margin[*] ≥2.0

[†] Includes assembly stress (tight snap fit connections, shrink fits, fastener preloads) and operational stress.

[‡] Yield strength defined by secant modulus to specified strain, by specified offset strain, or as otherwise defined by structural assessment requirements.

[#] Ultimate strength assessed against local maximum principal stress at stress concentrations (brittle material design rules) for low ductility materials.

[*] Margin = $[\sigma_{\text{design}}/(\sigma_{\text{operation}} * \textit{safety factor})] - 1$ (see commentary following Table 2)

4.3.2.2 Additive Manufacturing Risk

New opportunities presented by the AM process (e.g., previously impossible geometries) also present new risks in the use of the parts. Limitations in the ability to characterize defect attributes and verify defect densities in finished parts are prominent among these risks. The questions in the AM risk criteria table are phrased such that a positive answer corresponds to a zero score, not contributing to AM risk. A lower score equates to lower risk. Improved surfaces refer to areas that have had material removed from support structure mating surfaces such that only bulk material remains.

For each AM part, an AM risk assessment is to be conducted and compared against the table for the applicable feedstock type. If the summed AM risk scores less than 5, then the part will be assigned low AM risk and placed in subclass 2 or 4. If the summed AM risk scores greater than or equal to 5, then the part will be assigned high AM risk and placed in subclass 1 or 3.

In Table 4, "X" indicates the applicability of the AM risk. The intent is to capture differences in processes (e.g., DED or L-PBF) or materials (e.g., metallic or polymer). The numerical score assigned for each row is binary: either zero for Yes or the value listed in the "No" column.

Table 4—Assessment Criteria for Additive Manufacturing 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[1] based on stress state?	X	X	X	0	5	
As-built surface can be fully removed on all fatigue-critical surfaces[2]?	X	X		0	3	
Surfaces interfacing with support structures are fully accessible and the as-built surface removed?	X	X	X	0	3	
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	
Structural walls or protrusions are the equivalent of ≥2 trace, (e.g., melt pool, bead, scan path) widths in cross section?		X		0	2	
Critical regions of the part do not require support structure?	X	X	X	0	2	
[1] In the context of the assessment of AM risk, the adequacy of a proof test is determined by the degree to which the test meets its assigned objectives. For a workmanship proof test, at any given location in the part the proof test is considered adequate when the state of stress in the part during the proof test exceeds the state of stress in the part during operation by the required proof factor. If the proof test conditions do not fully replicate the operational environment, as is typically the case, the proof and operational stresses are compared using directional stress components with any needed corrections for environment. For the rare case of quantitative flaw screening by proof test as an anchor to fracture control requirements, the adequacy of the proof test is determined only by the ability of the applied proof test stress conditions to screen the critical initial flaw size for operation by causing failure, leak, or other clearly detectible damage to the part during the proof test. Just as in the workmanship proof test, the adequacy of a proof test for quantitative flaw screening is likely to vary throughout the part. Demonstrating the adequacy of a quantitative proof test is non-trivial and must be coordinated intently with the structures and fracture control communities.						
[2] Fatigue-critical surfaces are locations where fatigue analysis and surface condition assumptions influence the outcome of the structural assessment.						

4.4 Quality Assurance

4.4.1 Quality Management Systems

[AMR-13] A QMS compliant to SAE AS9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations, or an alternate QMS approved by the CEO and NASA, documented or referenced in the AMCP, **shall** be in place for all entities involved in the design, production, and post-processing of AM hardware.

[Rationale: A QMS is required to ensure necessary process controls and mitigate risks associated with noncompliance. The AS9100 QMS requirement applies because an AM process is considered "complex" per NPD 8730.5, NASA Quality Assurance Program Policy, due to

significant reliance on process controls for the reliability of the product. AM parts in Class A are also considered "critical" per NPD 8730.5.

Note: Alternate QMS standards or supplier accreditation systems are more likely to be relevant at the subtier supplier levels (e.g., raw materials, post-processing, etc.) and should be considered by the CEO and NASA whenever reasonable.

Nadcap™ accreditation for L-PBF is recommended but not required.

4.4.2 Quality Records

NASA will evaluate the supplier's adherence to AS9100 configuration management requirements by confirming that formal configuration management processes and systems are used to control the following work products, documents, data, and records, as a minimum:

1. *Process documents and specifications.*
2. *Part drawings.*
3. *Test reports (related to QMPs, witness tests, etc.).*
4. *Shop travelers.*
5. *Build files.*
6. *Build records.*
7. *Inspection results.*
8. *Nonconformance and corrective action records.*
9. *Records supporting the supplier's certification of product conformance.*

Requirements and processes for assurance of QMSs can be found in NPR 8735.2, Management of Government Quality Assurance Functions for NASA Contracts, and AS9100. Per these documents, projects are required to use a quality assurance surveillance plan that includes a focus on a supplier's QMS.

4.5 Equipment and Facility Control Plan (EFCP)

[AMR-14] All equipment integral to the AM process, and facility-specific processes and procedures, **shall** be under the control of a CEO-approved EFCP developed in accordance with NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facility Control, prior to the production of flight hardware.

[Rationale: Proper qualification, calibration, and maintenance of AM equipment and its associated equipment are essential to production of reliable AM parts.]

The AM part producer is expected to develop and maintain the EFCP, which is to be approved by the CEO. The requirement for the EFCP may be met by leveraging existing documentation for control of equipment and facilities if all requirements of this section are addressed, all *documents are configuration controlled in the QMS, and the documents that make up the EFCP are identified in the AMCP per section 4.5 of this NASA Technical Standard.*

4.6 Fracture Control

[AMR-15] All AM parts used in hardware subject to fracture control **shall** be classified and assessed to NASA-STD-5019 with the following limitations:

a. AM parts are not to be categorized as non-fracture critical low-risk parts, per NASA-STD-5019.

b. AM parts are not to be categorized as fracture critical lines, fittings, and other pressurized components, per NASA-STD-5019, section 7.2.4, and instead are to follow the general approach for assessing fracture critical metallic parts per NASA-STD-5019, section 7.3.

[Rationale: For hardware with NASA-STD-5019 imposed, AM parts, like all others, are subject to the fracture control process. The "low risk" and "pressurized lines, fittings, and components" categories assume the use of materials with low risk of having defects introduced during all manufacturing processes, which permits reduced inspection and assessment requirements. As currently defined in NASA-STD-5019, sections 6.2.5 and 7.2.4(a), these categories are considered insufficient to manage the process control risks inherent to AM parts.]

Note that sub-part (b) of this requirement does not prohibit the use of AM for fracture critical pressurized lines, fittings, and other components. Instead, it prohibits the use of NASA-STD-5019, section 7.2.4(a), as the sole means of fracture control for fracture critical pressurized AM parts and invokes the full content of NASA-STD-5019, section 7.3, for this purpose. It is assumed that the design burst, proof pressure, leak test, and other applicable requirements in AIAA S-080, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, are met for any fracture critical pressurized AM parts.

This NASA Technical Standard relies upon the latitude granted to the responsible fracture control board (RFCB) by NASA-STD-5019 to determine the adequacy of the overall fracture control rationale for AM hardware. It is expected that fracture control will frequently be implemented through an RFCB-approved alternative approach (see NASA-STD-5019) that uses a combination of process control, inspections, proof and other acceptance tests, analysis, and/or damage tolerance testing.

4.7 Unplanned Interruptions

[AMR-16] Any unplanned build interruption, including planned interruptions occurring outside approved limits, **shall** be documented as a nonconformance and traceable via a records management system controlled by the QMS.

[Rationale: Unplanned interruptions in the AM process are a sign of a deviation in the steady-state process, often resulting from an imperfection in the build or a fault in the machine. Treating an unplanned interruption as a nonconformance ensures the quality risk is characterized and mitigated.]

Every effort should be made to eliminate build interruptions.

Unplanned build interruptions may be restarted only if a nonconformance is documented and qualified restart procedures exist and are followed. The QMP defines the limitations for a planned interruption and qualifies the procedures for handling the interruption and restoration of the build process.

4.8 Nondestructive Evaluation (NDE)

4.8.1 Class A Parts

4.8.1.1 Quantitative NDE

[AMR-17] All Class A parts **shall** receive quantitative NDE with full coverage of the surface and volume of the part, including verifiable detection of critical initial flaw size in fracture critical damage tolerant parts, with any coverage limitations due to NDE technique(s) and/or part geometry documented in the PPP per section 7.3 of this NASA Technical Standard.

[Rationale: NDE provides a necessary degree of quality assurance for AM parts in addition to the process controls of this NASA Technical Standard. No methodology currently exists to preclude all AM process failure modes through the available manufacturing process controls.]

4.8.1.2 NASA-STD-5009 Special NDE Approach

[AMR-18] The NDE approach for Class A parts **shall** meet the Special NDE requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components, and be documented in the PPP.

[Rationale: The defects of interest in AM are of a different nature than those listed in Tables 1 and 2 of NASA-STD-5009, and AM microstructures can impact the effectiveness of NDE methods. Therefore, all inspections of fracture critical AM hardware should be treated as Special NDE.]

The minimum detectable flaw sizes (see Table 1 of NASA-STD-5009) may be used as a guide but must be demonstrated prior to use as acceptance criteria. All method-specific requirements listed in the Standard NDE section should be used as guidance for traditional NDE methods.

AM processes offer a unique opportunity to build hardware for demonstration of defect detection directly in the part. A demonstration part with simulated defects, surface connected and volumetric, can be built with modest development investment.

Alternative flaw screening methods for Class A parts (e.g., proof testing) may be feasible with full justification provided in the PPP.

4.8.2 Class B Parts

4.8.2.1 Process Control NDE

[AMR-19] All Class B parts **shall** receive NDE for process control with full coverage of the surface and volume of the part, with any coverage limitations due to NDE technique(s) and/or part geometry documented in the PPP.

[Rationale: NDE for process control requires the use of physical reference standards for calibration and acceptance criteria based on the capability of the NDE technique but does not require quantitative validation of flaw detection.]

Targeted approaches for NDE can be proposed and approved per the PPP.

4.8.2.2 NASA-STD-5009 NDE Approach

[AMR-20] The NDE approach for Class B parts **shall** meet the requirements of NASA-STD-5009 and be documented in the PPP.

[Rationale: The requirements in NASA-STD-5009 establish important controls, including the definition, validation, documentation, and approval of all NDE procedures, standards, methods, and acceptance criteria; certification of NDE inspectors; NDE capability requirements; detection and reporting requirements; disposition of flaws; documentation control; and records retention.]

Alternative post-build quality assurance methods for Class B parts (e.g., proof testing), as well as a reduction in NDE scope for Class B parts, may be feasible with full justification provided in the PPP.

Accommodations for Class B inspections may be appropriate (e.g., using a radiographic inspection sensitivity level of 2-2T).

Standards with NDE acceptance criteria for welding or casting quality are not generally considered applicable to AM parts but may be used for guidance.

A full-height contingency witness specimen as described in Table 5 of this NASA Technical Standard can be inspected to investigate abnormal build conditions that may have occurred.

For additional commentary on NDE methods and techniques for metal AM spaceflight hardware, see MSFC-STD-3716, Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals, Appendix B, section 6.2.14.2, and ASTM E3166, Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build.

Nonconformance findings related to NDE are controlled by the QMS similar to other scenarios; for Class A parts, NDE indications of cracks, crack-like defects, volumetric defects, or other findings of undetermined source should be elevated to senior review and disposition as required by the applicable fracture control policy (e.g., a RFCB).

Each project and CEO will have defined rules for resolution of nonconformance items, including which items are elevated for higher level review and risk visibility. Senior review of crack-like defects is important not only for the integrity of the nonconforming part, but also for understanding the process escape that created the condition. The common forum for senior nonconformance review in the NASA system is the Material Review Board (MRB). For fracture critical AM parts, the RFCB should be made aware of nonconformances in flight hardware involving defects.

4.9 In-situ Process Monitoring

[AMR-21] Prior to use as a quantitative indicator of part quality for part acceptance, passive *in-situ* process monitoring technologies **shall** be qualified by the CEO to the satisfaction of NASA in a manner analogous to other NDE techniques.

[Rationale: All processes that are used to establish quantifiable quality assurance metrics are qualified against established criteria to verify detection reliability, calibration, and implementation. If in-situ monitoring techniques are employed for such purposes, the need for such qualification is unchanged.]

Certification of a passive in-situ process monitoring technology relies on a thorough understanding of the physical basis for the measured phenomena, a proven causal correlation of the measured phenomena to a defined defective process state, and a proven level of reliability for detection of the defective process state.

If qualified in the manner stated above, an in-situ process monitoring technique can be used to complement NDE in the Integrated Structural Integrity Rationale of the PPP. At this time, even a qualified in-situ process monitoring method cannot be considered a complete replacement for NDE.

Even if qualification is not desired, the use of in-situ process monitoring is encouraged as a source of process control data. This data can also be used to help guide targeted inspection.

As discussed in section 1.4.2 of this NASA Technical Standard, closed-loop process control based on adaptive in-situ monitoring technologies that alter the defined AM process in response to monitored phenomena are not currently applicable technology per this NASA Technical Standard and cannot be used without prior approved tailoring. See further discussion on the concerns with qualification of closed-loop controls in section 1.4.2 of this NASA Technical Standard.

4.10 Repair and Rework

[AMR-22] Explicit provisions controlling any operation used to repair or rework an AM part due to a defect (e.g., short feeds/fractures, cracks) or nonconformance (e.g., warping) **shall** be documented and implemented as follows for Class A and B parts:

a. Repair operations require prior written authorization from the contract authority, as described in the AMCP.

b. All repair operations require full documentation as a nonconformance record and are included in the production engineering record of the part.

c. Unplanned part operations not part of the QPP that constitute a repair or rework include, but are not limited to, bending, blending, sanding, peening, grinding, machining, welding, or brazing for the purposes of defect removal and/or part restoration to drawing allowances.

d. All repair operations require validation on material manufactured using the same QMP.

[Rationale: Uncontrolled or undocumented repair is not allowed for two reasons: first, such repairs are a danger to the integrity of the part; and second, such repairs obfuscate process escapes and hinder the development and implementation of corrective actions.]

See section 3.2 of this NASA Technical Standard for definitions of rework and repair.

See section 8 in this NASA Technical Standard for additional information regarding the QPP.

4.11 Witness Testing for Statistical Process Control

Use of witness specimens provides evidence of process control throughout the build cycle. This concept is based on the assumption that process development is complete and that a fixed "steady state" process has been reached. The implementation of witness sampling will vary from part to part depending on part class, the build layout, and specific part requirements. The PPP is used to document the approach to witness specimen testing.

The test direction of witness specimens is almost always in the Z-direction defined by the build height since the properties in that direction are typically most sensitive to degradation in the build process. Testing should be performed during process development to determine the appropriate test direction or directions for a particular AM process, machine, or material.

The direction, diameter, length, and shape of the witness specimens should be the same as the QMP specimens. Geometric differences in specimens can cause differences in the measured strength and ductility, which can prevent statistical combination or comparison of qualification *and production witness data. All samples should have consistent surface finish between witness and QMP specimens; with the exception of surface-finish-dependent-testing (e.g., fatigue testing), it is recommended that all samples be fully machined. The locations of the witness specimens in the build volume or on the build plate should be specified and kept consistent for all builds.*

Because acceptable witness specimen test results are a prerequisite to part acceptance, significant programmatic risks occur when witness specimen testing lags continued part processing and additional part production. Witness specimen test results should be generated as soon as possible to reveal potential systemic changes to the AM process so rapid intervention can reduce the impact to production.

Witness specimens are used to identify systemic changes in process control. By their nature, build witness specimens represent a small sample of the spatial (location in build volume) and time aspects of the build; they cannot necessarily indicate local, transient, or intermittent loss of process control during a build.

This NASA Technical Standard requires SPC to monitor the results of witness specimen testing. Witness specimens are intended to provide a final evaluation of the complete AM process following any necessary post-build material processes (e.g., heat treating or curing). The application of SPC to operational aspects of the AM machine is highly encouraged; not every control factor with process influence can be monitored using witness specimen testing.

The remainder of this section provides requirements and associated guidance for witness specimen evaluations for either builds evaluated independently per section 4.11.1 or builds evaluated in the framework of continuous production per section 4.11.2 of this NASA Technical Standard. See the definitions of "Independent Build" and "Continuous Production Build" in section 3.2 of this NASA Technical Standard.

See section 7.4.1 of this NASA Technical Standard for control and documentation requirements and any deviations for using custom witness specimen test approaches that are part specific.

The PCRD is a simple statistical model of witness specimen test results. PCRDs whose characteristics are determined to be acceptable (e.g., variance, skew) are used to set acceptance limits for the witness specimen tests. Witness specimen test results that fail to meet the acceptance limits or that negatively affect the PCRD's characteristics are used as indicators of a degradation in or loss of process stability that may influence a production part's material properties. See section 6.9 in this NASA Technical Standard.

There are two primary methods of SPC available to the user depending on the chosen witness specimen testing methodology: "continuous production" SPC and "independent build" SPC. Continuous production SPC is based on the classic methodology of tracking the process over time using control charts to identify changes or trends in process performance. The control chart acceptance criteria are based on the PCRD definition of the nominal process performance, or *the control charts may provide the definition of nominal performance and acceptance metrics based on standard control chart procedures (e.g., ASTM E2587, Standard Practice for Use of Control Charts in Statistical Process Control). In the latter case, the control charts and their acceptance criteria directly serve the purpose of the PCRD. With the benefit of a continuous performance history, the quantity of witness specimen tests required per build operation is reduced compared with the independent build scenario, but there are operational requirements levied on the AM machine to maintain the status of being in continuous production (see section 4.11.3 of this NASA Technical Standard).*

An important aspect of these operational requirements is a periodic SPC evaluation build, potentially using the same sample set as a Sub-QMP, which evaluates a broader range of material and build performance. Note that "continuous production" implies the machine operates continuously under the same or equivalent QMPs. It does not mean a single part is in continuous production. A variety of parts can be produced on a machine in continuous production. Most AM machines that are fully qualified to the requirements of this NASA Technical Standard should be capable of continuous production status.

Another available method of SPC is associated with the independent build. The application of SPC in this scenario differs from the classic construct of SPC in that it does not have the advantage of build history and trending, but rather evaluates systemic build quality based only on the available witness specimen test information from that build. A higher quantity of witness specimen tests is required for this approach to allow an improved engineering assessment of build performance. This method is considered a form of SPC because, through the use of the PCRD and its associated statistically based acceptance criteria, the process performance is monitored for consistency within the limits of pragmatic sample quantities. This insight into process control is not available from simplistic minimum value acceptance criteria.

The independent build scenario is useful for accepting parts while developing the needed witness specimen performance history for continuous production SPC. It is also of value for smaller build runs that may take place on controlled AM machines that do not yet meet the prerequisites to qualify for continuous production.

A witness sub-article is a chosen portion or representative geometry of a part that is produced concurrently as a witness article during the build. The use of witness sub-articles is not mandatory for every part. The witness sub-article allows for evaluation, inspection, or dissection of challenging representative geometry when direct evaluation of the feature on the actual part is not possible. For example, a small representative section of a complex, thin-walled heat exchanger may be built alongside the actual part. Under the assumption that the process performance is reasonably equivalent for both, the witness sub-article can be sectioned to look at the quality of the thin walls. Witness sub-articles may be used to provide sufficient process control evidence for part features that cannot otherwise be inspected or verified in the part directly and may be used for any appropriate evaluation (e.g., mechanical, metallurgical, dimensional, surface texture, calibration of nondestructive inspection tools, etc.).

Witness articles for Class A1 parts are required for parts that have high structural demand and high AM risk based on a lack of complete inspection capability (first criterion in Table 2). One witness article is required to be evaluated for every six flight parts produced. The witness article is evaluated according to the preproduction article evaluation criteria specified by the PPP. Rationale for tailoring this requirement will be part- and situation-specific and is presented and approved through the PPP.

See MSFC-STD-3716, Appendices B and C, for additional commentary on witness testing and SPC.

4.11.1 Witness Testing for Independent Builds

[AMR-23] All AM parts manufactured by an independent build **shall** include witness specimens integral to the build of the types and quantities required in Table 5, Metals Witness Testing Quantities and Acceptance Results for Independent Builds (metals), and Table 6, Polymer Witness Testing Quantities and Acceptance Results for Independent Builds (polymers), exposed to the same post-processing documented in the QMP, and evaluated per the acceptance methodologies in Tables 5 and 6, such that any witness test failing to meet the defined acceptance criteria is documented as a nonconformance and traceable via a records management system controlled by the QMS.

[Rationale: Witness sampling is required to provide evidence of process control throughout the build cycle for independent builds, the witness sampling requirements provide sufficient data to reasonably evaluate the build solely on its own content.]

See Table 13, Minimum Mechanical Property Tests for Metal QMP Builds; Table 14, Minimum Mechanical Property Tests for Metal Sub-QMP and SPC Evaluation Builds; Table 15, Minimum Mechanical Property Tests for Polymeric QMP Builds; and Table 16, Minimum Mechanical Property Tests for Polymeric Sub-QMP and SPC Evaluation Builds in section 5.5.3.5 for recommended test specifications.

Further discussion on the intent and implementation of witness testing can be found in MSFC-STD-3716, Appendix B, section B6.2.2.1.

The witness sample requirements for an independent build are scoped to generate sufficient evidence during a single build operation to conclude that material rendered by the machine and feedstock at the time of the build is consistent with past performance and supports the assumptions in the MPS.

It is highly recommended that the results of independent builds be tracked whenever possible using process control charts and following the other policies of sections 6.9 and 6.10 of this NASA Technical Standard to establish or maintain process performance history. A build with witness sampling adequate for an independent build can also be a part of a continuous operation build because the sampling requirements are enveloped.

Witness sample geometries may vary depending on the AM process being used. Witness specimens built alongside the part are capable of capturing a representative thermal history of the part. Some processes (e.g., DED) challenge this methodology. For these systems, material from tag ends, prolongations, or other features may be used as the material for witness specimens.

Because they challenge the layer-by-layer methodology, these systems also require tensile and microstructure samples to confirm system performance has not changed since the build process began.

For efficiency, witness specimens may serve multiple witness requirements, such as using specimen grip ends for metallurgical evaluations, so long as witness data are not compromised.

For the purposes of this NASA Technical Standard, integral to the build means produced during a process development production run or during a part production run, and for the latter, simultaneously with the production part.

Table 5—Metals Witness Testing Quantities and Acceptance Results for Independent Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	6	6	6	6	6	6	6	6	2
FH Contingency*	1	1	1	1	1	1	-	-	-
Post-build Tensile**	6	6	6	6	6	6	6	6	2
Microstructure	2	2	1	1	1	1	-	-	-
Post-build Microstructure†	2	2	1	1	1	1	-	-	-
Chemistry	1	1	-	-	-	-	-	-	-
HCF	2	2	2	2	2	-	-	-	-
Low Margin Point	A/R	A/R	-	-	-	-	-	-	-
Witness Sub-article	A/R	-	A/R	-	A/R	-	-	-	-
Witness Article	1 for 6	-	-	-	-	-	-	-	-
Customized QMP	A/R	A/R	A/R	A/R	A/R	A/R	A/R	A/R	-

Notes:
*FH contingency = Full-height contingency specimen for PBF only
**Post-build tensile = Post-build tensile specimens required for DED only
†Post-build microstructure = Post-build microstructure specimens required for DED only
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction).
See Tables 13 through 16 in section 5.5.3.5 in this NASA Technical Standard for recommended test specifications.

b. Basis for Acceptance of Witness Specimen Results

Class

	A1	A2	A3	A4	B1	B2	B3	B4	C
Tensile	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	>85% typical
FH Contingency*	A/N	A/N	A/N	A/N	A/N	A/N	-	-	-
Post-build Tensile**	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	>85% typical
Microstructure	Comp	Comp	Comp	Comp	Comp	Comp	-	-	-
Post-build Microstructure†	Comp	Comp	Comp	Comp	Comp	Comp	-	-	-
Chemistry	A/S	A/S	-	-	-	-	-	-	-
HCF	PCRD	PCRD	PCRD	PCRD	PCRD	-	-	-	-
Low Margin Point	DV Min	DV Min	-	-	-	-	-	-	-
Witness Sub-article	Comp	-	Comp	-	Comp	-	-	-	-
Witness Article	Comp	-	-	-	-	-	-	-	-
Customized QMP	A/S	A/S	A/S	A/S	A/S	A/S	A/S	A/S	-

Notes:
PCRD = Process Control Reference Distribution defined acceptance criteria
A/N = As needed
>85% typical = Average to be within 15% of typical value
*PBF only
**Post-build tensile = Post-build tensile specimens required for DED only
†Post-build microstructure = Post-build microstructure specimens required for DED only
Comp = Comparative assessment based on defined criteria in the QMP/QPP, or
PPP in the case of Witness Articles or Witness Sub-articles
A/S = Acceptance as specified in the QMP/QPP

Table 6—Polymer Witness Testing Quantities and Acceptance Results for Independent Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				6	6	6	6	2
FH Contingency					1	1	-	-	-
Microstructure					1	1	-	-	-
Flexural					A/R	A/R	-	-	-
Compression					A/R	A/R	-	-	
Density					1	1	-	-	-
Witness Sub-article					A/R	-	-	-	-
Sustained Load					1	1	-	-	-
Customized QMP					A/R	A/R	A/R	A/R	-

Notes:
FH contingency = Full-height contingency specimen
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction).
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

b. Basis for Acceptance of Witness Specimen Results

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				PCRD	PCRD	PCRD	PCRD	>85% typical
FH Contingency					A/N	A/N	-	-	-
Microstructure					Comp	Comp	Comp	Comp	-
Flexural					A/S	A/S	-	-	-
Compression					A/S	A/S	-	-	
Density					1	1	-	-	-
Witness Sub-article					A/S	-	-	-	-
Sustained Load					1	1	-	-	-
Customized QMP					A/S	A/S	A/S	A/S	-

Notes:
PCRD = Process Control Reference Distribution defined acceptance criteria
A/N = As needed
A/S = Acceptance as specified in the QMP/QPP
Comp = Comparative assessment based on defined criteria in the QMP/QPP, or PPP in the case of Witness Articles or Witness Sub-articles
>85% typical = Average to be within 15% of typical value
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

4.11.2 Witness Testing for Continuous Production Builds

[AMR-24] All AM parts manufactured by a continuous production build **shall** include witness specimens integral to the build of the types and quantities required in Table 7, Metals Witness Testing Quantities and Acceptance Results for Continuous Builds, and Table 8, Polymer Witness Testing Quantities and Acceptance Results for Continuous Builds, exposed to the same post-processing as documented in the QMP and evaluated per the acceptance methodologies of Tables 7 and 8.

[Rationale: Witness sampling is required to provide evidence of systemic process control throughout the build cycle.]

See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

The continuous production build process allows for a reduced quantity of witness specimens compared with independent builds.

Witness specimen geometries may vary depending on the AM process being used. Witness specimens built alongside the part are capable of capturing a representative thermal history of the part. Some processes (e.g., DED) challenge this methodology. For these systems, material from tag ends, prolongations, or other features may be used as the material for witness specimens.

For the purposes of this NASA Technical Standard, integral to the build means produced during a process development production run or during a part production run, and for the latter, simultaneously with the production part.

Table 7—Metals Witness Testing Quantities and Acceptance Results for Continuous Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	4	4	4	4	4	4	4	4	2
FH Contingency*	1	1	1	1	1	1	1	1	-
Post-build Tensile**	4	4	4	4	4	4	4	4	2
Microstructure	1	1	1	1	-	-	-	-	-
Post-build Microstructure†	1	1	1	1	-	-	-	-	-
Chemistry	1	1	-	-	-	-	-	-	-
HCF	-	-	-	-	-	-	-	-	-
Low Margin Point	A/R	A/R	-	-	-	-	-	-	-
Witness Sub-article	A/R	-	A/R	-	A/R	-	-	-	-
Witness Article	1 for 6	-	-	-	-	-	-	-	-
Customized QMP	A/R	A/R	A/R	A/R	A/R	A/R	-	-	-

Notes:
*FH contingency = Full-height contingency specimen for PBF only
**Post-build tensile = Post-build witness tensile specimens required for DED only
†Post-build microstructure = Post build microstructure specimens required for DED only
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction)
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications

b. Basis for Acceptance of Witness Specimen Results

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	CC	CC	CC	CC	CC	CC	CC	CC	>85% typical
FH Contingency	A/N	A/N	A/N	A/N	A/N	A/N	A/N	A/N	-
Post-build Tensile*	CC	CC	CC	CC	CC	CC	CC	CC	>85% typical
Microstructure	Comp	Comp	Comp	Comp	-	-	-	-	-
Post-build Microstructure**	Comp	Comp	Comp	Comp	-	-	-	-	-
Chemistry	A/S	A/S	-	-	-	-	-	-	-
HCF	-	-	-	-	-	-	-	-	-
Low Margin Point	DV Min	DV Min	-	-	-	-	-	-	-
Witness Sub-article	Comp	-	Comp	-	Comp	-	-	-	-
Witness Article	Comp	-	-	-	-	-	-	-	-
Customized QMP	A/S	A/S	A/S	A/S	A/S	A/S	-	-	-

Notes:
CC = Control chart statistical process control acceptance limits
A/N = As needed
A/S = Acceptance as-specified in the QMP/QPP
Comp = Comparative assessment based on defined criteria in the QMP/QPP, or PPP in the case of Witness Articles or Witness Sub-articles
DV Min = Results exceed the design value in the MPS for that point condition
>85% typical = Average to be within 15% of typical value
*Post-build tensile = Post-build witness tensile specimens required for DED only
**Post-build microstructure = Post-build microstructure specimens required for DED only
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications

Table 8—Polymer Witness Testing Quantities and Acceptance Results for Continuous Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

Class

	A1	A2	A3	A4	B1	B2	B3	B4	C
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				4	4	4	4	2
FH Contingency					1	1	1	1	-
Microstructure					-	-	-	-	-
Flexural					-	-	-	-	-
Compression									
Density					-	-	-	-	-
Witness sub-article					A/R	-	-	-	-
Sustained Load					-	-	-	-	-
Customized QMP					A/R	A/R	-	-	-

Notes:
FH Contingency = Full-height contingency specimen
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction).
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

b. Basis for Acceptance of Witness Specimen Results

Class

	A1	A2	A3	A4	B1	B2	B3	B4	C
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				CC	CC	CC	CC	>85% typical
FH Contingency					A/N	A/N	A/N	A/N	-
Microstructure					-	-	-	-	-
Flexural					-	-	-	-	-
Compression									
Density					-	-	-	-	-
Witness sub-article					Comp	-	-	-	-
Sustained Load					-	-	-	-	-
Customized QMP					A/S	A/S	-	-	-

Notes:
CC = Control Chart Statistical Process Control Acceptance Limits
A/N = As needed
A/S = Acceptance as specified in the QMP/QPP
Comp = Comparative assessment based on defined criteria in the QMP/QPP
>85% typical = Average to be within 15% of typical value
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

4.11.3 Continuous Production Build SPC Requirements

[AMR-25] For Class A and B parts, to be eligible for continuous production build witness sampling, the AM machine **shall** be under SPC by meeting each of the following criteria:

a. Machine maintains an active qualification status per NASA-STD-6033.

b. Machine operates under the same or equivalent QMPs since the last successful SPC evaluation build or qualification build.

c. Machine has produced an SPC evaluation build within 60 days, using the sample set given in Table 14 or Table 16 and meeting the requirements of section 5.5 of this NASA Technical Standard.

d. A minimum of 30 data points are collected from at least 10 of the most recent builds to establish control charts for ultimate strength, yield strength, and elongation.

> *This will show a history of control. This requirement is for the formal establishment and reestablishment of control charts. Control charts are not to be updated on a continuing basis.*

e. Control charts for ultimate strength, yield strength, and elongation are established according to ASTM E2587 and controlled by the QMS, with control limits compatible with the applicable PCRD.

f. All witness specimens are exposed to the same post-processing as documented in the QMP.

g. Builds with tensile results that violate control chart acceptance criteria are assigned a nonconformance in the QMS that initiates an evaluation of the part and the AM machine’s process history.

h. Corrective actions are taken for any control chart nonconformance that cannot be specifically isolated to the nonconforming build.

i. Any machine associated with an open SPC nonconformance is given inactive qualification status until the root cause evaluation concludes, the necessary corrective actions are complete, and the CEO concurs with the resolution.

j. The root cause/corrective action record for a nonconformance contains the decision to either return the machine to active qualification or requalify the machine, and the bases for that decision.

[Rationale: The reduced witness sampling in continuous build operations depends on a rigorously defined, steady-state production environment that is monitored and controlled to provide rationale for part quality and reliability. These SPC requirements provide for that SPC environment.]

Note that Class C parts should be treated as independent builds. Due to the reduced witness requirements for Class C parts, these SPC requirements are not warranted.

Tailoring of the default 60-day SPC evaluation build interval may be proposed within the AMCP, with justification, if needed, to better suit the production environment. Alternative intervals may be set on the number of builds, machine hours, or other quantifiable metrics that provide monitoring at a comparable interval.

All requirements of section 4.11.2 of this NASA Technical Standard have to be met prior to using the continuous production build SPC methodology. Builds used to develop the required history of control may be any that are conducted in full compliance with an approved QMP. Acceptance of builds prior to establishing the continuous production build SPC will need to be in compliance with witness testing for independent builds.

4.12 Serialization

[AMR-26] For Class A and B parts, serialization (or equivalent) **shall** be used to provide part traceability to the AM build cycle, the location on the build area/platform within the build, all other production records, governing engineering documentation, and feedstock lots.

[Rationale: The AM process is sensitive to variation in process control, such that each instance of the process has the likelihood of uniqueness; traceability by part back to that process is essential to managing part and inventory risk.]

4.13 Digital Thread

The process of taking a design and creating a finished AM part requires the creation of multiple derivative files along the way. This can include, but is not limited to, computer-aided design (CAD) files, drawings, neutral geometry definition files, witness specimen geometry files, the part build file (i.e., parts, witness specimens, and support structures), Standard Tessellation Language (STL) files, tool path files, parameter files, log files, and execution scripts. Figure 5, Creating Electronic Records of Design/Creation of AM Parts, provides a graphical representation of the creation of these files, which should be considered only as an example as it contains only a fraction of the file types that can be derived during AM processing. These electronic records are considered in the same context of material traceability. It is required to know the source of each file and subsequent version control between files. In some cases, file operations are transient (e.g., the export of an STL or toolpath). In these cases, log files or other records are to document all parameters controlling the operation. The method for documenting and archiving these files will vary depending on the systems that are available at the CEO or qualified supplier. The requirements for configuration *control will be satisfied as long as the files and associated records of parameters are kept under configuration control and are version controlled.*

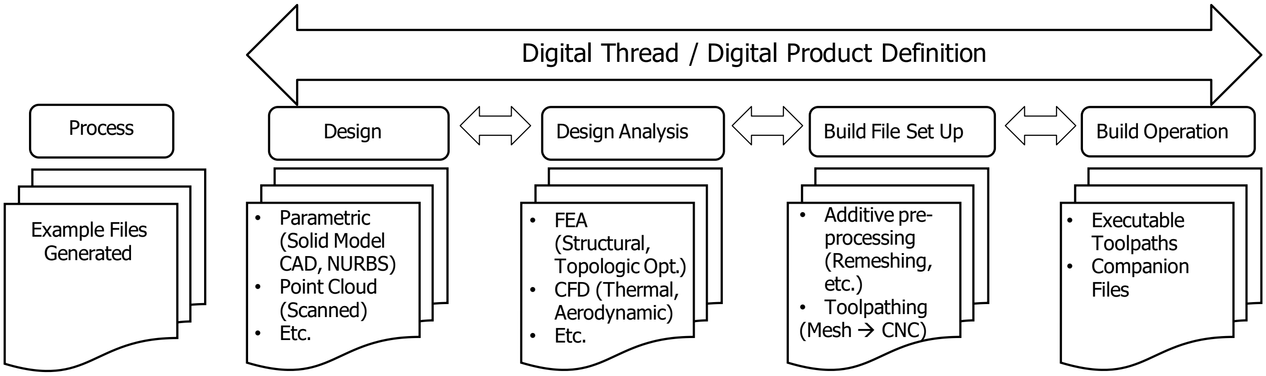


Figure 5—Creating Electronic Records of Design/Creation of AM Parts

4.13.1 Maintaining File Identity and Integrity in the Digital Thread

[AMR-27] All electronic files relevant to the digital thread for an AM part **shall** be controlled by the QMS within a file management system with full version control and appropriate security, with an allowance for files to be removed from the file management system only if they are fingerprinted with a cryptographic hash to ensure unambiguous identity and integrity of the file.

[Rationale: Maintaining unambiguous identity and integrity of all files in the digital thread is essential to controlled production of AM parts. A version-tracking file management system is considered adequate for these purposes as long as the files remain within the file management system. Files, or copies thereof, that have to be removed from the file management system for transfer to a remote server-based system or by any portable storage device are at risk for corruption or tampering. Fingerprinting of every file removed from the file management system provides the means to control identity, version, and integrity of the file.]

Files in scope of this requirement (those relevant to the digital thread) are all files necessary to reproduce fully all aspects of the part design, preparation for the build, and the build and post-build processes. Note that to maintain the validity of the files in the digital thread, software used to process the files also have to be controlled for compatibility in version and configuration.

The 128-bit MD5, SHA-2, and SHA-3 cryptographic hash are examples of industry standard algorithms that may be used to fingerprint digital files and ensure sustainable configuration management.

In accordance with NRRS 1441.1, NASA Records Retention Schedules, and contract and QMS requirements, all part records are archived for the prescribed period and remain fully traceable, including those provided by external suppliers for operations such as heat treating, machining, or inspection. All witness specimen test results and records, as well as nonconformance *documentation, are included in the certification of compliance records for the part. When complete, it is recommended that a final, summarized certification-of-conformance record be generated to demonstrate that all requirements have been met, all nonconformances have been resolved, and the part is fit for service.*

4.13.2 Part Model Integrity

[AMR-28] For Class A and B parts, a methodology for verifying the integrity of part model(s) throughout all stages of the digital part definition associated with the AM process **shall** be documented and implemented via the AMCP.

[Rationale: Verification of the digital part definition ensures that subsequent and derivative digital products are produced to the correct and uncorrupted files. Model validation's role in digitally identifying discrepancies can be crucial for ensuring the integrity of downstream AM products.]

Conformance to this requirement can be demonstrated by using a methodology that includes considerations for digitally sensitive processes (e.g., meshing process and subsequent analysis for the quality of meshed models). Software characterizing and controlling embedded information within the digital part definition can be crucial to supporting an assessment regarding digital quality. Common practices to maintain part model integrity ensure that data formats, coordinate systems, and digital tolerances are identified and conserved through the digital thread. Although software validating portions of the digital thread exist (e.g., those providing CAD validation), demonstrating part model integrity requires the combination of numerous digital considerations identifying and controlling the AM process. These practices are supported through standards (e.g., ASME Y14.41, Digital Product Definition Data Practices: Engineering Product Definition and Related Documentation Practices, and ASME V&V 40, Assessing Credibility of Computational Modeling through Verification and Validation: Application to Medical Devices). It should be noted that standards for quality assurance of digital aspects of the AM process are still being actively developed; consequently, the number of relevant standards demonstrating digital product control will increase with the maturity and adoption of AM.

4.13.3 On-Machine Execution

[AMR-29] Any unplanned modifications to the build file on the machine during AM process setup and/or execution **shall** be assigned a nonconformance and traceable via a records management system controlled by the QMS.

[Rationale: Modifications to the build file during process execution is a deviation from the QPP.]

Some AM software requires the location of the digital model to be placed or located in the build volume on the machine. Location in the build volume is considered part of the QPP; therefore, a placement in the build volume that differs from this location is considered a nonconformance. At the point of build file execution, digital alterations to the build file are treated as a nonconformance.

4.14 Production Engineering Record

[AMR-30] For Class A and B parts, the AM part production process **shall** be controlled by a revision-controlled production engineering record, consistent with the QPP, that contains, at a minimum and when applicable, records of production for the following:

The production engineering record is commonly called a shop traveler, manufacturing router, production planning, or engineering master. The production engineering record derives from and is traceable to the QPP and is consistent with the QMS; see section 8 of this NASA Technical Standard. The production engineering record not only describes the sequence of actions and verifications applicable to the process but can also be a mechanism, particularly when managed digitally, for acquiring process step completion data and in-process verification results, installing hold-points for mandatory inspection points, and documenting process metadata (e.g., dates, operators, digital threat revisions, procedure revisions, etc.).

Note that the production engineering record may reference other revision-controlled processes and procedures.

a. Feedstock removal for any part with geometry precluding line-of-sight confirmation.

Feedstock remaining in the part presents hazards to proper part and system operations. For example, removing residual material following a hot isostatic pressing (HIP) process for metallics or an ultraviolet (UV)-curing process for polymerics may not be feasible. Therefore, it is important that all passages are verified to be clear of material prior to this step. Proper cleanliness may be impossible to achieve later in post-processing, particularly for debris-sensitive hardware. Powder removal on surfaces that do have line of sight are assumed to be addressed by contamination/cleanliness requirements.

b. As-built part visual inspections for any indications of build anomalies prior to processes that may alter the as-built state of the part.

All anomalies should be recorded in detail and be traceable via a records management system controlled by the QMS. Many indicators of AM process quality are best evaluated prior to further part processing, including many indicators (e.g., coloration or support damage) that may be eliminated during further part processing. Build anomalies include, but are not limited to, witness lines on the part surface (if applicable to the AM technology), unusual discoloration, laminar defects (e.g., cracks or tears), separation of part from support structures, and geometric distortion. High-quality photographs to document the as-built part inspection process are recommended, particularly for unusual observations or anomalies.

c. Platform removal.

The sequence and process of platform removal should be controlled to prevent part damage and to ensure interfacing part surfaces retain their intended quality and part traceability is maintained.

d. Support structure removal.

The process for support structure removal should be controlled to prevent part damage, to ensure interfacing part surfaces retain their intended quality, and to maintain part and specimen location and orientation when required.

e. Machining.

Machining operations should be properly staged relative to joining operations, inspections, and thermal processing to ensure part integrity is maintained and verifiable.

f. Thermal processing: environmental conditions (times, temperatures, atmosphere/media), process specifications, quenching media, surface condition of the part, etc.

Part performance is assumed to follow properties developed with microstructures evolved through thermal processes defined in the QMP. Without proper thermal processing controls, part materials may not perform as intended. Industry standards for heat treatment that are not AM specific can be used and referenced to fulfill this requirement.

g. Light-activated curing: environmental conditions (times, ambient light, temperature, atmosphere/media), process specifications, part orientations, wavelength, intensity, duration, etc.

Part performance for processes (e.g., vat photopolymerization) is assumed to follow properties developed with increased polymerization, evolved through light-activated curing defined in the QMP. Without proper processing controls, part materials may not perform as intended.

h. Joining operations (e.g., welding, brazing, soldering, adhesive bonding) that were developed and qualified to an appropriate aerospace standard using representative AM material.

Joining operations on AM parts are not exempted from standard joining process controls as implemented through NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, and NASA-STD-5006, General Welding Requirements for Aerospace Materials. Unique preparation and sequencing may be involved in the joining of AM parts.

An example includes the sequencing of welding operations by the production engineering record to accommodate machining to remove remnants of as-built AM surface from weld lands and to stage heat treatment operations to optimize weld performance and minimize weld residual stress.

This NASA Technical Standard does not levy specific inspection requirements for welds on AM hardware. Inspections are dictated by standard practice based on the class of weld or the fracture control classification of the weld.

Welding standards will typically be levied by the program or project through materials and processes requirements (NASA-STD-6016 and NASA-STD-5006) and tailored by the CEO.

If adhesive bonding processes are applied to AM parts, all surface treatment processes should also be characterized and controlled.

i. Surface treatments that are influential to the performance of the part, structural or otherwise.

Surface treatment operations can have significant impact on part performance and may underlie assumptions of material capability such as fatigue performance. Improperly controlled surface treatments can adversely affect part quality and safety.

j. Part marking: part identifiers and serial numbers, including the locations and method for all marking.

Uncontrolled marking procedures present unwarranted risk to the part. Incorporation of a static part identifier directly in the build geometry is acceptable as long as it is protected during post-build operations, does not interfere with part acceptance inspections, and does not impact the performance of the part (e.g., laser marking or vibro peening, which impacts fatigue resistance). The use of the AM build process to implement serialization is not compatible with a fixed QPP and should not be used.

k. Cleaning and part cleanliness.

Failure to properly control cleaning procedures can lead to contamination-related failures within the part or system. Cleanliness levels and methods of verification are governed by the contamination control plan for the hardware and comply with appropriate standards, such as IEST-STD-CC1246, Product Cleanliness Levels - Application, Requirements, and Determination, or MSFC-SPEC-164, Cleanliness of Components for Use in Oxygen, Oxidizer, Fuel, and Pneumatic Systems, Specification for.

l. Inspections, including, but not limited to, dimensional inspections, surface texture measurements, and NDE.

See section 4.8 of this NASA Technical Standard for additional information regarding NDE.

Confirmation of physical measurements and inspections is important for part conformance but is also an aspect of AM process control. Dimensional errors and flaws for the AM process can be an indication of process escape. Internal measurements may be confirmed using computed tomography, provided that a part analog reference is used to confirm accuracy and precision of the measurements as well as calibration of the tool and data post-processing methods.

m. Part handling, packaging, and shipping.

Part integrity can only be maintained when proper handling and packaging controls are in place to preclude damage. An example of packaging controls may be found in NPR 6000.1, Requirements for Packaging, Handling, and Transportation for Aeronautical and Space Systems, Equipment, and Associated Components.

[Rationale: The production engineering record creates traceability between the qualified AM process conditions and controls, the execution of that process, and final product conformance. The complex nature of AM parts creates a product assurance dependency on the acquisition of objective evidence of process conformance. Minimum criteria for build-specific data acquisition are built into the production engineering record for this purpose.]

For proper AM part traceability, it is important that the production engineering record unambiguously define which records are required to establish the complete production data package for the part.

Applicable processes contained in the production engineering record should be all processing described by the QPP; see section 8 of this NASA Technical Standard.

As a quality record, the production engineering record may also be used as the documentation source of process control requirements and, depending on its implementation, a record of verifications made during the process. The production engineering record may reference other checklists or operating instructions that are controlled by the QMS.

In accordance with contract and QMS requirements, all part records are archived for the prescribed period and remain fully traceable, including those provided by external suppliers for operations such as heat treating, machining, or inspection. All witness specimen test results and records, as well as nonconformance documentation, are included in the certification of compliance records for the part. When complete, it is recommended that a final, summarized certification-of-conformance record be generated to demonstrate that all requirements have been met, all nonconformances have been resolved, and the part is fit for service.

4.15 Preproduction Articles

[AMR-31] For Class A and B parts, a preproduction article evaluation verifying quality of part and material **shall** be conducted for all AM parts, with the plan for evaluation being approved as part of the PPP.

[Rationale: A preproduction article evaluation is necessary to confirm that the design intent of the part is fully realized by the defined part process. Many aspects of part quality vary with part process and can only be verified through the preproduction article assessment (e.g., material internal quality and mechanical performance).]

To meet the intent of this requirement, a preproduction article evaluation has to be based on the finalized build configuration. This configuration includes all parts, supports, and witness specimens, and uses all processes impacting the material condition of the part, beginning with the AM build process through part marking and final acceptance.

The preproduction article evaluation plan, given in the PPP or referenced therein as a separate plan, includes a complete description of each stage of the evaluation, with emphasis on evaluations needed as the part proceeds through processing. Some preproduction article evaluations may require more than one part to adequately capture all objectives. The preproduction article evaluation plan, process, and report should follow the intent of SAE AS9102, Aerospace First Article Inspection Requirement, except that as a preproduction article (as opposed to "first article"), the evaluations extend beyond the production engineering requirements to matters of material internal quality and mechanical performance. The preproduction article evaluation plan is approved as part of the PPP.

At a minimum, the preproduction article evaluation plan should address the following topics, although relevance and importance are expected to vary by part:

- *Material removal and confirmation techniques.*
- *Platform removal procedures.*
- *Thermal processing procedures (where applicable).*
- *Light-activated curing procedures (where applicable).*
- *Dimensional inspections, accessible and post-sectioning.*
- *Surface improvement procedures, sufficiency, and coverage.*
- *Surface texture measurements, accessible and post-sectioning.*
- *Part sectioning cut plans.*
- *Testing within part: microstructure, chemistry, mechanical.*
- *AM risk area evaluations: sectioning and tests target any high AM risk areas of the part.*
- *Witness specimen evaluation: all defined witness specimens for the build are tested and reported.*
- *Part cleaning requirements.*

4.16 Proof Testing

[AMR-32] All Class A and B AM parts **shall** be proof tested as part of acceptance testing unless otherwise substantiated as part of the Integrated Structural Integrity Rationale in an approved PPP.

[Rationale: Proof testing can provide direct confirmation of structural integrity and may be a significant contributor to the structural integrity rationale. Structural failure risks due to defects, uncontrolled processes, or errant workmanship are mitigated though the proof test acceptance test.]

This requirement provides for a proof acceptance test on each part as a fundamental aspect of part quality assurance to protect against manufacturing process escapes that may impact structural integrity. For Class A parts, the proof test is typically one aspect of a larger rationale for part integrity. For Class B parts, in particular those that are fail-safe by redundancy, the proof test helps defend against "common cause" failures due to manufacturing process escapes that may affect multiple parts yet go undetected due to relaxed inspection requirements in this part class.

Although a proof test may potentially be used to quantitatively screen parts for defects as an aspect of fracture control in Class A parts, this requirement levies only a "workmanship" proof, which does not necessitate a quantitative assessment of defect screening. Proof tests levied by other structural requirements automatically satisfy this requirement. If the proof test is not meaningful, beneficial, or practical, then the rationale for not performing the proof test, including planned actions that mitigate the risk of not proof testing, may be described and approved as part of the Integrated Structural Integrity Rationale within the PPP (see section 7.3 of this NASA Technical Standard). In cases where the proof test is performed solely due to this quality assurance requirement, proof test factors and other precautions should follow the trends for similar hardware scenarios provided by structural requirements. In the absence of other suitable guidance, a proof factor of 1.2 on limit conditions with proper environmental corrections for strength are considered appropriate for part acceptance.

It is highly recommended that all AM parts, including Class C parts, be proof tested as effectively as their design will accommodate. For fracture critical/damage tolerant parts, the integrity proof test assessment may also require an evaluation of the flaw size screened in proof and the estimated life assured by proof testing. Proof test cyclic life evaluations may occur analytically or experimentally.

The requirement for proof testing is governed by the program or project structural design and verification requirements. The approval of the proof test and the specifics of the test itself are reviewed and approved by the delegated Technical Authority.

4.17 Qualification Testing

[AMR-33] All AM parts in Classes A1 through B2 **shall** be subject to a qualification test program that demonstrates that part performance and functionality meet the mission design requirements, life factors, and life-cycle capability, given the following stipulations:

a. Parts for qualification testing are produced to a QPP.

b. Any AM part that functions as part of a mechanism is subject to the qualification, design life verification, and acceptance testing defined by NASA-STD-5017, Design and Development Requirements for Mechanisms.

c. The protoflight approach to qualification of hardware as defined in NASA-STD-5001 or JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, which does not include a dedicated test article, is not considered applicable to AM hardware of Classes A1 through B2, nor is the "no test" option for verification by analysis only.

[Rationale: Given the current maturity of the AM design process and the potential for unanticipated failure modes, the need for experimental evidence confirming the design performance of AM parts through a performance qualification test series exists.]

Parts may be qualified individually (if applicable) as part of a subsystem qualification or as part of an overall system qualification. Qualification tests are recommended for AM parts of all classes. If direct qualification testing is not feasible for a part in Classes A1 through B2, then an alternative rationale for part qualification may be proposed in the PPP.

The requirement for qualification testing is governed by the program or project structural design and verification requirements. The approval of the qualification test and the specifics of the test itself are reviewed and approved by the delegated Technical Authority.

4.18 Part Acceptance

4.18.1 Part Acceptance, Class A and B Parts

[AMR-34] For Class A and B parts, data that are objective evidence of part conformance **shall** be a prerequisite for acceptance of the part by the CEO and made available to NASA upon request, including, but not limited to, information showing compliance to all part acceptance items listed in an approved PPP (see section 7.6 of this NASA Technical Standard).

[Rationale: Objective evidence of part conformance is necessary for the CEO to confirm acceptability of parts received.]

Production engineering records should be retained for the life of the program. Records for program residual hardware should be delivered to the procuring authority as part of contract termination.

AM part acceptance, in the majority of cases, is expected to be done by a party other than NASA. This NASA Technical Standard does not require a formal End item Data Package (EIDP) deliverable subject to review and approval by NASA or its program(s), although acquirers may stipulate otherwise by contract.

4.18.2 Part Acceptance, Class C Parts

[AMR-35] For Class C parts, a certificate of conformance (CoC) **shall** be a prerequisite for acceptance of the part by the CEO and made available to NASA upon request.

[Rationale: A manufacturer-issued CoC is a definitive statement that a delivered product meets all requirements and is used by the accepting authority as evidence of conformance, particularly in the absence of lot-specific or unit-specific quality verification inspection results or test data.]

5. QUALIFIED MATERIAL PROCESS (QMP)

The QMP provides a validated, verified, and maintained record of AM process controls that provides assurance of process repeatability for the foundational elements of the AM process (i.e., feedstock material quality, machine controls, and post-processing controls). The use of a QMP, the associated Material Properties Suite (MPS), and first-article inspection results provide the basis for an AM production item's material performance capability. The QMP and MPS provide quantifiable metrics used to monitor the repeatability of the process over time using results of material tests on witness specimens. A QMP is classified as either a QMP-A, QMP-B, or QMP-C, corresponding to the part classification per Figure 4 (i.e., A, B, or C) for which the QMP has been developed. A QMP can be used to produce parts of equal or lower classification (e.g., a QMP-A can be used for Class A, B, or C parts, but a QMP-B can only be used for Class B and C parts).

The QMP method of process development and qualification requires that the AM machine parameter sets and conditions remain constant throughout the build. This means that a model pre-processor does not alter process parameter settings or values based on a prediction of build state, nor does the machine use process feedback to alter the parameter set during the build. This does not imply a limit on the number of fixed parameters that are used to define a parameter set. A variety of fixed parameters consistently applied to model volumes or surfaces is expected (e.g., contour, fill, or "down-skin" parameters in a L-PBF process definition). This base assumption limits the scope of qualification testing and identifies an AM process that has a high likelihood of producing a quality part.

Most importantly, the concept of the QMP is based on a fixed parameter set(s). Therefore, AM processes that alter the parameter set based on process feedback are currently out of scope for this NASA Technical Standard. Common examples of these adaptive AM processes include the typical implementation of EB-PBF and some DED processes that use feedback. The qualification approach for adaptive processes would differ because it adds the scope of qualifying the adaptive algorithm.

Most aspects of this NASA Technical Standard may be applied to such processes, but these parts have to be produced under a "point design" philosophy, which means the part quality and material performance has to be explicitly determined for each part once a part production process is defined. In an adaptive AM process, a majority of the part quality burden is held at the part-centric QPP state.

Requirements for defining a Candidate QMP are given in section 5.4 in this NASA Technical Standard. QMPs are associated with a specific AM machine serial number. For instances when multiple machines and processes are identical per sections 5.2 and 5.5.1, the identical machine's QMPs may be classified as Sub-QMPs and, as such, are subject to reduced qualification requirements per section 5.5.1 in this NASA Technical Standard. Once defined, the Candidate QMP is then qualified through material evaluation and capability demonstration to establish a QMP. Requirements to qualify the material process are given in section 5.5 in this NASA Technical Standard. Following qualification, QMPs are then associated with or "registered to" an MPS that is used to derive the material allowables and associated design values that are used to determine the suitability of the QMP for manufacturing of a given part design. The process for registering a QMP with a MPS is given in section 5.6 in this NASA Technical Standard. For processes using a QMP-C specification, minimums and commercial AM specifications may be used for qualification and properties data. Methodology for compliance with the requirements of this section will be documented in the AMCP (see section 4.2 of this NASA Technical Standard) by referencing the AM manufacturer's internal documents and relevant sections therein and providing a brief description or summary of the content. The expectation is that the QMP requirements in section 5 of this NASA Technical Standard are implemented through an internal AM process specification from the CEO or AM part producer.

5.1 Process Development

This NASA Technical Standard does not define the path the user should take to prepare a candidate material process for qualification. The user is expected to have a thorough understanding of the process and high confidence that the candidate process will meet the requirements of the qualification process before beginning. The effort required to reach high confidence in a candidate process may be negligible for a known, stable AM machine platform with a defined machine setup and parameter settings. Conversely, if the candidate material process involves a new material on a new machine platform, then the development of material specifications and process parameters is likely to be an extensive effort on a scale many times that of the final qualification process.

Figure 6, Overview of AM Production Activities and Sequence, provides an overview of the necessary activities to meet this NASA Technical Standard. The development phase of this flow is a prerequisite but is not controlled by the requirements of this NASA Technical Standard. These activities are essential to establish a reliable candidate material process.

The QMP process should be considered a confirmation and record that the identified candidate material process is mature, stable, and achieves the intended AM material state. The QMP process is not an AM material development activity.

The part producer will demonstrate which parameters, and interactions thereof, are critical to the process and which are not, and implement appropriate control plans for both. Statistically designed experiments (i.e., a design of experiment (DOE) approach) may be useful for this purpose. Each key process variable should be demonstrated to meet requirements throughout the process window (i.e., at the extremes of the parameter settings, considering tolerance) defined within the applicable specification. Those process variables that have a significant impact on requirements are identified as key process variables and become part of the fixed process.

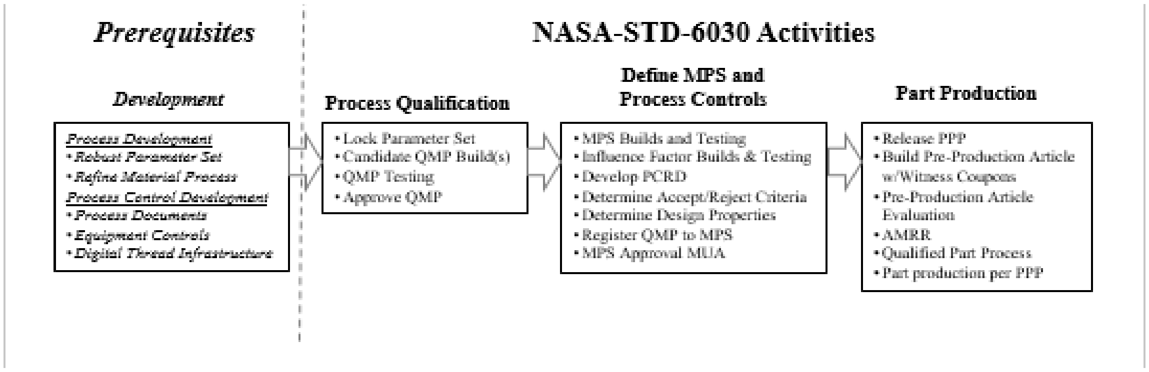


Figure 6—Overview of AM Production Activities and Sequence

5.2 Unique QMPs, Minimum Control Categories

[AMR-36] Each AM machine used to fabricate hardware **shall** have at least one QMP for each unique combination of the following control categories that affect the material condition:

a. Feedstock specification and associated controls per section 5.4.1 of this NASA Technical Standard.

b. Associated machine, build process controls, and restart procedures per section 5.4.2 of this NASA Technical Standard.

c. Post-processing requirements per section 5.4.3 of this NASA Technical Standard.

[Rationale: The QMP provides definition and control for foundational AM processes, enabling parts to be built with a process of verified material quality. These three parameter categories are fundamental to ensuring process repeatability.]

Note: AM machines may operate under the auspices of multiple unique QMPs if variations in controls or material post-processing exist.

5.3 Configuration Management

[AMR-37] Each QMP **shall** be controlled by the QMS and subject to configuration control.

[Rationale: Maintaining QMP integrity is a foundational AM process control enabling parts to be built with a consistent process of verified material quality. QMP configuration control, as defined by the QMS, provides reassurance that any changes to factors that affect a machine's ability to produce consistent material will be qualified and validated. Tracking of QMP revisions for process changes is critical to the fundamental concepts of material integrity and process control.]

Individual QMPs are not expected or required to be explicitly referenced within the AMCP.

5.4 Definition of a Candidate Material Process

Before any candidate material process can be qualified, it must be adequately defined. As represented in Figure 2, the three required elements that define a candidate material process according to this NASA Technical Standard are (1) a feedstock specification, (2) control factors governing the AM process, and (3) requirements for post-AM processing. This section defines the variables, methodologies for their control, and minimum levels of characterization that must occur to define a candidate material process. Once a candidate material process is defined, it is then systematically evaluated for qualification as a QMP.

5.4.1 Feedstock

5.4.1.1 Virgin Feedstock Procurement

[AMR-38] Feedstock to be used for a Candidate QMP **shall** be controlled by industry standard specifications or configuration-controlled material specifications that levy requirements, including tolerances when applicable, to ensure consistent performance in the process and govern, at a minimum, the aspects of virgin feedstock production and procurement defined in Table 9, Virgin Powder Feedstock Controls, for powders; Table 10, Wire Feedstock Controls, for wire; Table 11, Filament Feedstock Controls, for filament; and Table 12, Liquid Feedstock Controls, for liquid feedstock.

[Rationale: Control of feedstock is essential to consistent performance of the AM process. Each of these controls is specified to minimize the likelihood of potential process failures related to the feedstock.]

Controls listed in the tables below that are not applicable to a specific process should be identified in the QMP. It is important to note that not all controls listed have governing industry standards. In these cases, the content of the feedstock material specification must be augmented to define the missing control factor. It may not be feasible to statistically describe some control factors; in such cases, these will need to be specified qualitatively.

5.4.1.1.1 Metal and Thermoplastic Powder

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.*	

5.4.1.1.2 Metal Wire

Table 10—Wire Feedstock Controls

Wire	
a	Requiring wire producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, or an equivalent approved by the CEO.
b	Specifying unambiguously the method of wire manufacture, including rolling and drawing.
c	Specifying wire chemistry requirements, including acceptable methods of measurement and tolerance.
d	Specifying geometric constraints and length requirements, including explicit tolerance.
e	Specifying finish requirements, including explicit tolerance.
f	Specifying permissible method of joining both ends for repair or break during wire processing at the production facility.
g	Providing requirements for wire cleanliness and contamination control.
h	Providing requirements for wire winding packaging, labeling, and environmental controls.
i	Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each wire lot and the date and location of wire production.

5.4.1.1.3 Thermoplastic Filament

Table 11—Filament Feedstock Control

Filament	
a	Requiring filament producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, or an equivalent approved by the CEO.
b	Specifying unambiguously the method of filament manufacture.
c	Specifying filament chemistry requirements, including acceptable methods of measurement and tolerance.
d	Specifying geometric constraints and length requirements, including acceptable methods of measurement and tolerance.
e	Specifying moisture requirements, including acceptable methods of measurement and tolerance.
f	Specifying permissible method of joining both ends for repair or break during filament processing at the production facility, if applicable.
g	Providing requirements for filament cleanliness and contamination control.
h	Providing requirements for filament winding packaging, labeling, and environmental controls.
i	Providing batch monitoring requirements for differential scanning calorimetry.
j	Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each filament lot and the date and location of filament production.

5.4.1.1.4 Photopolymeric Thermoset Resin

Table 12—Liquid Feedstock Controls

Liquid	
a	Requiring resin producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, or an equivalent approved by the CEO.
b	Specifying unambiguously the method of liquid manufacture.
c	Specifying liquid chemistry requirements, including acceptable methods of measurement and tolerance.
d	Specifying liquid viscosity, including explicit tolerance.
e	Prohibiting post-production additions to the material lot for control of chemistry (doping).
f	Providing requirements for liquid cleanliness and contamination control.
g	Providing requirements for liquid packaging, labeling, and environmental controls.
h	Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each material lot and the date and location of material production.

5.4.1.2 Feedstock Reuse Requirements

[AMR-39] For a candidate QMP-A or candidate QMP-B, a feedstock reuse protocol governed by the following rules **shall** be defined and implemented:

a. Metrics are defined for tracking the progression of feedstock reuse for each unique machine operated per the QMP.

b. Limits on feedstock reuse are defined and implemented based on metrics.

c. The performance of AM material produced from reused feedstock up to the defined limit of reuse is tested and substantiated through material characterization in the MPS per the requirements of section 6.6 of this NASA Technical Standard.

d. Feedstock at the defined limit of reuse cycles continues to meet all requirements of the original feedstock specification.

e. For powder feedstock systems, used feedstock is sieved in accordance with the coarse particle limits of the particle size distribution specification and remixed and/or blended with additional virgin powder to eliminate particle size segregation after every cycle through the build process.

f. Once a reused portion of a feedstock blend reaches the reuse limit, the feedstock blend is no longer used in part production under the auspices of the QMP.

g. Feedstock blends that have reached the reuse limit may still be used in material characterization builds used to evaluate reuse limits on material properties.

h. Reuse limits may be reevaluated and expanded as long as the requirements of items “c” and “d” of this section are met.

i. When a reused feedstock no longer meets the virgin feedstock requirements, the addition of virgin feedstock or other additions to bring the feedstock back into specification is not allowed.

[Rationale: Feedstock can degrade through reuse due to changes in chemistry and morphology, each of which can affect the quality of the material process and the resulting hardware integrity. The acceptability of allowing feedstock reuse has been demonstrated when proper controls are verified and maintained.]

Metrics for tracking feedstock reuse include machine operation hours, the number of days feedstock is present in the machine, the number of build operations, or likely a combination of such metrics. Other metrics for monitoring feedstock reuse may be proposed.

Feedstock reuse blends exceeding the reuse limit may be used in developmental or nonproduction builds.

The feedstock reuse protocol may be specified in the QMP or internal specification, or described more generally by the AMCP required by this NASA Technical Standard (see section 4.2).

5.4.2 Build Process

5.4.2.1 AM Build Process

[AMR-40] The AM build process **shall** be defined in the Candidate QMP by a comprehensive list of fixed, key process variables of known influence on the AM build process for any given AM machine.

[Rationale: Identifying the set of key process variables for a specific AM machine, model, and serial number makes the process unique to that machine. The machine configuration, parameter settings, and firmware and software versions are all important to the process.]

Key process variables may include, but are not limited to, feedstock characteristics (e.g., size distribution, shape, chemistry, cleanliness, handling, and storage), environmental conditions in the AM equipment (e.g., temperature, gas flow rate, humidity, gas chemistry), process parameter settings (e.g., layer height, beam power, translation speed, beam spot size), tool path settings (e.g., hatch spacing, area fill schemes, tool path distribution across the entire build area, start/stop sequences), and time (e.g., dwell times, pauses between layers).

Any factors identified with the potential to influence the AM process are intended to be included in the definition of the build controls. Multiple parameter sets may be defined to accommodate specific geometries (e.g., thin sections or overhung surfaces). Some control parameters may be defined as a range of allowed values to accommodate variations from preceding process steps or other dependencies. These parameter ranges and associated guidelines have to be documented in the QMP.

Controls related to the system are typically defined by an electronic parameter file on the machine. This file may be developed by the AM part producer or may be supplied as a non-editable parameter set by the machine manufacturer. These controls are preferably defined as a set using this parameter file. 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. See the discussion of the cryptographic hash and its use in section 4.13.1 of this NASA Technical Standard.

5.4.2.2 Process Restart Procedures

[AMR-41] If a capability to restart the AM process is intended, criteria for determining the suitability for process restart and the detailed procedures for restarting the AM process **shall** be defined as part of the Candidate QMP specific to the AM equipment for which the material process applies.

[Rationale: Restart of a stopped AM process represents a significant risk to part integrity. These risks can only be mitigated if the soundness of the restart procedure is evaluated to established criteria, and, if restarted, such operations are controlled by detailed, qualified procedures.]

Examples of restart criteria include, but are not limited to, the reason for the process stop, maximum allowed stop time, build platform cooling limits, and the condition of the last part layer. The restart procedures are specific to the AM equipment for which the material process is being defined and exist in the form of a detailed procedure or checklist. These criteria and procedures may be documented directly with the QMP, or the material process may reference criteria and procedures established in other configuration-controlled documentation that is controlled by the QMS. Establishing and qualifying a process restart capability does not imply that parts built to the QMP will always be successfully restarted. All planned restarts are qualified in the development of the QPP, and all unplanned restarts are assigned nonconformance status per the QMS pending disposition of the part. In situ monitoring systems may inform the restart procedure. Feedback from in situ monitoring systems may become part of the parameters associated with restart rationale and guidelines.

5.4.3 Post-Processing

[AMR-42] All AM post-processing (e.g., thermal processing, photo processing, curing) that affects bulk material condition **shall** be defined in the Candidate QMP to manage property and microstructural evolution from the as-built state to the final state.

[Rationale: This NASA Technical Standard requires post-build thermal processes to evolve hardware bulk microstructure or polymerized linkages toward a uniform and orderly state to mitigate risks, both known and unknown, associated with material performance due to the complex as-built microstructure or polymerization from the AM process.]

5.4.3.1 Control of Thermal Post-Processing

[AMR-43] Control of thermal post-processing operations **shall** be compliant with SAE AMS2750, Pyrometry, or similar approved standard.

[Rationale: Essential controls on the thermal process are necessary to ensure part reliability.]

5.4.3.2 Variations in Post-Processing

[AMR-44] Variations on post-processes that affect material condition (e.g., thermal or photo process) **shall** be included in the definition of the Candidate QMP and each unique variation qualified and documented per section 5 of this NASA Technical Standard through demonstration that the performance of the resulting material is equivalent to that of the baseline.

[Rationale: Allowing for variations in the thermal or photo-process definition of the candidate material process reduces the burden of developing QMPs for each variant. Allowing such variants is acceptable only when it can be shown that equivalent material is produced; otherwise, part reliability could be compromised relative to performance expectations.]

To determine whether the variation in post-processing produces an equivalent material, an appropriate statistical test would be applied to demonstrate equivalence.

An example of a thermal process variation is the addition of a second solution treatment cycle following welding processes prior to aging a welded assembly. In such cases, the material unaffected by the weld cannot be adversely affected by the second solution heat treatment. Variations to heat treatment that affect material properties or result in material with a different microstructure than the baseline are intended to be qualified separately as different AM metallurgical processes.

An example of a photo process variation is the addition of a second photo treatment cycle following support structure removal. In such cases, the material unaffected by the removal of the support structure should not be adversely affected by the second photo processing treatment. Variations to photo treatment that affect material properties or result in material with a different polymerization than the baseline are intended to be qualified separately as different stereolithography (SLA) thermoset processes.

5.4.3.3 Hot Isostatic Pressing (HIP)

[AMR-45] MPs used for metallic Class A, B1, and B2 part production **shall** include HIP.

[Rationale: This NASA Technical Standard requires HIP for metallic Class A, B1, and B2 parts to mitigate risks, both known and unknown, that are associated with material performance due to the complex as-built microstructure and voids inherent with AM processes.]

Depending on the alloy system being used, HIP can have a dramatic effect on the fatigue and fracture performance of the material. Specific exceptions to this requirement may be approved via the PPP: (a) when sufficient evidence shows that HIP provides little to no performance improvement for that material and use case, and/or (b) when a component is too large for currently available HIP facilities. Omission of HIP for metallic Class A, B1, and B2 have to be documented as part of an integrated structural integrity rationale in a PPP to meet the requirements of section 7.3 of this NASA Technical Standard and as part of the associated QMP.

5.4.4 Customized Material Process

[AMR-46] Any candidate material process using specific controls or unique witness specimen testing to achieve and/or demonstrate particular material performance characteristics **shall** be identified as a customized material process and include the following in the definition of the candidate material process:

a. Description of the desired performance characteristics.

b. Definition of the unique process controls used to achieve the desired material performance characteristics, if any.

c. Definition of the requisite witness specimen tests and acceptance criteria used to confirm the desired performance characteristics of the material.

[Rationale: The identification and definition of customized material processes prevent the loss of unique process controls that may be critical to part integrity.]

Customized material processes are those that require specific controls or unique witness specimen testing beyond the basic controls levied by this NASA Technical Standard to achieve a particular performance characteristic (e.g., cryo-fracture toughness) important to successful use in design. When these unique process controls and witness testing procedures are required to achieve a performance characteristic that is reflected in the MPS and assumed present by the structural design assessment, then the material process is identified as a customized material process. Once qualified per section 5.5 of this NASA Technical Standard, the process is considered a Customized QMP.

5.5 Qualification of a Candidate Material Process

This section defines the requirements for qualifying a candidate material process as a QMP. There is an allowance for reduced qualification burden using the concept of a Sub-QMP. The builds used for process qualification are required to be standardized for consistency and uniformity. The criteria for qualification include verification of the as-built material quality, evaluation of material microstructure and its evolution (as applicable), evaluation of as-built surface texture and detail resolution, evaluation of mechanical performance, and finally, registration of the QMP to an MPS by verification of "engineering equivalence" of the QMP material to that of the applicable MPS.

[AMR-47] All candidate material processes **shall** be qualified as either a QMP-A, QMP-B, or QMP-C prior to production use, with an option to use a sub-QMP if the process commonality criteria of section 5.5.1 of this NASA Technical Standard are met.

[Rationale: The qualification process ensures the defined candidate QMP yields material of the intended quality and reliability. Hardware produced under the auspices of this document is to be produced using a QMP of equal or higher classification.]

5.5.1 Subsequent Qualified Material Process (Sub-QMP)

[AMR-48] A candidate material process **shall** share the following commonality criteria with an existing, approved QMP to enable the use of a Sub-QMP:

a. Feedstock controls are identical.

b. The AM build process definition is equivalent, meaning:

   (1) Same make of AM machine with equivalent configuration and build volume.
   (2) Same make and model of printer head hardware.
   (3) Same scheme for setting build path and assigning parameters.
   (4) Same layer thickness.

c. Post-AM process definition is identical.

[Rationale: The use of a Sub-QMP provides efficiencies by leveraging existing QMPs that are consistent based on machine and process commonality.]

If a candidate material process meets the commonality criteria for an existing, approved QMP, then that candidate material process may be qualified as a Sub-QMP. Leveraging the success of an existing QMP to qualify Sub-QMPs allows for reduced documentation of material evolution and reduced mechanical evaluation for registration to the MPS. The acceptance criteria of the "parent" QMP for material quality, microstructure, and reference part metrics are intended for qualifying candidate material processes as Sub-QMPs.

The sub-QMP is assigned the same class (i.e., -A, -B, or -C) of the parent QMP.

Once established, a Sub-QMP is independent of the QMP on which it was based. The sub-QMP is not affected if the machine associated with the "parent" QMP is removed from service, undergoes maintenance, is updated or moved, or undergoes another similar change that requires a requalification. If issues are discovered that uncover fundamental flaws with the "parent" QMP, then additional verification will be required for all associated Sub-QMPs to ensure those flaws do not invalidate the Sub-QMP's qualification status.

5.5.2 Standardized Content for Builds Used for Qualification

[AMR-49] A set of builds that specifies the content, geometry, and layout of all evaluation specimens needed for qualification of the candidate material process as QMP-A, QMP-B, QMP-C, or associated Sub-QMP **shall** be standardized for use in the evaluations required by section 5.5.3 of this NASA Technical Standard.

[Rationale: The use of standardized content in the builds used for qualification of candidate material processes maintains the necessary consistency and traceability in the qualification and requalification methodology for AM processes and machines.]

Each standard qualification build set should be designed to efficiently and consistently achieve the required qualification evaluations. These standard qualification builds are also used to maintain the active status of QMPs when requalifying machines. Witness specimen geometry should be consistent with specimens used for qualification and qualification maintenance to ensure data are as consistent as possible for evaluating equivalency.

Although the intent is to maintain consistent, standardized specimen geometry and location in the qualification process, the content of the qualification builds may evolve to improve efficiency or improve upon the quality of the qualification process.

For QMP-C qualification builds, it is acceptable to build the specimens alongside the part to streamline the qualification and build process.

Mechanical property evaluations for the QMP have been defined to investigate common failure modes related to tensile strength, ductility, cyclic fatigue initiation, and fracture toughness per Table 13, Minimum Mechanical Property Tests for Metal QMP Builds, and Table 15, Minimum Mechanical Property Tests for Polymeric QMP Builds. Sub-QMPs are qualified with a reduced quantity of mechanical property evaluation requirements, as shown in Table 14, Minimum Mechanical Property Tests for Metal Sub-QMP and SPC Evaluation Builds, and Table 16, Minimum Mechanical Property Tests for Polymeric Sub-QMP and SPC Evaluation Builds.

The specified specimen quantities in section 5.5.3 of this NASA Technical Standard are considered minimum quantities for QMP qualification. A higher quantity of specimens or other test articles may be needed to meet all the QMP qualification objectives. For example, the number of specimens needed to adequately represent process quality for a large-format L-PBF machine is likely to be greater than the quantities specified in the tables.

For candidate material processes that allow for a process restart, the restart procedure is qualified using specimens whose build process includes a process restart for evaluation of microstructure and mechanical properties (see section 4.11 of this NASA Technical Standard). Allowance for this restart condition can impact the design of the standardized content in the qualification builds. For some metallic AM processes (e.g., laser blown powder systems), the number of possible process *restart scenarios requires users to develop evaluation methodology and criteria specific to their process.*

5.5.3 Qualification Criteria

A candidate material process is qualified as a QMP-A, -B, -C, or an associated Sub-QMP upon successful completion of the evaluations prescribed in the following requirements and the outcome recorded as part of the QMP record, as specified in section 5.5.4 of this NASA Technical Standard.

[AMR-50] For AM machines with multiple energy sources, all evaluations and qualification criteria of section 5.5.3 of this NASA Technical Standard **shall** apply independently to each energy source.

[Rationale: Each energy source within an AM machine has potential independent failure modes for performance; thus, the standardized qualification content must provide for qualification of each energy source independently.]

A candidate material process applies to the overall machine, inclusive of all energy sources; thus, the resulting QMP is assigned to the overall machine rather than to individual energy sources. The supporting data and evaluations substantiating the QMP are expected to be traceable to their associated energy source and location in the build, and to permit evaluations of equivalency.

5.5.3.1 Quality of the As-built Material, Metals

[AMR-51] For QMP-A and QMP-B, the as-built material **shall** be demonstrated free of detrimental defects for each of the following cases when evaluated in cross-section at a minimum magnification of 50x, with resolution sufficient to distinguish defects common to the process and a combined area of evaluation ≥6 cm^2 (0.93 in^2) when combined across all cases and evaluations listed here:

a. Survey of consistency throughout the build area.

b. Demonstration that the process window remains free of detrimental defects at the credible extremes of the process (i.e., at the limiting range, given allowed tolerances of key process variable parameter settings, or at the extremes of thermal history due to geometry and scan/deposition pattern).

c. Restart-layer interfaces.

d. Interfaces or overlaps in build path (e.g., striping, islands, multi-laser overlap zones), surface contours, cosmetic passes, including any interface associated with a unique build parameter set (e.g., down-facing, or low-angle surfaces).

e. Typical geometry of the as-built deposition layer characterized for record using an unaltered final deposition layer for specimens representing nominal process conditions, to include metrics such as depth of the melt-pool and depth of melt-pool overlaps normalized by nominal layer thickness averaged over a minimum of measurements. *(See commentary.)*

[Rationale: The quality of the as-built microstructure produced by the machine, with no post-processing, establishes the basis for AM part integrity. Therefore, the AM process is required to demonstrate refinement that precludes detrimental defects created by the AM process.]

For this requirement, defects in the material's as-built structure do not have to result in measurable impact on material performance to be considered detrimental. Such defects may be considered detrimental because they indicate a poorly tuned process or a lack of process control.

For example, to meet the intent of this requirement for L-PBF, detrimental defects may include, but are not limited to, evidence of unmelted powder particles, lack-of-fusion defects, microcracking, organized porosity related to scan strategy, weld melt-pool keyhole defects, overall porosity fraction greater than 0.25% by volume, individual porosity greater than 100 µm (0.004 in), and epitaxial grain growth greater than five layer thicknesses. Randomly dispersed porosity representing less than 0.25% by volume in the as-built microstructure is not necessarily cause for rejection.

For these evaluations, metallurgical cross sections are made parallel to the axis of the build (Z-axis as defined in ISO/ASTM 52921, Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies). Depending on the AM process, additional sample directions may be warranted. Interface evaluations in bulk material may also benefit from evaluations in a plane parallel to the build platform (normal to Z).

Evaluation and characterization of the top-layer melt-pool geometry provides a clear, quantitative record and strong indication of how robustly a process is operating. These characteristics are recorded but are not required to have accept/reject criteria, although such criteria are recommended. Characterizations such as melt-pool depth and overlap depth relative to layer thickness provide insight into the potential for defects, as well as provide a baseline for the process condition for comparison during requalification. See further discussion and figures for typical L-PBF top-layer melt-pool characterization in section 4.2.3.2 and Appendix A of MSFC-STD-3717, Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes.

5.5.3.2 Quality of the As-built Material, Polymer

[AMR-52] For QMP-B, the as-built material **shall** be demonstrated free of detrimental defects for each of the following cases when evaluated in cross section at a minimum magnification of 50x, with resolution sufficient to distinguish defects common to the process and a total area of evaluation ≥6 cm^2 (0.93 in^2) when combined across all cases listed here:

a. Survey of consistency throughout the build area.

b. Demonstration that the process window remains free of detrimental defects at the credible extremes of the process (i.e., at the extremes of the parameter settings, considering tolerance, or at the extremes of thermal history due to geometry and scan pattern).

c. Restart layer interfaces.

d. Interfaces or overlaps in build path (striping, islands, multi-processed zones), surface contours, and cosmetic passes, including any interface associated with a unique build parameter set (e.g., down-facing surfaces for relevant overhang angles).

e. Typical geometry of the as-built deposition layer characterized for record using an unaltered final deposition layer for specimens representing nominal process conditions, to include measures such as the depth of the melt-pool and depth of melt-pool overlaps normalized by nominal layer thickness, averaged over a minimum of ten measurements.

[Rationale: The quality of the as-built microstructure establishes the basis for AM part integrity; therefore, the AM process is required to demonstrate refinement that precludes detrimental defects in the base process.]

For this requirement, defects in the AM as-built structure are considered detrimental not only if they impact material performance, but also if they result from a process that is either inconsistent or operating beyond the limits of an acceptable process box.

For these evaluations, microstructure cross sections are made parallel to the axis of build (i.e., Z-axis as defined in ISO/ASTM 52921). Depending on the AM process, additional sample directions may be warranted. Interface evaluations in bulk material may also benefit from evaluations in a plane parallel to the build platform (normal to Z). Evaluation and characterization of the top layer geometry provides a strong indication of how robustly a process is operating. Characterizations such as melt-pool depth, overlap, and penetration into preceding layers provide insight into polymeric microstructure characteristics.

The morphology of polymers can vary widely depending on their composition and material process. These materials may exhibit a range of microstructural features, depending on their crystallinity. Generally, AM thermoplastics demonstrate crystalline to semi-crystalline structures (e.g., polyether ether ketone (PEEK) or Nylon), while AM thermosets exhibit nearly amorphous morphology (e.g., *photosensitive acrylates and methacrylates). The crystallinity is conventionally lower than those evident in metals and ceramics; consequently, the optical examination of the polymer microstructure is critical in developing an independent understanding of the behavior of a given materials system. The use of fillers, for example, requires an understanding of all processing steps that affect their distribution, alignment, and volume fraction, especially relative to geometric features in first articles.*

The examination of the microstructure, in addition to studying fillers, should look at void content and orientation, the distribution and relative volume fractions of multi-component systems (e.g., co-polymers, etc.), as well as inclusions from processing or reuse of feedstock materials. For a given materials system, 50x represents a reasonable starting point; but the precise magnification used to examine effects must reflect the relative microstructural features (e.g., 50x magnification may not resolve agglomeration or aggregation of fillers sufficiently). Other microstructural features (e.g., residual stress crazing from processing) may be present in the material, although care must be taken to ensure that any crazing or similar strain-induced features are a result of processing and not the cross-sectioning and polishing processes.

5.5.3.3 Material Microstructural Evolution

[AMR-53] The candidate material process **shall** be evaluated for objective evidence of controlled evolution of the material microstructure as follows:

a. QMP-A and QMP-B: from the as-built to the final material structure, including all intermediate post-processing steps that alter the material structure.

b. Sub-QMP-A and Sub-QMP-B: as-built and final material structure.

c. QMP-C: the final material structure.

[Rationale: The requirements levied in this NASA Technical Standard are predicated upon material processes that evolve the microstructure in a consistent manner from the complex, as-built state to a final state more closely representing familiar structure of common product forms. This requirement minimizes potential failure mechanisms associated with native AM microstructures (e.g., strong anisotropy, complex residual stress states, and fatigue and crack growth characteristics).]

For a QMP-A or QMP-B, the microstructure is documented at each step of post-processing, starting with the as-built state and continuing with each intermediate stage to reveal recrystallization and/or evolution through to the final microstructure. Documentation of how a material evolves during each stage of process evolution is important for root cause and corrective action processes following a process escape.

Polymeric processes that do not evolve microstructures can indicate exceptions to this requirement in the QMP.

5.5.3.3.1 Material Microstructural Evolution Acceptance Criteria

[AMR-54] The microstructural evolution acceptance criteria **shall** be documented for:

a. QMP-A and QMP-B: the as-built and the final material structure, at minimum.

b. Sub-QMP-A and Sub-QMP-B: as-built and final material structure.

c. QMP-C: the final material structure.

[Rationale: Microstructural acceptance criteria defined by the QMP are used to maintain consistent process control by establishing uniform standards for requalification, for qualifying Sub-QMPs, and for parts requiring microstructural evaluation for witness test acceptance.]

The defined acceptance criteria are intended to be appropriately adapted to the material and sufficiently complete to ensure that reliable material process control is maintained.

Examples of appropriate metallic microstructural acceptance criteria in the as-built state include interpretation of the criteria required by sections 5.5.3.1 and 5.5.3.3 of this NASA Technical Standard, as rendered in the alloy and by the AM machine and post-processing. For the final state microstructure, acceptance criteria should be applied to the results of evaluations such as average grain size, grain shape, grain boundary appearance, presence or lack of certain phases (e.g., precipitates, carbides), or other features appropriate to the alloy.

For process consistency, Sub-QMPs use the same acceptance criteria as the "parent" QMP.

Polymeric processes that do not evolve microstructures can indicate exceptions to this requirement in the QMP.

5.5.3.4 Surface Texture and Detail Resolution

[AMR-55] For QMP-A and QMP-B, as-built surface texture and detail resolution capability of the AM process **shall** be evaluated using reference part(s) from a minimum of two locations in the build area:

a. Near the center of the build area.

b. The edge of the build area or other process-sensitive location identified with reduced build quality.

[Rationale: The rendering capability of an AM process is commonly not uniform across the build area due to machine influences (e.g., laser incidence angle, light-curing plane, and multiple parameter sets for a given process). These two evaluation locations are intended to bound the process capability.]

This NASA Technical Standard does not levy specific quality criteria for surface texture and detail resolution for the purposes of qualifying a material process. The QMP should be refined regarding these qualities to meet part performance goals or to satisfy material property performance goals (e.g., fatigue life).

Variations of reference parts (i.e., small complex parts that push the limits of the AM process) are used to understand surface texture and detail resolution of an AM system. When the AM process is pushed to the limits of its operational capability, it will become more sensitive to perturbations in operational parameters. By monitoring the reference parts for variations, an AM part producer will have an indication of process capability limitations, as well as early indications of process change during production. The reference part is intended to provide quantitative criteria to judge process performance and repeatability in development of QMPs, AM machine qualification, and AM part production. When used for such purposes, reference part metrics defined by the QMP process are used as acceptance criteria.

5.5.3.4.1 Surface Texture Metrics and Acceptance Criteria

[AMR-56] For each QMP-A and QMP-B, consistent measures of as-built surface texture and detail resolution with associated acceptance criteria **shall** be defined.

[Rationale: To maintain consistency in the AM process, surface texture and detail resolution for process requalification or the development of Sub-QMPs are evaluated with reference parts using the acceptance criteria of the applicable QMP. In many cases, consistency in surface texture and detail are critical to part performance.]

5.5.3.5 Mechanical Properties

[AMR-57] Mechanical properties **shall** be evaluated for all candidate material processes with, at minimum, the specimen quantities according to Tables 13, 14, 15, or 16, as applicable.

[Rationale: Mechanical property performance is a fundamental measure of the quality of the candidate material process and forms the basis for evaluation of material engineering equivalence for the applicability of material allowables and design values.]

Per section 5.5 of this NASA Technical Standard, minimum specimen quantities apply to each individual energy source in the machine.

Table 13 is applicable to evaluate QMPs in metals of Classes A, B, or C.

Table 14 is applicable to evaluate Sub-QMPs in metals of Classes A, B, or C, and for builds used for SPC supporting continuous build operations for witness sampling.

Table 15 is applicable to evaluate QMPs in polymers of Classes B or C.

Table 16 is applicable to evaluate Sub-QMPs in polymers of Classes B or C and for builds used for SPC supporting continuous build operations for witness sampling.

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.

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.

Table 15—Minimum Mechanical Property Tests for Polymeric QMP Builds

QMP Item	Property	ASTM Standard*	Quantity			Notes
			QMP-A	QMP-B	QMP-C	
1	Tensile	D638/D5766/D6742	Not Applicable	15	6	Survey of build area and materials using machined tensile specimens from "hot" and "cold" process variants
2	Tensile, with Process Restart	D638/D5766/D6742		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	Density	*See commentary*		5	-	
4	Flexural	D790		3	-	Method that determines the modulus of elasticity and flexural strength of reinforced and unreinforced plastic.
5	Compression	D695/D6742/D6484		3	-	Method used in determining a material's modulus of elasticity and compressive offset yield strength.
6	Sustained load	D2990		3	-	Stiffness, offset bearing strength, and ultimate bearing strength.
7	Customized QMP	As Specified		2	-	Test at conditions defined by the candidate material process required for acceptance, minimum two (2) tests at condition.

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

The preferred methods for density measurements are still evolving. Standard test methods that may be considered are ASTM D792, ASTM D1505, ISO 1183, and void sampling in cross-section.

Table 16—Minimum Mechanical Property Tests for Polymeric Sub-QMP and SPC Evaluation Builds

Sub QMP and SPC Build Item	**Property**	**ASTM Standard***	**Quantity**			**Notes**
			QMP-A	**QMP-B**	**QMP-C**	
1	Tensile	D638/D5766/ D6742	Not Applicable	10	4	Survey of build area locations using machined tensile specimens.
2	Tensile, with Process Restart	D638/D5766/ D6742		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	Density	*See commentary*		3	-	Not required for sub-QMP (only QMP).
4	Flexural	D790		3	-	Method that determines the modulus of elasticity and flexural strength of reinforced and unreinforced plastic.
5	Compression	D695/D6742/ D6484		3	-	Method used in determining a material's modulus of elasticity and compressive offset yield strength.
6	Sustained Load	D2990		3	-	Not required for sub-QMP (only QMP).
7	Customized QMP	As Specified		2	-	Test at conditions defined by the candidate material process required for acceptance, minimum two (2) tests at condition.

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

The preferred methods for density measurements are still evolving. Standard test methods that may be considered are ASTM D792, ASTM D1505, ISO 1183, and void sampling in cross-section.

5.5.4 Qualified Material Process Record

[AMR-58] A candidate material process **shall** become fully qualified (i.e., a QMP) when:

a. A configuration-controlled record is established containing the complete definition of the QMP and all necessary supporting information substantiating that the qualification requirements of section 5 of this NASA Technical Standard have been satisfied.

b. The CEO has verified it to be complete and satisfactory.

c. Items (a) and (b) are documented and controlled by the QMS.

[Rationale: The QMP is a core governing document of AM process control and, as such, requires proper substantiation, documentation, and approval.]

See section 5.2 of this NASA Technical Standard for additional information regarding candidate material processes and unique QMPs.

This requirement intends the following: Once documented, the CEO approves QMPs; and following this approval, a QMP record defines a fixed process for which changes are prohibited without formal reevaluation and approval.

The development of candidate material processes and execution of the evaluations to qualify them as QMPs are typically the responsibility of the AM part producer. A partnership between the CEO and the AM part producer, if not the same entity, is required for successful implementation of these requirements.

A QMP may be treated as proprietary information. NASA may review a QMP and its supporting data at any time.

5.6 Registration of a Candidate Material Process to an MPS

[AMR-59] Each candidate material process for a QMP-A or QMP-B **shall** be registered to an MPS through confirmation of the properties listed in Table 17, Properties and Controls to Register a Candidate Material Process to an MPS, that have been tested per Tables 13 through 16.

Table 17—Properties and Controls to Register a Candidate Material Process to an MPS

Property	Metals	Polymers
Feedstock specification and feedstock controls are the same as those in the MPS.	X	X
Documentation is available to verify that the material process definition was established and adhered to continuously during the development of evaluation materials.	X	X
Microstructural characteristics are consistent with those of the MPS.	X	X
Tensile strengths and ductility are accepted to the tensile PCRDs of the MPS.	X	X
Measured high cycle fatigue life is accepted to the fatigue PCRD of the MPS.	X	
Measured low-cycle fatigue life is consistent with MPS data.	X	
Measured fracture toughness is consistent with MPS data.	X	
For QMP-A and QMP-B, if applicable, tensile properties at temperature are consistent with MPS data.	X	
Measured density is consistent with density of MPS data.		X
Measured flexural modulus of elasticity and/or flexural strength is consistent with MPS data.		X
Measured compression modulus of elasticity is consistent with MPS data.		X
Measured sustained load performance is consistent with MPS data.		X
Documentation substantiating this confirmation will be configuration controlled within the QMS and recorded within the qualified material process record.	X	X

[Rationale: The material property registration process provides traceability between process capability as demonstrated through QMP qualification and the material property values that will be defined by the MPS and used to determine design manufacturability when using that QMP for a production build. Due to the sensitivity of the AM process implementation, it is not legitimate to assume material allowables or design values associated with previously used but differently controlled AM processes are applicable. The registration process evaluates the key failure mechanisms for design/material/process compatibility (e.g., strength, ductility, cyclic damage, and fracture toughness). While often correlated, these failure modes may act independently.]

Upon successful registration, the material property data should be added to the MPS database. The CEO is responsible for the registration process and eventual final approval of the candidate process as a QMP. For property evaluations where PCRD criteria are not established, candidate data are determined to be consistent with the MPS if the average result of the candidate data lies within the statistical range of existing data in the MPS. If outlier data exist, such test results and associated specimens should be evaluated to determine cause. If outlier data are the result of systemic process issues, then registration should be withheld pending correction and reevaluation. Other metrics for determining data to be consistent may be proposed. The CEO has latitude in making the final determination of registration of a material process to an MPS. If aspects of registration data do not fully meet the criteria above but the MPS appropriately accommodates the difference, such rationale may be provided in the QMP record. If the data do not register to the MPS, then the CEO may opt to gather additional data, continue to improve the process, or develop a new MPS that represents the measured material performance. Note, PCRDs are not required for QMP-Cs.

As per the definition, the PCRD is a simple statistical model used to create acceptance criteria for evaluation of witness specimens used to monitor the AM process. The goal of the PCRD is to employ SPC to protect the process from drift by keeping the properties consistent with those in the MPS. The use of the PCRD in witness testing justifies the continued validity of the material allowables during ongoing AM operations. Control charts use acceptance limits for visualizing process stability and identifying production runs or units whose attribute(s) exceed the limits. Many times it is important to define multiple PCRDs per the QMP.

It is recommended that properties not required for registering a candidate material process to the MPS still be measured and controlled when important to the design. An example is provided with respect to the fracture toughness of a polymeric material. Although a requirement is not placed for measuring this property of a polymer for successful MPS registration (by virtue of implied structural considerations of Class B parts), characterizing fracture toughness provides insight into plane-strain fracture behavior. To assess the correlating properties, conducting ASTM D5045 will indicate a polymer's rate of crack propagation through its plane-strain energy release rate. The applicability of this investigation varies with the polymer and may be more relevant to those exhibiting brittle fracture (e.g., a filled polyamide).

For example, in metallic AM builds, four PCRDs are defined for each MPS: ultimate tensile strength (UTS), yield strength, elongation, and fatigue life at a fixed cyclic stress condition. The choice of defined PCRDs may change with AM process and material depending on which properties are determined most useful to process control. The PCRDs and their associated acceptance criteria are best documented in a manner that allows for occasional revision and sustained use as witness specimen testing acceptance criteria for part acceptance.

5.6.1 Bootstrapping a QMP and MPS

When new AM processes are first established, an MPS may not yet exist to conduct the registration process. In such cases, the material test data generated to produce the QMP are also used to generate the initial MPS (i.e., bootstrapping), and the QMP is registered to the new MPS by default.

Additional data generated from the QMP are used to populate preliminary MPS PCRDs and other material properties to enable registration of additional QMPs.

In these cases, the QMP can be executed with a single feedstock lot to create the initial MPS, but additional lot and variability requirements are governed by the MPS requirements in section 6 of this NASA Technical Standard.

5.7 Qualified Material Process Record

[AMR-60] A candidate QMP **shall** become fully qualified (i.e., a QMP) when:

a. A configuration-controlled record is established containing the complete definition of the candidate QMP and all necessary supporting information substantiating that the qualification requirements in section 5 of this NASA Technical Standard have been satisfied.

b. The CEO has verified it to be complete and satisfactory.

c. Items (a) and (b) are documented and controlled by the QMS.

[Rationale: The QMP is a core governing document of AM process control and, as such, has to be properly substantiated, approved, and documented.]

See section 5.2 of this NASA Technical Standard for additional information regarding candidate material processes and unique QMPs.

This requirement intends the following: The CEO approves QMPs. Once approved and documented, a QMP record defines a fixed process such that changes are prohibited without formal reevaluation and approval. A QMP may be treated as proprietary information. NASA may review a QMP and its supporting data at any time. The development of candidate QMPs is typically the responsibility of the AM part producer. A partnership between the CEO and the AM part producer, if not the same entity, is required for successful implementation of these requirements.

6. MATERIAL PROPERTY SUITE (MPS)

6.1 MPS for Class A and B Parts

[AMR-61] For Class A and B parts, an MPS **shall** be developed and maintained to substantiate the design and production of AM parts.

[Rationale: The four components of the MPS (i.e., material property data, material allowables and associated design values, PCRD, and SPC criteria) are required to integrate the fundamentals of reliable AM part design and production.]

In an effort to maintain consistency with developing aerospace industry consensus in terminology, this NASA Technical Standard uses the terms "material allowable" and "design value" when referring to the properties of AM materials (see the definitions in section 3.2 of this NASA Technical Standard). Material allowable is used to represent the bulk properties of the AM material absent the influencing effects of environment, surface finish, or other factors affecting material performance. The material allowable is intended to include the fundamental sources of variability (e.g., feedstock lots, allowable variations in key process variables, heat treating, machine-to-machine and build-to-build variability, and build-dependent microstructural variability), which may lead to differences in performance between specimen and parts. Note that, for brevity, the term "material allowable" is also occasionally used herein as a general term referring to statistically characterized material properties. The term "design value" represents a material property as applied to the AM part design to assess structural capability. In some situations, the material allowable is directly applicable to the design and, in such cases, the material allowable is used directly as the design value. In many cases, the material property used in the design assessment has to take into account factors that influence the material behavior, such as environment, surface quality, thin sections, or part-specific features. Design values that include these effects are often based on the material allowables through the application of a multiplicative "influence factor" or "scale factor" to alter the material allowable value to represent these effects. A temperature adjustment of the material allowable to create a design value to assess the part at operational temperature is the most common application of this. In some cases, design values may be generated with statistical basis independent of the material allowable. This is most common when the influence factor being assessed for the design value represents a new and significant source of variability not represented in the assessment of the material allowables. In these cases, it is important that the independent assessment of a design value also include the sources of variability represented in bulk material.

Note: Data collected during the development of a QMP may be included in the MPS.

Requirements and further discussion on the development of material allowables and design values are in section 6.11.1 of this NASA Technical Standard.

6.2 Material Properties for Class C Parts

[AMR-62] For Class C parts, all required material properties needed to substantiate the manufacturability of the design and classification of the part **shall** be documented through the MUA process or the PPP, but may be of typical basis.

[Rationale: Understanding of material behavior is required for Class C components to ensure they are properly placed in Class C and perform their intended purpose.]

Material properties for Class C parts may be at a design basis (i.e., bounded statistically or by engineering judgment) or of typical basis (i.e., average values).

An MPS meeting the requirements for Class A and B parts is also acceptable for Class C parts.

6.3 MPS Approval

[AMR-63] An MUA per NASA-STD-6016 **shall** be submitted for MPS review and approval by NASA and, at a minimum, address the following:

a. Documentation substantiating the development, implementation, and maintenance of the MPS (for Class A and B parts).

b. Documentation that addresses, at minimum, the requirements given in sections 6.4 through 6.10 of this NASA Technical Standard, and all subsections relevant to the applicable material allowables and associated design values in sections 6.11.2 and 6.11.5 of this NASA Technical Standard.

c. For Class A and B parts, material allowables and associated design values, PCRDs, and all other supporting data of the MPS are made available for NASA review as requested.

d. For Class C parts, material properties are documented as required to substantiate the design and classification.

[Rationale: Material properties specific to the AM product form and its unique characteristics are required for reliable structural design assessment. Maintaining a suite of material allowables and associated design values along with the supporting data provides the basis for criteria used to monitor process control.]

Except for projects with few AM parts, the MUA addressing the MPS is usually part agnostic. Instead of addressing part-specific properties, the MUA covers the methodology for the development and maintenance of the MPS for use with any appropriate part. A separate, part-specific MUA is required when lot-provisional material allowables and associated design values are used for Class B part production (see section 6.5 in this NASA Technical Standard).

In this NASA Technical Standard, material properties have a role in both design and process control and are maintained as an MPS. The MPS consists of four entities:

(1) Material property data developed for a specific AM material and condition.

(2) The material allowables and design values derived from the data used in structural assessment.

(3) PCRDs derived from the data to describe the material's nominal performance and variability.

(4) SPC criteria based on the PCRD used in evaluating the AM process to ensure the integrity of the material allowables is maintained.

The collection of mechanical properties in this NASA Technical Standard was given a unique name (i.e., MPS) because it serves two purposes: (1) creating a reference of expected performance for use in process control and (2) establishing material allowables and associated design values. For conventional materials, the statistical relationship between process control and material allowables is evaluated at a moment in time and rarely reexamined. In contrast, in the methodology of this NASA Technical Standard, new process control data are continuously monitored and compared with the reference data to demonstrate that the process is not changing. Activities that use these SPC constructs include witness testing, registration of newly qualified AM processes through equivalency evaluation, and requalification of AM processes after machine maintenance or updates. To meet the intent of this requirement, an MPS has to be capable of accommodating new data in an organized manner and maintaining the data traceability over time. While material allowables are expected to remain static, reevaluation of the MPS data is a recurring task to reaffirm the validity of the material allowables and perform equivalency tests for QMP registration and other ongoing needs.

When developed as required by this NASA Technical Standard and implemented in conjunction with ongoing process control monitoring schemes, the material allowables and associated design values in the MPS meet the intent of the requirements for material property reliability for use in structural analysis.

The MUA process in NASA-STD-6016 is the prescribed method for documenting and obtaining approval for the MPS because neither material allowables nor the methodology for developing AM material allowables are currently covered by the MMPDS or CMH-17, Composites Materials Handbook-17, so the MPS will require an MUA (NASA-STD-6016, MPR 38). Other means of documenting and approving the MPS, such as a prescribed data requirement serving the purpose, are acceptable when defined in the AMCP.

6.4 Process Control in Material Property Development

[AMR-64] For Class A and B parts, documented process controls **shall** be implemented on any AM build used to create material for characterization, including the use of a QMP and witness testing with specimens and acceptance criteria equivalent to a Class B1 part, per Tables 5 and 6.

[Rationale: Material properties are reliable only if generated on material produced under defined and controlled processes.]

This requirement applies to any build used to produce material to support the data population of the MPS for a given AM process or for developing process control baseline data. A controlled AM process is a prerequisite to the development of material properties; characterization builds follow a QMP developed per section 5 of this NASA Technical Standard (see section 5.6.1). The process control requirements and prerequisites for producing AM materials for characterization are similar to those required for parts.

6.5 Lot Variability Impact on Material Allowables

[AMR-65] Each material allowable within an MPS **shall** be designated either lot-mature when based on the minimum unique chemistry feedstock lot quantities in Table 18, Required Lot Quantities for Lot-Mature Metal MPS Properties, and Table 19, Required Lot Quantities for Lot-Mature Polymeric MPS Properties, or lot-provisional if not, where:

a. A lot-mature material allowable is applicable to material used in parts of all classes.

b. A lot-provisional material allowable is applicable to material used in Class B parts that are built with a feedstock lot directly represented in the MPS and that have an approved, part-specific MUA.

c. Lot-provisional material allowables are applicable to material used in Class C parts without feedstock restrictions or a part-specific MUA.

[Rationale: Variations in the chemistry and morphology of the feedstock, even within specification limits, result in variability in the performance of material produced using the AM process; so this source of variability has to be incorporated into design values for reliable structural assessment.]

See section 6.11.3 in this NASA Technical Standard for additional insight into how lot-mature and lot-provisional properties impact material allowables and the integrated structural integrity rationale for any given part.

Note that the same material input lot (e.g., heat number from a primary mill) can be used to make many different feedstock lots.

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

Lot-provisional material allowables containing fewer lots than required in Tables 18 and 19 (as few as one lot) may be used for Class B parts with an approved, part-specific MUA. To be approved, the MUA is expected to substantiate that the lot-provisional material allowables have a quantity of data sufficient to make an informed engineering assessment of the quality and statistical significance of the material allowables. The MUA is expected to demonstrate that the feedstock lot used in the production of parts has a meaningful representation in the MPS, typically taken as a minimum of 15% of the population.

In Table 18, a "nominally balanced lot contribution" means that each lot has sufficient representation in the total population to be influential in contributing to the evaluation of variability, and that no single lot, or small quantity of lots, constitutes a majority of the data population. For example, an acceptable working definition of nominally balanced lot contributions would be each lot contributing 10 to 30% of the data population when the number of lots is ≤5, and each lot contributing 5 to 15% of the data population when the number of lots is between 5 and 10. Similar ratios would follow as lot quantities grow beyond 10. Other interpretations for nominally balanced lot contributions are allowed if substantiated in the MPS documentation.

The MPS may contain both lot-mature and lot-provisional material allowables. It is natural for a developing database to contain differing quantities of data used for determining individual material allowables and associated design values.

Feedstock lot variability requirements are recommended but not required for Class C parts.

6.6 Used Feedstock Lot Controls

[AMR-66] When printing Class A and B parts using AM processes capable of feedstock reuse, limiting metrics for feedstock reuse **shall** be established and implemented to ensure the following:

a. The effects of reuse on material performance are either demonstrated as negligible or material property data representing the limiting reuse state are incorporated directly into the MPS population.

b. Parts are not built with feedstock exceeding the reuse limits.

c. The methodology for incorporating the influence of feedstock reuse into the design values of each MPS is described as part of the MUA substantiating the methodology of the MPS development.

[Rationale: For AM processes where feedstock reuse is feasible (e.g., PBF), the AM process has the potential to degrade the feedstock with continued reuse. Degradation mechanisms vary by material and AM process; an understanding of feedstock reuse effects is required, and the AM process is to be controlled to preclude feedstock reuse from affecting part quality.]

Examples of feedstock degradation by reuse include introducing contaminants (e.g., oxygen or combustion by-products), or changing a powder feedstock's morphology and rheology characteristics. The effects of feedstock reuse are material specific; the intent is to evaluate feedstock reuse effects on material properties using only material procured to the feedstock specification identified by the QMP.

The CEO, in collaboration with the AM part producer, is responsible for ensuring feedstock reuse metrics are defined and implemented in accordance with this requirement. The expectation is that the efficacy of the reuse metrics is substantiated through a dedicated test plan and subsequent data that characterize the influence of feedstock reuse on material performance or demonstrate that powder at the limiting reuse metric has a negligible influence on material performance.

6.7 Influence Factors

This NASA Technical Standard uses the term "influence factor" to describe any factor that has the capacity to alter the baseline performance of the material (i.e., the material allowable). These factors include those commonly evaluated for other material product forms, such as environment (e.g., temperature, humidity) or surface condition. For AM materials, influence factors may be fundamentally unique to the AM process, such as the unique impact of down-facing surfaces in the L-PBF process, local feature-driven anisotropy, or even part-specific geometric features whose performance can only be captured through part-analog specimens using a "building block" approach to design values.

6.7.1 Identification and Characterization of Influence Factors

[AMR-67] For Class A and B parts, the CEO **shall** provide for the systematic identification and characterization of any known factor having influence on the bulk or local performance of the AM material for the purpose of establishing design values.

[Rationale: As with all materials, the performance of AM materials is influenced by multiple factors that have to be taken into account for successful part design; all such factors with potential to alter material performance have to be identified and characterized as part of MPS development.]

Examples of influence factor evaluations expected in the MPS include, but are not limited to:

(1) Effects of surface texture, as-built or improved, on material performance as a function of build orientation, particularly in fatigue.

(2) Effects of as-built surface texture and microstructure on thin-section performance, including geometric effects of realized cross section and mechanical property debits.

(3) Effects of the build process pause and restart allowance in the QMP demonstrating that effects are negligible on material performance.

(4) Effects of test specimen geometry for non-standard configurations, the evaluation of part-specific features through building-block tests, or evaluation of material taken from parts (e.g., in preproduction article evaluation).

(5) Effects of feature-specific deposition tool paths, including starts, stops, changes in direction, and intersections of adjacent or crossing deposition paths on alignment of material features.

(6) Effects of feature-specific anisotropy within a part.

For comparison, the following are examples of variability that are not typically tracked as influence factors but are incorporated into the material allowables:

(1) Feedstock lots, heat treating, and machine-to-machine and build-to-build variability.

(2) Allowable variation in key process variables.

(3) Effects of nominally occurring anisotropy in material physical and mechanical properties.

(4) Effects of microstructure differences occurring spatially throughout a build due to AM build history (e.g., thermal, light curing processes, scan strategies, and interpass time or interpass temperature influences).

6.7.2 Influence Factor Effect on Material Allowables

[AMR-68] For Class A and B parts, when required for part assessment, design values appropriate to each identified influence factor **shall** be developed and incorporated into the MPS.

[Rationale: Influence factors alter the AM material performance and have to be incorporated rigorously into the design framework to establish reliable AM part design and production.]

In this methodology, each known and applicable influence factor is evaluated for its effect on the material allowable and is used to create a design value applicable to the AM part's use condition. Any design value developed through the characterization of influence factors have to maintain or bound the level of statistical significance required of its associated material allowable. In some cases, the variability incorporated into the material allowable (e.g., feedstock lots, builds, machines, thermal history) may be satisfactorily imparted to a design value through an experimentally substantiated multiplicative scale factor. In other cases where the influence factor presents a new and significant source of variability (e.g., surface finish effects in fatigue), the design value is independently substantiated, including all sources of variability required of its associated material allowable.

6.7.3 Explicit Evaluation of Anisotropy

[AMR-69] Each MPS for Class A and B parts **shall** explicitly include supporting data necessary to evaluate the effects of anisotropy present in the AM material produced to a QMP such that anisotropy is either properly incorporated into the material allowables and associated design values, or rationale for a bounding isotropic assumption is established.

[Rationale: The AM process creates material using a directional process where the likelihood of the process yielding anisotropic material is high unless controls are in place to minimize this effect; quantifying the effects of anisotropy and rendering appropriate material properties is important to valid structural integrity assessment.]

To make anisotropy evaluations feasible, the build orientation should always be identified and maintained for all material property development activities.

Material allowables and design values developed from the supporting data in the MPS are not required to be orientation-specific if the values of the bounding orientation are used and anisotropy is demonstrated as negligible, typically accepted as a less than a 5% difference in properties by orientation. If the anisotropy is not negligible, then orientation-specific properties are required; and complexity in process qualification and part qualification will follow.

6.8 Criteria for the Use of External Data in the MPS

[AMR-70] For Class A and B parts, material property data generated outside the jurisdiction of this NASA Technical Standard (e.g., prior industry or government data), **shall** meet each of the following criteria prior to incorporation into or establishment of an MPS:

a. Properties are generated from material produced by a documented AM process fundamentally the same as those already registered to the MPS.

b. Authenticating records of traceability are available for the feedstock chemistry and post-AM operations (e.g., heat treatment).

c. Properties are generated from material tested in a material condition (e.g., heat treatment and microstructure) equivalent to that defined by QMPs registered to the MPS.

d. Authenticating records of traceability are available that illustrate the material internal quality and final microstructure.

e. The size, geometry, build orientation, and surface condition of test specimens are defined.

f. The specifications governing the material test methods are defined.

g. The external data are provided in the form of actual test results to allow material allowables and PCRD criteria to be established or independently verified.

h. Demonstration that active QMP(s) produce(s) materials equivalent in structure and mechanical properties, based on the registration process in section 5.6 of this NASA Technical Standard.

[Rationale: The incorporation of prior databases for AM material properties into an MPS will become standard practice as the technology matures. These criteria ensure the database contains sufficient information to follow the process controls required by this NASA Technical Standard.]

6.9 Process Control Reference Distribution (PCRD)

[AMR-71] For Class A and B parts, a PCRD **shall** be established as part of the MPS for each material property identified in Tables 5 and 6 requiring a PCRD for witness specimen test acceptance.

[Rationale: Maintaining consistency of material performance in AM parts is essential to structural integrity. To ensure this control is sustained throughout all AM operations requires a reference definition of expected material performance by which process performance can be evaluated. The PCRD provides this reference.]

As per the definition, the PCRD is a simple statistical model used to create acceptance criteria for evaluation of witness specimens used to monitor the AM process. The goal of the PCRD is to employ SPC to alert the manufacturer when the process control has failed and the printed items' material properties are no longer in the same statistical population as those in the MPS. Control charts provide a visualization and tracking tool for upper and lower acceptance limits and the process's results. Many times it is important to define multiple PCRDs per QMP. For example, in metallic AM builds, four PCRDs are defined for each MPS: UTS, yield strength, elongation, and fatigue life at a fixed cyclic stress condition. The choice of defined PCRDs may change with AM process and material, depending on which properties are determined to be most useful for monitoring process control.

The PCRDs and their associated acceptance criteria are best documented in a manner that allows for occasional revision and sustained use as an acceptance criteria for witness specimen testing for part acceptance.

The type of statistical distribution or other metrics used for the PCRD is not dictated by this NASA Technical Standard. The distribution model should be chosen based on the quality of the distribution's fit to the data or the ability of the metrics to describe the nominal material performance. Any appropriate distribution and associated characteristic parameters may be used to define the PCRD.

For additional commentary for PCRDs, see Appendix C of MSFC-STD-3716.

6.10 PCRD Maintenance

[AMR-72] For Class A and B parts, PCRDs specific to each MPS **shall** be reevaluated regularly following the incorporation of new witness data and updated as required.

[Rationale: The PCRDs associated with an MPS need to represent the current, evolving state of the data within the MPS, reflecting process variability as data are added; PCRDs have to be evaluated to ensure they accurately represent the witness specimen population of the associated MPS and updated as necessary because they are used to define acceptance criteria.]

Prior to meeting the criteria for lot-maturity, PCRD updates are considered an integral part of verifying QMP stability with new sources of data coming from ongoing witness testing. Maintenance of the PCRD is necessary to preserve the functional process control relationships among the PCRD, observed process performance, and the material allowables of the MPS. If the distribution of the PCRD changes, it is important to evaluate that the witness specimen acceptance criteria are still valid and the material allowables are protected. Because it is disruptive to alter process controls, acceptance criteria, and material allowables, these updates should be carefully considered but implemented when necessary.

An example interval for reevaluating the PCRDs is given in Table 20, Notional Example for Reevaluating PCRDs per Number of Builds, or with a review prompted whenever a witness specimen fails to meet the PCRD. Reevaluation intervals may also be based on time or maintenance activities. Initially, lot variability may be lacking in the PCRD data set, and adjustments may be expected. Careful review is warranted whenever a PCRD is adjusted. Witness specimen data that fail to meet the PCRD acceptance criteria need particular attention. As part of the review and disposition of the nonconformance associated with the witness specimen test failure, the failing witness data need to be marked for inclusion or exclusion from the PCRD update process.

Table 20—Notional Example for Reevaluating PCRDs per Number of Builds

Number of Builds	Update Frequency
1 to 10	Every 5
11 to 50	Every 10
51 to 100	Every 20
101 to 500	Every 50
501 to 1000	Every 100
Greater than 1000	Every 250

6.11 Development of Material Allowables and Design Values

[AMR-73] For Class A and B parts, material allowables and design values specific to each AM material and condition **shall** be developed or otherwise substantiated according to the requirements and guidance of section 6.11 of this NASA Technical Standard for all applicable properties and environments required for structural assessment.

[Rationale: Material allowables and design values will differ with AM process and material condition; properties specific to each AM material and condition have to be established to enable reliable structural assessment.]

This section provides requirements and guidance related to the methodology of establishing material allowable and design values for AM materials accounting for unique aspects of the product form and function. To meet the intent of these requirements, the material testing for physical or mechanical properties is based on applicable testing standards (e.g., ASTM E8/E8M, Standard Test Method for Tension Testing of Metallic Materials for tensile testing; ASTM E466, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials, for fatigue testing; or ASTM E1820, Standard Test Method for Measurement of Fracture Toughness, for fracture toughness testing); and the tests are executed by a test laboratory accredited through Nadcap™, the American Association of Laboratory Accreditation (A2LA), or another nationally accepted accreditation body, or by direct approval of the CEO.

6.11.1 Configuration Control of Material Allowables and Design Values

[AMR-74] For Class A and B parts, material allowables and design values **shall** be maintained under configuration control as an integral part of an MPS.

[Rationale: Material allowables and design values are the end-product of an MPS that is made available to the design and analysis community; a methodology to maintain configuration control of the disseminated content is necessary to ensure reliable use of such content in design assessment.]

In this context, all derived materials properties used for AM part design assessment are included in this configuration control requirement.

6.11.2 Design Values Development

[AMR-75] For Class A and B parts, design values established to incorporate the effects of influence factors **shall** be developed on the AM material and have a statistical significance equivalent to the respective type of material allowable.

[Rationale: Design values require the same, or equivalent, reliability as material allowables.]

The development of design values to incorporate the effects of identified influence factors may require a variety of techniques and methodologies. The performance of non-AM product forms (e.g., *forging, bar, plate, etc.) is not intended to be used to infer the performance the AM product form despite the similarity of the basis bulk material and part geometry.*

Design values are to include statistical assessment of the same or equivalent sources of variability required of material allowables. If it can be justified that the influence factor does not add an additional source of variability, ratio methods anchored to the material allowables are generally appropriate, with proper precautions (see MMPDS). If the influence factor does add a source of variability, then a methodology to include this additional variability is required, or the design value is to be developed independent of the material allowable while incorporating all lot and specimen variability requirements.

6.11.2.1 Design Value Margin

Although not required by this NASA Technical Standard, it is recommended that the conservatism of all design values and their respective material allowables be objectively evaluated for potential programmatic risks of redesign efforts if these values have to be lowered as a result of currently unknown sources of variability. The risk of uncovering unanticipated variability is not negligible due to the relative immaturity and continued rapid evolution of AM technologies. The requirements of this NASA Technical Standard make all reasonable efforts to preclude this pitfall, including the minimum variability requirements of section 6.11.3; users are recommended to maintain a design value margin applied judiciously to any material allowable that is not fully lot mature or that is set at or near the statistical tolerance limit requirement. In this context, the design value margin may be considered as an influence factor associated with material property risk that is applied as appropriate to material allowables when creating design values. If a design value has been developed independent of a material allowable, then the design value margin simply represents an additional factor lowering its value to hedge against this risk. A design value margin formulated as a function of the coefficient of variation (CoV) provides a design value margin that scales according to need.

6.11.3 Minimum Variability Requirements for Strength-Related Material Allowables

[AMR-76] Statistical assessment of material data for strength-related material allowables **shall** incorporate a minimum CoV according to Table 21, Required Minimum Coefficient of Variation in Metallic Strength Material Allowables, unless the data set specifically includes data representing variability attributable to differences between specimen and part performance, in addition to all other specified requirements for variability in section 6.5 of this NASA Technical Standard.

[Rationale: The minimum CoV is required to improve the likelihood that material allowables will accommodate the variability and differences in strength properties between qualification/witness samples and flight parts.]

If the CoV of the data set is equal to or greater than the minimum, no change is required. If the CoV of the data set is less than the specified minimum, then the data set is transformed, keeping a constant mean, to have a CoV equal to or greater than the required minimum. Methods for *transforming a data set to a minimum CoV can be found in the CMH-17 and in DOT/FAA/AR-03/19, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure."*

When well controlled, the AM process has the ability to produce very repeatable results in standard specimen geometries, particularly for a given platform and within a single feedstock lot. This makes tracking of process performance by control charts of witness testing attractive, but it also means that it is feasible, or even likely, to generate data sets that do not adequately represent the variability that is induced when building parts due to various geometry features and thermal history during the build process. The analogy in AM is similar to that of generating composite material allowables on well-controlled sub-size panels for application to parts with unique fabrication procedures. In addition to using the building block approach, the CMH-17 philosophy is to maintain an assumed minimum variability to help protect against non-conservative material allowables.

If the material data set can be shown to incorporate specimen-to-part variability sufficient to establish material allowables that effectively include this source of variability, then the requirements for the minimum CoV may be tailored out on a case-by-case basis by MUA.

Table 21—Required Minimum Coefficient of Variation in Metallic Strength Material Allowables

Quantity of Specimens	Required Minimum CoV, Metals	Required Minimum CoV, Polymers
≤30	5%	7%
31 to 60	4.5%	6.5%
61 to 99	4%	6%
100 to 299	3.5%	5%
≥300	3%	4%

6.11.4 Methods for Establishing Material Allowables and Design Values for Metals

6.11.4.1 Physical and Constitutive Properties

Physical and constitutive properties are presented as typical basis (mean value) and are defined as a function of temperature. These values are intended to be generated on the AM material product form. These values are generated as described by the MMPDS.

6.11.4.2 Material Allowables for Tension Properties

[AMR-77] For Class A and B parts, statistical assessment of metallic AM material test data to derive material allowables for ultimate strength, yield strength, and elongation shall be governed by the following:

a. Test specimens are machined to represent bulk AM material and are tested according to ASTM E8/E8M or an equivalent standard.

b. Material allowables are bounded by the 99% probability at a 95% confidence one-sided tolerance limit estimated for the population using a properly fit statistical distribution.

c. A minimum of 100 specimens, distributed according to the lot requirements found in section 6.5 of this NASA Technical Standard, are required to initially establish material allowables.

d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.

e. The tensile property database is maintained by the CEO and updated on a periodic basis as additional data become available from process control-related activities, including witness sampling, preproduction article evaluations, QMP development, and machine qualification.

f. Data analysis methodologies, except as noted in this requirement, follow the intent of the MMPDS guidelines for static tensile property development.

[Rationale: These requirements for material allowables development are designed to accommodate the unique, process-sensitive scenario of AM materials, while achieving the level of reliability associated with traditional metallic material allowables.]

The intent of the static strength property requirements of NASA-STD-6016 are satisfied when all material characterizations and process controls of this NASA Technical Standard are fully implemented. The submittal of an MUA describing the substantiation of the MPS satisfies the NASA-STD-6016 material property control requirements. This MPS documentation also satisfies material property requirements levied by other structural requirements documents, such as NASA-STD-5012 or JSC 65828.

When established material allowables decrease, the programmatic costs are significant. It is strongly recommended that initial material allowables incorporate a design value margin sufficient to guard against such a decrease as the supporting data population of the MPS grows and periodic reassessments of material allowables occur. As AM processes and the MPS data population reach maturity, conservatism can be reduced by reducing the design value margin, if the data support.

6.11.4.3 Secondary Properties

[AMR-78] For Class A and B parts, statistical assessment of the secondary properties of metallic AM materials to derive material allowables **shall** be governed by the following:

a. Test specimens are machined to represent bulk AM material and are tested according to industry standard procedures.

b. Material allowables are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population using a properly fit statistical distribution.

c. A minimum of 20 specimens, distributed according to the lot requirements found in section 6.5 of this NASA Technical Standard, are required to establish material allowables for secondary properties.

d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.

e. The secondary property database is maintained by the CEO and considered for updating if there is a change in properties.

f. Test and data analysis methodologies, except as noted in this requirement, should follow the intent of the MMPDS guidelines.

[Rationale: These requirements for secondary properties development are designed to accommodate the unique, process-sensitive scenario of AM materials, while achieving the level of reliability associated with traditional metallic material allowables.]

The most common secondary properties are compression yield, shear ultimate, and bearing strength. In cases of minor anisotropy, tension properties in orientations other than the primary one can usually be treated as secondary properties.

If secondary properties are not used in the design, then they generally do not have to be derived. If the design has high margins for secondary properties, then a statistically derived secondary property may not be necessary either; but limited testing should be performed to demonstrate the margin and substantiated in an MUA.

6.11.4.4 Fatigue Material Allowables

[AMR-79] For Class A and B parts, as required for structural assessment or at customer discretion, the MPS for any AM material **shall** include material allowables for fatigue developed in accordance with the following policies:

a. Fatigue initiation life properties are developed in the form of stress-life or strain-life curves through testing according to recognized industry standards (e.g., ASTM E466, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials, or ASTM E606/606M, Standard Test Method for Strain-Controlled Fatigue Testing).

b. Specimens are machined to represent the bulk AM material and meet the surface finish requirements of fatigue test standards.

c. Ten or more tests are used to define a fatigue curve for a given condition and, for HCF, a minimum of four tests are within 10% of the stress defined as the fatigue limit (see the definition of fatigue limit for this NASA Technical Standard).

d. Fatigue properties are subject to the lot requirements of section 6.5 of this NASA Technical Standard.

e. The process for developing material allowable fatigue curves from the test data is described in the documentation of MPS development per section 6.3 of this NASA Technical Standard.

f. All fatigue curves are labeled with their basis (e.g., typical or bounding).

g. If the MPS fatigue material allowables are applied to Class A and B parts with cycle counts $\geq 10^8$, then fatigue test data are required to substantiate the fatigue curve in this regime, except for Class B parts, where a methodology for conservatively estimating such fatigue limits based on fatigue data at cycle counts $<10^8$ may be employed when properly documented.

[Rationale: Fatigue properties are critical to AM part integrity. The baseline properties of the bulk material in material allowables are important to understand the relative effects of influence factors used to develop fatigue design values.]

It is important that the fatigue curve basis be consistent with the analytical methodology prescribed by governing structural requirements.

6.11.4.5 Fatigue Design Values

If a fatigue assessment is required and involves influence factors not represented in the fatigue allowables (see section 6.11.4.4 of this NASA technical standard), the development of fatigue design curves is required by section 6.11.2 of this NASA Technical Standard.

Most factors that influence fatigue also include the propensity for increased variability. Unlike tensile design values, it is uncommon to sufficiently represent the fatigue influence factor through a simple multiplicative factor applied to the entire fatigue allowable curve. As such, fatigue design curves are developed from additional testing and largely independent of the baseline fatigue allowable curves. In such cases, it is important that sample size and lot (e.g., feedstock, heat, build) be considered when independently developing fatigue design curves. Documentation of these curves would be expected in the MUA or the PPP. The following aspects are important to the development of fatigue design values:

a. Effects of surface textures rendered by the AM process are important influence factors that are expected to be evaluated.

b. Surface treatment methods (e.g., honing or polishing) that do not ensure complete, uniform removal of all as-built surface remnants from all treated surfaces are expected to be evaluated as fatigue influence factors.

c. With confirmation tests, fully machined AM surfaces may use standard surface finish influence factors applied to the neutral-surface fatigue material allowable curves.

d. Surface treatments (e.g., peening) that improve fatigue life by altering the near-surface stress state without actually removing the surface are expected to be directly evaluated as fatigue influence factors.

e. Surface treatments used to improve fatigue capability are intended to be controlled by a process specification and placed under process control according to section 7.4.3 of this NASA Technical Standard, with the application of such processes addressed in the PPP and evaluated in the preproduction article.

6.11.4.6 Fracture Mechanics

[AMR-80] For Class A and B parts, when a design assessment includes evaluation of crack-like defects by fracture mechanics, the MPS **shall** include fracture toughness and fatigue crack growth-rate properties, in the worst-case material orientation, tested from AM material produced to an appropriate QMP, with lot requirements per section 6.5 of this NASA Technical Standard.

[Rationale: Fracture mechanics properties vary with material product form; characterization of these properties is required in the AM product form.]

Fracture mechanics properties may be bookkept as material allowables or design values, as appropriate.

6.11.4.7 Stress Rupture and Creep Deformation

[AMR-81] For Class A and B parts, when required for part assessment, the MPS **shall** include material properties for stress rupture or creep mechanisms tested from AM material produced to an appropriate QMP, with lot requirements per section 6.5 of this NASA Technical Standard.

[Rationale: Stress rupture and creep properties vary with alloy product form; characterization of these properties is required in the AM product form.]

Stress rupture and creep properties may be bookkept as material allowables or design values, as appropriate.

6.11.4.8 Joining (Welding/Brazing/Soldering)

[AMR-82] For Class A and B parts, material properties for joined AM components **shall** be developed through testing according to recognized industry standards (e.g., AWS B4.0) and incorporated into the applicable MPS with a statistical significance comparable to the base AM material properties using specimens from AM material manufactured from representative QMPs.

[Rationale: For structural reliability, joining properties require an equivalent reliability to that of the base materials. Because joint performance varies with alloy product form, characterization of joining properties is required to use the AM product form.]

Joining properties may be developed as either material allowables or design values depending on how the tests are conducted and how the data are applied in the structural assessment. These properties are intended to meet the intent of specimen and lot requirements of the base AM materials and be assessed to similar statistical significance. The methodology for developing joining properties, in particular, the approach to lot variability, is expected to be included in the documentation of MPS development per section 6.3 of this NASA Technical Standard.

6.11.5 Methods for Establishing Material Allowables and Design Values for Polymers

Test standards for a majority of these material characterizations are available from ASTM International under the jurisdiction of the ASTM D20 Committee on Plastics.

There are numerous properties of polymeric materials not discussed in this section that may be highly influential part design and application. Requirements for many of these properties are driven by part performance or safety. When safety related, these characterization requirements are generally under the auspices of NASA-STD-6016. Examples of such properties outside the scope of this NASA Technical Standard include outgassing characteristics, dielectric properties, surface/volume electrical resistivity, and flammability.

6.11.5.1 Common Aspects Required of AM Polymer Material Characterization

6.11.5.1.1 Importance of Anisotropy Characterization

Due to limitations in the ability to affect microstructural evolution in polymeric AM materials, evaluation of the effects of anisotropy on mechanical properties may require more detailed evaluation than for metallic materials with fully recrystallized microstructures (see section 6.7.3 in this NASA Technical Standard.)

6.11.5.1.2 Viscoelastic and Viscoplastic Response in Mechanical Properties

[AMR-83] For Class B parts, loading rate dependence of mechanical properties, commensurate with application environments, **shall** be accounted for during material characterization and derivation of material allowables and design values.

[Rationale: Mechanical response of polymeric materials may demonstrate significant load rate dependence. Understanding application loading rates and testing the material accordingly is required for accurate material characterization.]

Awareness of strain rate in testing plastic materials is required by the common test standards (e.g., ASTM D638). These test methods typically target a standardized testing rate that leads to specimen failure in 0.5 to 5 minutes. If the service environment includes higher strain rates, then this requirement intends that material properties also be evaluated at a strain rate equal to or greater than that of the service environment.

6.11.5.1.3 Notch Sensitivity

[AMR-84] For Class B parts, materials with plastic tensile strain capability less than 3% **shall** be evaluated for notch sensitivity, commensurate with the applicable design criteria and structural assessment methods.

[Rationale: The effects of stress concentrations on materials with limited ductility may be unpredictable for brittle anisotropic AM materials with potentially unique failure mechanisms. Testing is required to confirm assessment failure criteria assumptions.]

Materials with limited ductility, defined here as materials with less than 3% tensile elongation (plastic strain), should be assessed using a "brittle material" design criteria (e.g., evaluation of the peak maximum principal stress at the surface of the stress concentration). Consult structural assessment requirements for policy.

Test configurations for notches and test methods are not dictated by this NASA Technical Standard. A range of stress concentration values oriented to act on the plane of least ductility is recommended for evaluation.

6.11.5.1.4 Determination or Knowledge of T_g for Design

[AMR-85] Class B parts **shall** not be used in environments with an operational range that causes the part to pass through its glass transition temperature (T_g), measured in accordance with ASTM D7028, Standard Test Method for Glass Transition Temperature (DMA T_g) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA), or equivalent, unless otherwise substantiated as part of the integrated structural integrity rationale in the PPP (see section 7.3 of this NASA Technical Standard).

[Rationale: Polymeric material response may differ greatly at temperatures above and below the T_g*; part applications are designed to remain either above or below the* T_g *to avoid the risk of highly variable material response.]*

The "acceptable" tolerance varies with respect to the crystallinity of the respective polymer. For amorphous thermoplastics, a material-dependent margin exists around T_g *prior to reaching altered mechanical response due to increased polymeric chain mobility at elevated temperatures. Additionally, as* T_g *is an intrinsic property with respect to a material's chemical composition, more than one* T_g *may exist for a given material under different crystallinity phases. Crystalline and semi-crystalline thermoplastics additionally exhibit their crystallization (*T_c*) and melt temperature (*T_m*) as an indicator of transitioning through the amorphous phase into the crystalline phase. Note: The physical properties of thermoplastics can vary significantly as they transition through these stages.*

The heat deflection temperature (HDT) is commonly mistaken as an interchangeable property with T_g*. The HDT is an independent characteristic of a material's deflection at increased temperature and is not applicable for characterizing the* T_g *of a polymer. Measuring the HDT of a thermoplastic, however, can provide useful information for understanding material stiffness at elevated temperatures and is recommended for parts under applicable load cases.*

A common method for measuring the HDT of a polymer is through ASTM D648, Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position.

6.11.5.1.5 Conditioning of Specimens for Moisture Content

[AMR-86] For Class B parts, the moisture content of all polymeric test materials **shall** be known and controlled during property characterization to within a user-defined predetermined range.

[Rationale: Moisture content can have significant influence on the performance of many polymeric materials.]

The interaction of moisture content and temperature is known to influence polymer material behavior; application temperature (or bounding values of temperature) should be included in the evaluation.

6.11.5.1.6 Use of Filled or Reinforced Polymer Materials

[AMR-87] For Class B parts, structural reinforcement added to AM polymer materials **shall** be of nominally random orientation.

[Rationale: Directional or continuous structural fiber reinforcement is currently not allowed in the scope of the NASA Technical Standard for AM parts due to the risk in process and characterization.]

Non-structural directional reinforcement used for other purposes is permitted (e.g., thermal conductivity, dielectric performance, electrical traces, etc.).

6.11.5.2 Mandatory Environmental Influence Factors for Design Values

There are environmental factors that are considered essential to the development and application of reliable design values in polymeric materials.

6.11.5.2.1 Temperature and Environmental Effects

[AMR-88] For Class B parts, as required for part assessment, the MPS **shall** include the effect of temperature, moisture, and other environmental effects on material properties based on testing of the AM product form.

[Rationale: Temperature and environmental effects can vary with material product form; characterization of these effects on properties is required in the AM product form.]

6.11.5.2.2 Chemical Compatibility

[AMR-89] For Class B parts, compatibility of the polymeric AM material with any chemicals with a known potential for exposure to the AM material during manufacture or in service **shall** be evaluated for any detrimental influence on material performance.

[Rationale: Polymer material response varies greatly when exposed to a variety of chemicals present in spacecraft systems and associated manufacturing processes, leading to the potential to significantly reduced material performance.]

These chemical compatibility tests are intended to take place on AM materials produced to a QMP representative of that used for the parts.

6.11.5.3 Physical and Constitutive Properties

[AMR-90] For Class B parts, all physical and constitutive properties required for proper design assessment **shall** be evaluated on representative AM polymeric materials.

[Rationale: Physical and constitutive properties of materials can be a function of the AM process generating the final product form; evaluation of AM materials is required.]

Physical and constitutive properties are commonly presented as typical basis (mean value) and can be defined as a function of environmental conditions (e.g., temperature, humidity, pressure, etc.). Note that the relevance of specific properties varies with respect to polymeric process and application. Useful guidance for the test and evaluation of these properties can be found in CMH-17.

Examples of physical and constitutive properties include T_g*, thermal conductivity, elastic moduli, Poisson's ratio, and heat deflection temperature.*

6.11.5.4 Material Allowables for Tension and Compression Properties

[AMR-91] For Class B parts, derivation of static strength material allowables in tension and compression **shall** be governed by the following:

a. Test specimens are machined to represent bulk AM material and are tested according to appropriate polymer material test standards.

b. Material allowables are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population, using a properly fit statistical distribution.

c. A minimum of 100 specimens, distributed according to the lot requirements in section 6.5 of this NASA Technical Standard, are required to initially establish material allowables.

d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.

e. The property database is maintained by the CEO and updated on a periodic basis as additional data become available from process control-related activities, including witness sampling, preproduction article evaluations, QMP development, and machine qualification.

f. Test and data analysis methodologies, except as noted in this requirement, follow the intent of the CMH-17 guidelines for static tensile property development.

[Rationale: These criteria partially adapt a combination of CMH-17 and MMPDS requirements for design values to meet the unique, process-sensitive scenario of AM polymeric materials.]

An assumption of symmetry in tensile and compressive response for strength and moduli may be inappropriate for many of the polymeric AM materials; each of these properties is evaluated explicitly.

When established design values decrease, the programmatic costs are significant. It is strongly recommended that initial design values incorporate a design value margin sufficient to guard against such a decrease as the supporting data population of the MPS grows and periodic reassessments of design values occur. As AM processes and the MPS data population reaches maturity, the design values may be allowed to increase by reducing the design value margin if the data support.

The intent of the static strength property requirements of NASA-STD-6016 are satisfied when all material characterizations and process controls of this NASA Technical Standard are fully implemented. The submittal of an MUA describing the substantiation of the MPS satisfies the NASA-STD-6016 material property control requirements. This MPS documentation also satisfies material property requirements levied by other structural requirements documents (e.g., NASA-STD-5012 or JSC 65828).

6.11.5.5 Shear Properties

[AMR-92] For Class B parts, material allowables for shear strength **shall** be explicitly characterized, as required for structural assessment, according to the following:

a. Test specimens are machined to represent bulk AM material and are tested according to appropriate polymer material test standards.

b. Material allowables are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population, using a properly fit statistical distribution.

c. A minimum of 20 specimens, distributed according to the lot requirements found in section 6.5 of this NASA Technical Standard, is required to initially establish material allowables.

d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.

e. The property database is maintained by the CEO and updated on a periodic basis as additional data become available.

f. Test and data analysis methodologies, except as noted in this requirement, follow the intent of the CMH-17 guidelines for static tensile property development.

[Rationale: Assumptions that shear properties will follow from isotropic continuum rules is not appropriate for AM materials that are prone to anisotropy and planes of reduced shear capability.]

The small quantity of test specimens for shear properties relies on an assumption that these properties can leverage the tension and/or compression tests through ratio methods. If the variability demonstrated by the shear tests is not comparable to the tension/compression data, then more tests will typically be needed for an independent evaluation.

6.11.5.6 Flexural Properties

[AMR-93] For Class B parts manufactured using material with plastic tensile strain capability less than 3%, the flexural strength **shall** be evaluated, if required, for the following scenarios:

a. If used in structural assessment, providing confirmation of design criteria and structural assessment methods.

b. If used as a process control indicator, providing criteria for process qualification and production process monitoring.

[Rationale: Flexural properties are valuable indicators of capability, particularly for materials with asymmetry in tension and compression behavior and capability. This property can be used as a convenient process monitoring evaluation.]

The use of flexural properties directly in design is less common than for use as a process control indicator. The statistical treatment of the data is not specified, but when implemented, the statistical significance of the data is expected to be commensurate with its use.

6.11.5.7 Fatigue Material Allowables and Design Values

[AMR-94] For Class B parts, when required for structural assessment or by the customer, the MPS for AM polymer materials **shall** include material allowables and/or design values for fatigue developed in accordance with the intent of the requirements in sections 6.11.4.4 and 6.11.4.5 of this NASA Technical Standard, with appropriate accommodations for polymeric material test standards and test methods.

[Rationale: Fatigue properties are critical to AM part integrity. There are currently no other sources providing these AM material characterization requirements.]

It is important that the fatigue curve basis be consistent with the analytical methodology prescribed by governing structural requirements.

6.11.5.8 Fracture Mechanics

For Class B applications in low ductility polymeric materials, evaluation of defect resistance due to fracture is highly recommended, particularly if there are preferential planes of low ductility.

6.11.5.9 Sustained Load Creep Deformation and Stress Cracking

[AMR-95] For Class B parts, if applicable to part design and required for structural assessment, the material response under sustained load conditions leading to creep mechanisms, crazing, or stress cracking **shall** be evaluated from AM material produced to an appropriate QMP, with lot requirements per section 6.5 of this NASA Technical Standard.

[Rationale: Stress rupture and creep properties vary with material product form; characterization of these properties is required in the AM product form.]

This may be considered a bounding case of viscoplastic rate effects for static load conditions. The statistical significance of these properties is not specified. Conservatism is expected to be maintained either through bounding the material response or through generous factors applied in the structural assessment.

6.11.5.10 Joining

[AMR-96] For Class B parts, material properties for joining polymer AM products **shall** be developed to a statistical significance comparable to the base AM material properties using AM product manufactured from the same QMPs and incorporated into the applicable MPS.

[Rationale: Properties vary with material product form; characterization of these joining properties is required in the AM product form.]

Joining of polymeric AM parts includes adhesive bonding as well as processes that affect the AM material directly (e.g., chemical or friction joining).

7. PART PRODUCTION PLAN (PPP)

[AMR-97] A PPP for each AM part **shall** be developed by the CEO to address all requirements of this section, subject to review and approval by NASA.

[Rationale: The PPP is required for two primary purposes. First, the PPP serves as a mechanism to define process controls unique to a particular part design/build, capturing those process criteria that are not on the drawing. Second, the PPP serves as the primary means of communication of the part production intent and the level of risk associated with the AM part.]

The PPP is intended to be a configuration-controlled document developed by the CEO that conveys, in a concise manner, the full intent for the design, production, and use of the AM part. The combined content of the engineering drawing, the PPP, and the AMCP is used to establish the complete production engineering controls governing the execution of all steps in the part production process.

The form and format of the PPP are not specified. They should be adapted to suit the prevailing engineering and quality control documentation system of the CEO. The PPP should be a self-substantiating document; but when needed to streamline the document, the PPP may reference other configuration-controlled documentation that is available to NASA on request.

The method of approval for the PPP by NASA may be adapted to suit the contractual system established between NASA and the CEO.

For Class C parts, the PPP need only include a part classification rationale and witness testing.

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.

[Rationale: This information is necessary to communicate the proposed configuration of the AM part to NASA and provide an objective comparison with the final build configuration for the qualified part process (see section 8 in this NASA Technical Standard)].

Revision numbers or dates for the above items do not need to be included in the PPP. If they are included, revisions to the above do not require re-review and approval of the PPP by NASA unless the criteria in section 7.7 of this NASA Technical Standard are met.

7.2 Part Classification and Associated Rationale

[AMR-99] The PPP **shall** state the part classification and provide a detailed rationale for the classification given.

[Rationale: Part classification is necessary to determine the applicable requirements of this NASA Technical Standard and to ensure suitable technical oversight by the CEO and NASA.]

See section 4.3 of this NASA Technical Standard for additional information regarding AM part classification.

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.

[Rationale: Articulation of an integrated structural integrity rationale in the PPP ensures that the design state of the part and any associated quality assurance processes are mature prior to PPP approval.]

The integrated structural integrity rationale is not intended to levy new performance or quality requirements on a part. It is not intended to supersede existing standards but is intended instead to put all of the relevant information in one place for NASA review. The integrated structural integrity rationale describes in a succinct manner how the quality assurance activities imposed on the part, when considered as a whole, form sufficient rationale for structural integrity. Quality assurance activities commonly include, but are not limited to, AM process controls, NDE, functional acceptance testing, proof testing, and leak testing. For leak testing methodology guidance, see NASA-STD-7012, Leak Test Requirements. The rationale needs to be commensurate with the part's classification. Class A parts typically require a quantitative rationale through, for example, inspections of known detection capability. Parts may rely on multiple quality assurance activities to achieve full coverage of the part, particularly those classified with high AM risk. The rationale also identifies areas or volumes of the part relying solely on process controls (i.e., not verifiable by post-build inspection) as risk areas for further consideration.

For additional commentary, see MSFC-STD-3716, Appendix B, section 6.1.4.

7.4 AM Part Production Summary

[AMR-101] For Class A and B parts, the PPP **shall** provide a summary list or table with primary production steps, critical to successful part production and performance, in sequence as governed by the production engineering record.

[Rationale: Identifying the primary production steps and their sequence is essential to reliable AM part design and production. Given the criticality of production sequencing, the PPP reports these primary production steps to provide a meaningful and efficient overview of the part production sequence necessary for PPP approval.]

The comprehensive sequence of part production steps in the Production Engineering Record can be lengthy and represents more information than needed for the PPP review. The production sequence reported in the PPP is intended to contain the primary steps with potential significant influence on part quality. An example of primary production steps reported in the PPP for a L-PBF part would commonly include the following: build cycle, powder removal confirmation steps, all thermal process steps, build platform removal, machining, surface treatment operations, all NDE performed, all welding operations, and proof testing or other acceptance testing.

7.4.1 Witness Testing

[AMR-102] The PPP **shall** describe the witness testing for the part, meeting the requirements in section 4.11 of this NASA Technical Standard or deviations therein, including the specimen types, designs, and quantities, and their layout in the build volume, test methods, and acceptance criteria.

[Rationale: Witness testing is required to provide evidence of systemic process control throughout the build cycle. The implementation of witness sampling will vary from part to part depending on part class, the build layout, and specific part requirements; the PPP is used to document the witness sampling approach supporting the establishment of a QPP.]

Thorough descriptions of witness testing in the PPP are particularly important for any witness specimen of a part-specific nature that requires unique definition, specifically, low margin point, witness sub-articles, witness articles, and customized QMP testing.

7.4.2 Planned Interruptions

[AMR-103] For Class A and B parts, the PPP **shall** document all planned interruptions of the AM build, including allowable build height range(s) for the interruption and planned post-build evaluations of the process restart interface.

[Rationale: Build interruptions that are known to be required (e.g., for powder refilling), are planned to allow confirmation of the interruption in the preproduction article and to emphasize inspections and witness specimen evaluations at the interruption.]

Every effort should be made to eliminate build interruptions.

Planned build interruptions are allowed only if qualified procedures exist and are followed. The QMP defines the limitations for a planned interruption and qualifies the procedures for handling the interruption and restoration of the build process.

7.4.3 Post-Build Operations Requiring Specific Controls

[AMR-104] For Class A and B parts, the PPP **shall** describe or reference any specific controls required for post-build part processing operations that are process sensitive.

[Rationale: Some operations may have significant impact on part performance and may underlie assumptions of material capability. Some operations have the potential to impact the performance of other hardware in the system.]

Process-sensitive operations are those where the outcome of the operation is difficult to verify but is critical to part performance.

Examples may include, but are not limited to:

- *Support structure removal that require unique methods.*
- *Thermal treatments (e.g., SAE AMS2750, pyrometry).*
- *Photo processing (e.g., UV exposure for thermoset polymers).*
- *Unique machining operations (e.g., laser ablation, water jet).*
- *Mechanical surface treatments (e.g., shot peening, grinding).*
- *Chemical processing (e.g., passivation, etching).*
- *Cleaning.*
- *Non-line-of-sight feedstock removal.*
- *Joining (e.g., welding and bonding).*

Also see section 4.14 of this NASA Technical Standard.

7.5 Preproduction Article Requirements

[AMR-105] For Class A and B parts, the PPP **shall** describe a preproduction article evaluation verifying quality of part and material.

[Rationale: A preproduction article evaluation is necessary to confirm that the design intent of the part is fully realized by the defined part process.]

See section 4.15 of this NASA Technical Standard for additional information regarding preproduction articles.

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).

[Rationale: For proper AM part traceability, it is important that the PPP and eventual production engineering record unambiguously define which records are required to establish the complete production data package for the part. Without such accounting, data packages for parts may be incomplete, resulting in parts with insufficient quality rationale.]

The build designation is any unique and unambiguous identification that enables distinct and direct reference to any given build.

7.7 Part Production Plan (PPP) Revisions

[AMR-107] A revision to the PPP **shall** be submitted to NASA for review and approval, for any of the following:

a. Changes to QMP(s) specified for production.

b. Changes to part classification (e.g., Class B to C, or Class B1 to B3, etc.).

c. Changes to part geometry.

d. Changes to build layout.

e. Changes to witness testing.

f. Changes to preproduction article.

g. Any other change that impacts the form, fit, or function of the part.

[Rationale: Changes to an existing QMP that require a full new qualification or the need to use new QMPs that do not meet the criteria of a Sub-QMP require a new preproduction article to ensure process differences do not manifest in changes to the part.]

7.7.1 Rebuild of Preproduction Article

[AMR-108] For all Class A and B parts, a new build of the preproduction article **shall** be evaluated when a new QMP is used for part production, or the QMP specified by the QPP requires requalification due to changes of the QMP definition, per section 8.4 of this NASA Technical Standard.

[Rationale: Changes to an existing QMP that require a full new qualification or the need to use new QMPs that do not meet the criteria of a Sub-QMP require a new preproduction article to ensure process differences do not manifest in changes to the part.]

When a QMP is requalified, it has to meet the acceptance criteria established in the original QMP. In these cases, a preproduction article does not need to be repeated. If changes made to a QMP definition result in a process that no longer meets the original acceptance criteria, a new preproduction article is required.

8. QUALIFIED PART PROCESS (QPP)

[AMR-109] An AM Readiness Review, defining a qualified part process, **shall** be conducted for all Class A and B parts.

[Rationale: A formal review of parts prior to flight production is required to ensure that all stakeholders have reviewed the design and manufacturing process(es) and that the part will meet all system and project requirements.]

Note that an AMRR for Class C parts is not required by this NASA Technical Standard but is highly encouraged.

8.1 AM Production Readiness Review (AMRR)

[AMR-110] The CEO **shall** conduct an AMRR at the completion of all activities outlined in the PPP and prior to the production of the first deliverable AM part, meeting the following criteria:

a. Attendees, including, but not limited to:

   (1) CEO (chair).
   (2) Discipline representatives for Class A and B parts:
      A. Design.
      B. Structures.
      C. M&P.
      D. AM manufacturing production.
      E. Safety and mission assurance/quality assurance.

   Note: If an AMRR is held for a Class C part, attendance is at the discretion of the CEO.

   (3) NASA M&P representative or delegate (with a minimum of 14 calendar days' notice):
      A. Attendance is required for all Class A1 and A2 parts.
      B. Attendance is at NASA's discretion for Class A3, A4, and B parts.
      C. NASA only needs to be notified at the completion of an AMRR or the establishment of a QPP for Class C parts.

b. Topics, including, but not limited to:
   (1) Maturity of all manufacturing controls (e.g., QMP) and AM performance (e.g., MPS).
   (2) Results from the preproduction article.
   (3) Validation that part will meet minimum project requirements.

c. Required minimum approvals: CEO.

[Rationale: The AMRR process is required to confirm that the requirements of the production engineering record are complete and will render a part that meets the requirements of the certified design. The multidisciplinary AMRR process provides a record of authorization to proceed to production with a QPP.]

For the AMRR process, all constituents of a candidate part process are assembled for review, including the candidate production engineering record, part drawing, approved PPP, successful preproduction article report, and any additional documentation influential to the part production process.

If the AMRR team is not satisfied with the candidate part process, the AMRR team clearly identifies all deficiencies. Once deficiencies are corrected, the candidate part process is subject to another AMRR.

For the purposes of this document, a Manufacturing Readiness Review corresponds to a Production Readiness Review, as referenced in NPR 8735.2.

8.2 Additive Manufacturing Readiness Review (AMRR) Documentation and Approval

[AMR-111] The outcome of the AMRR **shall** be documented in the relevant QMS, subject to review and approval by the CEO, including, but not limited to, the following copies of reviewed materials:

a. Presentation materials.
b. Attendance.
c. Minutes.
d. Actions.
e. Concurrences.
f. Dissenting opinions.

[Rationale: A thorough documentation of the outcome of the AMRR is vital in the event there are issues during fabrication of production parts or performance issues after delivery.]

8.3 Qualified Part Process (QPP): Establishment

[AMR-112] The QPP **shall** be established following approval of the AMRR by the CEO, or as defined in the AMCP for Class C parts, with no further changes to the build configuration, its electronic files, or post-build processes permitted without the written approval of the CEO.

[Rationale: Establishing the QPP formally defines and places the process for part production under configuration control provided by the QMS. The quality and consistency of AM parts cannot be assured without establishing a QPP.]

For Class A and B parts, approval of the AMRR by the CEO, as specified in section 8.2 of this NASA Technical Standard, can serve as approval of the QPP. For Class C parts, a different mechanism for approval needs to be defined in the AMCP since a formal AMRR is not required for Class C parts.

The establishment of a QPP is the technical authorization to proceed with part production.

This requirement intends that the content of the build cannot be altered relative to that used in the preproduction article qualification process—no parts, supports, or specimens are added, subtracted, rearranged, or altered in the build.

8.4 Qualified Part Process (QPP): Modifications

[AMR-113] For Class A and B parts, the CEO **shall** define the methodology for changing and requalification of the part production process when changes to a QPP are required, including when the AMRR process is used to reestablish the QPP following any modifications.

[Rationale: It is acknowledged that occasionally circumstances arise where changes to the fixed process are necessary. Defining in the AMCP the methodology for requalifying the part production process following a change ensures that rigorous, proportionate, and consistent requalification procedures are followed.]

A QMP is considered nominally similar if it can meet the Sub-QMP commonality criteria as stated in section 5.5.1 of this NASA Technical Standard. Incremental or partial requalification schemes are allowed for minor changes. Changes that impact the part geometry or support structures or that may otherwise impact the manufacturing process are expected to repeat the preproduction article process. The AMRR process is intended to be used to reestablish the QPP following any modifications.

Allowing additional AM machines (QMPs) to produce parts under the QPP is a common modification; the following criteria may be included in the AMCP as a preapproved method for a QPP change for additional QMPs.

Additional QMPs may be added to a QPP under the following scenario:

a. The addition of the new QMP is the only change to the QPP.

b. The new QMP is to be used by the same AM part producer and facility for which the QPP was established.

c. The new QMP is nominally similar to the baseline QMP.

d. The new QMP is properly registered to the MPS for the part.

e. The new QMP has documentation of a successful preproduction article evaluation of the part.

For this requirement, the digital product definition (DPD) includes any electronic data source or record that would be needed to fully reproduce the build as it was defined at the time the part process was qualified as a QPP, including any manually set parameters in software used to process the part from CAD to the final, assembled build file, which includes support structures, witness specimens, and any other content in the build.

Each file necessary to create the build is identified by filename and its cryptographic hash as part of the QPP definition. To maintain traceability, electronic data are archived with necessary safeguards against loss as required by the QMS.

Electronic data that contains information considered proprietary or controlled under regulations such as the International Traffic in Arms Regulations should be marked and controlled according to regulation. Note that these rules require appropriate access control to data marked with such restrictions at all stages of producing AM parts.

8.5 Build Execution

[AMR-114] For both preproduction and production builds, the production engineering record for the QPP **shall** be controlled by the QMS and contain steps that are fully traceable to procedures and checklists governing setup and initiation of builds.

[Rationale: Reliable part production can only occur with properly controlled production planning.]

See section 4.14 of this NASA Technical Standard for additional information regarding the production engineering record.

8.6 Control of Digital Thread for Part Production

[AMR-115] The QPP **shall** document the digital thread.

[Rationale: The QPP has to contain or reference the complete digital thread to maintain part production integrity.]

See section 4.13 of this NASA Technical Standard for additional information regarding the digital thread.

APPENDIX A

REQUIREMENTS COMPLIANCE MATRIX

A.1 PURPOSE

Due to the complexity and uniqueness of space flight, it is unlikely that all of the requirements in a NASA Technical Standard will apply. The Requirements Compliance Matrix below contains this NASA Technical Standard's technical authority requirements and may be used by programs and projects to indicate requirements that are applicable or not applicable to help minimize costs. Enter "Yes" in the "Applicable" column if the requirement is applicable to the program or project or "No" if the requirement is not applicable to the program or project. The "Comments" column may be used to provide specific instructions on how to apply the requirement or to specify proposed tailoring.

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1	Tailoring of this NASA Technical Standard's Requirements	[AMR-1] Program and/or project managers **shall** formally document and approve all tailoring of requirements in this NASA Technical Standard with the concurrence of the responsible NASA Materials and Processes (M&P) organization and the delegated Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements, or NPR 7120.8, NASA Research and Technology Program and Project Management Requirements.		
4.2	Additive Manufacturing Control Plan (AMCP)	[AMR-2] The CEO responsible for the design, acquisition, and conformance of AM hardware **shall** submit a consolidated AMCP addressing all applicable AM processes for review and approval by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization, that does the following: a. Documents the means of conformance and method of implementation for each of the requirements of this NASA Technical Standard and NASA-STD-6033 (see section 4.5 of this NASA Technical Standard). b. Documents and provides rationale for any tailoring of the requirements of this NASA Technical Standard. c. Provides for complete governance for the implementation of AM on the program or project such that, once approved, the AMCP becomes the controlling document for implementation and verification of AM requirements of this NASA Technical Standard.		
4.2.1	Applicable Documents, AMCP	[AMR-3] All applicable documents cited in the AMCP **shall** be controlled by the QMS, subject to configuration control, and made available for review when requested by NASA, the CEO, or any designated representatives.		

<table>
<tr><th colspan="5">NASA-STD-6030</th></tr>
<tr><th>Section</th><th>Description</th><th>Requirement in this Standard</th><th>Applicable (Enter Yes or No)</th><th>Comments</th></tr>
<tr><td>4.2.2</td><td>Supplier Compliance with the AMCP</td><td>[AMR-4] The CEO **shall** ensure flow-down of the requirements of this NASA Technical Standard, as tailored per the AMCP, through all relevant tiers of the supply chain and ensure that the relevant documents controlled by subtier suppliers are made available to NASA upon request.</td><td></td><td></td></tr>
<tr><td>4.3.1</td><td>Primary Classification</td><td>[AMR-5] The CEO **shall** assign a primary classification (i.e., Class A, B, or C) to all AM parts in accordance with the content of Figure 4.

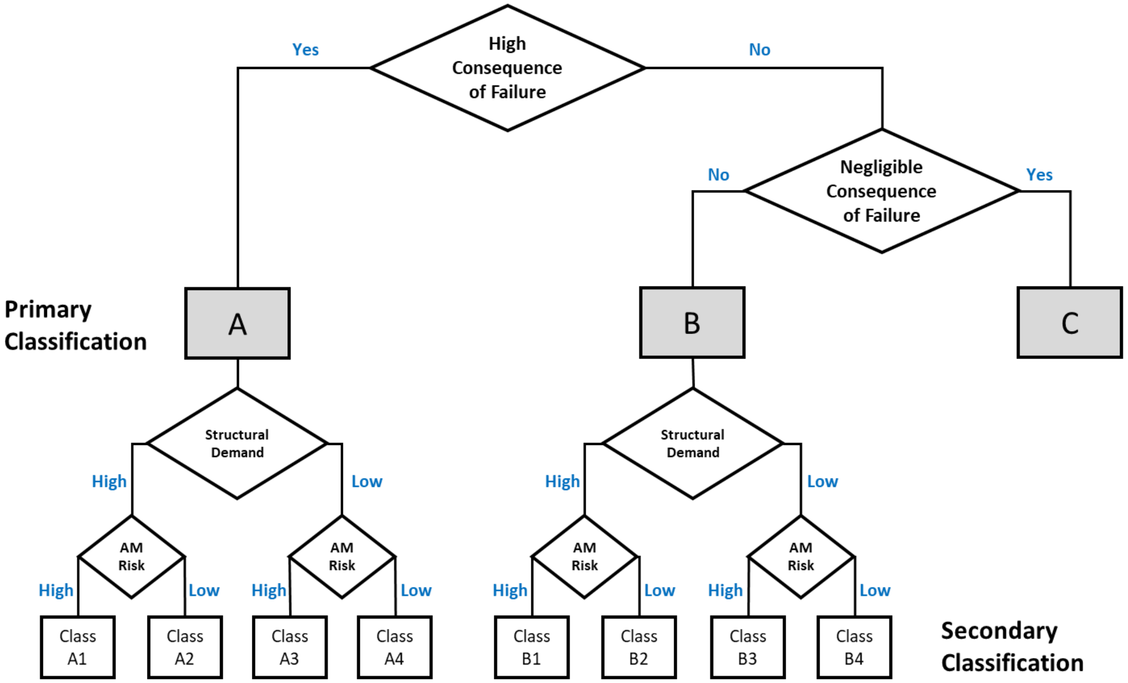


Figure 4—AM Part Classification</td><td></td><td></td></tr>
<tr><td>4.3.1.1</td><td>Class A Parts</td><td>[AMR-6] A part **shall** be designated as Class A, High Consequence of Failure, if failure of the part leads to a catastrophic, critical, or safety hazard and/or the part is defined as mission critical by the program or project.</td><td></td><td></td></tr>
<tr><td>4.3.1.1.1</td><td>Class A Part Restrictions</td><td>[AMR-7] Class A parts **shall** not:
a. Be made from polymeric materials.
b. Be fasteners.
c. Contain printed threads.</td><td></td><td></td></tr>
</table>

NASA-STD-6030

Section	Description	Requirement in this Standard	Applicable (Enter Yes or No)	Comments
4.3.1.2	Class B Parts	[AMR-8] Parts not designated Class A or Class C **shall** be designated as Class B.		
4.3.1.2.1	Class B Part Restrictions	[AMR-9] Class B parts **shall** not: a. Be fasteners. b. Contain printed threads		
4.3.1.3	Class C Parts	[AMR-10] A part **shall** be designated as Class C, Negligible Consequence of Failure, provided that <u>ALL</u> of the following criteria are satisfied: 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.		
4.3.1.4	Exempt Parts	[AMR-11] A part **shall** be designated as Exempt provided that all of the following criteria are satisfied and it meets all criteria for Class C (see section 4.3.1.3), which exempts it from all other requirements in this NASA Technical Standard: a. The part does not require any form of structural assessment. b. The part does not permanently interface to, or attach to, the launch vehicle, spacecraft, habitable module, or any subsystems thereof. c. Except for use in habitable crew spaces, the part does not provide any functionality or serve any purpose to the launch vehicle, spacecraft, or any subsystems thereof.		
4.3.2	Secondary Classification	[AMR-12] For Class A and B parts, a secondary classification **shall** be assigned based on structural demand and AM risk, according to Table 2, Structural Demand, Metallic AM Parts, Table 3, Structural Demand, Polymeric AM Parts, and Table 4, Assessment Criteria for Additive Manufacturing Risk (also see Figure 4).		

Table 2—Structural Demand, Metallic AM Parts

Analysis Input/Material Property	Criteria for Low Structural Demand
Load cases	Well-defined or bounded loads environment

<table>
<tr><th colspan="5">NASA-STD-6030</th></tr>
<tr><th>Section</th><th>Description</th><th>Requirement in this Standard</th><th>Applicable (Enter Yes or No)</th><th>Comments</th></tr>
<tr><td></td><td></td><td>
<table>
<tr><td>Environmental degradation</td><td>Only due to temperature</td></tr>
<tr><td>Ultimate strength</td><td>Minimum margin[*] ≥0.3</td></tr>
<tr><td>Yield strength</td><td>Minimum margin[*] ≥0.2</td></tr>
<tr><td>Point strain</td><td>Local plastic strain <0.005</td></tr>
<tr><td>High cycle fatigue, improved surfaces</td><td>Cyclic stress range (including any required factors) ≤80% of applicable fatigue limit</td></tr>
<tr><td>High cycle fatigue, as-built surfaces</td><td>Cyclic stress range (including any required factors) ≤60% of applicable fatigue limit</td></tr>
<tr><td>Low cycle fatigue</td><td>No predicted cyclic plastic strain</td></tr>
<tr><td>Fracture mechanics life</td><td>20x life factor</td></tr>
<tr><td>Creep strain</td><td>No predicted creep strain</td></tr>
</table>
[*] Margin = [σ_{design}/($\sigma_{\text{operation}}$ * *safety factor*)] – 1 (see commentary)

Table 3—Structural Demand, Polymeric AM Parts
<table>
<tr><th>Analysis Input/Material Property</th><th>Criteria for Low Structural Demand</th></tr>
<tr><td colspan="2">**All materials**</td></tr>
<tr><td>Load cases</td><td>Well-defined or bounded loads environment</td></tr>
<tr><td>Environmental Degradation</td><td>Only allowed due to temperature and moisture, if specific environmental performance data exist. Design environment temperature does not cross the *Tg*.</td></tr>
<tr><td>Fatigue</td><td>Cyclic stress range (including any required factors) ≤50% of applicable fatigue limit</td></tr>
<tr><td>Sustained stress/creep strain</td><td>No sustained stress[†] and no predicted creep strain</td></tr>
<tr><td colspan="2">**Material with elongation at failure ≥3% in application environment**</td></tr>
<tr><td>Ultimate strength</td><td>Minimum margin[*] ≥0.5</td></tr>
<tr><td>Yield strength[‡]</td><td>Minimum margin[*] ≥0.3</td></tr>
</table>
</td><td></td><td></td></tr>
</table>

Material with elongation at failure <3% in application environment	
Ultimate strength[#]	Minimum margin[*] ≥2.0

[†] Includes assembly stress (tight snap fit connections, shrink fits, fastener preloads) and operational stress.

[‡] Yield strength defined by secant modulus to specified strain, by specified offset strain, or as otherwise defined by structural assessment requirements.

[#] Ultimate strength assessed against local maximum principal stress at stress concentrations (brittle material design rules) for low ductility materials.

[*] Margin = [$\sigma_{\text{design}}/(\sigma_{\text{operation}} * \textit{safety factor})$] – 1 (see commentary following Table 2)

Table 4—Assessment Criteria for Additive Manufacturing 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[1] based on stress state?	X	X	X	0	5	
As-built surface can be fully removed on all fatigue-critical surfaces[2]?	X	X		0	3	
Surfaces interfacing with support structures are fully accessible and the as-built surface removed?	X	X	X	0	3	
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	
Structural walls or protrusions are the equivalent of ≥2 trace, (e.g., melt pool, bead, scan path) widths in cross section?		X		0	2	
Critical regions of the part do not require support structure?	X	X	X	0	2	

[1] In the context of the assessment of AM risk, the adequacy of a proof test is determined by the degree to which the test meets its assigned objectives. For a workmanship proof test, at any given location in the part the proof test is considered adequate when the state of stress in the part during the proof test exceeds the state of stress in the part during operation by the required proof factor. If the proof test conditions do not fully replicate the operational environment, as is typically the case, the proof and operational stresses are compared using directional stress components with any needed corrections for environment. For the rare case of quantitative flaw screening by proof test as an anchor to fracture control requirements,

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		the adequacy of the proof test is determined only by the ability of the applied proof test stress conditions to screen the critical initial flaw size for operation by causing failure, leak, or other clearly detectible damage to the part during the proof test. Just as in the workmanship proof test, the adequacy of a proof test for quantitative flaw screening is likely to vary throughout the part. Demonstrating the adequacy of a quantitative proof test is non-trivial and must be coordinated intently with the structures and fracture control communities. [2] Fatigue-critical surfaces are locations where fatigue analysis and surface condition assumptions influence the outcome of the structural assessment.		
4.4.1	Quality Management Systems	[AMR-13] A QMS compliant to SAE AS9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations, or an alternate QMS approved by the CEO and NASA, documented or referenced in the AMCP, **shall** be in place for all entities involved in the design, production, and post-processing of AM hardware.		
4.5	Equipment and Facility Control Plan (EFCP)	[AMR-14] All equipment integral to the AM process, and facility-specific processes and procedures, **shall** be under the control of a CEO-approved EFCP developed in accordance with NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facility Control, prior to the production of flight hardware.		
4.6	Fracture Control	[AMR-15] All AM parts used in hardware subject to fracture control **shall** be classified and assessed to NASA-STD-5019 with the following limitations: a. AM parts are not to be categorized as non-fracture critical low-risk parts, per NASA-STD-5019. b. AM parts are not to be categorized as fracture critical lines, fittings, and other pressurized components, per NASA-STD-5019, section 7.2.4, and instead are to follow the general approach for assessing fracture critical metallic parts per NASA-STD-5019, section 7.3.		
4.7	Unplanned Interruptions	[AMR-16] Any unplanned build interruption, including planned interruptions occurring outside approved limits, **shall** be documented as a nonconformance and traceable via a records management system controlled by the QMS.		
4.8.1.1	Quantitative NDE	[AMR-17] All Class A parts **shall** receive quantitative NDE with full coverage of the surface and volume of the part, including verifiable detection of critical initial flaw size in fracture critical damage tolerant parts, with any coverage limitations due to NDE technique(s) and/or part geometry documented in the PPP per section 7.3 of this NASA Technical Standard.		
4.8.1.2	NASA-STD-5009 Special NDE Approach	[AMR-18] The NDE approach for Class A parts **shall** meet the Special NDE requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components, and be documented in the PPP.		
4.8.2.1	Process Control NDE	[AMR-19] All Class B parts **shall** receive NDE for process control with full coverage of the surface and volume of the part, with any coverage limitations due to NDE technique(s) and/or part geometry documented in the PPP.		
4.8.2.2	NASA-STD-5009 NDE Approach	[AMR-20] The NDE approach for Class B parts **shall** meet the requirements of NASA-STD-5009 and be documented in the PPP.		
4.9	In-situ Process Monitoring	[AMR-21] Prior to use as a quantitative indicator of part quality for part acceptance, passive *in-situ* process monitoring technologies **shall** be qualified by the CEO to the satisfaction of NASA in a manner analogous to other NDE techniques.		

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.10	Repair and Rework	[AMR-22] Explicit provisions controlling any operation used to repair or rework an AM part due to a defect (e.g., short feeds/fractures, cracks) or nonconformance (e.g., warping) **shall** be documented and implemented as follows for Class A and B parts: a. Repair operations require prior written authorization from the contract authority, as described in the AMCP. b. All repair operations require full documentation as a nonconformance record and are included in the production engineering record of the part. c. Unplanned part operations not part of the QPP that constitute a repair or rework include, but are not limited to, bending, blending, sanding, peening, grinding, machining, welding, or brazing for the purposes of defect removal and/or part restoration to drawing allowances. d. All repair operations require validation on material manufactured using the same QMP.		
4.11.1	Witness Testing for Independent Builds	[AMR-23] All AM parts manufactured by an independent build **shall** include witness specimens integral to the build of the types and quantities required in Table 5, Metals Witness Testing Quantities and Acceptance Results for Independent Builds (metals), and Table 6, Polymer Witness Testing Quantities and Acceptance Results for Independent Builds (polymers), exposed to the same post-processing documented in the QMP, and evaluated per the acceptance methodologies in Tables 5 and 6, such that any witness test failing to meet the defined acceptance criteria is documented as a nonconformance and traceable via a records management system controlled by the QMS.		

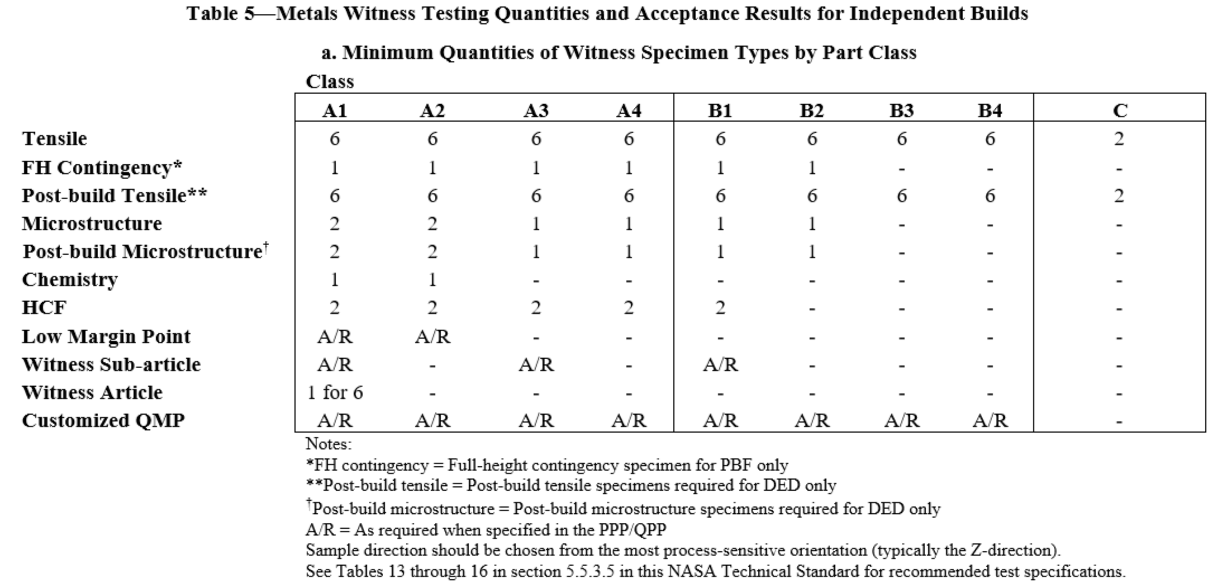
NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
				

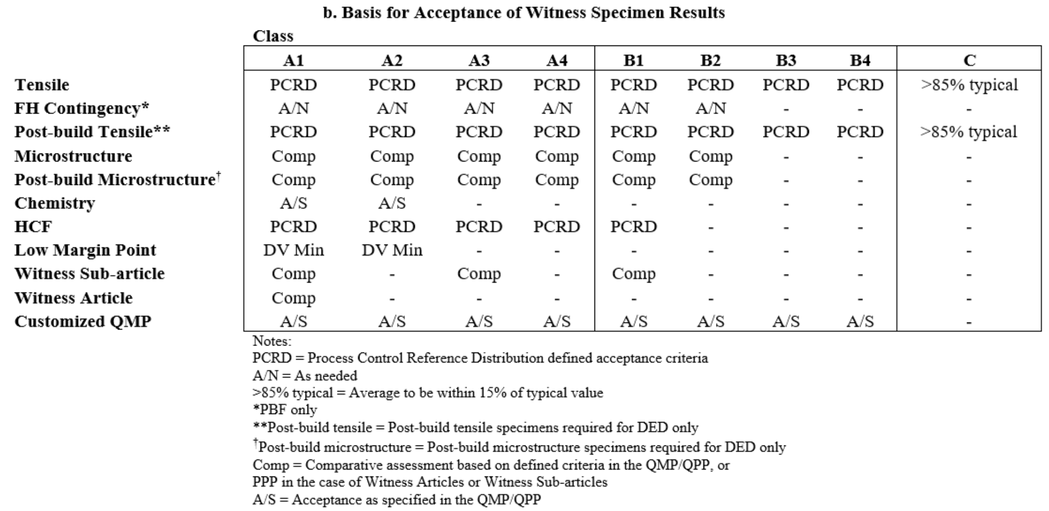
Table 5—Metals Witness Testing Quantities and Acceptance Results for Independent Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	6	6	6	6	6	6	6	6	2
FH Contingency*	1	1	1	1	1	1	-	-	-
Post-build Tensile**	6	6	6	6	6	6	6	6	2
Microstructure	2	2	1	1	1	1	-	-	-
Post-build Microstructure[†]	2	2	1	1	1	1	-	-	-
Chemistry	1	1	-	-	-	-	-	-	-
HCF	2	2	2	2	2	-	-	-	-
Low Margin Point	A/R	A/R	-	-	-	-	-	-	-
Witness Sub-article	A/R	-	A/R	-	A/R	-	-	-	-
Witness Article	1 for 6	-	-	-	-	-	-	-	-
Customized QMP	A/R	A/R	A/R	A/R	A/R	A/R	A/R	A/R	-

Notes:
*FH contingency = Full-height contingency specimen for PBF only
**Post-build tensile = Post-build tensile specimens required for DED only
[†] Post-build microstructure = Post-build microstructure specimens required for DED only
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction).
See Tables 13 through 16 in section 5.5.3.5 in this NASA Technical Standard for recommended test specifications.

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**



b. Basis for Acceptance of Witness Specimen Results

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	>85% typical
FH Contingency*	A/N	A/N	A/N	A/N	A/N	A/N	-	-	-
Post-build Tensile**	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	PCRD	>85% typical
Microstructure	Comp	Comp	Comp	Comp	Comp	Comp	-	-	-
Post-build Microstructure[†]	Comp	Comp	Comp	Comp	Comp	Comp	-	-	-
Chemistry	A/S	A/S	-	-	-	-	-	-	-
HCF	PCRD	PCRD	PCRD	PCRD	PCRD	-	-	-	-
Low Margin Point	DV Min	DV Min	-	-	-	-	-	-	-
Witness Sub-article	Comp	-	Comp	-	Comp	-	-	-	-
Witness Article	Comp	-	-	-	-	-	-	-	-
Customized QMP	A/S	A/S	A/S	A/S	A/S	A/S	A/S	A/S	-

Notes:
PCRD = Process Control Reference Distribution defined acceptance criteria
A/N = As needed
>85% typical = Average to be within 15% of typical value
*PBF only
**Post-build tensile = Post-build tensile specimens required for DED only
[†]Post-build microstructure = Post-build microstructure specimens required for DED only
Comp = Comparative assessment based on defined criteria in the QMP/QPP, or
PPP in the case of Witness Articles or Witness Sub-articles
A/S = Acceptance as specified in the QMP/QPP

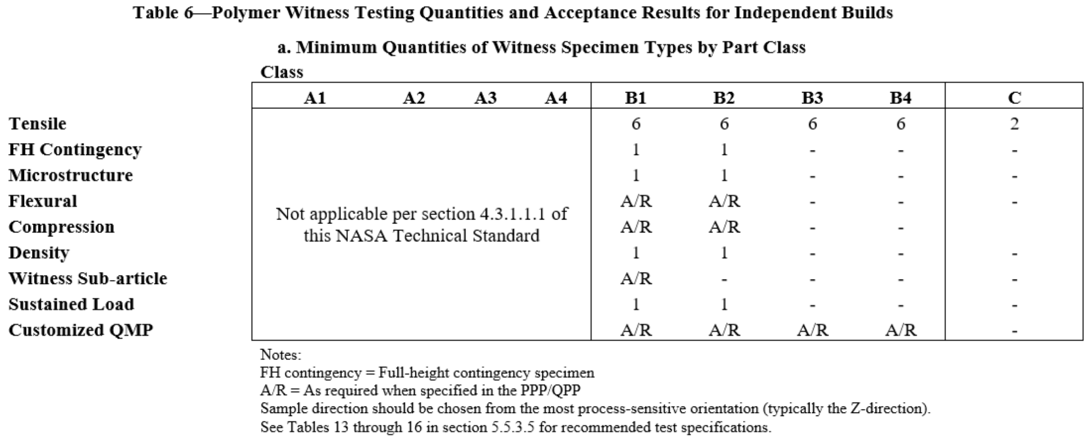


Table 6—Polymer Witness Testing Quantities and Acceptance Results for Independent Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

	Class								
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				6	6	6	6	2
FH Contingency					1	1	-	-	-
Microstructure					1	1	-	-	-
Flexural					A/R	A/R	-	-	-
Compression					A/R	A/R	-	-	
Density					1	1	-	-	-
Witness Sub-article					A/R	-	-	-	-
Sustained Load					1	1	-	-	-
Customized QMP					A/R	A/R	A/R	A/R	-

Notes:
FH contingency = Full-height contingency specimen
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction).
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

<table>
<tr><th colspan="5">NASA-STD-6030</th></tr>
<tr><th>Section</th><th>Description</th><th>Requirement in this Standard</th><th>Applicable (Enter Yes or No)</th><th>Comments</th></tr>
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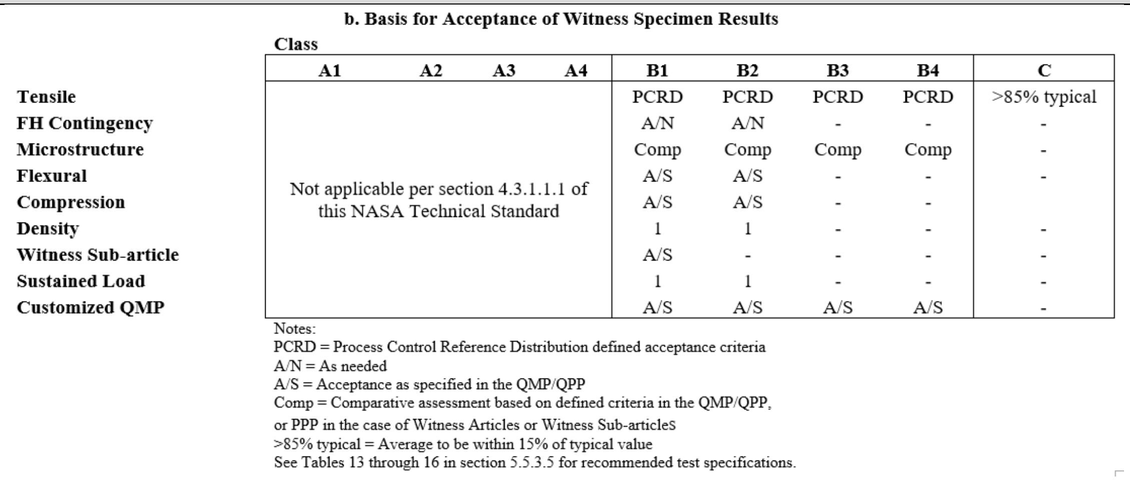

b. Basis for Acceptance of Witness Specimen Results

<table>
<tr><th></th><th colspan="9">Class</th></tr>
<tr><th></th><th>A1</th><th>A2</th><th>A3</th><th>A4</th><th>B1</th><th>B2</th><th>B3</th><th>B4</th><th>C</th></tr>
<tr><td>Tensile</td><td colspan="4" rowspan="9">Not applicable per section 4.3.1.1.1 of this NASA Technical Standard</td><td>PCRD</td><td>PCRD</td><td>PCRD</td><td>PCRD</td><td>>85% typical</td></tr>
<tr><td>FH Contingency</td><td>A/N</td><td>A/N</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Microstructure</td><td>Comp</td><td>Comp</td><td>Comp</td><td>Comp</td><td>-</td></tr>
<tr><td>Flexural</td><td>A/S</td><td>A/S</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Compression</td><td>A/S</td><td>A/S</td><td>-</td><td>-</td><td></td></tr>
<tr><td>Density</td><td>1</td><td>1</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Witness Sub-article</td><td>A/S</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Sustained Load</td><td>1</td><td>1</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Customized QMP</td><td>A/S</td><td>A/S</td><td>A/S</td><td>A/S</td><td>-</td></tr>
</table>

Notes:
PCRD = Process Control Reference Distribution defined acceptance criteria
A/N = As needed
A/S = Acceptance as specified in the QMP/QPP
Comp = Comparative assessment based on defined criteria in the QMP/QPP,
or PPP in the case of Witness Articles or Witness Sub-articles
>85% typical = Average to be within 15% of typical value
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.
</td><td></td><td></td></tr>
<tr><td>4.11.2</td><td>Witness Testing for Continuous Production Builds</td><td>[AMR-24] All AM parts manufactured by a continuous production build shall include witness specimens integral to the build of the types and quantities required in Table 7, Metals Witness Testing Quantities and Acceptance Results for Continuous Builds, and Table 8, Polymer Witness Testing Quantities and Acceptance Results for Continuous Builds, exposed to the same post-processing as documented in the QMP and evaluated per the acceptance methodologies of Tables 7 and 8.</td><td></td><td></td></tr>
</table>

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<tr><th>Section</th><th>Description</th><th>Requirement in this Standard</th><th>Applicable (Enter Yes or No)</th><th>Comments</th></tr>
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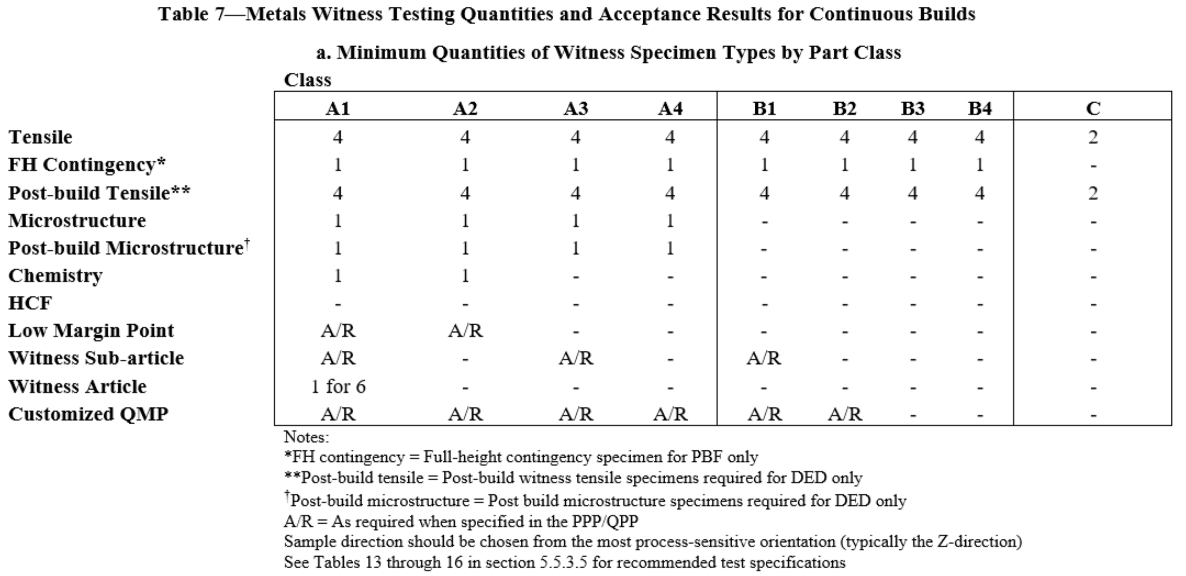

Table 7—Metals Witness Testing Quantities and Acceptance Results for Continuous Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

<table>
<tr><th></th><th>Class</th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th></tr>
<tr><th></th><th>A1</th><th>A2</th><th>A3</th><th>A4</th><th>B1</th><th>B2</th><th>B3</th><th>B4</th><th>C</th></tr>
<tr><td>Tensile</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>2</td></tr>
<tr><td>FH Contingency*</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>-</td></tr>
<tr><td>Post-build Tensile**</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>4</td><td>2</td></tr>
<tr><td>Microstructure</td><td>1</td><td>1</td><td>1</td><td>1</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Post-build Microstructure†</td><td>1</td><td>1</td><td>1</td><td>1</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Chemistry</td><td>1</td><td>1</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>HCF</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Low Margin Point</td><td>A/R</td><td>A/R</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Witness Sub-article</td><td>A/R</td><td>-</td><td>A/R</td><td>-</td><td>A/R</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Witness Article</td><td>1 for 6</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Customized QMP</td><td>A/R</td><td>A/R</td><td>A/R</td><td>A/R</td><td>A/R</td><td>A/R</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Notes:
*FH contingency = Full-height contingency specimen for PBF only
**Post-build tensile = Post-build witness tensile specimens required for DED only
†Post-build microstructure = Post build microstructure specimens required for DED only
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction)
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications
</td><td></td><td></td></tr>
</table>

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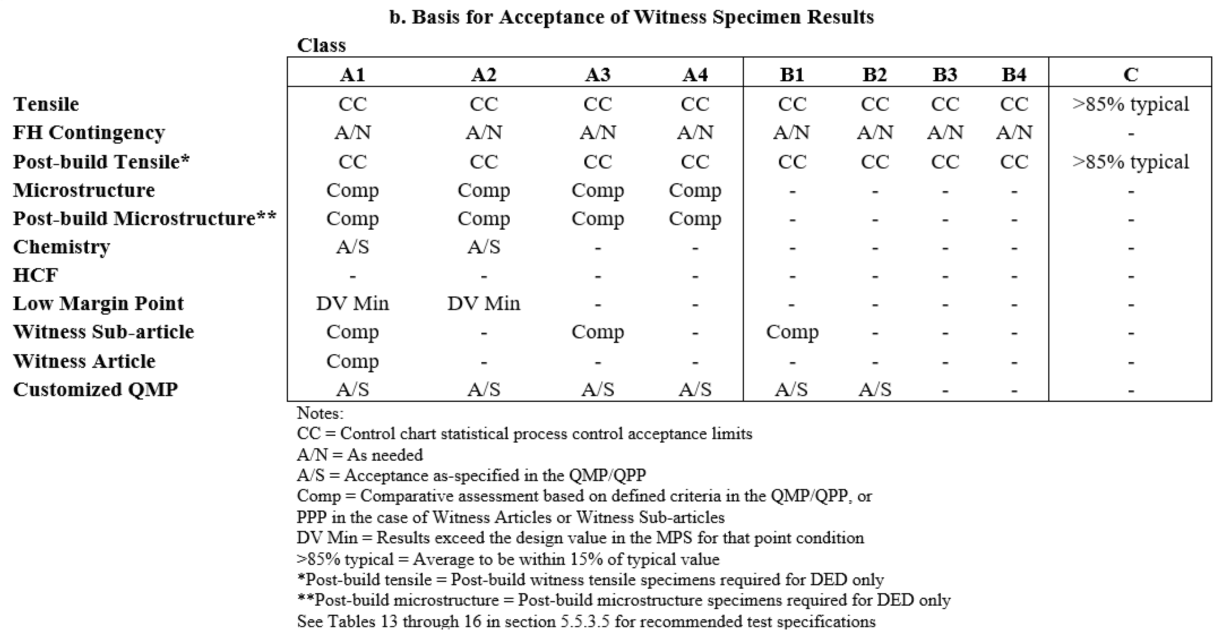


b. Basis for Acceptance of Witness Specimen Results

<table>
<tr><th></th><th colspan="9">Class</th></tr>
<tr><th></th><th>A1</th><th>A2</th><th>A3</th><th>A4</th><th>B1</th><th>B2</th><th>B3</th><th>B4</th><th>C</th></tr>
<tr><td>Tensile</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>>85% typical</td></tr>
<tr><td>FH Contingency</td><td>A/N</td><td>A/N</td><td>A/N</td><td>A/N</td><td>A/N</td><td>A/N</td><td>A/N</td><td>A/N</td><td>-</td></tr>
<tr><td>Post-build Tensile*</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>CC</td><td>>85% typical</td></tr>
<tr><td>Microstructure</td><td>Comp</td><td>Comp</td><td>Comp</td><td>Comp</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Post-build Microstructure**</td><td>Comp</td><td>Comp</td><td>Comp</td><td>Comp</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Chemistry</td><td>A/S</td><td>A/S</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>HCF</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Low Margin Point</td><td>DV Min</td><td>DV Min</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Witness Sub-article</td><td>Comp</td><td>-</td><td>Comp</td><td>-</td><td>Comp</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Witness Article</td><td>Comp</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Customized QMP</td><td>A/S</td><td>A/S</td><td>A/S</td><td>A/S</td><td>A/S</td><td>A/S</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Notes:
CC = Control chart statistical process control acceptance limits
A/N = As needed
A/S = Acceptance as-specified in the QMP/QPP
Comp = Comparative assessment based on defined criteria in the QMP/QPP, or PPP in the case of Witness Articles or Witness Sub-articles
DV Min = Results exceed the design value in the MPS for that point condition
>85% typical = Average to be within 15% of typical value
*Post-build tensile = Post-build witness tensile specimens required for DED only
**Post-build microstructure = Post-build microstructure specimens required for DED only
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications
</td><td></td><td></td></tr>
</table>

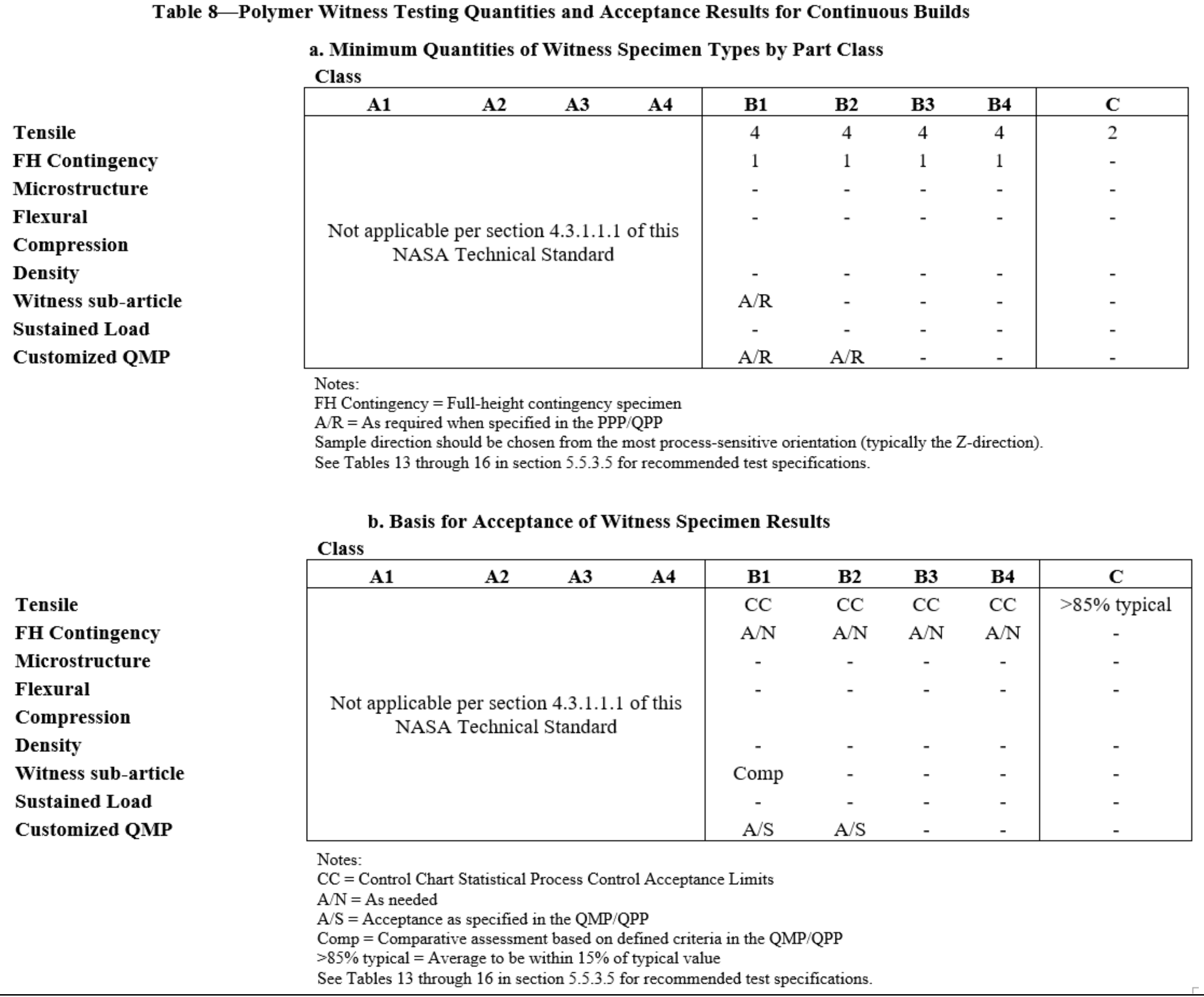
NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
				

Table 8—Polymer Witness Testing Quantities and Acceptance Results for Continuous Builds

a. Minimum Quantities of Witness Specimen Types by Part Class

Class

	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				4	4	4	4	2
FH Contingency					1	1	1	1	-
Microstructure					-	-	-	-	-
Flexural					-	-	-	-	-
Compression									
Density					-	-	-	-	-
Witness sub-article					A/R	-	-	-	-
Sustained Load					-	-	-	-	-
Customized QMP					A/R	A/R	-	-	-

Notes:
FH Contingency = Full-height contingency specimen
A/R = As required when specified in the PPP/QPP
Sample direction should be chosen from the most process-sensitive orientation (typically the Z-direction).
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

b. Basis for Acceptance of Witness Specimen Results

Class

	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C**
Tensile	Not applicable per section 4.3.1.1.1 of this NASA Technical Standard				CC	CC	CC	CC	>85% typical
FH Contingency					A/N	A/N	A/N	A/N	-
Microstructure					-	-	-	-	-
Flexural					-	-	-	-	-
Compression									
Density					-	-	-	-	-
Witness sub-article					Comp	-	-	-	-
Sustained Load					-	-	-	-	-
Customized QMP					A/S	A/S	-	-	-

Notes:
CC = Control Chart Statistical Process Control Acceptance Limits
A/N = As needed
A/S = Acceptance as specified in the QMP/QPP
Comp = Comparative assessment based on defined criteria in the QMP/QPP
>85% typical = Average to be within 15% of typical value
See Tables 13 through 16 in section 5.5.3.5 for recommended test specifications.

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.11.3	Continuous Production Build SPC Requirements	[AMR-25] For Class A and B parts, to be eligible for continuous production build witness sampling, the AM machine **shall** be under SPC by meeting each of the following criteria: a. Machine maintains an active qualification status per NASA-STD-6033. b. Machine operates under the same or equivalent QMPs since the last successful SPC evaluation build or qualification build. c. Machine has produced an SPC evaluation build within 60 days, using the sample set given in Table 14 or Table 16 and meeting the requirements of section 5.5 of this NASA Technical Standard. d. A minimum of 30 data points are collected from at least 10 of the most recent builds to establish control charts for ultimate strength, yield strength, and elongation. e. Control charts for ultimate strength, yield strength, and elongation are established according to ASTM E2587 and controlled by the QMS, with control limits compatible with the applicable PCRD. f. All witness specimens are exposed to the same post-processing as documented in the QMP. g. Builds with tensile results that violate control chart acceptance criteria are assigned a nonconformance in the QMS that initiates an evaluation of the part and the AM machine's process history. h. Corrective actions are taken for any control chart nonconformance that cannot be specifically isolated to the nonconforming build. i. Any machine associated with an open SPC nonconformance is given inactive qualification status until the root cause evaluation concludes, the necessary corrective actions are complete, and the CEO concurs with the resolution. j. The root cause/corrective action record for a nonconformance contains the decision to either return the machine to active qualification or requalify the machine, and the bases for that decision.		
4.12	Serialization	[AMR-26] For Class A and B parts, serialization (or equivalent) **shall** be used to provide part traceability to the AM build cycle, the location on the build area/platform within the build, all other production records, governing engineering documentation, and feedstock lots.		
4.13.1	Maintaining File Identity and Integrity in the Digital Thread	[AMR-27] All electronic files relevant to the digital thread for an AM part **shall** be controlled by the QMS within a file management system with full version control and appropriate security, with an allowance for files to be removed from the file management system only if they are fingerprinted with a cryptographic hash to ensure unambiguous identity and integrity of the file.		
4.13.2	Part Model Integrity	[AMR-28] For Class A and B parts, a methodology for verifying the integrity of part model(s) throughout all stages of the digital part definition associated with the AM process **shall** be documented and implemented via the AMCP.		
4.13.3	On-Machine Execution	[AMR-29] Any unplanned modifications to the build file on the machine during AM process setup and/or execution **shall** be assigned a nonconformance and traceable via a records management system controlled by the QMS.		
4.14	Production Engineering Record	[AMR-30] For Class A and B parts, the AM part production process **shall** be controlled by a revision-controlled production engineering record, consistent with the QPP, that contains, at a minimum and when applicable, records of production for the following: a. Feedstock removal for any part with geometry precluding line-of-sight confirmation.		

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Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		b. As-built part visual inspections for any indications of build anomalies prior to processes that may alter the as-built state of the part. c. Platform removal. d. Support structure removal. e. Machining. f. Thermal processing: environmental conditions (times, temperatures, atmosphere/media), process specifications, quenching media, surface condition of the part, etc. g. Light-activated curing: environmental conditions (times, ambient light, temperature, atmosphere/media), process specifications, part orientations, wavelength, intensity, duration, etc. h. Joining operations (e.g., welding, brazing, soldering, adhesive bonding) that were developed and qualified to an appropriate aerospace standard using representative AM material. i. Surface treatments that are influential to the performance of the part, structural or otherwise. j. Part marking: part identifiers and serial numbers, including the locations and method for all marking. k. Cleaning and part cleanliness. l. Inspections, including, but not limited to, dimensional inspections, surface texture measurements, and NDE. m. Part handling, packaging, and shipping.		
4.15	Preproduction Articles	[AMR-31] For Class A and B parts, a preproduction article evaluation verifying quality of part and material **shall** be conducted for all AM parts, with the plan for evaluation being approved as part of the PPP.		
4.16	Proof Testing	[AMR-32] All Class A and B AM parts **shall** be proof tested as part of acceptance testing unless otherwise substantiated as part of the Integrated Structural Integrity Rationale in an approved PPP.		
4.17	Qualification Testing	[AMR-33] All AM parts in Classes A1 through B2 **shall** be subject to a qualification test program that demonstrates that part performance and functionality meet the mission design requirements, life factors, and life-cycle capability, given the following stipulations: a. Parts for qualification testing are produced to a QPP. b. Any AM part that functions as part of a mechanism is subject to the qualification, design life verification, and acceptance testing defined by NASA-STD-5017, Design and Development Requirements for Mechanisms. c. The protoflight approach to qualification of hardware as defined in NASA-STD-5001 or JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, which does not include a dedicated test article, is not considered applicable to AM hardware of Classes A1 through B2, nor is the “no test” option for verification by analysis only.		
4.18.1	Part Acceptance, Class A and B Parts	[AMR-34] For Class A and B parts, data that are objective evidence of part conformance **shall** be a prerequisite for acceptance of the part by the CEO and made available to NASA upon request, including, but not limited to, information showing compliance to all part acceptance items listed in an approved PPP (see section 7.6 of this NASA Technical Standard).		
4.18.2	Part Acceptance, Class C Parts	[AMR-35] For Class C parts, a certificate of conformance (CoC) **shall** be a prerequisite for acceptance of the part by the CEO and made available to NASA upon request		

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
5.2	Unique QMPs, Minimum Control Categories	[AMR-36] Each AM machine used to fabricate hardware **shall** have at least one QMP for each unique combination of the following control categories that affect the material condition: a. Feedstock specification and associated controls per section 5.4.1 of this NASA Technical Standard. b. Associated machine, build process controls, and restart procedures per section 5.4.2 of this NASA Technical Standard. c. Post-processing requirements per section 5.4.3 of this NASA Technical Standard.		
5.3	Configuration Management	[AMR-37] Each QMP **shall** be controlled by the QMS and subject to configuration control.		
5.4.1.1	Virgin Feedstock Procurement	[AMR-38] Feedstock to be used for a Candidate QMP **shall** be controlled by industry standard specifications or configuration-controlled material specifications that levy requirements, including tolerances when applicable, to ensure consistent performance in the process and govern, at a minimum, the aspects of virgin feedstock production and procurement defined in Table 9, Virgin Powder Feedstock Controls, for powders; Table 10, Wire Feedstock Controls, for wire; Table 11, Filament Feedstock Controls, for filament; and Table 12, Liquid Feedstock Controls, for liquid feedstock.		

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.*

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**

Table 10—Wire Feedstock Controls

Wire	
a	Requiring wire producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, or an equivalent approved by the CEO.
b	Specifying unambiguously the method of wire manufacture, including rolling and drawing.
c	Specifying wire chemistry requirements, including acceptable methods of measurement and tolerance.
d	Specifying geometric constraints and length requirements, including explicit tolerance.
e	Specifying finish requirements, including explicit tolerance.
f	Specifying permissible method of joining both ends for repair or break during wire processing at the production facility.
g	Providing requirements for wire cleanliness and contamination control.
h	Providing requirements for wire winding packaging, labeling, and environmental controls.
i	Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each wire lot and the date and location of wire production.

Table 11—Filament Feedstock Control

Filament	
a	Requiring filament producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, or an equivalent approved by the CEO.

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**

b	Specifying unambiguously the method of filament manufacture.
c	Specifying filament chemistry requirements, including acceptable methods of measurement and tolerance.
d	Specifying geometric constraints and length requirements, including acceptable methods of measurement and tolerance.
e	Specifying moisture requirements, including acceptable methods of measurement and tolerance.
f	Specifying permissible method of joining both ends for repair or break during filament processing at the production facility, if applicable.
g	Providing requirements for filament cleanliness and contamination control.
h	Providing requirements for filament winding packaging, labeling, and environmental controls.
i	Providing batch monitoring requirements for differential scanning calorimetry.
j	Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each filament lot and the date and location of filament production.

Table 12—Liquid Feedstock Controls

Liquid	
a	Requiring resin producers and distributors to operate under a QMS conforming to SAE AS9100, SAE AS9120, or an equivalent approved by the CEO.
b	Specifying unambiguously the method of liquid manufacture.

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Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		c Specifying liquid chemistry requirements, including acceptable methods of measurement and tolerance. **d** Specifying liquid viscosity, including explicit tolerance. **e** Prohibiting post-production additions to the material lot for control of chemistry (doping). **f** Providing requirements for liquid cleanliness and contamination control. **g** Providing requirements for liquid packaging, labeling, and environmental controls. **h** Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each material lot and the date and location of material production.		
5.4.1.2	Feedstock Reuse Requirements	[AMR-39] For a candidate QMP-A or candidate QMP-B, a feedstock reuse protocol governed by the following rules **shall** be defined and implemented: a. Metrics are defined for tracking the progression of feedstock reuse for each unique machine operated per the QMP. b. Limits on feedstock reuse are defined and implemented based on metrics. c. The performance of AM material produced from reused feedstock up to the defined limit of reuse is tested and substantiated through material characterization in the MPS per the requirements of section 6.6 of this NASA Technical Standard. d. Feedstock at the defined limit of reuse cycles continues to meet all requirements of the original feedstock specification. e. For powder feedstock systems, used feedstock is sieved in accordance with the coarse particle limits of the particle size distribution specification and remixed and/or blended with additional virgin powder to eliminate particle size segregation after every cycle through the build process. f. Once a reused portion of a feedstock blend reaches the reuse limit, the feedstock blend is no longer used in part production under the auspices of the QMP. g. Feedstock blends that have reached the reuse limit may still be used in material characterization builds used to evaluate reuse limits on material properties.		

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		h. Reuse limits may be reevaluated and expanded as long as the requirements of items “c” and “d” of this section are met. i. When a reused feedstock no longer meets the virgin feedstock requirements, the addition of virgin feedstock or other additions to bring the feedstock back into specification is not allowed.		
5.4.2.1	AM Build Process	[AMR-40] The AM build process **shall** be defined in the Candidate QMP by a comprehensive list of fixed, key process variables of known influence on the AM build process for any given AM machine.		
5.4.2.2	Process Restart Procedures	[AMR-41] If a capability to restart the AM process is intended, criteria for determining the suitability for process restart and the detailed procedures for restarting the AM process **shall** be defined as part of the Candidate QMP specific to the AM equipment for which the material process applies.		
5.4.3	Post-Processing	[AMR-42] All AM post-processing (e.g., thermal processing, photo processing, curing) that affects bulk material condition **shall** be defined in the Candidate QMP to manage property and microstructural evolution from the as-built state to the final state.		
5.4.3.1	Control of Thermal Post-Processing	[AMR-43] Control of thermal post-processing operations **shall** be compliant with SAE AMS2750, Pyrometry, or similar approved standard.		
5.4.3.2	Variations in Post-Processing	[AMR-44] Variations on post-processes that affect material condition (e.g., thermal or photo process) **shall** be included in the definition of the Candidate QMP and each unique variation qualified and documented per section 5 of this NASA Technical Standard through demonstration that the performance of the resulting material is equivalent to that of the baseline.		
5.4.3.3	Hot Isostatic Pressing (HIP)	[AMR-45] MPs used for metallic Class A, B1, and B2 part production **shall** include HIP.		
5.4.4	Customized Material Process	[AMR-46] Any candidate material process using specific controls or unique witness specimen testing to achieve and/or demonstrate particular material performance characteristics **shall** be identified as a customized material process and include the following in the definition of the candidate material process: a. Description of the desired performance characteristics. b. Definition of the unique process controls used to achieve the desired material performance characteristics, if any. c. Definition of the requisite witness specimen tests and acceptance criteria used to confirm the desired performance characteristics of the material.		
5.5	Qualification of a Candidate Material Process	[AMR-47] All candidate material processes **shall** be qualified as either a QMP-A, QMP-B, or QMP-C prior to production use, with an option to use a sub-QMP if the process commonality criteria of section 5.5.1 of this NASA Technical Standard are met.		

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
5.5.1	Subsequent Qualified Material Process (Sub-QMP)	[AMR-48] A candidate material process **shall** share the following commonality criteria with an existing, approved QMP to enable the use of a Sub-QMP: a. Feedstock controls are identical. b. The AM build process definition is equivalent, meaning: (1) Same make of AM machine with equivalent configuration and build volume. (2) Same make and model of printer head hardware. (3) Same scheme for setting build path and assigning parameters. (4) Same layer thickness. c. Post-AM process definition is identical.		
5.5.2	Standardized Content for Builds Used for Qualification	[AMR-49] A set of builds that specifies the content, geometry, and layout of all evaluation specimens needed for qualification of the candidate material process as QMP-A, QMP-B, QMP-C, or associated Sub-QMP **shall** be standardized for use in the evaluations required by section 5.5.3 of this NASA Technical Standard.		
5.5.3	Qualification Criteria	[AMR-50] For AM machines with multiple energy sources, all evaluations and qualification criteria of section 5.5.3 of this NASA Technical Standard **shall** apply independently to each energy source.		
5.5.3.1	Quality of the As-built Material, Metals	[AMR-51] For QMP-A and QMP-B, the as-built material **shall** be demonstrated free of detrimental defects for each of the following cases when evaluated in cross-section at a minimum magnification of 50x, with resolution sufficient to distinguish defects common to the process and a combined area of evaluation ≥6 cm^2 (0.93 in^2) when combined across all cases and evaluations listed here: a. Survey of consistency throughout the build area. b. Demonstration that the process window remains free of detrimental defects at the credible extremes of the process (i.e., at the limiting range, given allowed tolerances of key process variable parameter settings, or at the extremes of thermal history due to geometry and scan/deposition pattern). c. Restart layer interfaces. d. Interfaces or overlaps in build path (e.g., striping, islands, multi-laser overlap zones), surface contours, cosmetic passes, including any interface associated with a unique build parameter set (e.g., down-facing, or low-angle surfaces). e. Typical geometry of the as-built deposition layer characterized for record using an unaltered final deposition layer for specimens representing nominal process conditions, to include metrics such as depth of the melt-pool and depth of melt-pool overlaps normalized by nominal layer thickness averaged over a minimum of measurements.		
5.5.3.2	Quality of the As-built Material, Polymers	[AMR-52] For QMP-B, the as-built material **shall** be demonstrated free of detrimental defects for each of the following cases when evaluated in cross section at a minimum magnification of 50x, with resolution sufficient to distinguish defects common to the process and a total area of evaluation ≥6 cm^2 (0.93 in^2) when combined across all cases listed here: a. Survey of consistency throughout the build area.		

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		b. Demonstration that the process window remains free of detrimental defects at the credible extremes of the process (i.e., at the extremes of the parameter settings, considering tolerance, or at the extremes of thermal history due to geometry and scan pattern). c. Restart layer interfaces. d. Interfaces or overlaps in build path (striping, islands, multi-processed zones), surface contours, and cosmetic passes, including any interface associated with a unique build parameter set (e.g., down-facing surfaces for relevant overhang angles). e. Typical geometry of the as-built deposition layer characterized for record using an unaltered final deposition layer for specimens representing nominal process conditions, to include measures such as the depth of the melt-pool and depth of melt-pool overlaps normalized by nominal layer thickness, averaged over a minimum of ten measurements.		
5.5.3.3	Material Microstructural Evolution	[AMR-53] The candidate material process **shall** be evaluated for objective evidence of controlled evolution of the material microstructure as follows: a. QMP-A and QMP-B: from the as-built to the final material structure, including all intermediate post-processing steps that alter the material structure. b. Sub-QMP-A and Sub-QMP-B: as-built and final material structure. c. QMP-C: the final material structure.		
5.5.3.3.1	Material Microstructural Evolution Acceptance Criteria	[AMR-54] The microstructural evolution acceptance criteria **shall** be documented for: a. QMP-A and QMP-B: the as-built and the final material structure, at minimum. b. Sub-QMP-A and Sub-QMP-B: as-built and final material structure. c. QMP-C: the final material structure.		
5.5.3.4	Surface Texture and Detail Resolution	[AMR-55] For QMP-A and QMP-B, as-built surface texture and detail resolution capability of the AM process **shall** be evaluated using reference part(s) from a minimum of two locations in the build area: a. The near center of the build area. b. The edge of the build area or other process-sensitive location identified with reduced build quality.		
5.5.3.4.1	Surface Texture Metrics and Acceptance Criteria	[AMR-56] For each QMP-A and QMP-B, consistent measures of as-built surface texture and detail resolution with associated acceptance criteria **shall** be defined.		
5.5.3.5	Mechanical Properties	[AMR-57] Mechanical properties **shall** be evaluated for all candidate material processes with, at minimum, the specimen quantities according to Tables 13, 14, 15, or 16, as applicable. **Table 13—Minimum Mechanical Property Tests for Metal QMP Builds**		

<table>
<tr><th colspan="5">NASA-STD-6030</th></tr>
<tr><th>Section</th><th>Description</th><th>Requirement in this Standard</th><th>Applicable (Enter Yes or No)</th><th>Comments</th></tr>
<tr><td></td><td></td><td>
<table>
<tr><th>QMP Item</th><th>Property</th><th>ASTM Standard*</th><th colspan="3">Quantity</th><th>Notes</th></tr>
<tr><th></th><th></th><th></th><th>QMP-A</th><th>QMP-B</th><th>QMP-C</th><th></th></tr>
<tr><td>1</td><td>Tensile</td><td>E8/E8M</td><td>15</td><td>15</td><td>6</td><td>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.</td></tr>
<tr><td>2</td><td>Tensile, with Process Restart</td><td>E8/E8M</td><td>5</td><td>5</td><td>-</td><td>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.</td></tr>
<tr><td>3</td><td>High Cycle Fatigue (HCF)</td><td>E466</td><td>10</td><td>5</td><td>-</td><td>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.</td></tr>
<tr><td>4</td><td>Low Cycle Fatigue (LCF)</td><td>E606/E606M</td><td>5</td><td>5</td><td>-</td><td>Five (5) tests at a cyclic strain range represented in MPS data.</td></tr>
<tr><td>5</td><td>Fatigue, with Process Restart</td><td>E466,
E606/E606M</td><td>5</td><td>5</td><td>-</td><td>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.</td></tr>
<tr><td>6</td><td>Fracture Toughness</td><td>E1820, E399</td><td>3</td><td>0</td><td>-</td><td>Tests with crack in worst-case orientation relative to build plane.</td></tr>
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NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**

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.

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).

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**

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.

Table 15—Minimum Mechanical Property Tests for Polymeric QMP Builds

QMP Item	**Property**	**ASTM Standard***	**Quantity**			**Notes**
			QMP-A	**QMP-B**	**QMP-C**	
1	Tensile	D638/D5766/D6742	Not Applicable	15	6	Survey of build area and materials using machined tensile specimens from “hot” and “cold” process variants
2	Tensile, with Process Restart	D638/D5766/D6742		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	Density	*See commentary*		5	-	

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**

4	Flexural	D790		3	-	Method that determines the modulus of elasticity and flexural strength of reinforced and unreinforced plastic.
5	Compression	D695/D6742/D6484		3	-	Method used in determining a material's modulus of elasticity and compressive offset yield strength.
6	Sustained load	D2990		3		Stiffness, offset bearing strength, and ultimate bearing strength.
7	Customized QMP	As Specified		2	-	Test at conditions defined by the candidate material process required for acceptance, minimum two (2) tests at condition.

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

Table 16—Minimum Mechanical Property Tests for Polymeric Sub-QMP and SPC Evaluation Builds

Sub QMP and SPC Build Item	Property	ASTM Standard*	Quantity			Notes
			QMP-A	QMP-B	QMP-C	
1	Tensile	D638/D5766/ D6742	Not Applicable	10	4	Survey of build area locations using machined tensile specimens.
2	Tensile, with Process Restart	D638/D5766/ D6742		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	Density	*See commentary*		3	-	Not required for sub-QMP (only QMP).

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<tr><td></td><td></td><td>
<table>
<tr><td>4</td><td>Flexural</td><td>D790</td><td></td><td>3</td><td>-</td><td>Method that determines the modulus of elasticity and flexural strength of reinforced and unreinforced plastic.</td></tr>
<tr><td>5</td><td>Compression</td><td>D695/D6742/ D6484</td><td></td><td>3</td><td>-</td><td>Method used in determining a material’s modulus of elasticity and compressive offset yield strength.</td></tr>
<tr><td>6</td><td>Sustained Load</td><td>D2990</td><td></td><td>3</td><td>-</td><td>Not required for sub-QMP (only QMP).</td></tr>
<tr><td>7</td><td>Customized QMP</td><td>As Specified</td><td></td><td>2</td><td>-</td><td>Test at conditions defined by the candidate material process required for acceptance, minimum two (2) tests at condition.</td></tr>
</table>
*Other test standards approved by the CEO may be used.</td><td></td><td></td></tr>
<tr><td>5.5.4</td><td>Qualified Material Process Record</td><td>[AMR-58] A candidate material process shall become fully qualified (i.e., a QMP) when:
a. A configuration-controlled record is established containing the complete definition of the QMP and all necessary supporting information substantiating that the qualification requirements of section 5 of this NASA Technical Standard have been satisfied.
b. The CEO has verified it to be complete and satisfactory.
c. Items (a) and (b) are documented and controlled by the QMS.</td><td></td><td></td></tr>
<tr><td>5.6</td><td>Registration of a Candidate Material Process to an MPS</td><td>[AMR-59] Each candidate material process for a QMP-A or QMP-B shall be registered to an MPS through confirmation of the properties listed in Table 17, Properties and Controls to Register a Candidate Material Process to an MPS, that have been tested per Tables 13 through 16.

Table 17—Properties and Controls to Register a Candidate Material Process to an MPS
<table>
<tr><th>Property</th><th>Metals</th><th>Polymers</th></tr>
<tr><td>Feedstock specification and feedstock controls are the same as those in the MPS.</td><td>X</td><td>X</td></tr>
<tr><td>Documentation is available to verify that the material process definition was established and adhered to continuously during the development of evaluation materials.</td><td>X</td><td>X</td></tr>
<tr><td>Microstructural characteristics are consistent with those of the MPS.</td><td>X</td><td>X</td></tr>
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<tr><td></td><td></td><td>
<table>
<tr><td>Tensile strengths and ductility are accepted to the tensile PCRDs of the MPS.</td><td>X</td><td>X</td></tr>
<tr><td>Measured high cycle fatigue life is accepted to the fatigue PCRD of the MPS.</td><td>X</td><td></td></tr>
<tr><td>Measured low-cycle fatigue life is consistent with MPS data.</td><td>X</td><td></td></tr>
<tr><td>Measured fracture toughness is consistent with MPS data.</td><td>X</td><td></td></tr>
<tr><td>For QMP-A and QMP-B, if applicable, tensile properties at temperature are consistent with MPS data.</td><td>X</td><td></td></tr>
<tr><td>Measured density is consistent with density of MPS data.</td><td></td><td>X</td></tr>
<tr><td>Measured flexural modulus of elasticity and/or flexural strength is consistent with MPS data.</td><td></td><td>X</td></tr>
<tr><td>Measured compression modulus of elasticity is consistent with MPS data.</td><td></td><td>X</td></tr>
<tr><td>Measured sustained load performance is consistent with MPS data.</td><td></td><td>X</td></tr>
<tr><td>Documentation substantiating this confirmation will be configuration controlled within the QMS and recorded within the qualified material process record.</td><td>X</td><td>X</td></tr>
</table>
</td><td></td><td></td></tr>
<tr><td>5.7</td><td>Qualified Material Process Record</td><td>[AMR-60] A candidate QMP shall become fully qualified (i.e., a QMP) when:
a. A configuration-controlled record is established containing the complete definition of the candidate QMP and all necessary supporting information substantiating that the qualification requirements in section 5 of this NASA Technical Standard have been satisfied.
b. The CEO has verified it to be complete and satisfactory.
c. Items (a) and (b) are documented and controlled by the QMS.</td><td></td><td></td></tr>
<tr><td>6.1</td><td>MPS for Class A and B Parts</td><td>[AMR-61] For Class A and B parts, an MPS shall be developed and maintained to substantiate the design and production of AM parts.</td><td></td><td></td></tr>
<tr><td>6.2</td><td>Material Properties for Class C Parts</td><td>[AMR-62] For Class C parts, all required material properties needed to substantiate the manufacturability of the design and classification of the part shall be documented through the MUA process or the PPP, but may be of typical basis.</td><td></td><td></td></tr>
<tr><td>6.3</td><td>MPS Approval</td><td>[AMR-63] An MUA per NASA-STD-6016 shall be submitted for MPS review and approval by NASA and, at a minimum, address the following:</td><td></td><td></td></tr>
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<tr><th colspan="5">NASA-STD-6030</th></tr>
<tr><th>Section</th><th>Description</th><th>Requirement in this Standard</th><th>Applicable (Enter Yes or No)</th><th>Comments</th></tr>
<tr><td></td><td></td><td>a. Documentation substantiating the development, implementation, and maintenance of the MPS (for Class A and B parts).
b. Documentation that addresses, at minimum, the requirements given in sections 6.4 through 6.10 of this NASA Technical Standard, and all subsections relevant to the applicable material allowables and associated design values in sections 6.11.2 and 6.11.5 of this NASA Technical Standard.
c. For Class A and B parts, material allowables and associated design values, PCRDs, and all other supporting data of the MPS are made available for NASA review as requested.
d. For Class C parts, material properties are documented as required to substantiate the design and classification.</td><td></td><td></td></tr>
<tr><td>6.4</td><td>Process Control in Material Property Development</td><td>[AMR-64] For Class A and B parts, documented process controls shall be implemented on any AM build used to create material for characterization, including the use of a QMP and witness testing with specimens and acceptance criteria equivalent to a Class B1 part, per Tables 5 and 6.</td><td></td><td></td></tr>
<tr><td>6.5</td><td>Lot Variability Impact on Material Allowables</td><td>[AMR-65] Each material allowable within an MPS shall be designated either lot-mature when based on the minimum unique chemistry feedstock lot quantities in Table 18, Required Lot Quantities for Lot-Mature Metal MPS Properties, and Table 19, Required Lot Quantities for Lot-Mature Polymeric MPS Properties, or lot-provisional if not, where:
a. A lot-mature material allowable is applicable to material used in parts of all classes.
b. A lot-provisional material allowable is applicable to material used in Class B parts that are built with a feedstock lot directly represented in the MPS and that have an approved, part-specific MUA.
c. Lot-provisional material allowables are applicable to material used in Class C parts without feedstock restrictions or a part-specific MUA.

Table 18—Required Lot Quantities for Lot-Mature Metal MPS Properties
<table>
<tr><th>Properties</th><th>Feedstock Lots
(nominally balanced*)</th><th>Build/Heat Treat Lots
(nominally balanced*)</th></tr>
<tr><td>Physical and constitutive</td><td>3</td><td>5</td></tr>
<tr><td>Tensile</td><td>5</td><td>10</td></tr>
<tr><td>Secondary</td><td>3</td><td>5</td></tr>
<tr><td>Fatigue</td><td>5</td><td>10</td></tr>
<tr><td>Fracture mechanics</td><td>3</td><td>5</td></tr>
<tr><td>Stress rupture/creep</td><td>3</td><td>5</td></tr>
</table>
* Nominally balanced lot contributions as described in commentary.

Table 19—Required Lot Quantities for Lot-Mature Polymeric MPS Properties</td><td></td><td></td></tr>
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<tr><td></td><td></td><td>
<table>
<tr><th>Properties</th><th>Feedstock Lots</th><th>Build Lots</th></tr>
<tr><td>Physical and constitutive</td><td>3</td><td>5</td></tr>
<tr><td>Tensile/compression[†]</td><td>5</td><td>10</td></tr>
<tr><td>Shear</td><td>5</td><td>10</td></tr>
<tr><td>Flexural</td><td>5</td><td>10</td></tr>
<tr><td>Fatigue</td><td>5</td><td>10</td></tr>
<tr><td>Creep/sustained load</td><td>5</td><td>10</td></tr>
</table>
[†] Including notch testing, if required</td><td></td><td></td></tr>
<tr><td>6.6</td><td>Used Feedstock Lot Controls</td><td>[AMR-66] When printing Class A and B parts using AM processes capable of feedstock reuse, limiting metrics for feedstock reuse **shall** be established and implemented to ensure the following:
a. The effects of reuse on material performance are either demonstrated as negligible or material property data representing the limiting reuse state are incorporated directly into the MPS population.
b. Parts are not built with feedstock exceeding the reuse limits.
c. The methodology for incorporating the influence of feedstock reuse into the design values of each MPS is described as part of the MUA substantiating the methodology of the MPS development.</td><td></td><td></td></tr>
<tr><td>6.7.1</td><td>Identification and Characterization of Influence Factors</td><td>[AMR-67] For Class A and B parts, the CEO **shall** provide for the systematic identification and characterization of any known factor having influence on the bulk or local performance of the AM material for the purpose of establishing design values.</td><td></td><td></td></tr>
<tr><td>6.7.2</td><td>Influence Factor Effect on Material Allowables</td><td>[AMR-68] For Class A and B parts, when required for part assessment, design values appropriate to each identified influence factor **shall** be developed and incorporated into the MPS.</td><td></td><td></td></tr>
<tr><td>6.7.3</td><td>Explicit Evaluation of Anisotropy</td><td>[AMR-69] Each MPS for Class A and B parts **shall** explicitly include supporting data necessary to evaluate the effects of anisotropy present in the AM material produced to a QMP such that anisotropy is either properly incorporated into the material allowables and associated design values, or rationale for a bounding isotropic assumption is established.</td><td></td><td></td></tr>
<tr><td>6.8</td><td>Criteria for the Use of External Data in the MPS</td><td>[AMR-70] For Class A and B parts, material property data generated outside the jurisdiction of this NASA Technical Standard (e.g., prior industry or government data), **shall** meet each of the following criteria prior to incorporation into or establishment of an MPS:
a. Properties are generated from material produced by a documented AM process fundamentally the same as those already registered to the MPS.
b. Authenticating records of traceability are available for the feedstock chemistry and post-AM operations (e.g., heat treatment).</td><td></td><td></td></tr>
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<tr><td></td><td></td><td>c. Properties are generated from material tested in a material condition (e.g., heat treatment and microstructure) equivalent to that defined by QMPs registered to the MPS.
d. Authenticating records of traceability are available that illustrate the material internal quality and final microstructure.
e. The size, geometry, build orientation, and surface condition of test specimens are defined.
f. The specifications governing the material test methods are defined.
g. The external data are provided in the form of actual test results to allow material allowables and PCRD criteria to be established or independently verified.
h. Demonstration that active QMP(s) produce(s) materials equivalent in structure and mechanical properties, based on the registration process in section 5.6 of this NASA Technical Standard.</td><td></td><td></td></tr>
<tr><td>6.9</td><td>Process Control Reference Distribution (PCRD)</td><td>[AMR-71] For Class A and B parts, a PCRD **shall** be established as part of the MPS for each material property identified in Tables 5 and 6 requiring a PCRD for witness specimen test acceptance.</td><td></td><td></td></tr>
<tr><td>6.10</td><td>PCRD Maintenance</td><td>[AMR-72] For Class A and B parts, PCRDs specific to each MPS **shall** be reevaluated regularly following the incorporation of new witness data and updated as required.</td><td></td><td></td></tr>
<tr><td>6.11</td><td>Development of Material Allowables and Design Values</td><td>[AMR-73] For Class A and B parts, material allowables and design values specific to each AM material and condition **shall** be developed or otherwise substantiated according to the requirements and guidance of section 6.11 of this NASA Technical Standard for all applicable properties and environments required for structural assessment.</td><td></td><td></td></tr>
<tr><td>6.11.1</td><td>Configuration Control of Material Allowables and Design Values</td><td>[AMR-74] For Class A and B parts, material allowables and design values **shall** be maintained under configuration control as an integral part of an MPS.</td><td></td><td></td></tr>
<tr><td>6.11.2</td><td>Design Values Development</td><td>[AMR-75] For Class A and B parts, design values established to incorporate the effects of influence factors **shall** be developed on the AM material and have a statistical significance equivalent to the respective type of material allowable.</td><td></td><td></td></tr>
<tr><td>6.11.3</td><td>Minimum Variability Requirements for Strength-Related Material Allowables</td><td>[AMR-76] Statistical assessment of material data for strength-related material allowables **shall** incorporate a minimum CoV according to Table 21, Required Minimum Coefficient of Variation in Metallic Strength Material Allowables, unless the data set specifically includes data representing variability attributable to differences between specimen and part performance, in addition to all other specified requirements for variability in section 6.5 of this NASA Technical Standard.
Table 21—Required Minimum Coefficient of Variation in Metallic Strength Material Allowables<table><tr><th>Quantity of Specimens</th><th>Required Minimum CoV, Metals</th><th>Required Minimum CoV, Polymers</th></tr></table></td><td></td><td></td></tr>
</table>

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<tr><th colspan="5">NASA-STD-6030</th></tr>
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<tr><td></td><td></td><td><table>
<tr><td>≤30</td><td>5%</td><td>7%</td></tr>
<tr><td>31 to 60</td><td>4.5%</td><td>6.5%</td></tr>
<tr><td>61 to 99</td><td>4%</td><td>6%</td></tr>
<tr><td>100 to 299</td><td>3.5%</td><td>5%</td></tr>
<tr><td>≥300</td><td>3%</td><td>4%</td></tr>
</table></td><td></td><td></td></tr>
<tr><td>6.11.4.2</td><td>Material Allowables for Tension Properties</td><td>[AMR-77] For Class A and B parts, statistical assessment of metallic AM material test data to derive material allowables for ultimate strength, yield strength, and elongation **shall** be governed by the following:
a. Test specimens are machined to represent bulk AM material and are tested according to ASTM E8/E8M or an equivalent standard.
b. Material allowables are bounded by the 99% probability at a 95% confidence one-sided tolerance limit estimated for the population using a properly fit statistical distribution.
c. A minimum of 100 specimens, distributed according to the lot requirements found in section 6.5 of this NASA Technical Standard, are required to initially establish material allowables.
d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.
e. The tensile property database is maintained by the CEO and updated on a periodic basis as additional data become available from process control-related activities, including witness sampling, preproduction article evaluations, QMP development, and machine qualification.
f. Data analysis methodologies, except as noted in this requirement, follow the intent of the MMPDS guidelines for static tensile property development.</td><td></td><td></td></tr>
<tr><td>6.11.4.3</td><td>Secondary Properties</td><td>[AMR-78] For Class A and B parts, statistical assessment of the secondary properties of metallic AM materials to derive material allowables **shall** be governed by the following:
a. Test specimens are machined to represent bulk AM material and are tested according to industry standard procedures.
b. Material allowables are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population using a properly fit statistical distribution.
c. A minimum of 20 specimens, distributed according to the lot requirements found in section 6.5 of this NASA Technical Standard, are required to establish material allowables for secondary properties.
d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.
e. The secondary property database is maintained by the CEO and considered for updating if there is a change in properties.</td><td></td><td></td></tr>
</table>

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		f. Test and data analysis methodologies, except as noted in this requirement, should follow the intent of the MMPDS guidelines.		
6.11.4.4	Fatigue Material Allowables	[AMR-79] For Class A and B parts, as required for structural assessment or at customer discretion, the MPS for any AM material **shall** include material allowables for fatigue developed in accordance with the following policies: a. Fatigue initiation life properties are developed in the form of stress-life or strain-life curves through testing according to recognized industry standards (e.g., ASTM E466, Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials, or ASTM E606/606M, Standard Test Method for Strain-Controlled Fatigue Testing). b. Specimens are machined to represent the bulk AM material and meet the surface finish requirements of fatigue test standards. c. Ten or more tests are used to define a fatigue curve for a given condition and, for HCF, a minimum of four tests are within 10% of the stress defined as the fatigue limit (see the definition of fatigue limit for this NASA Technical Standard). d. Fatigue properties are subject to the lot requirements of section 6.5 of this NASA Technical Standard. e. The process for developing material allowable fatigue curves from the test data is described in the documentation of MPS development per section 6.3 of this NASA Technical Standard. f. All fatigue curves are labeled with their basis (e.g., typical or bounding). g. If the MPS fatigue material allowables are applied to Class A and B parts with cycle counts $\geq 10^8$, then fatigue test data are required to substantiate the fatigue curve in this regime, except for Class B parts, where a methodology for conservatively estimating such fatigue limits based on fatigue data at cycle counts $<10^8$ may be employed when properly documented.		
6.11.4.6	Fracture Mechanics	[AMR-80] For Class A and B parts, when a design assessment includes evaluation of crack-like defects by fracture mechanics, the MPS **shall** include fracture toughness and fatigue crack growth-rate properties, in the worst-case material orientation, tested from AM material produced to an appropriate QMP, with lot requirements per section 6.5 of this NASA Technical Standard.		
6.11.4.7	Stress Rupture and Creep Deformation	[AMR-81] For Class A and B parts, when required for part assessment, the MPS **shall** include material properties for stress rupture or creep mechanisms tested from AM material produced to an appropriate QMP, with lot requirements per section 6.5 of this NASA Technical Standard.		
6.11.4.8	Joining (Welding/Brazing/ Soldering)	[AMR-82] For Class A and B parts, material properties for joined AM components **shall** be developed through testing according to recognized industry standards (e.g., AWS B4.0) and incorporated into the applicable MPS with a statistical significance comparable to the base AM material properties using specimens from AM material manufactured from representative QMPs.		
6.11.5.1.2	Viscoelastic and Viscoplastic Response in	[AMR-83] For Class B parts, loading rate dependence of mechanical properties, commensurate with application environments, **shall** be accounted for during material characterization and derivation of material allowables and design values.		

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Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
	Mechanical Properties			
6.11.5.1.3	Notch Sensitivity	[AMR-84] For Class B parts, materials with plastic tensile strain capability less than 3% **shall** be evaluated for notch sensitivity, commensurate with the applicable design criteria and structural assessment methods.		
6.11.5.1.4	Determination or Knowledge of T_g for Design	[AMR-85] Class B parts **shall** not be used in environments with an operational range that causes the part to pass through its glass transition temperature (T_g), measured in accordance with ASTM D7028, Standard Test Method for Glass Transition Temperature (DMA T_g) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA), or equivalent, unless otherwise substantiated as part of the integrated structural integrity rationale in the PPP (see section 7.3 of this NASA Technical Standard).		
6.11.5.1.5	Conditioning of Specimens for Moisture Content	[AMR-86] For Class B parts, the moisture content of all polymeric test materials **shall** be known and controlled during property characterization to within a user-defined predetermined range.		
6.11.5.1.6	Use of Filled or Reinforced Polymer Materials	[AMR-87] For Class B parts, structural reinforcement added to AM polymer materials **shall** be of nominally random orientation.		
6.11.5.2.1	Temperature and Environmental Effects	[AMR-88] For Class B parts, as required for part assessment, the MPS **shall** include the effect of temperature, moisture, and other environmental effects on material properties based on testing of the AM product form.		
6.11.5.2.2	Chemical Compatibility	[AMR-89] For Class B parts, compatibility of the polymeric AM material with any chemicals with a known potential for exposure to the AM material during manufacture or in service **shall** be evaluated for any detrimental influence on material performance.		
6.11.5.3	Physical and Constitutive Properties	[AMR-90] For Class B parts, all physical and constitutive properties required for proper design assessment **shall** be evaluated on representative AM polymeric materials.		
6.11.5.4	Material Allowables for Tension and Compression Properties	[AMR-91] For Class B parts, derivation of static strength material allowables in tension and compression **shall** be governed by the following: a. Test specimens are machined to represent bulk AM material and are tested according to appropriate polymer material test standards. b. Material allowables are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population, using a properly fit statistical distribution. c. A minimum of 100 specimens, distributed according to the lot requirements in section 6.5 of this NASA Technical Standard, are required to initially establish material allowables. d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard.		

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Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		e. The property database is maintained by the CEO and updated on a periodic basis as additional data become available from process control-related activities, including witness sampling, preproduction article evaluations, QMP development, and machine qualification. f. Test and data analysis methodologies, except as noted in this requirement, follow the intent of the CMH-17 guidelines for static tensile property development.		
6.11.5.5	Shear Properties	[AMR-92] For Class B parts, material allowables for shear strength **shall** be explicitly characterized, as required for structural assessment, according to the following: a. Test specimens are machined to represent bulk AM material and are tested according to appropriate polymer material test standards. b. Material allowables are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population, using a properly fit statistical distribution. c. A minimum of 20 specimens, distributed according to the lot requirements found in section 6.5 of this NASA Technical Standard, is required to initially establish material allowables. d. Material allowables incorporate the minimum CoV requirements of section 6.11.3 of this NASA Technical Standard. e. The property database is maintained by the CEO and updated on a periodic basis as additional data become available. f. Test and data analysis methodologies, except as noted in this requirement, follow the intent of the CMH-17 guidelines for static tensile property development.		
6.11.5.6	Flexural Properties	[AMR-93] For Class B parts manufactured using material with plastic tensile strain capability less than 3%, the flexural strength **shall** be evaluated, if required, for the following scenarios: a. If used in structural assessment, providing confirmation of design criteria and structural assessment methods. b. If used as a process control indicator, providing criteria for process qualification and production process monitoring.		
6.11.5.7	Fatigue Material Allowables and Design Values	[AMR-94] For Class B parts, when required for structural assessment or by the customer, the MPS for AM polymer materials **shall** include material allowables and/or design values for fatigue developed in accordance with the intent of the requirements in sections 6.11.4.4 and 6.11.4.5 of this NASA Technical Standard, with appropriate accommodations for polymeric material test standards and test methods.		
6.11.5.9	Sustained Load Creep Deformation and Stress Cracking	[AMR-95] For Class B parts, if applicable to part design and required for structural assessment, the material response under sustained load conditions leading to creep mechanisms, crazing, or stress cracking **shall** be evaluated from AM material produced to an appropriate QMP, with lot requirements per section 6.5 of this NASA Technical Standard.		
6.11.5.10	Joining	[AMR-96] For Class B parts, material properties for joining polymer AM products **shall** be developed to a statistical significance comparable to the base AM material properties using AM product manufactured from the same QMPs and incorporated into the applicable MPS.		
7.	Part Production Plan (PPP)	[AMR-97] A PPP for each AM part **shall** be developed by the CEO to address all requirements of this section, subject to review and approval by NASA.		

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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.		
7.2	Part Classification and Associated Rationale	[AMR-99] The PPP **shall** state the part classification and provide a detailed rationale for the classification given.		
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.		
7.4	AM Part Production Summary	[AMR-101] For Class A and B parts, the PPP **shall** provide a summary list or table with primary production steps, critical to successful part production and performance, in sequence as governed by the production engineering record.		

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7.4.1	Witness Testing	[AMR-102] The PPP **shall** describe the witness testing for the part, meeting the requirements in section 4.11 of this NASA Technical Standard or deviations therein, including the specimen types, designs, and quantities, and their layout in the build volume, test methods, and acceptance criteria.		
7.4.2	Planned Interruptions	[AMR-103] For Class A and B parts, the PPP **shall** document all planned interruptions of the AM build, including allowable build height range(s) for the interruption and planned post-build evaluations of the process restart interface.		
7.4.3	Post-Build Operations Requiring Specific Controls	[AMR-104] For Class A and B parts, the PPP **shall** describe or reference any specific controls required for post-build part processing operations that are process sensitive.		
7.5	Preproduction Article Requirements	[AMR-105] For Class A and B parts, the PPP **shall** describe a preproduction article evaluation verifying quality of part and material.		
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).		
7.7	Part Production Plan (PPP) Revisions	[AMR-107] A revision to the PPP **shall** be submitted to NASA for review and approval, for any of the following: a. Changes to QMP(s) specified for production. b. Changes to part classification (e.g., Class B to C, or Class B1 to B3, etc.). c. Changes to part geometry. d. Changes to build layout. e. Changes to witness testing. f. Changes to preproduction article. g. Any other change that impacts the form, fit, or function of the part.		
7.7.1	Rebuild of Preproduction Article	[AMR-108] For all Class A and B parts, a new build of the preproduction article **shall** be evaluated when a new QMP is used for part production, or the QMP specified by the QPP requires requalification due to changes of the QMP definition, per section 8.4 of this NASA Technical Standard.		

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Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
8.	Qualified Part Process (QPP)	[AMR-109] An AM Readiness Review, defining a qualified part process, **shall** be conducted for all Class A and B parts.		
8.1	AM Production Readiness Review (AMRR)	[AMR-110] The CEO **shall** conduct an AMRR at the completion of all activities outlined in the PPP and prior to the production of the first deliverable AM part, meeting the following criteria: a. Attendees, including, but not limited to: (1) CEO (chair). (2) Discipline representatives for Class A and B parts: A. Design. B. Structures. C. M&P. D. AM manufacturing production. E. Safety and mission assurance/quality assurance. (3) NASA M&P representative or delegate (with a minimum of 14 calendar days' notice): A. Attendance is required for all Class A1 and A2 parts. B. Attendance is at NASA's discretion for Class A3, A4, and B parts. C. NASA only needs to be notified at the completion of an AMRR or the establishment of a QPP for Class C parts. b. Topics, including, but not limited to: (1) Maturity of all manufacturing controls (e.g., QMP) and AM performance (e.g., MPS). (2) Results from the preproduction article. (3) Validation that part will meet minimum project requirements. c. Required minimum approvals: CEO.		
8.2	Additive Manufacturing Readiness Review (AMRR) Documentation and Approval	[AMR-111] The outcome of the AMRR **shall** be documented in the relevant QMS, subject to review and approval by the CEO, including, but not limited to, the following copies of reviewed materials: a. Presentation materials. b. Attendance. c. Minutes. d. Actions. e. Concurrences. f. Dissenting opinions.		
8.3	Qualified Part Process (QPP): Establishment	[AMR-112] The QPP **shall** be established following approval of the AMRR by the CEO, or as defined in the AMCP for Class C parts, with no further changes to the build configuration, its electronic files, or post-build processes permitted without the written approval of the CEO.		

NASA-STD-6030				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
8.4	Qualified Part Process (QPP): Modifications	[AMR-113] For Class A and B parts, the CEO **shall** define the methodology for changing and requalification of the part production process when changes to a QPP are required, including when the AMRR process is used to reestablish the QPP following any modifications.		
8.5	Build Execution	[AMR-114] For both preproduction and production builds, the production engineering record for the QPP **shall** be controlled by the QMS and contain steps that are fully traceable to procedures and checklists governing setup and initiation of builds.		
8.6	Control of Digital Thread for Part Production	[AMR-115] The QPP **shall** document the digital thread.		

APPENDIX B

NON-CREWED AND ROBOTIC MISSION TAILORING GUIDELINES

B.1 OVERVIEW

This Appendix is intended to cover the recommended tailoring for NASA-STD-6030 for non-crewed space applications, which includes science missions and launch vehicles for said missions, as well as related hardware. This Appendix is not a mandatory part of the standard, and the information contained herein is intended for guidance only.

B.2 TAILORING RECOMMENDATIONS

All tailoring contained in this Appendix should be done in consultation with NASA Materials and Processes (M&P) Engineering, and in the case of a hosted payload, with the cognizant NASA M&P Engineering staff on the primary payload system. A NASA M&P engineer will be best suited to ensure the appropriate balance between the technical needs and risk tolerance of the program. If AM subject matter expertise is not immediately available to the program, please contact the NASA Engineering and Safety Center for assistance. Failure to seek out such expertise will likely result in significant programmatic risks (e.g., cost, schedule, and technical).

Recommended tailoring for non-crewed space flight programs is limited almost exclusively to the topics of allowable technologies in section 1.4.2 and part classification in section 4.2 of this NASA Technical Standard. More specifically, the recommendations for tailoring apply to defining “down” the classification of any given part. By adjusting the definition of what is and is not a Class A, B, or C part, M&P engineers and programs are able to minimize the overall tailoring of this document. This decreases project management complexity and increases the likelihood that different projects and different Centers are able to leverage the experiences and technologies within NASA, its developers, and the overall supply chain. Said another way, by minimizing the tailoring of these requirements, current projects are more likely to be able to manufacture Class A parts to previously approved processes.

B.3 RISK ASSESSMENTS

A part whose failure could lead to personal injury or loss of life should *always* be classified as Class A, regardless of the size or risk posture of the program. This requirement should not be tailored. Additionally, this explicitly covers hardware that is not intended for flight (e.g., ground support equipment) but poses a significant risk to the mission such as NASA critical infrastructure and personnel. The total usage of the equipment has to be considered (e.g., will it be subjected to vibration or other testing providing an opportunity for failure).

Non-crewed missions are encouraged to consider more explicitly defining for their own purposes what constitutes “Mission Critical.” Most non-crewed missions have both “primary mission objectives” and “secondary mission objectives” (or similar). For the least Risk Tolerant Missions (i.e., Class A or Class B as defined by NPR 8705.4), programs are encouraged to retain, at a minimum, the requirement that if failure of a component would result in the loss of a primary mission objective, that part will be defined as Class A. In this scenario, if failure of a component would result in the loss of a *secondary* mission objective, and not otherwise meet the criteria of Class C, that part will be defined as Class B.

For more risk tolerant missions (i.e., Class C and D as defined by NPR 8705.4), failure of a part that would lead to the loss of a primary mission objective could be classified as Class B and the loss of a secondary mission objective as Class C, with all other parts that do not pose a risk to safety also being Class C. The most risk tolerant projects (i.e., Class D as defined by NPR 8705.4, NPR 7120.8, “Do No Harm”, etc.), all parts whose failure does not pose a safety hazard could be classified as Class C, or these requirements could be omitted altogether. The risk characterization for Class C parts is governed by section 4.3.13 of NASA-STD-6030. However, given the alternate risk postures for non-crewed spacecraft, a recommended tailoring approach for those requirements for various mission classes is listed in Table 21. The recommended approach denotes sections which should not be tailored for a given mission class.

In cases of hosted payloads, which are often more risk tolerant than prime spacecraft, the risk postures of the prime spacecraft and its myriad requirements have to be taken into consideration. For example, the cleanliness requirements of the prime spacecraft will translate into requirements for the Class C or Class D hosted payloads, which cannot waive those requirements. Similarly, “do no harm” risk postures have to be adapted to the characterization and risk tolerance of the additively manufactured hardware as it relates to the prime mission. This concurs with the typical NASA approach, such as the requirements levied upon CubeSats per LSP-REQ-317.01. Similar approaches are defined for Department of Defense systems (e.g., launch systems) per MIL-STD-882E, System Safety.

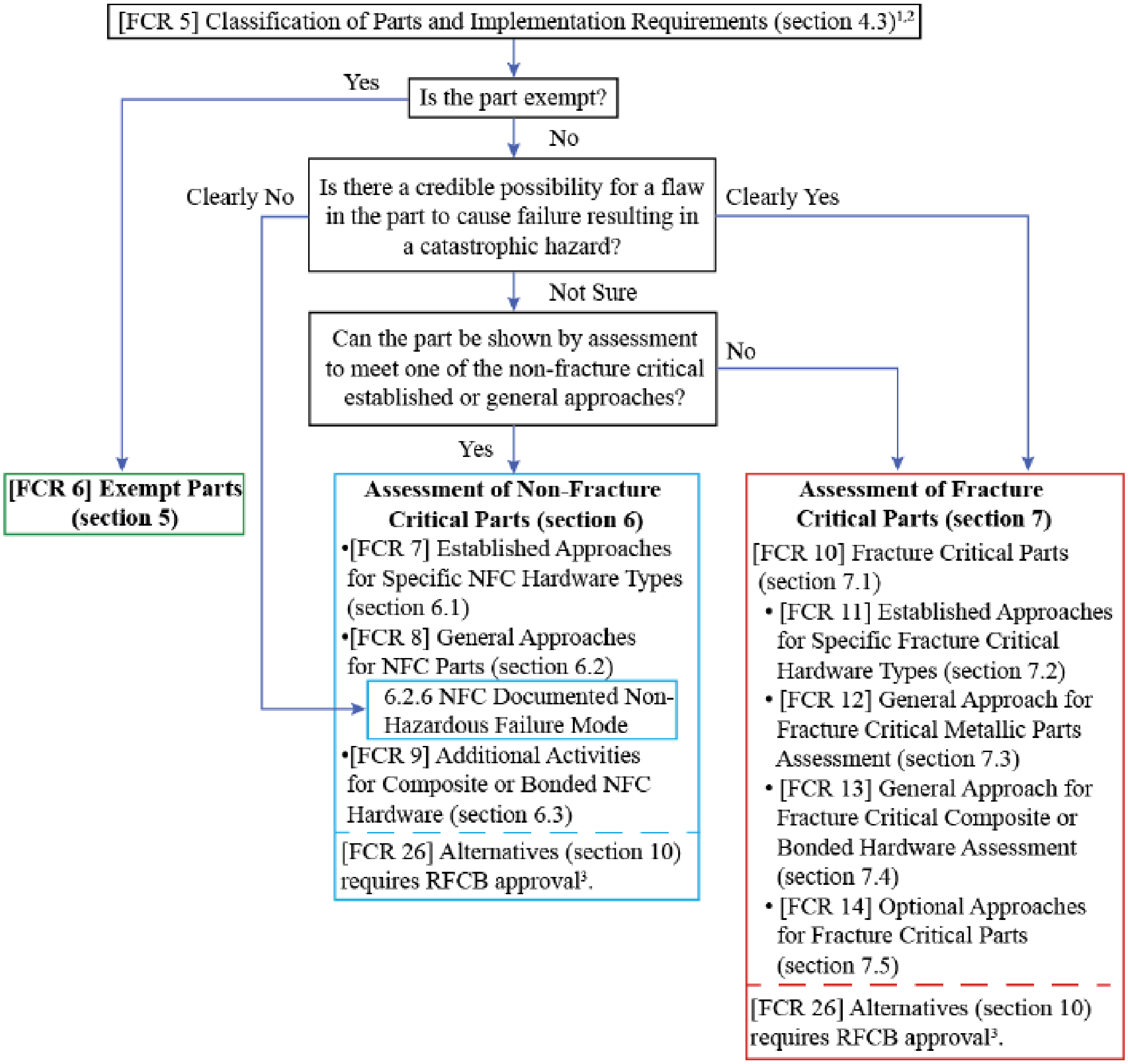
Given the different risk postures that can be tailored for non-crewed missions, more leeway can be given for use of alternate additive manufacturing technologies. Table 22, Listing of Requirements that Can and Cannot be Tailored for Class C Part Characterization, contains a listing of the risk postures recommended by NASA; the risks that a given project is willing to undertake have to be discussed with the relevant NASA M&P Engineering Staff prior to choosing a less-well-characterized processing approach.

Table 22—Listing of Requirements that Can and Cannot be Tailored for Class C Part Characterization; Specifications that Can be Tailored are Denoted "Y"

Section 4.3.13 Requirements	**Mission Class**		
Subsection	**A/B**	**C**	**D**
Failure of part does not lead to any form of hazardous or unsafe condition	N	N	N
Failure of part does not adversely affect mission objectives	N	N	N
Failure of part does not adversely affect other systems or operations	N	N	N
Failure of part does not alter structural margins or related evaluations on other hardware	N	N	N
Failure of part causes only minor inconvenience operations	N	N	N
Failure of part does not cause debris or contamination concerns	N	N	Y
Failed part would not require repair or replacement	N	Y	Y
Part is not a protoflight article	N	N	Y
Load environments are defined	N	Y	Y
Part is not exposed to environment with potential for material degradation over the expected service life	N	Y	Y
Part is not primary structure	N	Y	Y
Part does not serve as redundant structure for fail-safe criteria per NASA-STD-5019	N	Y	Y
Part is not designated "Non-Hazardous Leak Before Burst" per NASA-STD-5019	N	Y	Y
Part does not serve as primary or secondary containment	N	Y	Y
Part is not subjected to impact loads	N	Y	Y
Part has no printed threads	N	Y	Y
Part is not a fastener nor does it serve the purpose of a fastener	N	Y	Y
If a structural analysis is required, margin of safety ultimate tensile strength (UTS) >6 on local maximum principal tensile stress	N	Y	Y

B.4 FRACTURE CONTROL

The fracture control assessment methodology remains consistent for all part classes, per NASA-STD-5019A. This applies to all systems, regardless of mission class, for applications such as propellant tanks and is governed by range safety requirements at NASA's launch sites. Regardless of additive manufacturing process methodology, the same screening approach applies; see Figure 7, Fracture Control Classification logic Diagram (NASA-STD-5019A). The risk classification methodology above for Class C parts is intentionally designed to avoid allowing fracture critical hardware to be downrated to a lower risk posture, so that it does not conflict with other NASA policies. Any questions regarding appropriate fracture control classification should be directed, early in the design process, to the relevant NASA M&P Engineering staff, for appropriate adjudication. Not all NASA Centers maintain active Fracture Control Boards, so expertise may be required from another NASA Center to properly rate a piece of hardware.



Notes:

1. Each part is demonstrated to satisfy the selected classification by a process with documentation cited in the Fracture Control Summary Report.
2. A part may always be classified as fracture critical if there is doubt or concern related to demonstrating that it is NFC or exempt.
3. An alternative approach to any classification or category may be developed and presented with rationale to the RFCB for approval in accordance with section 10 in this Standard.

Legend:

NDE	non-destructive evaluation
NFC	non-fracture critical
RFCB	Responsible Fracture Control Board

Figure 7—Fracture Control Classification Logic Diagram (NASA-STD-5019A)

B.5 APPLICABLE TECHNOLOGIES

Given the different risk postures that can be tailored for non-crewed missions, more leeway can be given for use of alternate additive manufacturing technologies. Table 22 contains a listing of the risk postures recommended by NASA; the risks that a given project is willing to undertake must be discussed with the relevant NASA M&P Engineering Staff prior to choosing a less-well-characterized processing approach. Table 23 provides applicable AM technologies and materials types by part class.

Table 23—Applicable AM Technologies and Material Types by Part Class

				Class		
Category	Technology		Materials Type	A	B	C
Metals	L-PBF		Powder	X	X	X
	DED		Wire	X	X	X
	DED		Blown Powder	X	X	X
	EB-PBF		Powder			X
Polymers	L-PBF		Polymer Powder		X	X
	Vat Photopolymerization		Photopolymer Resin			X
	Material Extrusion		Filament			X
	Polyjetting		Various			X

Additionally, ceramic additive manufacturing, while disallowed for use in crewed spaceflight, may be considered for non-crewed spaceflight, particularly for non-structural applications such as science instruments, where it can enable alternate sensor designs or similar activities. The process approach has to be well-understood, as well as properly characterizing the part class, per section 4.3.13 of this NASA Technical Standard.

APPENDIX C

REFERENCES

C.1 PURPOSE

This Appendix provides references to guidance documents related to this NASA Technical Standard.

C.2 REFERENCES

NPR 8705.4, Risk Classification for NASA Payloads

NPR 8715.3D, NASA General Safety Program Requirements

NPD 8730.5, NASA Quality Assurance Program Policy

NPR 8735.2, Management of Government Quality Assurance Functions for NASA Contracts

NPR 6000.1, Requirements for Packaging, Handling, and Transportation for Aeronautical and Space Systems, Equipment, and Associated Components.

NRRS 1441.1, NASA Records Retention Schedules (Refer to NPR 1441.1)

NASA-STD-5006, General Welding Requirements for Aerospace Materials

NASA-STD-5012, Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines

NASA-STD-7012, Leak Test Requirements

NASA-STD-8709.20, Management of Safety and Mission Assurance Technical Authority (SMA TA) Requirements

MSFC-SPEC-164, Specification for Cleanliness of Components for Use in Oxygen, Oxidizer, Fuel, and Pneumatic Systems

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

MSFC-STD-3717, Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

MSFC Form 4657, Change Request for a NASA Engineering Standard

DOT/FAA/AR-03/19, “Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure

MIL-STD-882E, System Safety

AIAA S-080, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

ASME Y14.41, Digital Product Definition Data Practices: Engineering Product Definition and Related Documentation Practices

ASME V&V 40, Assessing Credibility of Computational Modeling through Verification and Validation: Application to Medical Devices

ASTM B243, Standard Terminology of Powder Metallurgy

ASTM D648, Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position

ASTM D792, Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement

ASTM D1505, Standard Test Method for Density of Plastics by the Density-Gradient Technique

ASTM D5045, Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials

ASTM E3166, Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build.

ASTM F1877, Standard Practice for Characterization of Particles

AWS B4.0, Standard Methods for Mechanical Testing of Welds

IEST-STD-CC1246, Product Cleanliness Levels - Application, Requirements, and Determination

ISO 1183, Plastics - Methods for determining the density of non-cellular plastics - Part 2: Density gradient column method

ISO/ASTM 52921, Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

SAE AS9102, Aerospace First Article Inspection Requirement