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This file is for reference
use, it should be compared
current revision of NASA-STD-6033
a separate worksheet taking
NASA-STD-6033 Main

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

[AMR-9] Class B parts shall not:

- a. Be fasteners.
- b. Contain printed threads

[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.
- 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.

[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.

[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).

[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.

[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.

[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.

[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.

[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.

[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.

[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.

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

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.
- 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.

[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.

[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.

[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.

[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).

[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

[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.

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

[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.

[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.

[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.

[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.

[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.

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

[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.

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

[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.

[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.

[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.

[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.

[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.

[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 $\geq 6 \text{ cm}^2$ (0.93 in²) 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.

[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 $\geq 6 \text{ cm}^2$ (0.93 in²) 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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

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

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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 ≥ 108 , 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 < 108 may be employed when properly documented.

[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.

[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.

[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.

[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.

[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.

[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).

[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.

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

[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.

[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.

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

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

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

[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.

[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.

[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.

[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.

[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.

[AMR-105] For Class A and B parts, the PPP **shall** describe a preproduction article evaluation verifying quality of part and material.

[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).

[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.

[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.

[AMR-109] An AM Readiness Review, defining a qualified part process, **shall** be conducted for all Class A and B parts.

[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.

[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.

[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.

[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.

[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.

[AMR-115] The QPP **shall** document the digital thread.

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Section Description

4.1	Tailoring of this NASA Technical Standard's Requirements
4.2	Before u cl See
4.3.1	
4.3.2	
4.3.3	
4.3.3.1	
4.3.3.2	Wire Feedstock Lot Control Requirements in AM Machines
4.3.3.3	Cleaning Procedures for Removal of Residual Feedstock
4.3.4	Feedstock Blending at the AM Part Producer

4.3.5 Contamination and Foreign Object
Debris Control

4.4.1 Computer Security

4.4.2 Records Retention

4.4.3 Sensitive Data

4.5 Installation Controls

4.6.1 Operational Procedures and Checklists

4.6.2 In Situ Monitoring

4.6.3 Configuration Management of AM
Machines

4.6.4 Maintenance

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4.6.6 Associated Equipment

4.6.7.1 Calibration Schedules

4.6.7.2 Optical System Calibration

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4.6.7.4 Calibration State

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4.7 AM Machine Qualification

4.7.1 AM Machine Qualification Status for
Production

4.7.2 Establishing Initial Qualification

4.7.3 Reestablishing Qualification

4.8 Operator Certification

4.8.1 Training Program

Requirement in this Standard

[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 NRP

This file is for reference
use, it should be compared
current revision of NASA-STD-6030
separate worksheet tab
NASA-STD-6030 Material

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

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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).

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

[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.

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

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

[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.

[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.

[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.

[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).

[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.

[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.

[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.

[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.

[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.

[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.

[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.

[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.

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