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ADDITIVE MANUFACTURING REQUIREMENTS FOR EQUIPMENT AND FACILITY CONTROL

DOCUMENT HISTORY LOG

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Baseline			2021-04-21	Initial Release
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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 is an applicable document to NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems, and implements the requirements for control of additive manufacturing (AM) equipment, associated facilities, and training of personnel, which are to be documented in an Equipment and Facility Control Plan (EFCP). Qualification of the AM process on each AM machine is essential, just as is required in the commonplace qualification of welding processes in aerospace practice. The methodology for qualification of the AM process has been standardized by NASA-STD-6030.

Process qualification depends upon a known state of calibration and qualification of the AM machine, as well as the quality of controls over the supporting facility (e.g., the storage and handling of feedstock powder). Regardless of the level of automation, AM is a complex and meticulous process requiring practitioners with proper education, experience, and skills to achieve the expectations of quality for aerospace applications.

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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1. SCOPE

This NASA Technical Standard is directed toward equipment and facilities used to produce additive manufacturing (AM) parts for NASA spacecraft systems, including, but not limited to, crewed, non-crewed, robotic, launch vehicle, lander, and spacecraft program/project hardware elements. Requirements in this NASA Technical Standard assume the AM facility is already compliant with all applicable federal, state, or local laws regarding environmental, health, or safety regulations. The requirements in this NASA Technical Standard respond to section 4.5 of NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems.

Equipment and facilities used to produce AM parts for 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 equipment and facilities used for AM processes that are used for AM part production of spaceflight systems, including, but not limited to, hardware used for spacecraft, launch vehicles, in-space and extraterrestrial surface systems.

1.2 Applicability

This NASA Technical Standard is applicable to facilities operating under the auspices of NASA-STD-6030 that are used to produce AM parts for spaceflight systems, including hardware used for spacecraft and launch vehicles, and AM parts used to interface with spaceflight hardware or other GSE. This NASA Technical Standard may also apply to AM parts used for NASA non-crewed missions (e.g., robotic missions).

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 “EFCR” (Equipment and Facilities Control Requirement), numbered, and indicated by the word “shall”; this NASA Technical Standard contains 31 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

The focus of this NASA Technical Standard is to define minimum requirements for control of AM equipment and facilities. These controls are defined and implemented by the AM part producer through an Equipment and Facility Control Plan (EFCP) and approved by the cognizant engineering organization (CEO), which is unique to the AM facility. This plan defines procedures and work instructions for production operations (e.g., powder feedstock management, contamination control, computer security, and the maintenance and calibration of AM machines).

This NASA Technical Standard requires certified operators based on an operator training and certification program to ensure AM operations are executed by personnel with proper knowledge of the AM process, all related equipment, procedural controls levied by qualified processes, and engagement of the Quality Management System (QMS). This is considered foundational to the qualification processes and methodologies of NASA-STD-6030 and are to be established prior to hardware production.

Figure 1, Topical Outline for NASA-STD-6030; Figure 2, Key Products and Processes for NASA-STD-6030; and Figure 3, Symbol Legend for Key Products and Processes, reproduced from NASA-STD-6030, illustrate how the content of this NASA Technical Standard relates to NASA-STD-6030. See NASA-STD-6030 for a detailed discussion of these figures.

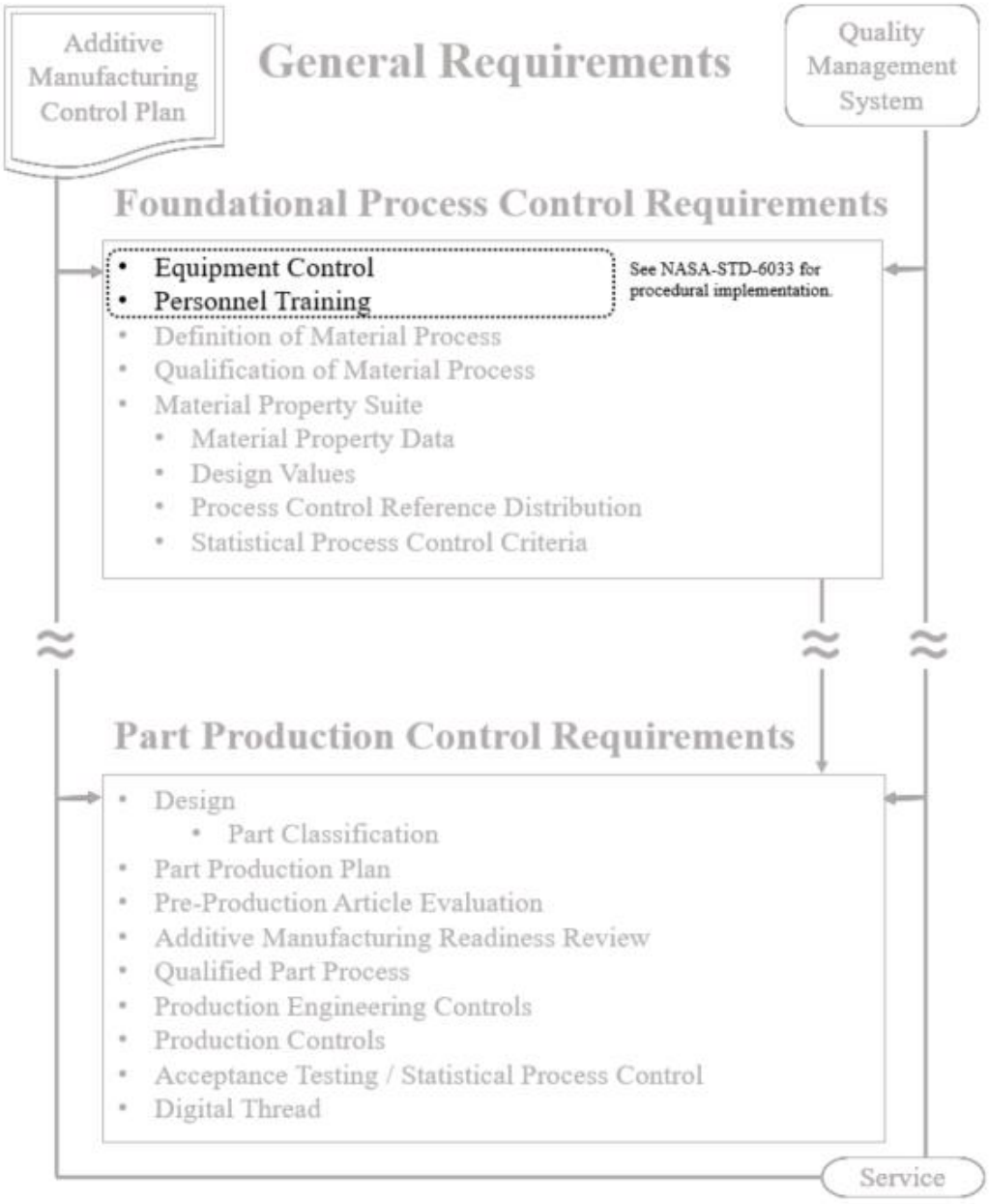

Figure 1—Topical Outline for NASA-STD-6030

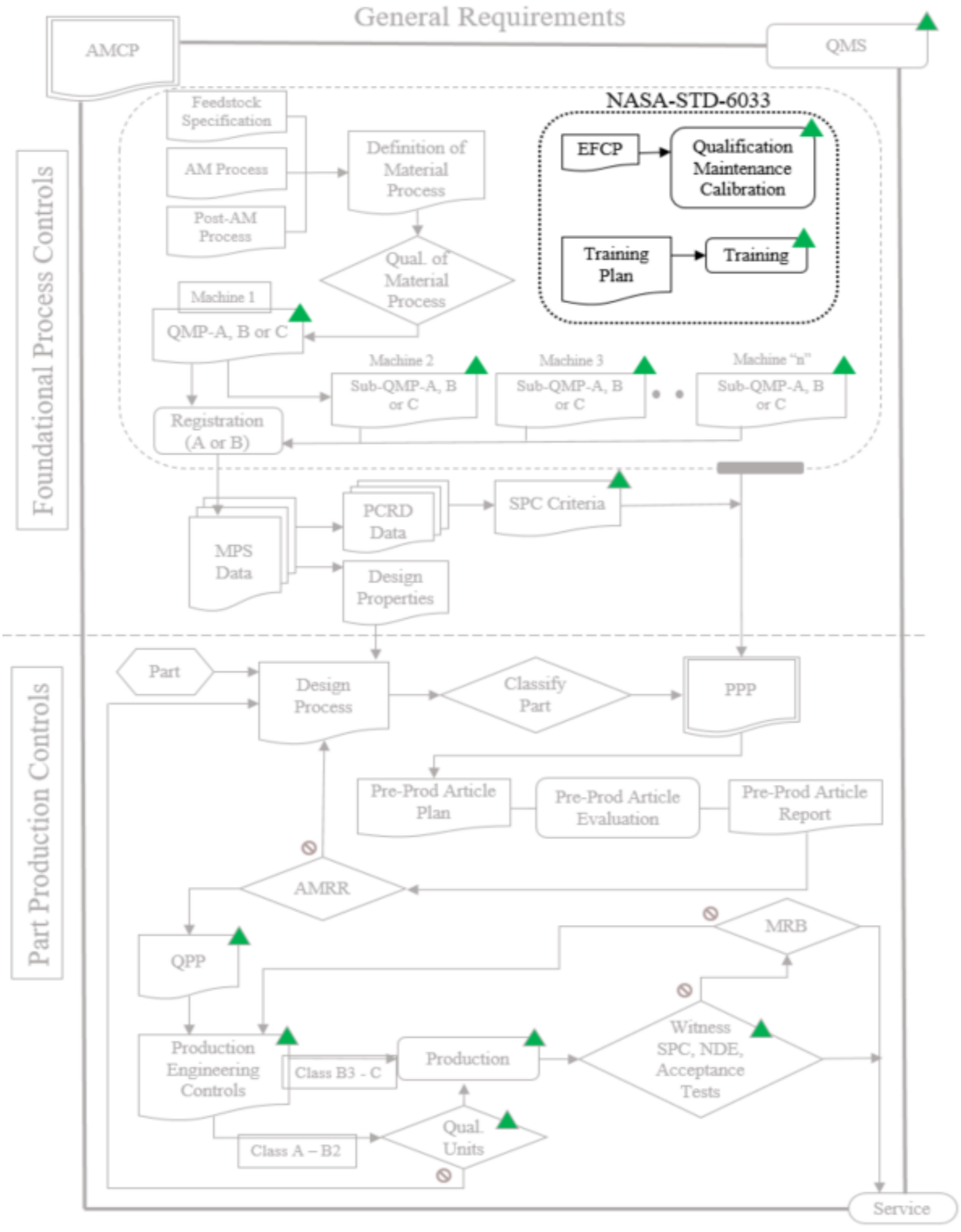

Figure 2—Key Products and Processes for NASA-STD-6030

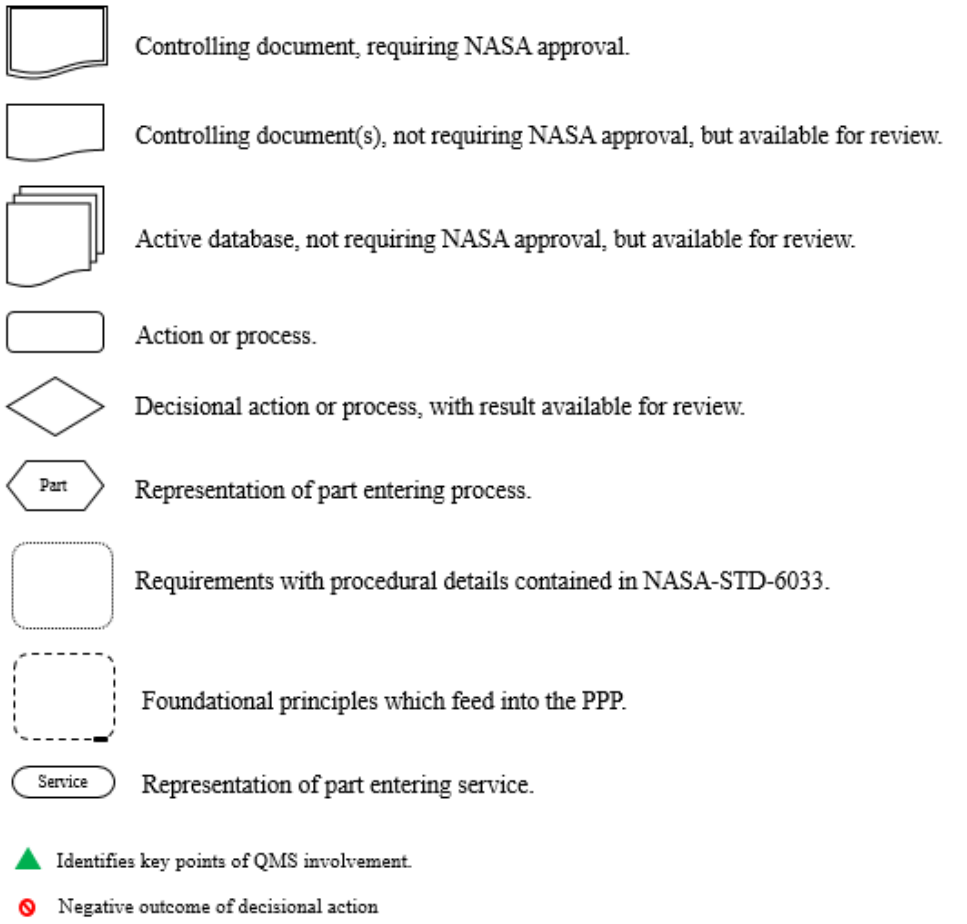

Figure 3—Symbol Legend for Key Products and Processes

1.4.1 Deliverables

This NASA Technical Standard outlines the EFCP as a discrete deliverable that will be created by the CEO and/or part producer, referenced by the applicable Additive Manufacturing Control Plan (AMCP), and made available to NASA for review.

1.4.2 Applicable Technologies

This NASA Technical Standard is designed to be applicable to facilities using mature materials and technologies as described by section 1.4.2 of NASA-STD-6030.

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 or https://nodis3.gsfc.nasa.gov/main_lib.cfm.

2.1.5 References are provided in Appendix C.

2.2 Government Documents

National Aeronautics and Space Administration (NASA)

NASA-STD-6030	Additive Manufacturing Requirements for Spaceflight Systems
NPR 7120.5	NASA Space Flight Program and Project Management Requirements
NPR 7120.8	NASA Research and Technology Program and Project Management Requirements

2.3 Non-Government Documents

None.

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, AND DEFINITIONS

3.1 Acronyms and Abbreviations

AM	Additive Manufacturing/Additively Manufactured
AMCP	Additive Manufacturing Control Plan
AMRR	Additive Manufacturing Readiness Review
CEO	Cognizant Engineering Organization
EFCP	Equipment and Facility Control Plan
EFCR	Equipment and Facilities Control Requirement
FFRDC	Federally Funded Research and Development Center
ft	Foot/Feet
GSE	Ground Support Equipment
L-PBF	Laser Powder Bed Fusion
m	Meter(s)
M&P	Materials and Processes
MPS	Material Property Suite
MRB	Material Review Board
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NIST	National Institute of Standards and Technology
NRRS	NASA Records Retention Schedule
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PCRD	Process Control Reference Distribution
PPP	Part Production Plan
Prod	Production
QMP	Qualified Material Process
QMS	Quality Management System
QPP	Qualified Part Process
Qual.	Qualification
SI	Système Internationale or metric system of measurement
SPC	Statistical Process Control
STD	Standard
Sub	Subsequent

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.

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 qualified part process (QPP).

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 qualified material process (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, executable file that requires no further software to execute the AM fabrication process.

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

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.

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.

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 is 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.

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 statistical process control (SPC) for the AM process.

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.

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

Operator: Personnel involved directly in the production of AM parts, from manipulation of the digital product definition in preparation for the AM build through the completion of the build process.

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.

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

Qualified Material Process (QMP), Subsequent QMP (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.

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

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

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.

4. GENERAL REQUIREMENTS

4.1 Tailoring of this NASA Technical Standard's Requirements

[EFCR-1] Tailoring of this NASA Technical Standard's requirements in the EFCP **shall** be formally documented as part of program or project requirements and approved by the responsible program/project NASA Materials and Processes (M&P) organization, the responsible project/program, 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 includes using existing or previously developed contractor processes and standards as a submittal of the various required plans. Otherwise, the tailoring of requirements may be documented in the EFCP, per section 4 of this NASA Technical Standard, by providing the means of conformance, the method of implementation, and the tailoring rationale for each requirement identified here. When an EFCP has been approved by the responsible CEO/program/project as an acceptable means of compliance with the technical requirements of this NASA Technical Standard, the EFCP may be used for the implementation and verification of AM requirements on the applicable program/project.

4.2 Equipment and Facility Control Plan

[EFCR-2] Prior to approval of an AMCP created under the auspices of NASA-STD-6030, a CEO-approved EFCP **shall** be developed and controlled by the QMS, addressing, at a minimum, the means of conformance, the method of implementation, and the tailoring rationale for each EFCR requirement in this NASA Technical Standard.

[Rationale: The EFCP provides for consistent definition and implementation of equipment and facility controls necessary for reliable AM part production.]

The AM part producer is intended to develop and maintain the EFCP with the concurrence of the CEO. The requirement for the EFCP may be met by leveraging existing documentation for control of equipment and facilities if all the requirements of this section are addressed, all documents are configuration controlled by the QMS, and the documents that make up the EFCP are identified in the AMCP per NASA-STD-6030.

4.3 Feedstock Management

Proper control of feedstock is essential to safe and reliable AM processes. This section provides requirements for storage and handling, material lot control in AM machines, and blending operations.

4.3.1 Feedstock Traceability

[EFCR-3] Traceability of the feedstock materials and the certificate of compliance **shall** be maintained throughout the lifecycle of the part.

[Rationale: Maintaining feedstock traceability is critical to tracking feedstock usage, life limits, and special usage requirements, and enables resolution of nonconformances involving feedstock.]

4.3.2 Feedstock Storage and Handling

[EFCR-4] The EFCP **shall** specify policies and procedures controlling the storage and handling of feedstock material, including, at a minimum, the following aspects:

a. Identification of the individual responsible for controlling access to feedstock and tracking usage.

b. Health and safety hazards.

c. Fire hazards associated with feedstock.

d. Safety Data Sheets.

e. Material and lot number identification for every container.

f. Storage in area with controlled access and suitable environmental controls and conditions (e.g., temperature and humidity control).

g. Control of opened, partially used feedstock containers.

h. Tracking of feedstock expiration date when applicable.

i. Control of contamination and feedstock cross-contamination.

j. Procedural implementation of feedstock reuse controls per section 6.6 of NASA-STD-6030 required by the CEO-approved AMCP.

k. Disposal procedures.

[Rationale: Proper management of feedstock is essential to ensuring safety in the facility, controlling raw materials for the process, and ensuring overall reliability of the AM process.]

Reuse of feedstock materials in AM processes used for NASA programs has to be controlled and implemented through the applicable EFCP and addressed in the applicable MPS per section 6 of NASA-STD-6030.

4.3.3 Material Exclusivity in AM Systems using Powder Feedstock

[EFCR-5] Each AM machine using powder feedstock **shall** be dedicated to a single material.

[Rationale: The presence of different materials within the machine presents an unacceptable risk of cross-contamination of feedstock materials.]

Feedstock cross-contamination in powder-based systems presents a major risk due to the difficulty in verifying system cleanliness after a material is removed from the system. As new AM

systems are designed, some of these configurations will lend themselves more readily than others to changing materials. For system configurations that allow for simplified material changes, tailoring of this requirement will be necessary in the EFCP.

4.3.3.1 Powder or Liquid Feedstock Lot Control Requirements in AM Machines

[EFCR-6] The number of feedstock lots present in a powder- or liquid-based AM machine at any given time **shall** be controlled based on maximum machine build volume:

a. Only one feedstock lot is allowed in AM machines with a build volume capacity less than or equal to 0.05 m^3 (1.75 ft^3).

b. A maximum of two feedstock lots is allowed in AM machines with a build volume capacity greater than 0.05 m^3 (1.75 ft^3).

[Rationale: Maintaining unique traceability in powder or liquid lots for AM parts is essential to managing the scope of potential feedstock nonconformance. For small volume machines, the cost and effort of maintaining a single feedstock lot in the machine are negligible and provide clear containment bounds for a feedstock nonconformance. For larger volume machines, it is acknowledged that limiting to a single feedstock lot may impede operation. The two-lot limitation balances nonconformance risk against operational necessity.]

At changing of feedstock lots, this requirement intends a nominal cleaning of the AM machine per section 4.3.3.3 of this NASA Technical Standard to remove the prior lot of material, but does not intend a disruptive cleaning throughout the machine for small residuals of the prior powder lot unless the prior lot was found to be nonconforming.

Note: For machines using two lots of feedstock material, the certificate of compliance for each lot will need to be documented in the end item data package.

4.3.3.2 Wire Feedstock Lot Control Requirements in AM Machines

[EFCR-7] AM machines using wire feedstock **shall** be limited to a single feedstock lot present in the machine at any time.

[Rationale: Maintaining unique traceability in wire lots for AM parts is essential to managing the scope of potential feedstock nonconformance. Large-scale AM systems that require feedstock reloading during a large build or systems with multiple heads must use the same feedstock lot throughout the build process.]

Some operations (e.g., gradient materials) may require multiple alloys. In that case, each alloy has to be controlled in the same manner as the individual alloy processes.

4.3.3.3 Cleaning Procedures for Removal of Residual Feedstock

[EFCR-8] Each AM machine building Class A or B hardware per NASA-STD-6030 **shall** have documented procedures for cleaning out residual feedstock and evaluating cleanliness, which are used prior to introducing new material lots per the material exclusivity requirements of section 4.3.3 of this NASA Technical Standard, or when thorough cleanouts associated with removing nonconforming lots or material changover are required.

[Rationale: Cross-contamination of powder lots or different materials poses a risk to material quality and tracability.]

AM machines should be cleaned after the removal of remnants of an old powder lot and before a new lot is used. To allow changing of materials in a system, documented processes and procedures for cleaning and verification of cleanliness that account for individual system designs must be created. Should materials be switched, the system has to be verified clean before qualification or requalification activities begin.

4.3.4 Feedstock Blending at the AM Part Producer

[EFCR-9] Powder or liquid blending operations occurring at the AM part producer **shall** be controlled by procedures in the EFCP to prevent contamination and cross-contamination of feedstock materials or feedstock lots, and to provide for safety in operations.

[Rationale: Blending operations (e.g., tumbling) are intended to ensure uniformity in powder particle distribution by reducing segregation as a result of handling and other operations that tend to segregate feedstocks. The blending process at the AM part producer has to follow established procedures; otherwise, required control of the feedstock material may be lost.]

Blending of feedstock materials at the AM part producer assumes that the feedstock materials to be blended still meet the applicable feedstock specifications and reuse limits. Blending of feedstock materials helps ensure uniformity of the material and does not constitute a recertification of the material.

4.3.5 Contamination and Foreign Object Debris Control

[EFCR-10] Plans and policies for the prevention of contamination and foreign object debris, as defined and controlled by the QMS and referenced in the EFCP, **shall** be actively enforced during all operations of AM machines and associated equipment.

[Rationale: Contamination and foreign object debris can easily undermine the integrity of the AM process and frequently are the result of unintended and unnoticed actions. The requirement to formalize and enforce plans and policies to preclude such contamination are essential to the long-term integrity of the AM process.]

Contamination control policies are intended to address the specifics of all operations, from storage and handling of feedstock throughout the AM process to the removal of excess feedstock from the machine during powder lot changeovers, in order to mitigate the risk of process contamination, particularly during off-nominal operations (e.g., atypical maintenance or repair) that may bring unusual opportunities for contamination. These policies should be addressed specifically in the training for all personnel with unsupervised access to the AM machine environment.

4.4 Digital Thread

4.4.1 Computer Security

[EFCR-11] Continuous computer security (i.e., cybersecurity or information technology security) **shall** be established and maintained on all computer systems and related devices that are associated with any aspect of the AM part design and build process, including storage devices used to transfer files.

[Rationale: The AM process is fully dependent on digital programs and digitally stored and manipulated data. The integrity of the AM process cannot be assured if the computer systems associated with all aspects of the process are not properly secured.]

The CEO and AM part producer share responsibilities in maintaining computer security commensurate with data integrity requirements. In the event that a computer cannot be secured using software or similar means, the computer or control unit should be placed in a physically controlled environment (e.g., standalone) or controlled access room.

4.4.2 Records Retention

[EFCR-12] Digital records considered to be part of the production engineering record according to NASA-STD-6030 **shall** be retained in accordance with the contract or QMS requirements.

[Rationale: Records for all components of the digital thread have to be archived for the prescribed period and remain fully traceable, including those provided by external suppliers.]

4.4.3 Sensitive Data

[EFCR-13] All AM-related data, including build parameters and part designs that are designated as sensitive, as defined by the contract, **shall** be handled with commensurate protections during all stages of transfer and storage.

[Rationale: Implementing the AM process involves the transfer, manipulation, and storage of data, electronic or otherwise, that are potentially deemed sensitive and protected by law from unauthorized disclosure. This requirement ensures all entities are aware that such precautions may be necessary.]

Both the CEO and the AM part producer are responsible for implementing the requirement across all facilities and data-transfer operations. This requirement applies to any data, including, but not limited to, drawings, models, and build files, which the CEO deems sensitive.

Policies and designations for data marking continuously evolve and vary by organization. Examples of designations for sensitive data include Sensitive But Unclassified, Proprietary, Limited Rights, International Traffic in Arms Regulations, Export Administration Regulations, or Controlled Item per the United States Munitions List.

4.5 Installation Controls

[EFCR-14] Prior to beginning production on any AM equipment, the AM part producer **shall** verify the following:

a. Installation conditions (e.g., temperature, humidity, floor profile and level) meet original equipment manufacturer (OEM) guidelines.

b. Utilities (e.g., required process gasses, power, chilled/cooling water, etc.) are available at required quantity or rating.

c. Ventilation needs and byproducts produced by AM equipment meet all applicable environmental and safety standards.

d. All factory acceptance testing and site acceptance testing required by the machine manufacturer has been successfully completed.

e. Hazard mitigation systems (e.g., fire protection and electrostatic grounding) are consistent with OEM recommendations and all applicable environmental, health, and safety standards.

[Rationale: Installation qualification ensures AM equipment and process installations meet OEM and regulatory guidelines for installation, environment, health, and safety.]

Installation controls are intended to verify AM process equipment has been installed and commissioned per the OEM guidelines and recommendations. This includes facility preparation to OEM specifications, safety and hazard requirements meeting all safety rules and regulations, and verification equipment performance to OEM guidelines. This body of work is critical to the establishment of safe and sustainable AM production.

4.6 Operational Controls

This section specifies required controls for equipment calibration, maintenance, monitoring, and procedure controls.

4.6.1 Operational Procedures and Checklists

[EFCR-15] Detailed operational procedures and checklists for all AM machines and associated equipment **shall** be used, and referenced in the EFCP, to ensure facility operations are standardized to the fullest extent possible, to provide operators with a proactive method to ensure all procedural steps are completed, and to provide traceability to the relevant QMS documents and forms (i.e., command media).

[Rationale: Consistency in the execution of sensitive processes, such as AM, is critical to maintaining control. Formalized procedures and checklists for complex operations are the key to achieving operational consistency.]

Development of these procedural work instructions or checklists is the responsibility of the AM part producer and may be implemented in any manner suiting the operational norms of the facility. Procedures or checklists are intended to be sufficiently detailed such that they are fully specific to a given machine or piece of equipment and are intended to be in place for all standard and readily foreseen contingency situations arising in normal operations (e.g., powder handling/filling, build setup and execution, build completion and removal of parts, powder removal from parts, machine cleaning, and other such common operations). Checklists also provide an easy way to confirm that all required steps were taken.

4.6.2 In Situ Monitoring

[EFCR-16] In situ monitoring systems **shall** be maintained and calibrated per a NASA-approved specification.

[Rationale: In situ monitoring systems are becoming increasingly common in AM and, if used, have to be maintained and calibrated on a regular basis.]

Maintenance and calibration guidelines supplied by the OEM may or may not be sufficient to meet the requirements of section 4.9 of NASA-STD-6030. The NASA-approved specification should contain the maintenance and calibration procedures and the schedules for these operations.

4.6.3 Configuration Management of AM Machines

[EFCR-17] A configuration management log for each AM machine **shall** be controlled by the QMS and include, at a minimum, the following events:

a. Maintenance, calibration, and qualification events.

b. Machine manufacturer service calls.

c. Repairs or other changes to machine.

d. Changes to associated computers used in production of files for printing (e.g., changes in computer-aided design and slicing software).

e. Updates to software and firmware versions.

[Rationale: Maintaining an accurate record of machine configuration is necessary to (1) establish the state of the AM machine at the time of qualification, (2) track or identify machine changes that may influence qualification status and the quality of the AM process, and (3) prevent unplanned or unintended loss of configuration control. Loss of AM machine configuration control negates the process control logic at the foundation of these requirements.]

In addition to the AM machine, changes in the way the computer model is rendered and sliced can affect the build with unintended consequences.

4.6.4 Maintenance

[EFCR-18] Comprehensive preventive maintenance schedules **shall** be established and enforced for all AM machines, facilities, and associated equipment.

[Rationale: Sustaining a continuously controlled AM process is only feasible if maintenance for the facility and all associated equipment is performed consistently and adequately.]

Facility and equipment maintenance is intended to be implemented through the EFCP under the auspices of the AM part producer. The preventive maintenance schedules should include, at a minimum, the recommended maintenance items identified by the AM machine manufacturer and other items unique to the installation or facility. The maintenance schedule should be reviewed periodically for each AM machine to ensure all maintenance needs and intervals are properly set, proactively taking into account observations of process quality and machine health during operations and prior maintenance activity. Critical associated equipment may include sieve equipment, measuring or calibration instruments, cleaning tools, and other such apparatus that are influential to continued successful operation of the AM process.

4.6.5 Minimum Maintenance

[EFCR-19] Preventative maintenance plans for AM equipment **shall** meet, at a minimum, those required by the machine OEM.

[Rationale: OEM required maintenance is considered the minimum effort required for AM equipment.]

4.6.6 Associated Equipment

[EFCR-20] Any associated equipment whose performance can impact the ability of the AM parts produced to meet the specified requirements (e.g., solvent tank or powder removal systems) **shall** be included in the maintenance plan.

[Rationale: All maintenance performed has to be documented in a log and maintained for a period compliant with applicable contracts and laws.]

4.6.7 Calibration

Calibration of AM machines and associated equipment is central to establishing the qualification of machines for production. This section provides minimum requirements for managing calibrations. The metrology and calibration requirements below are those that are unique and impactful for managing AM processes. See NPR 8735.2, Management of Government Quality Assurance Functions for NASA Contracts, and NASA-STD-8739.12, Metrology and Calibration, for requirements applicable to NASA programs and projects for using and flowing down metrology and calibration requirements to external suppliers.

4.6.7.1 Calibration Schedules

[EFCR-21] Each AM machine **shall** have comprehensive calibration schedules defined and implemented that meet the following minimum criteria:

a. Addresses all mechanical, optical, electrical, software, and firmware systems involved in controlling or monitoring the AM process.

b. Defines each calibration metric with nominal value(s) and acceptable tolerances.

c. Defines calibration intervals for each metric.

d. Is subject to the metrology and calibration program requirements imposed by the contract.

[Rationale: Equipment calibration is essential to reliable control of the AM process.]

Equipment calibration procedures are intended to be implemented through the EFCP under the auspices of the AM part producer. Calibration may also include or be limited to verification of

state, such as in the case of software or firmware versions. All aspects of the AM machine that are controlled, commanded, or monitored during execution of the AM process are intended to be included in the calibration and verification process. These include, but are not limited to, the ventilation system, oxygen sensing, and motion and alignment of mechanical systems (e.g., the recoater and build platform). Use of National Institute of Standards and Technology (NIST)-traceable standards for all calibration measurements is recommended. NASA-STD-6033 does not modify NASA metrology and calibration policy, which is found in NPR 8735.2 and NASA-STD-8739.12. Refer to the contract for calibration control requirements.

4.6.7.2 Optical System Calibration

[EFCR-22] As part of the calibration schedule, calibration of the optical system(s) (e.g., lasers, scanner heads, and associated optical path) of each laser/light-based AM machine **shall** include, at a minimum for each laser/scanner combination, the following metrics evaluated at the center and furthest attainable extremes of the build area (or individual laser scan area) in the build plane:

a. Laser/light power.

b. Laser/light spot size, shape, and profile.

c. Laser/light alignment (X, Y) to the build area and with relationship to additional lasers in the system.

d. Laser/light focal point alignment to the build plane.

e. Accuracy and precision of scanner head beam scanning.

f. Laser timing for on/off operations during a build.

[Rationale: The AM process is wholly dependent on optical system performance. AM machines are typically incapable of active feedback monitoring of optical system performance. These calibration requirements are established to provide consistent monitoring of optical system health.]

Depending on the capabilities of the AM part producer, optical system calibration is likely a set of measurements to verify that the health of the laser and optics system is consistent with metrics provided by the equipment manufacturer and consistent over time. Lasing purposeful markings into a flat, solid plate and evaluating the markings against metrics (based on past performance) may provide sufficient evidence of scanner head health.

4.6.7.3 Calibration Intervals

[EFCR-23] Maximum calibration intervals **shall** be as follows:

a. Optical system(s): 90 days.

b. All other systems: 180 days.

c. After any maintenance, repair, or replacement of any system (e.g., repairing the scan mirror system).

[Rationale: Calibration is effective only when maintained continuously. For pragmatic reasons, confirming calibration is not feasible on a per-build basis. This time-based calibration interval is set as a compromise between production efficiency and process assurance. In addition, calibrations have to be reestablished after working on the system to perform maintenance and repairs, as it is likely the system will be out of calibration initially.]

To accommodate part build times and schedules, these calibration intervals may be acceptably implemented at the completion of the last build that began within the interval. Policies for interpreting the calibration interval have to be clearly defined in the EFCP.

4.6.7.4 Calibration State

[EFCR-24] AM machines **shall** be considered in a calibrated state only when:

a. All scheduled maintenance items in section 4.6.4 of this NASA Technical Standard are completed within their prescribed maintenance intervals,

b. All calibration metrics in section 4.6.7.2 of this NASA Technical Standard are evaluated within their defined calibration intervals (maximums per section 4.6.7.3) and verified within specification limits, and

c. Maintenance and calibration records are documented as required by section 4.6 of this NASA Technical Standard.

[Rationale: An established and documented state of calibration is necessary to establish AM machine qualification for the production of parts.]

4.6.7.5 Calibration Nonconformance

[EFCR-25] Upon calibration, if any calibration metric is not within specification limits, a nonconformance **shall** be documented and controlled by the QMS for all parts produced since the last calibration.

[Rationale: Calibration metrics outside specification limits are considered a nonconformance to section 4.6.7.2 of this NASA Technical Standard.]

This requirement may influence the choice of calibration intervals to mitigate programmatic risk, particularly for AM machines whose calibration stability is not well characterized. Part nonconformance can be resolved at the discretion of the program, preferably once the root cause of the calibration error and its influence on the AM process is understood.

4.7 AM Machine Qualification

[EFCR-26] AM machines **shall** have active qualification status only when:

a. The AM machine is documented to be in the calibrated state per section 4.6.7.2 of this NASA Technical Standard,

b. A QMP or sub-QMP has been successfully established within 12 months, or the AM machine has been under continuous SPC monitoring as defined by NASA-STD-6030, and

c. No event (see the following examples) has occurred to negate the active qualification status of the machine:

(1) Changes to the machine other than predefined preventative maintenance.
(2) Updates to software or firmware.
(3) Replacement, repair, or alteration of predetermined list of critical components.
(4) Moving the machine.
(5) Changes to the machine setup or configuration within the facility.
(6) Any similar or unforeseen event that may credibly alter or influence the AM machine performance.
(7) There is no pending, unresolved nonconformance associated with compliance with the controls defined in section 4.6 of this NASA Technical Standard.

[Rationale: A clearly implemented definition of AM machine qualification status ensuring machine health is critical to the reliable production of AM parts.]

Predetermining an exhaustive list of events that negate the active qualification status of a machine is not practical, and determining which disruptive events reach this threshold can be subjective. The list of critical components of an AM system will vary depending on multiple factors (e.g., machine architecture and material). A list of these components have to be documented prior to a machine's initial qualification. Accurate documentation of all events, regardless of magnitude, in the machine configuration management log (see section 4.6.3 of this NASA Technical Standard) is important. Unforeseen events of questionable impact to qualification state should be arbitrated among the AM part producer and/or the CEO.

4.7.1 AM Machine Qualification Status for Production

[EFCR-27] AM parts **shall** be produced only to a QMP if the associated machine has active qualification status and such qualification status is posted directly on the machine.

[Rationale: The qualification of an AM machine and the qualification of its associated metallurgical processes are largely synonymous, given the machine is in a calibrated state. Verification of the quality of the metallurgical process establishes the AM machine's qualification; events that negate a machine's qualification status negate the ability to produce parts to associated QMPs until machine qualification status is reestablished. Posting of machine qualification status ensures operators are noticeably aware of a machine's status prior to use.]

4.7.2 Establishing Initial Qualification

[EFCR-28] Active qualification status of an AM machine **shall** be established initially through the following:

a. Verify the AM machine meets all OEM requirements and specifications and has been certified as operational by the OEM upon installation.

b. Verify the AM machine to be in a calibrated state per section 4.6.7.2 of this NASA Technical Standard.

c. Verify one QMP (or sub-QMP, as applicable) for the machine meets the requirements of section 5 of NASA-STD-6030 or the applicable AMCP approved by the CEO.

d. Record the active qualification status in the AM machine configuration log.

[Rationale: These requirements represent the minimally acceptable evaluations of AM machine performance prior to production of parts.]

4.7.3 Reestablishing Qualification

[EFCR-29] Active qualification status of an AM machine **shall** be reestablished following any event that negates its active qualification status through a minimum of the following:

a. Verify the event negating active qualification is resolved.

b. Verify the AM machine is in a calibrated state per section 4.6.7.2 of this NASA Technical Standard.

c. Verify the AM process using the SPC requirements of NASA-STD-6030, section 5.5, or the applicable AMCP approved by the CEO.

d. Record all related events in the AM machine configuration log.

[Rationale: These requirements represent the minimally acceptable evaluations of AM machine performance to requalify the machine for production of parts following an event that negates an active qualification status.]

An AM machine may have multiple associated QMPs (e.g., QMPs developed for various layer thicknesses). An AM machine without active qualification status may not produce to any of its associated QMPs. Reestablishing active qualification status and enabling all associated QMPs require reevaluation of the machine capability per NASA-STD-6030, section 5.5, or the applicable AMCP approved by the CEO for only one of the associated QMPs.

As discussed in the commentary for section 4.7 of this NASA Technical Standard, a broad variety of events may occur to negate the qualification status of an AM machine. The scope of requalification activities may be tailored to fit unique scenarios with written agreement of the AM part producer, the CEO, and the NASA customer.

4.8 Operator Certification

[EFCR-30] AM operations, defined in the context of this requirement as those actions spanning from the manipulation of the digital product definition to prepare for the build through removal of the completed part from the AM machine, **shall** only be performed by operators with applicable training certifications traceable via a records management system controlled by the QMS and to minimum training requirements defined by the machine's OEM.

[Rationale: Although automated, the AM process is highly sensitive and dependent on the inputs of the operators at all stages of the process. Operator certifications are essential to minimizing the risk of human error in the process. Operators should meet, at a minimum, the training requirements specified by the equipment OEMs.]

4.8.1 Training Program

[EFCR-31] An active operator training program **shall** be defined, maintained, and implemented to meet the following objectives:

a. Provide a consistent framework for training and certification requirements.

b. Provide clear delineations of abilities and responsibilities associated with granted certifications.

c. Provide operators with all necessary skills, knowledge, and experience to safely and reliably execute the responsibilities of their certification.

d. Provide for operator evaluations that demonstrate adequacy in skills, knowledge, and experience to grant certifications to personnel, ensuring only properly trained and experienced personnel have appropriate certifications.

e. Incorporate content regarding the importance, purpose, and use of the QMS for all aspects of the established AM process.

[Rationale: Operator certifications are only meaningful if granted from a properly structured and adequate training program.]

The CEO and AM part producers are jointly responsible for the adequacy of the implemented training program.

The intent of this requirement is to ensure appropriate depth in the knowledge and skills of the AM workforce involved in the production of aerospace parts per these NASA Technical Standards.

A list of key topics for training and an example of a training program can be found in extended commentary of Appendix B.

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-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1	Tailoring of this NASA Technical Standard's Requirements	**[EFCR-1]** Tailoring of this NASA Technical Standard's requirements in the EFCP **shall** be formally documented as part of program or project requirements and approved by the responsible program/project NASA Materials and Processes (M&P) organization, the responsible project/program, 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	Equipment and Facility Control Plan	**[EFCR-2]** Prior to approval of an AMCP created under the auspices of NASA-STD-6030, a CEO-approved EFCP **shall** be developed and controlled by the QMS, addressing, at a minimum, the means of conformance, the method of implementation, and the tailoring rationale for each EFCR requirement in this NASA Technical Standard.		
4.3.1	Feedstock Traceability	**[EFCR-3]** Traceability of the feedstock materials and the certificate of compliance **shall** be maintained throughout the lifecycle of the part.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.3.2	Feedstock Storage and Handling	**[EFCR-4]** The EFCP **shall** specify policies and procedures controlling the storage and handling of feedstock material, including, at a minimum, the following aspects: a. Identification of the individual responsible for controlling access to feedstock and tracking usage. b. Health and safety hazards. c. Fire hazards associated with feedstock. d. Safety Data Sheets. e. Material and lot number identification for every container. f. Storage in area with controlled access and suitable environmental controls and conditions (e.g., temperature and humidity control). g. Control of opened, partially used feedstock containers. h. Tracking of feedstock expiration date when applicable. i. Control of contamination and feedstock cross-contamination. j. Procedural implementation of feedstock reuse controls per section 6.6 of NASA-STD-6030 required by the CEO-approved AMCP. k. Disposal procedures.		
4.3.3	Material Exclusivity in AM Systems using Powder Feedstock	**[EFCR-5]** Each AM machine using powder feedstock **shall** be dedicated to a single material.		
4.3.3.1	Powder or Liquid Feedstock Lot Control Requirements in AM Machines	**[EFCR-6]** The number of feedstock lots present in a powder- or liquid-based AM machine at any given time **shall** be controlled based on maximum machine build volume: a. Only one feedstock lot is allowed in AM machines with a build volume capacity less than or equal to 0.05 m^3 (1.75 ft^3). b. A maximum of two feedstock lots is allowed in AM machines with a build volume capacity greater than 0.05 m^3 (1.75 ft^3).		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.3.3.2	Wire Feedstock Lot Control Requirements in AM Machines	**[EFCR-7]** AM machines using wire feedstock **shall** be limited to a single feedstock lot present in the machine at any time.		
4.3.3.3	Cleaning Procedures for Removal of Residual Feedstock	**[EFCR-8]** Each AM machine building Class A or B hardware per NASA-STD-6030 **shall** have documented procedures for cleaning out residual feedstock and evaluating cleanliness, which are used prior to introducing new material lots per the material exclusivity requirements of section 4.3.3 of this NASA Technical Standard, or when thorough cleanouts associated with removing nonconforming lots or material changover are required.		
4.3.4	Feedstock Blending at the AM Part Producer	**[EFCR-9]** Powder or liquid blending operations occurring at the AM part producer **shall** be controlled by procedures in the EFCP to prevent contamination and cross-contamination of feedstock materials or feedstock lots, and to provide for safety in operations.		
4.3.5	Contamination and Foreign Object Debris Control	**[EFCR-10]** Plans and policies for the prevention of contamination and foreign object debris, as defined and controlled by the QMS and referenced in the EFCP, **shall** be actively enforced during all operations of AM machines and associated equipment.		
4.4.1	Computer Security	**[EFCR-11]** Continuous computer security (i.e., cybersecurity or information technology security) **shall** be established and maintained on all computer systems and related devices that are associated with any aspect of the AM part design and build process, including storage devices used to transfer files.		
4.4.2	Records Retention	**[EFCR-12]** Digital records considered to be part of the production engineering record according to NASA-STD-6030 **shall** be retained in accordance with the contract or QMS requirements.		
4.4.3	Sensitive Data	**[EFCR-13]** All AM-related data, including build parameters and part designs that are designated as sensitive, as defined by the contract, **shall** be handled with commensurate protections during all stages of transfer and storage.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.5	Installation Controls	**[EFCR-14]** Prior to beginning production on any AM equipment, the AM part producer **shall** verify the following: a. Installation conditions (e.g., temperature, humidity, floor profile and level) meet original equipment manufacturer (OEM) guidelines. b. Utilities (e.g., required process gasses, power, chilled/cooling water, etc.) are available at required quantity or rating. c. Ventilation needs and byproducts produced by AM equipment meet all applicable environmental and safety standards. d. All factory acceptance testing and site acceptance testing required by the machine manufacturer has been successfully completed. e. Hazard mitigation systems (e.g., fire protection and electrostatic grounding) are consistent with OEM recommendations and all applicable environmental, health, and safety standards.		
4.6.1	Operational Procedures and Checklists	**[EFCR-15]** Detailed operational procedures and checklists for all AM machines and associated equipment **shall** be used, and referenced in the EFCP, to ensure facility operations are standardized to the fullest extent possible, to provide operators with a proactive method to ensure all procedural steps are completed, and to provide traceability to the relevant QMS documents and forms (i.e., command media).		
4.6.2	In Situ Monitoring	**[EFCR-16]** In situ monitoring systems **shall** be maintained and calibrated per a NASA-approved specification.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.6.3	Configuration Management of AM Machines	**[EFCR-17]** A configuration management log for each AM machine **shall** be controlled by the QMS and include, at a minimum, the following events: a. Maintenance, calibration, and qualification events. b. Machine manufacturer service calls. c. Repairs or other changes to machine. d. Changes to associated computers used in production of files for printing (e.g., changes in computer-aided design and slicing software). e. Updates to software and firmware versions.		
4.6.4	Maintenance	**[EFCR-18]** Comprehensive preventive maintenance schedules **shall** be established and enforced for all AM machines, facilities, and associated equipment.		
4.6.5	Minimum Maintenance	**[EFCR-19]** Preventative maintenance plans for AM equipment **shall** meet, at a minimum, those required by the machine OEM.		
4.6.6	Associated Equipment	**[EFCR-20]** Any associated equipment whose performance can impact the ability of the AM parts produced to meet the specified requirements (e.g., solvent tank or powder removal systems) **shall** be included in the maintenance plan.		
4.6.7.1	Calibration Schedules	**[EFCR-21]** Each AM machine **shall** have comprehensive calibration schedules defined and implemented that meet the following minimum criteria: a. Addresses all mechanical, optical, electrical, software, and firmware systems involved in controlling or monitoring the AM process. b. Defines each calibration metric with nominal value(s) and acceptable tolerances. c. Defines calibration intervals for each metric. d. Is subject to the metrology and calibration program requirements imposed by the contract.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.6.7.2	Optical System Calibration	**[EFCR-22]** As part of the calibration schedule, calibration of the optical system(s) (e.g., lasers, scanner heads, and associated optical path) of each laser/light-based AM machine **shall** include, at a minimum for each laser/scanner combination, the following metrics evaluated at the center and furthest attainable extremes of the build area (or individual laser scan area) in the build plane: a. Laser/light power. b. Laser/light spot size, shape, and profile. c. Laser/light alignment (X, Y) to the build area and with relationship to additional lasers in the system. d. Laser/light focal point alignment to the build plane. e. Accuracy and precision of scanner head beam scanning. f. Laser timing for on/off operations during a build.		
4.6.7.3	Calibration Intervals	**[EFCR-23]** Maximum calibration intervals **shall** be as follows: a. Optical system(s): 90 days. b. All other systems: 180 days. c. After any maintenance, repair, or replacement of any system (e.g., repairing the scan mirror system).		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.6.7.4	Calibration State	**[EFCR-24]** AM machines **shall** be considered in a calibrated state only when: a. All scheduled maintenance items of section 4.6.4 of this NASA Technical Standard are completed within their prescribed maintenance intervals, b. All calibration metrics in section 4.6.7.2 of this NASA Technical Standard are evaluated within their defined calibration intervals (maximums per section 4.6.7.3) and verified within specification limits, and c. Maintenance and calibration records are documented as required by section 4.6 of this NASA Technical Standard.		
4.6.7.5	Calibration Nonconformance	**[EFCR-25]** Upon calibration, if any calibration metric is not within specification limits, a nonconformance **shall** be documented and controlled by the QMS for all parts produced since the last calibration.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.7	AM Machine Qualification	**[EFCR-26]** AM machines **shall** have active qualification status only when: a. The AM machine is documented to be in the calibrated state per section 4.6.7.2 of this NASA Technical Standard, b. A QMP or sub-QMP has been successfully established within 12 months, or the AM machine has been under continuous SPC monitoring as defined by NASA-STD-6030, and c. No event (see the following examples) has occurred to negate the active qualification status of the machine: 1. Changes to the machine other than predefined preventative maintenance. 2. Updates to software or firmware. 3. Replacement, repair, or alteration of predetermined list of critical components. 4. Moving the machine. 5. Changes to the machine setup or configuration within the facility. 6. Any similar or unforeseen event that may credibly alter or influence the AM machine performance. 7. There is no pending, unresolved nonconformance associated with compliance with the controls defined in section 4.6 of this NASA Technical Standard.		
4.7.1	AM Machine Qualification Status for Production	**[EFCR-27]** AM parts **shall** be produced only to a QMP if the associated machine has active qualification status and such qualification status is posted directly on the machine.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.7.2	Establishing Initial Qualification	**[EFCR-28]** Active qualification status of an AM machine **shall** be established initially through the following: a. Verify the AM machine meets all OEM requirements and specifications and has been certified as operational by the OEM upon installation. b. Verify the AM machine to be in a calibrated state per section 4.6.7.2 of this NASA Technical Standard. c. Verify one QMP (or sub-QMP, as applicable) for the machine meets the requirements of section 5 of NASA-STD-6030 or the applicable AMCP approved by the CEO. d. Record the active qualification status in the AM machine configuration log.		
4.7.3	Reestablishing Qualification	**[EFCR-29]** Active qualification status of an AM machine **shall** be reestablished following any event that negates its active qualification status through a minimum of the following: a. Verify the event negating active qualification is resolved. b. Verify the AM machine is in a calibrated state per section 4.6.7.2 of this NASA Technical Standard. c. Verify the AM process using the SPC requirements of NASA-STD-6030, section 5.5, or the applicable AMCP approved by the CEO. d. Record all related events in the AM machine configuration log.		
4.8	Operator Certification	**[EFCR-30]** AM operations, defined in the context of this requirement as those actions spanning from the manipulation of the digital product definition to prepare for the build through removal of the completed part from the AM machine, **shall** only be performed by operators with applicable training certifications traceable via a records management system controlled by the QMS and to minimum training requirements defined by the machine's OEM.		

NASA-STD-6033				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.8.1	Training Program	**[EFCR-31]** An active operator training program **shall** be defined, maintained, and implemented to meet the following objectives: a. Provide a consistent framework for training and certification requirements. b. Provide clear delineations of abilities and responsibilities associated with granted certifications. c. Provide operators with all necessary skills, knowledge, and experience to safely and reliably execute the responsibilities of their certification. d. Provide for operator evaluations that demonstrate adequacy in skills, knowledge, and experience to grant certifications to personnel, ensuring only properly trained and experienced personnel have appropriate certifications. e. Incorporate content regarding the importance, purpose, and use of the QMS for all aspects of the established AM process.		

APPENDIX B

OPERATOR TRAINING

B.1 PURPOSE

This Appendix provides examples of key topics expected to be included in a training program and an example training protocol.

B.2 KEY TOPICS TO INCLUDE IN A TRAINING PROGRAM

Following are examples of key topics expected to be included in a training program (does not represent a comprehensive list):

- Health and safety.
- Understanding and using the QMS.
- Documentation requirements.
- Maintaining configuration control of digital files and equipment.
- Working with the digital product definition.
- The cryptographic hash and its use.
- Build files, support structures, slicing.
- Feedstock handling.
- Machine functionality: setup, operations, restarts, maintenance, calibration.
- AM process monitoring: understanding failure mechanisms in the process and the ability to identify and properly troubleshoot build errors.
- Understanding build capability: overhangs, surface quality, detail resolution.
- As-built part inspections for build quality and anomalies.
- Contamination and foreign object debris control.
- Execution and evaluation of standard qualification build sets for QMP and SPC purposes.
- Establishing QMPs and sub-QMPs.

B.3 EXAMPLE TRAINING PROTOCOL FOR LASER POWDER BED FUSION (L-PBF) MACHINE OPERATORS

The following example represents a training protocol for L-PBF machine operators with tiered implementation meeting the objectives of section 4.8.1 of this NASA Technical Standard:

Note: A similar training regiment, though perhaps not tiered, would be needed to cover topics related to working with the digital product definition (e.g., assembling builds, slicing, support generation, and related tasks).

Trainee

Prerequisites:

- No prior experience needed.

Typical duties:

- Trainee may participate in the day-to-day operations of L-PBF machines and associated equipment. A trainee is not to operate L-PBF machines or associated equipment without the supervision of at least a Level I Certified Operator.

Level I Certified Operator

Prerequisites:

- Minimum 3 months of experience under direct supervision of a Level II or III Certified Operator.
- Passed written and practical test administered by a Level III Certified Operator.
- Completed all basic training offered by the L-PBF machine manufacturer.
- Full understanding of applicable QMS and associated responsibilities.

Typical duties:

- Machine cleaning, operational checks.
- Basic machine operations.
- Execution of established builds.
- Operate under supervision of Level II or III Certified Operator.

Level II Certified Operator

Prerequisites:

- Met all Level I Certified Operator prerequisites.
- One-year minimum experience under direct supervision of a Level II or III Certified Operator.
- Passed written and practical test administered by a Level III Certified Operator.
- Completed all advanced training offered by the L-PBF machine manufacturer.
- Comprehensive knowledge of all machine functions.

Typical duties:

- Set up and troubleshoot L-PBF equipment.
- Execute and analyze standard qualification build sets.
- Troubleshoot and iteration of build schemes to optimize build performance.
- Build file generation in accordance with qualified part process requirements.
- Develop machine operation checklists.
- Operate under supervision of Level III Certified Operator.

Level III Certified Operator

Prerequisites:

- Met all Level II Certified Operator prerequisites.
- Minimum 3 years of experience.
- Understanding of the physics and metallurgy of the L-PBF process.
- Passed written and practical test administered by another Level III Certified Operator.

Typical duties:

- Develop QMPs.
- Establish proper QMS oversight for all L-PBF activities.
- Develop, implement, and approve production planning records.
- Set machine calibration metrics and intervals.
- Develop training and administer written and practical certification tests.

The structure provided above is a reference only and does not dictate how a training program is to be set up. There are many universities, standards developing organizations, and other entities that are developing training programs that may provide training resources to meet the needs of the organization and the requirements of this NASA Technical Standard. For example, in the tiered example provided above, courses such as Society of Manufacturing Engineers “Additive Manufacturing Technician Certification” or the ASTM “Additive Manufacturing Center of Excellence Training” may provide content needed for the Level III certified operator.

APPENDIX C

REFERENCES

C.1 PURPOSE

This Appendix provides references to guidance documents related to this NASA Technical Standard.

C.2 REFERENCES

MSFC Form 4657, Change Request for a NASA Engineering Standard

NASA-STD-8739.12, Metrology and Calibration

NPR 8735.2, Management of Government Quality Assurance Functions for NASA Contracts