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NASA TECHNICAL STANDARD

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Superseding NASA-STD-6016B

STANDARD MATERIALS AND PROCESSES REQUIREMENTS FOR SPACECRAFT

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DOCUMENT HISTORY LOG

Status	Document Revision	Change Number	Approval Date	Description
Interim			2006-09-11	Interim Release
Baseline			2008-07-11	Baseline Release Transitioned Interim Standard NASA-STD-(I)-6016 to NASA Technical Standard NASA-STD-6016.
Revision	A		2016-11-30	Significant changes were made to the document. It is recommended that the document be reviewed in its entirety before implementation. Key changes were: • Updated applicable standards to the latest verified acceptable versions. • Simplified requirements on M&P control process. • Revised requirements on material design values. • Restructured standard to place all heat treatment and weld process requirements in Processes section. • Added controls on use of pure tin (replacing previous prohibition). • Added first article and production controls for castings. • Imposed AWS and other voluntary consensus standards for welding as alternative to NASA-STD-5006A. • Added high-level requirement on additive manufacturing. • Added requirements on control of intermetallic compounds.

DOCUMENT HISTORY LOG (Continued)

Status	Document Revision	Change Number	Approval Date	Description
Revision	A			Continued • Replaced prohibition on liquid-locking compounds with imposition of (less restrictive) NASA-STD-5020. • Retired Category III MUA codes and incorporated rationales into the standard as exceptions to the requirements. • Added appendix with rationales for each requirement.
Revision	B		2020-05-14	Revised to add requirements to address potential ignition of materials in nitrogen tetroxide and other oxidizer systems—4.2.1.3e [MPR 210], 4.2.1.3.e(1) [MPR 211], and 4.2.1.3.f [MPR 212].
Revision	C		YYYY-MM-DD	Limited Revision: • Modified hazardous fluid compatibility requirement [MPR 47] to require MUA for compatibility verification. • Revised section 4.2.4.11 requirement [MPR 174] and guidance on additive manufacturing to cite NASA-STD-6030. • Added new guideline and requirement [MPR 213] on composite NDE to section 4.2.5.1 • Revised guidance on sandwich assemblies in section 4.2.6.2. • Changed requirement [MPR 188] on sandwich assemblies in section 4.2.6.2 to call out the requirements of CMH-17 Volume 6: Structural Sandwich

DOCUMENT HISTORY LOG (Continued)

Status	Document Revision	Change Number	Approval Date	Description
Revision	C			Continued Composites in place of SAE AMS-STD-401 (1999), Sandwich Constructions and Core Materials: General Test Methods. • Revised definitions of additive manufacturing and critical and catastrophic hazards in section 3.2.

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 endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

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

This NASA Technical Standard defines the minimum requirements for Materials and Processes (M&P) and provides a general control specification for incorporation in NASA program/project hardware procurements and technical programs.

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.

Ralph R. Roe, Jr. NASA Chief Engineer	Approval Date

NOTE: Per section 4.1.6: The use of M&P that do not comply with the requirements of this NASA Technical Standard may be acceptable in the actual hardware applications. MUAs are required for all M&P that are technically acceptable but do not meet the requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

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STANDARD MATERIALS AND PROCESSES REQUIREMENTS FOR SPACECRAFT

1. SCOPE

This NASA Technical Standard is directed toward materials and processes (M&P) used in the design, fabrication, and testing of space program flight hardware for NASA, including but not limited to crewed, uncrewed, robotic, launch vehicle, lander, in-space and surface systems, and spacecraft program/project hardware elements. All spaceflight hardware is covered by the M&P requirements of this document, including vendor-designed, off-the-shelf, and vendor-furnished items.

M&P used in interfacing ground support equipment (GSE), test equipment, hardware processing equipment, hardware packaging, and hardware shipment is covered by the M&P requirements of this NASA Technical Standard only to the extent required to prevent damage to or contamination of spaceflight hardware (see section 4). M&P used in NASA aircraft and aircraft operations are not covered by the M&P requirements of this document.

1.1 Purpose

The purpose of this NASA Technical Standard is to define the minimum requirements for M&P and to provide a general control specification for incorporation in NASA program/project hardware procurements and technical programs.

1.2 Applicability

The controls described here are applicable to all NASA spacecraft programs:

a. [MPR 1] Programs shall apply these controls to program/project hardware. Programs, projects, and elements are responsible for flowing requirements down to contractors, subcontractors, and the lowest component-level suppliers.

b. [MPR 2] Programs shall be responsible for demonstrating compliance with these requirements.

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 “MPR” (Materials and Processes Requirement), numbered, and indicated by the word “shall. This NASA Technical Standard contains 213 requirements. Explanatory or guidance text is indicated in italics beginning in section 4. To facilitate requirements selection by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A. This appendix also contains justifications for each verifiable requirement statement.

1.3 Tailoring

a. [MPR 3] Tailoring of this NASA Technical Standard’s requirements in the Materials and Processes Selection, Control, and Implementation Plan for specific programs/projects shall be formally documented as part of program or project requirements and approved by the responsible program/project NASA 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. These requirements may be tailored simply by constructing a matrix of applicable paragraphs and paragraphs that are not applicable. Tailoring also 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 Materials and Processes Selection, Control, and Implementation Plan by providing the degree of conformance and the method of implementation for each requirement identified here.

b. When a Materials and Processes Selection, Control, and Implementation Plan has been approved by the responsible program/project as an acceptable means of compliance with the technical requirements of this NASA Technical Standard, the Plan may be used for the implementation and verification of M&P requirements on the applicable program/project.

2. APPLICABLE DOCUMENTS

2.1 General

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

2.1.1 [MPR 4] The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 [MPR 5] Non-use of specifically designated versions shall be approved by the delegated Technical Authority.

The applicable documents are accessible at https://standards.nasa.gov, may be obtained directly from the Standards Developing Body or other document distributors, or information for obtaining the document is provided.

2.2 Government Documents

The documents in these paragraphs are applicable to the extent specified. The citations below refer to the sections in this NASA Technical Standard.

National Aeronautics and Space Administration (NASA)

NPR 7120.5 (Cited in section 1.3)	NASA Space Flight Program and Project Management Requirements
NPR 7120.8 (Cited in section 1.3)	NASA Research and Technology Program and Project Management Requirements
NPR 8715.3D (Cited in section 3.2)	NASA General Safety Program Requirements
NASA-STD-5006A with Change 1 (2016) (Cited in section 4.2.4.6)	General Welding Requirements for Aerospace Materials
NASA-STD-5009B (2019) (Cited in section 4.2.5.1)	Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
NASA-STD-5020 (2012) (Cited in section 4.2.6.6.1)	Requirements for Threaded Fastening Systems in Spaceflight Hardware
NASA-STD-6001B (2011) with Change 2 (2016) (Cited in sections 4.2.1, 4.2.1.1, 4.2.1.2, 4.2.1.4, and 4.2.1.5)	Flammability, Offgassing, and Compatibility Requirements and Test Procedures
NASA-STD-6012 (2012) (Cited in section 4.2.6.3)	Corrosion Protection for Space Flight Hardware
NASA-STD-6030 (2021)	Additive Manufacturing Requirements for Spaceflight Systems
JSC 20584 (2008) (Cited in	Spacecraft Maximum Allowable Concentrations for Airborne

section 4.2.1.2)	Contaminants
JSC 29353 (Cited in section 4.2.1.1)	Flammability Configuration Analysis for Spacecraft Applications
Materials and Processes Technical Information System (MAPTIS) (Cited in section 4.2.1.2)	Materials Selection List for Space Hardware Systems
MSFC-SPEC-445A (1990) (Cited in section 4.2.4.5)	Adhesive Bonding, Process and Inspection, Requirements for
MSFC-STD-3029A (2005) (Cited in section 4.2.2)	Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments

Department of Defense

MIL-STD-810G (2008), with Change 1 (2014) (Cited in section 4.2.3.8)	Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests
MIL-STD-1252 (1975) (Cited in section 4.2.4.6.4) (Inactive for New Design effective 3/11/1998 but determined by NASA to be the best existing standard for use)	Inertia Friction Welding Process, Procedure and Performance Qualification
MIL-HDBK-454B (Cited in section 4.2.3.8)	General Guidelines for Electronic Equipment
MIL-HDBK-6870B (2012) (Cited in section 4.2.5.1)	Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts

2.3 Non-Government Voluntary Consensus Standards

The citations below refer to the sections in this NASA Technical Standard.

ASTM International (ASTM)

ASTM B689-97 (Reapproved 2013) (Cited in section 4.2.4.10)	Standard Specification for Electroplated Engineering Nickel Coatings
ASTM B733-15 (Cited in sections 4.2.4.10 and 4.2.6.3)	Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal
ASTM E595-15 (Cited in section 4.2.3.6)	Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment
ASTM E1548 (2009) (Cited in section 4.2.6.7)	Standard Practice for Preparation of Aerospace Contamination Control Plans

American Welding Society (AWS)

AWS C3.2M/C3.2 (2008) (Cited in section 4.2.4.7)	Standard Method for Evaluating the Strength of Brazed Joints
AWS C3.3 (2008) (Cited in section 4.2.4.7)	Recommended Practices for Design, Manufacture, and Examination of Critical Brazed Components
AWS C3.4M/C3.4 (2016) (Cited in section 4.2.4.7)	Specification for Torch Brazing
AWS C3.5M/C3.5 (2016) (Cited in section 4.2.4.7)	Specification for Induction Brazing
AWS C3.6M/C3.6 (2016) (Cited in section 4.2.4.7)	Specification for Furnace Brazing
AWS C3.7M/C3.7 (2011) (Cited in section 4.2.4.7)	Specification for Aluminum Brazing
AWS C7.4/C7.4M (2008) (Cited in section 4.2.4.6.1)	Process Specification and Operator Qualification for Laser Beam Welding
AWS D17.1/D17.1M (2010) AMD1 (2012) (Cited in section 4.2.4.6.1)	Specification for Fusion Welding for Aerospace Applications
AWS D17.2/D17.2M (2013) (Cited in section 4.2.4.6.2)	Specification for Resistance Welding for Aerospace Applications

AWS D17.3/D17.3M (2016) (Cited in section 4.2.4.6.3)	Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications

Battelle Memorial Institute

MMPDS-10 (2015) (Cited in section 4.1.8.1, 4.1.8.2, and 4.2.4.1)	Metallic Materials Properties Development and Standardization (MMPDS)

Government Electronics and Information Technology Association (GEIA) (SAE International)

GEIA-STD-0005-1A (2012) (Cited in section 4.2.2.11)	Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-Free Solder
GEIA-STD-0005-2A (2012) (Cited in section 4.2.2.11)	Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems

National Aerospace Standards (NAS)

NAS 410, Revision 4 (2014) (Cited in section 4.2.5.1)	NAS Certification and Qualification of Nondestructive Test Personnel
NAS 412, Revision 1 (2013) (Cited in section 4.2.6.7)	Foreign Object Damage/Foreign Object Debris (FOD) Prevention

SAE International (SAE)

SAE AMS2175A (2010) (Cited in section 4.2.4.3)	Castings, Classification and Inspection of
SAE AMS2375D (2007, Reaffirmed 2012) (Cited in section 4.2.4.2)	Control of Forgings Requiring First Article Approval
SAE AMS2403N (2015) (Cited in section 4.2.4.10)	Plating, Nickel General Purpose
SAE AMS2404G (2013) (Cited in section 4.2.4.10 and 4.2.6.3)	Plating, Electroless Nickel

SAE AMS2423E (2015) (Cited in section 4.2.4.10)	Plating, Nickel Hard Deposit
SAE AMS2488D (2000, Reaffirmed 2011) (Cited in section 4.2.2.3.2)	Anodic Treatment - Titanium and Titanium Alloys Solution, pH 13 or Higher
SAE AMS2491F (2015) (Cited in section 4.2.3.10)	Surface Treatment of Polytetrafluoroethylene, Preparation for Bonding
SAE AMS2680C (2001, Reaffirmed 2010) (Cited in section 4.2.4.6.1)	Electron-Beam Welding for Fatigue Critical Applications
SAE AMS2759E (2008, Reaffirmed 2014) (Cited in section 4.2.4.1)	Heat Treatment of Steel Parts, General Requirements
SAE AMS2759/9D (2009) (Cited in sections 4.2.6.4)	Hydrogen Embrittlement Relief (Baking) of Steel Parts
SAE AMS2770N (2015) (Cited in section 4.2.4.1)	Heat Treatment of Wrought Aluminum Alloy Parts
SAE AMS2771E (2013) (Cited in section 4.2.4.1)	Heat Treatment of Aluminum Alloy Castings
SAE AMS2772G (2016) (Cited in section 4.2.4.1)	Heat Treatment of Aluminum Alloy Raw Materials
SAE AMS2773E (2013) (Cited in section 4.2.4.1)	Heat Treatment, Cast Nickel Alloy and Cobalt Alloy Parts
SAE AMS2774E (2016) (Cited in section 4.2.4.1)	Heat Treatment, Wrought Nickel Alloy and Cobalt Alloy Parts
SAE AMS2801B (2003, Reaffirmed 2014) (Cited in section 4.2.4.1 and 4.2.4.6.1)	Heat Treatment of Titanium Alloy Parts
SAE AMS-H-6875B (2010) (Cited in 4.2.4.1)	Heat Treatment of Steel Raw Materials

SAE AMS-H-81200D (2014) (Cited in sections 4.2.4.1 and 4.2.4.6.1)	Heat Treatment of Titanium and Titanium Alloys
SAE AS22759C (2014) (Cited in section 4.2.1.5)	Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy
SAE CMH-17:	
SAE CMH-17-1G (2012) (Cited in section 4.1.8.1)	Composite Materials Handbook Volume 1 - Polymer Matrix Composites Guidelines for Characterization of Structural Materials
SAE CMH-17-2G (2012) (Cited in section 4.1.8.1)	Composite Materials Handbook Volume 2 - Polymer Matrix Composites Materials Properties
SAE CMH-17-3G (2012) (Cited in section 4.1.8.1)	Composite Materials Handbook Volume 3 - Polymer Matrix Composites Materials Usage, Design, and Analysis
SAE CMH-17-4B (2013) (Cited in section 4.1.8.1)	Composite Materials Handbook Volume 4 - Metal Matrix Composites
SAE CMH-17-5 (2017) (Cited in section 4.1.8.1)	Composite Materials Handbook Volume 5 - Ceramic Matrix Composites
SAE CMH-17-6 (2013) (Cited in section 4.1.8.1)	Composite Materials Handbook Volume 6 – Structural Sandwich Composites

Refer to Appendix E for References.

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.

2.4.2 [MPR 6] Conflict between this NASA Technical Standard and other requirements documents shall be resolved by the delegated Technical Authority.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

/sec	Per Second
AIAA	American Institute of Aeronautics and Astronautics
AM	Additive Manufacturing
AMS	Aerospace Material Specification
ANSI	American National Standards Institute
AS	Aerospace Standard
ASTM	ASTM International (formerly American Society for Testing and Materials)
AWS	American Welding Society
BZT	Benzotriazole
CCP	Contamination Control Plan
CDR	Critical Design Review
cm	Centimeter
CMH	Composite Materials Handbook
COTS	Commercial Off-The-Shelf
CP	Commercially Pure
CR	Contractor Report
CVCM	Collected Volatile Condensable Materials
°C	Degrees Celsius
°F	Degrees Fahrenheit
D	Dimensional
DMLS	Direct Metal Laser Sintering
DOT	Department of Transportation
DRD	Data Requirements Description
EDM	Electrical Discharge Machining
EEE	Electrical, Electronic, and Electromechanical
ELI	Extra Low Interstitial
ESD	Electrostatic Discharge
ETFE	Ethylene Tetrafluoroethylene
FAA	Federal Aviation Administration
FEP	Fluorinated Ethylene Propylene
FFRDC	Federally Funded Research and Development Center
FOD	Foreign Object Damage/Debris
FRR	Flight Readiness Review
g	Gram
GEIA	Government Electronics and Information Technology Association
GOX	Gaseous Oxygen
GSE	Ground Support Equipment
HDBK	Handbook
HEE	Hydrogen Environmental Embrittlement

HRE	Hydrogen Reaction Embrittlement
IHE	Internal Hydrogen Embrittlement
in	Inch
JSC	Johnson Space Center
kPa	Kilopascals
ksi	Kilopounds per Square Inch
lb	Pound
LM	Laser Machining
LOX	Liquid Oxygen
M&P	Materials and Processes
MAPTIS	Materials and Processes Technical Information System
MIL	Military
MIUL	Materials Identification and Usage List
mm	Millimeter
MMPDS	Metallic Materials Properties Development and Standardization
MNL	Manual
MPa	Megapascals
MPR	Materials and Processes Requirement
MSFC	Marshall Space Flight Center
MUA	Material(s) Usage Agreement
NAS	National Aerospace Standard
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
NDT	Nondestructive Testing
NPR	NASA Procedural Requirements
PDF	Portable Document Format
PDP	Part Development Plans
PDR	Preliminary Design Review
PFA	Perfluoroalkoxy
PH	Precipitation Hardened/Hardenable
PQR	Procedure Qualification Record
PSIA	Pounds per Square Inch Absolute
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
RH	Relative Humidity
RSW	Resistance Spot Welding
RTV	Room Temperature Vulcanizing (rubber)
SAGBOE	Stress Assisted Grain Boundary Oxidation Embrittlement
SAE	SAE International (formerly Society of Automotive Engineers)

SDR	System Definition Review
sec	Second
SI	Système Internationale or metric system of measurement
SLM	Selective Laser Melting
SMAC	Spacecraft Maximum Allowable Concentration
SOW	Statement of Work
SPEC	Specification
SRR	System Requirements Review
STD	Standard
TM	Technical Memorandum
TML	Total Mass Loss
UTS	Ultimate Tensile Strength
UV	Ultraviolet
VCM	Volatile Condensable Materials
WPS	Welding Procedure Specification Weld Process Specification
WVR	Water Vapor Recovery

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. (Source: NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems)

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

Corrosive Environment: Solid, liquid, or gaseous environment that deteriorates the materials by reaction with the environment. Clean rooms and vacuum are normally considered noncorrosive.

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

Design Value: The design value is a statistically determined minimum value of a property, most commonly strength properties of materials, design features/elements, or components/parts used in the design of a structure. For A-basis strength properties, at least 99% of the population of strength values is expected to equal or exceed this lower bound with 95% confidence. For B-basis, 90% of the population of strength values is expected to equal or exceed this lower bound with 95% confidence. For metallic materials S-basis design values, the statistics defined by MMPDS are the same as for A-basis, but the test requirements are less comprehensive. Numbers of lots and test specimens required to develop design values are defined in applicable standards. The terms “material allowables,” “design allowables,” and “design values” are commonly used to address the design values used in structural analysis.

Fretting Corrosion: Occurs when two contacting surfaces under mechanical load are subjected to repeated relative surface motion. Mechanical wear and material transfer at the surfaces can lead to corrosion, metallic debris, and increased contact resistance due to the electrical insulating properties of corrosion products that may build up at the contact interfaces.

Mission Critical Hardware: Hardware, the failure of which may result in the inability to retain operational capability for mission continuation if a corrective action is not successfully performed.

Nondestructive Evaluation (NDE)/Nondestructive Testing (NDT): Inspection techniques which do not cause physical, mechanical, or chemical changes to the part being inspected or otherwise impair its adequacy for operational service. These inspection techniques are applied to materials and structures to verify required integrity and to detect flaws.

Refractory Alloys: Alloys with a melting point above 2000 °C (3632 °F), plus osmium and iridium.

Safety-Critical: Term describing any condition, event, operation, process, equipment, or system that could cause or lead to severe injury, major damage, or mission failure if performed or built improperly, or allowed to remain uncorrected.

Structural: Pertaining to structure.

Structural Adhesive Bond: Structural joint using adhesive bonds for the purpose of transferring structural load between structures.

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

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

Subcontractor: A hardware contractor that reports to a higher level contractor.

Technical Authority: Provides technical checks and balances by assuring that safety and mission success, relevant technical standards, engineering work, and safety and reliability analysis products are being conducted properly in accordance with established, high-reliability processes independent of nontechnical program/project constraints.

Tin Pest: The allotropic transformation of tin that may occur at or below 13.2 °C, where tin transforms from β-phase into its α-phase, a grey, brittle semiconductor that occupies about 27 percent greater volume than the β-phase.

Useful Life: Total life span, including storage life, installed life in a nonoperating mode, and operational service life.

Wet Installed: Fasteners covered with primer or sealant during installation to prevent moisture from penetrating the fastener joint and causing corrosion.

Whisker (Metal): A spontaneous growth that may form on surfaces of metals, primarily tin, zinc, and cadmium. Metal whiskers may also detach from the surfaces on which they form, producing conductive FOD.

4. REQUIREMENTS

Requirements for materials used in the fabrication and processing of spaceflight hardware are as follows:

a. [MPR 7] Materials shall meet the worst-case useful-life requirements for the particular application.

The useful-life requirements include, but are not limited to, the following:

(1) Operational temperature limits.
(2) Loads.
(3) Contamination.

(4) Life expectancy.
(5) Moisture or other fluid media exposure.
(6) Vehicle-related induced and natural space environments.

Experimental spaceflight hardware and other hardware that do not provide mission-critical functions may have no useful-life requirements, provided that the safety of the crew, the space vehicle, or launch vehicle are not compromised.

Properties to be considered in material selection include, but are not limited to, the following:

(1) Mechanical properties.
(2) Fracture toughness.
(3) Flammability and offgassing characteristics.
(4) Corrosion.
(5) Stress corrosion.
(6) Thermal and mechanical fatigue properties.
(7) Glass-transition temperature.
(8) Coefficient of thermal expansion mismatch.
(9) Vacuum outgassing.
(10) Fluids compatibility.
(11) Microbial resistance.
(12) Moisture resistance.
(13) Fretting.
(14) Galling.
(15) Susceptibility to electrostatic discharge (ESD).
(16) Susceptibility to contamination.

b. [MPR 8] M&P used in interfacing GSE, test equipment, hardware processing equipment, hardware packaging, and hardware shipment shall be controlled to prevent damage to or contamination of spaceflight hardware.

The M&P controls in NASA-STD-5005 (Revision D or later), Standard for the Design and Fabrication of Ground Support Equipment, are acceptable for meeting this requirement for interfacing GSE hardware.

4.1 General Requirements

4.1.1 Materials and Processes Selection, Control, and Implementation Plan

a. [MPR 9] Each organization that is responsible for the design and fabrication of spaceflight hardware shall provide a Materials and Processes Selection, Control, and Implementation Plan.

The Materials and Processes Selection, Control, and Implementation Plan documents the degree of conformance and method of implementation for each requirement in this NASA Technical Standard and identifies applicable in-house specifications used to comply with the requirement.

Other documents, such as contractor-specific M&P requirements documents and detailed requirements compliance matrices, can be used to form the basis of the Materials and Processes Selection, Control, and Implementation Plan, provided the content addresses the requirements.

b. [MPR 10] The Materials and Processes Selection, Control, and Implementation Plan shall also describe the methods used to control compliance with these requirements by subcontractors and vendors.

Prime contractors may require subcontractors and vendors to develop a tailored plan to comply with NASA-STD-6016 or a tailored plan to comply with the prime contractor's plan. Alternatively, prime contractors may flow down a limited subset of (or even no) requirements, with the prime making up the difference between the subset and materials control plan. Whichever approach is selected, prime contractors are responsible for ensuring that hardware designed and fabricated by their subcontractors meet the materials control plan or NASA-STD-6016.

c. [MPR 11] Upon approval by the procuring activity, the Materials and Processes Selection, Control, and Implementation Plan shall become the M&P implementation document used for verification.

The Materials and Processes Selection, Control, and Implementation Plan should be approved by the responsible design authority.

Additional requirements on the Materials and Processes Selection, Control, and Implementation Plan content follow in sections 4.1.1.1 through 4.1.1.3.

4.1.1.1 Coordination, Approval, and Tracking

[MPR 12] The Materials and Processes Selection, Control, and Implementation Plan shall identify the method of coordinating, approving, and tracking all engineering drawings, engineering orders, and other documents that establish or modify materials and/or processes usage.

4.1.1.2 Approval Signature

[MPR 13] The Materials and Processes Selection, Control, and Implementation Plan shall include a requirement that all hardware design drawings and revisions for spaceflight hardware that provides mission-critical functions contain an M&P approval block, or equivalent, to ensure that the design has been reviewed by the responsible M&P authority and complies with that document.

4.1.1.3 Manufacturing Planning

[MPR 14] The Materials and Processes Selection, Control, and Implementation Plan shall identify how the responsible M&P organization participates in manufacturing and inspection/verification planning to ensure compliance with M&P requirements.

4.1.2 M&P Controls

a. [MPR 15] All M&P for spaceflight hardware that provides mission-critical functions shall be defined by standards and specifications selected from government, industry, and company specifications and standards.

b. [MPR 16] All M&P for spaceflight hardware that provides mission-critical functions shall be identified directly on the appropriate engineering drawing.

c. [MPR 17] Company M&P specifications shall be identified by document number in the Materials and Processes Selection, Control, and Implementation Plan.

d. [MPR 18] All M&P specifications used to produce spaceflight hardware that provides mission-critical functions shall be made available to the responsible NASA Program or Project Office and M&P organization.

e. [MPR 19] Process specifications for spaceflight hardware that provides mission-critical functions shall define process steps at a level of detail that ensures a repeatable/controlled process that produces a consistent and reliable product.

f. [MPR 20] Process qualification shall be conducted to demonstrate the repeatability of all processes for spaceflight hardware that provides mission-critical functions where the quality of the product cannot be directly verified by subsequent monitoring or measurement.

Note: *The process requirements in section 4.2.4 of this NASA Technical Standard do not always define process steps at a level of detail that ensures a repeatable/controlled process that produces a consistent and reliable product, so it should not be assumed that they are suitable to be called out as process specifications on engineering drawings. They are intended as higher level documents that state minimum requirements and provide general directions for the design of hardware.*

4.1.2.1 Standard and Specification Obsolescence

[MPR 21] A process shall be established for ensuring that updated, alternate, or new material or process standards or specifications from those identified in the Materials and Processes Selection, Control, and Implementation Plan meet or exceed the technical requirements identified in the original material or process standards or specifications.

During a long-term program, M&P standards and specifications identified in this document or in contractor materials control plans could become obsolete. Continued use of obsolete standards and specifications is acceptable for manufacturing series or new-design hardware. Although updated M&P standards or specifications usually meet or exceed earlier standards and specifications, their use can result in requirements creep so that new hardware no longer meets the original design requirements.

4.1.3 Commercial Off-The-Shelf (COTS) Hardware

[MPR 22] A procedure shall be established to ensure that all vendor-designed, off-the-shelf, and vendor-furnished items are covered by the M&P requirements of this document, with the exception that M&P requirements for off-the-shelf hardware and other spaceflight hardware that do not provide mission-critical functions may be limited to those required to ensure safety of flight (for example, flammability, toxic offgassing) and vehicle compatibility (for example, vacuum outgassing).

4.1.4 M&P Control Panel

a. [MPR 23] An M&P control panel shall be established by each contractor hardware provider (excluding subcontractors).

b. [MPR 24] The M&P control panel's scope and membership shall be described in the Materials and Processes Selection, Control, and Implementation Plan.

The M&P control panel plans, manages, and coordinates the selection, application, procurement, control, and standardization of M&P for the contract.

The panel also resolves and dispositions M&P problems.

The responsible NASA M&P organization is an active member of the panel and has the right of disapproval of panel decisions.

4.1.5 M&P Usage Documentation

a. [MPR 25] M&P usage shall be documented in an electronic, searchable parts list or separate electronic searchable Materials Identification and Usage List (MIUL) with the following exceptions:

(1) Electrical, electronic, and electromechanical (EEE) parts other than wire, cable, and exposed surfaces of connectors.

(2) Materials used in hermetically sealed electronic containers (maximum leak rate less than 1 x 10^{-4} cm^3/sec).

b. [MPR 26] The documentation of M&P usage shall cover the final design as delivered.

c. [MPR 27] The documentation approach shall be defined in the Materials and Processes Selection, Control, and Implementation Plan.

Recommended MIUL content is described in Appendix D, Recommended Data Requirements Documents. Material codes and ratings for materials, standard and commercial parts, and components are available in the Materials and Processes Technical Information System (MAPTIS). When required, new material codes will be assigned by NASA's Marshall Space Flight Center (MSFC). In some cases, MAPTIS contains averages for ratings or test results for generic materials controlled by military or industry specifications; the material codes for the generic materials are used.

MAPTIS is accessible via the Internet at http://maptis.nasa.gov.

Note: *Accessibility to MAPTIS is by registration only.*

4.1.6 Material Usage Agreements (MUAs)

a. [MPR 28] MUAs containing sufficient information to demonstrate that the application is acceptable shall be submitted by the responsible M&P organization for all M&P that are technically acceptable but do not meet the requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

The use of M&P that do not comply with the requirements of this NASA Technical Standard may still be acceptable in the actual hardware applications.

In most cases, the requirements in this document identify technical requirements for which deviations may be accepted through the MUA process. However, in some cases, MUAs are specifically identified as required for documentation of hardware acceptability.

The MUA generation and approval system should be defined in the Materials and Processes Selection, Control, and Implementation Plan. A recommended MUA approach is described in Appendix D.

NOTE: Per section 4.1.6: The use of M&P that do not comply with the requirements of this NASA Technical Standard may be acceptable in the actual hardware applications. MUAs are required for all M&P that are technically acceptable but do not meet the requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

b. [MPR 29] MUAs shall not be used to change the M&P requirements for a nonconforming product.

When the nonconformance is a deviation from M&P requirements that is acceptable for future series hardware, an MUA may be generated to provide technical support for a change to the product baseline.

A typical MUA form is shown in Appendix B, Typical MUA Form.

4.1.6.1 Human-Rated Spacecraft

For human-rated spaceflight hardware, a tiered MUA system with three categories is recommended.

4.1.6.1.1 Category I MUAs

Category I MUAs are those that involve M&P usage that could affect the safety of the mission, crew, or vehicle or affect the mission success but have to be used for functional reasons.

Category I MUAs are delivered by the hardware developer and approved by the responsible NASA M&P organization and the NASA Program/Project Office.

4.1.6.1.2 Category II MUAs

Category II MUAs are those that involve M&P usage that fails a screening of M&P requirements and is not considered a hazard in its use application but for which no Category III rationale code exists. Category II MUAs are delivered by the hardware developer and approved by the responsible NASA M&P organization.

4.1.6.1.3 Category III MUAs

Contractors who want to use Category III rationale codes relevant to their hardware may do so through their Materials and Processes Selection, Control, and Implementation Plan. Category III MUAs are those that involve M&P that have not been shown to meet these requirements but have an appropriate rationale code listed in the Materials and Processes Selection, Control, and Implementation Plan. The rationale codes are approved as part of the overall Materials and Processes Selection, Control, and Implementation Plan approval. Category III rationale codes are evaluated and determined to be acceptable at the configuration/part level.

Approved Category III MUAs are reported in the MIUL system or electronic data system.

Category III MUAs are approved by the hardware developer and responsible M&P organization through acceptance of the MIUL. No MUA form is submitted.

NOTE: Per section 4.1.6: The use of M&P that do not comply with the requirements of this NASA Technical Standard may be acceptable in the actual hardware applications. MUAs are required for all M&P that are technically acceptable but do not meet the requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

Note: The Category III MUA rationale codes in the previous release of this NASA Technical Standard have been retired, either because the acceptance rationale was deemed inadequate or because the application was made an exception to the requirement. Retired codes are listed in Appendix C, Retired Category III MUA Rationale Codes, for continuity purposes but should not be used for hardware designed to this NASA-STD-6016 release unless they are listed as approved rationale codes in the Materials and Processes Selection, Control, and Implementation Plan.

4.1.7 Materials Certification and Traceability

a. [MPR 30] All parts or materials for spaceflight hardware that provides mission-critical functions shall be certified as to composition, properties, and requirements as identified by the procuring document.

b. [MPR 31] With the exception of off-the-shelf parts, parts and materials used in critical applications, such as life-limited materials and/or safety- and fracture-critical parts, shall be traceable through all processing steps defined in the engineering drawing to the end-item application.

c. [MPR 32] Distributors or other processors shall not heat treat, hot work, or cold work metal stock unless they take the responsibilities as the producer of the metal and produce a new certification.

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

4.1.8 Material Design Values

In the design and analysis of aerospace hardware, the terms "material allowables," "design allowables," and "design values" are commonly used to address the design values used in structural analysis. The term "design values" is used throughout this document which encompasses both the material and design feature performance, whichever is used to support the structural certification.

4.1.8.1 Requirements for Design Values

a. [MPR 33] A, B, or S-basis statistical values for mechanical properties of materials shall be utilized for the design and analysis of hardware for all applications where structural analysis is required.

Statistical design values are needed for any hardware where structural analysis is required to demonstrate positive margins of safety for the design loads and environments in combination with the factor of safety requirements.

Each distinct form of a material should be assumed to have unique design values unless testing and statistical analysis shows that design values are combinable. For example, rolled bar may have different design values than the same alloy in plate, forging, spin forming, extrusion, or casting. Different layups affect the properties of composite structures. Manufacturing methods, like welding, brazing, swaging, forming, diffusion bonding, adhesive bonding, and co-curing of sandwich alter the properties of the original materials. Design features, such as joints, ply-drops, and tapered ramps affect the design values of composites.

Design values are also required for other mechanical properties, such as dynamic properties like fatigue and fracture. The basis for these properties is not necessarily statistical, but the sampling is expected to be representative of the material, product form, and state used in the design. Some applications require lower bound, and others require typical properties. The specific requirement can be found in the governing specifications for the design, such as NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware, or NASA-STD-5012, Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines. See NASA-STD-6030 for requirements for design values for additively manufactured material.

b. [MPR 34] The sampling for other mechanical properties, such as dynamic properties like fatigue and fracture, and verification of design values shall be representative of the material, product form, and state used in the design.

The statistical basis for fatigue and fracture properties should be consistent with the governing specification. For example, NASA-STD-5019 allows for the use of typical fracture toughness and crack growth rate properties in the assessment of assumed defects; NASA-STD-5012 requires the use of bounding fatigue design curves for critical hardware in the primary load path. Fatigue data provided in MMPDS requires further analysis to derive a bounded design curve.

c. [MPR 35] A, B, or S-basis statistical methods shall be defined by, and values for mechanical properties in their design environment taken from MMPDS, Metallic Materials Properties Development and Standardization, or SAE CMH-17, Composite Materials Handbook.

S-basis statistical values apply to metallic structures only. Although SAE CMH-17 does use the term "S-basis," it is used only for screening composite materials and such values may not be used in design.

Design values in CMH-17 Volume 2 may be used only if each production facility substantiates that its material and process controls produce repeatable and reliable results that support the published design value. "Equivalency" test methods such as those outlined in DOT/FAA/AR-

03/19, Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure, are acceptable.

d. [MPR 36] For metallic materials, the alloy, heat treatment, product specification, product form, and thickness shall match the alloy, heat treatment, product specification, product form, and thickness in MMPDS.

Since the testing to develop design values is specific to alloy, heat treatment, specification and form, the statistical relationship is relevant only to that same combination. Thickness affects strength of metal because of metallurgical factors that influence strength, like heat transfer during heat treatment and variability of reduction during metal working.

SAE CMH-17 is composed of six volumes: SAE CMH-17-1G, Volume 1 – Polymer Matrix Composites Guidelines for Characterization of Structural Materials; SAE CMH-17-2G, Volume 2 – Polymer Matrix Composites Materials Properties; SAE CMH-17-3G, Volume 3 – Polymer Matrix Composites Materials Usage, Design, and Analysis; SAE CMH-17-4B, Volume 4 – Metal Matrix Composites; SAE CMH-17-5, Volume 5 – Ceramic Matrix Composites; and SAE CMH-17-6, Volume 6 – Structural Sandwich Composites.

Notes:

(1) *Design values of structural materials listed in later versions of MMPDS or SAE CMH-17 than those specified in section 2 may be used provided the methodology used to develop the allowable mechanical properties is at least as conservative.*

(2) *Published properties need to be appropriate for the design environment. For example, published properties at ambient temperature are not typically appropriate for applications in high-temperature environments.*

(3) *Design Values calculated based on regression analysis according to SAE CMH-17 (Volume 1, section 8.3.7) are acceptable.*

(4) *Caution is warranted for material properties that significantly exceed minimum specification values. Sensitivity to stress corrosion cracking, loss of ductility and fracture toughness, and degraded mechanical properties at cryogenic temperatures, may result in some alloys that are over-strengthened. For example, for quenched and tempered alloy steels, precipitation hardened steels, heat treatable aluminums etc., the durability and behavior in service environments may be adversely affected when they are strengthened significantly beyond their minimum strength requirements.*

(5) *Section 4.2.2 of this NASA Technical Standard contains requirements for test verification of the adequacy of the heat treatment process when metallic materials are user heat treated.*

(6) *For composite structures, "pristine" A and B-basis design values may not be appropriate as they can be compromised by manufacturing defects, mishandling, impacts, etc. Such damage is commonly in the form of subsurface delaminations that cannot be seen by visual inspection or detected by a practical NDE program. Degraded design values that take into account damage tolerance may be substantially lower than pristine design values and may be required in accordance with NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.*

e. [MPR 37] When statistical design values for new or existing structural materials are not available, they shall be determined by methods described in MMPDS or SAE CMH-17 and a report documenting the derivation of the new design values be made available to NASA for review.

Design values for polymeric materials other than composites are covered by this requirement but are not addressed by MMPDS or SAE CMH-17. The methods described in SAE CMH-17 are appropriate for such materials.

It is recognized that the development of statistical design values may, at times, be impractical for materials in extreme environments given project resource limitations. In such cases, the contractor should develop a tailored approach to adequately substantiate the design values for the environment and submit the approach and design values for approval via an MUA.

f. [MPR 38] The implementation of an approach for generating statistical design values that deviates from the sampling methodology and statistical methods in MMPDS or SAE CMH-17 and the use of design values that deviate from those published in MMPDS or SAE CMH-17 shall be approved with an MUA.

At a minimum, the following should be addressed in the MUA documenting the rationale for use of the alternative approach for generating statistical design values that deviate from the guidance in MMPDS or SAE CMH-17:

(1) Description of the statistical approach.

(2) Description of the number of test specimens, number of lots, heats, and/or production units, e.g., weld panels, castings, parts.

(3) Description of the range of relevant process parameters.

(4) Verification that the test specimens are representative of the product specification and product form used in the design (for metallic materials, the heat treatment and thickness also need to be verified as representative).

The following should be addressed in the MUA documenting the rationale for use of the alternative design values:

(1) *How the design values have been derived.*

(2) *How future material lots will be verified for performance.*

(3) *Justification for use of the alternate statistical methods or the use of engineering reduction factors.*

For new or modified production methods, consistency with the original qualification testing and the associated design values should be demonstrated at an appropriate structural scale.

g. [MPR 39] All contractor-developed mechanical and physical property data shall be made available to the responsible NASA M&P organization.

4.1.8.2 Design Value Implementation in Design

a. [MPR 40] Material “B” design values shall not be used except in redundant structure in which the failure of a component would result in a safe redistribution of applied loads to other load-carrying members.

Material “B” or “B-basis” design values are specified to assure reliability for redundant structures, which are typically components or structural elements with a redundant load path. Material “A” or “A-basis” design values may be used in lieu of Material “B” or “B-basis” because they are derived using a more conservative statistical method.

Note: For nonmetallic structures, this requirement applies only to pristine material “B” design values. For fracture-critical nonmetallic structures, B-basis design values should be used in accordance with the methods outlined in NASA-STD-5019. B-basis design values developed for intentionally damaged structure as part of damage tolerance assessment may be acceptable for non-redundant structure. As strength and life verification of composites requires empirical testing, it may become necessary to first develop design values representing the intrinsic material constitutive properties, and then separately establish design values for discrete design features which cannot be adequately correlated via traditional stress analysis. Examples may include complex ply-drop scenarios, discontinuities, composite/metallic interfaces, sandwich ramps, or unique bonded/bolted joints. In such cases, strictly using “material” design values rather than establishing design values specific to the design feature may result in an inadequately designed structure.

[Composite damage tolerance is outside the scope of this NASA Technical Standard; NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware, contains requirements on this subject.]

b. [MPR 41] Minimum property acceptance values in material specifications (specification minimums) not explicitly published as “S” design values in MMPDS shall require an approved MUA for use as design values.

MMPDS requires three distinct lots of metal be tested and the data statistically analyzed and tested before the “S” design values are published in the handbook.

To minimize MUA activity, a process or set of standardized criteria can be defined in the Materials and Process Control Plan to allow the use of specification minimums for design without MUAs. Approaches could include extra lot testing, proof testing, substantiating the “S” basis over time, high margin applications, or the use of substantiated engineering reduction factors.

4.1.8.3 Structural Fastener Design Values

[MPR 42] Structural fastener design values shall be defined by minimum load test requirements in the applicable part and/or procurement specification (government, aerospace industry consensus, company-specific, or custom specification).

MMPDS design values are not transferrable to fasteners because raw material used to make fasteners is reprocessed using various metallurgical practices such as hot heading, thread rolling, and heat treating. These processes change the strength of the metal from the original bar stock. NASA has chosen to adopt lot tested design strength defined in the specific fastener part and procurement specifications as the design value instead of the certifications of the original bar stock.

Other structural fastener requirements are identified in section 4.2.6.6.

4.2 Detailed Requirements

4.2.1 Flammability, Offgassing, and Compatibility Requirements

[MPR 43] Materials shall meet the requirements of NASA-STD-6001B, Flammability, Offgassing, and Compatibility Requirements and Test Procedures, as described below.

4.2.1.1 Flammability Control

[MPR 44] Materials that are nonflammable or self-extinguishing in their use configuration as defined by NASA-STD-6001B, Test 1 or an appropriate configurational flammability test per NASA-STD-6001B, shall be used for flammability control with the following exceptions:

a. Ceramics, metal oxides, and inorganic glasses are exempt.

b. Materials that are designed to ignite and burn in their use application (for example, pyrotechnic materials) are exempted from flammability requirements, provided that systems/experiments using such materials are designed so that the burning materials cannot act as an ignition source for other hardware.

c. Materials used in minor quantities (dimensions controlled so the potential fire propagation path is less than 15 linear cm (6 linear in) and the surface area is no more than 80 cm^2 (12 square in)) in crew environments and 30 linear cm (12 linear in) for external materials) with no propagation path or ignition source.

d. Materials used in sealed containers are exempt because insufficient oxygen is available to maintain combustion.

e. Materials within vented electronics packages with metallic cases and no forced air convection are exempt because of the self-extinguishing effect of expanding combustion gases in a constrained volume.

f. Materials that have been shown by test to meet the requirements of NASA-STD-6001B may be used in an environment with an oxygen concentration lower than the test level without further testing (provided that the oxygen partial pressure is no greater than the partial pressure at the test level or general test data exist to demonstrate that the higher oxygen partial pressure is outweighed by the lower percentage concentration for the environments in question).

g. Materials are acceptable when used on a metal substrate that provides an adequate heat sink. A heat sink is considered adequate in the use configuration by test or analysis. When testing is conducted, materials passing the flammability test on a metal substrate are acceptable on metal substrates of the same thickness or greater. Materials that are flammable but have a thickness less than 0.25 mm (0.010 in) and are attached to a metallic surface greater than 1.6 mm (0.062 in) thick are acceptable by analysis.

h. Materials are unexposed, overcoated with a verified fire-blocking material, or no more than ¼ inch thick and sandwiched between nonflammable materials with only the edges exposed.

Many situations arise where flammable materials are used in an acceptable manner without test, using mitigation practices and the MUA approval system. Guidelines for hardware flammability *assessment and mitigation can be found in JSC 29353, Flammability Configuration Analysis for Spacecraft Applications.*

i. Flammability configuration analysis in accordance with JSC 29353 shows hardware configuration to be self-extinguishing.

Material flammability ratings and tests based on NASA-STD-6001B for many materials are found in the MAPTIS database.

4.2.1.2 Toxic Offgassing

a. [MPR 45] All nonmetallic materials used in habitable flight compartments, with the exception of ceramics, metal oxides, inorganic glasses, and materials used in sealed container (maximum leak rate less than 1 x 10^{-4} cm^3/sec), shall meet the offgassing requirements of Test 7 of NASA-STD-6001B.

b. [MPR 46] Spacecraft maximum allowable concentration (SMAC) values shall be obtained from JSC 20584 (2008), Spacecraft Maximum Allowable Concentrations for Airborne Contaminants, or from MAPTIS for compounds for which no SMAC values are found in JSC 20584.

4.2.1.3 Fluid Compatibility (Fluids Other Than Oxygen)

a. [MPR 47] An MUA shall be written rationalizing the selection of materials if any of the following conditions apply:

(1) If a material is exposed directly to a hazardous fluid[1].
(2) If a material is exposed directly to a hazardous fluid vapor.
(3) If a material is exposed to a hazardous fluid liquid or a vapor by failure of a single barrier seal.
(4) If a material is exposed to a hazardous fluid liquid or a vapor by leakage or permeation through a single or multiple seals.

The number of seals to be considered for hazardous fluid exposure by leakage or permeation will be dictated by the system criticality and imposed fault tolerance.

The MUA is always required for hardware acceptability and needs to document how new or historical test data demonstrate materials acceptability of all exposed materials at worst-case

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[1] For the purpose of this NASA Technical Standard, the definition of hazardous fluids includes gaseous oxygen (GOX), liquid oxygen (LOX), fuels, oxidizers, and other fluids that are critical or catastrophic hazards due to chemical or physical degradation of the materials in the system, corrosion (with the exception of general corrosion covered by NASA-STD-6012), or causing an exothermic reaction.

operating conditions. When historical data are referenced, the references need to be included. Potential effects of reactions between the hazardous fluids and external environments need to be considered.

NASA-STD-6001B, Test 15, is a 48-hour screening test for short-term exposure to fuels and oxidizers.

b. [MPR 48] Appropriate long-term tests to simulate the worst-case use environment and operational conditions that would enhance reactions or degradation shall be conducted for materials with long-term exposure to liquid fuels, oxidizers, and other hazardous liquids.

The test program needs to demonstrate that materials will not degrade sufficiently to affect hardware performance before, during, and after the actual time of hazardous fluid exposure, including ground processing prior to flight, flight exposure, dormant periods, post-flight processing prior to decontamination, and the decontamination process. It also needs to demonstrate that otherwise acceptable materials do not cause unacceptable degradation of the fluid or unacceptable release of gases/vapors. Use of elevated temperatures to accelerate the test and/or extrapolation of minor degradation from the test duration to the actual time of hazardous fluid exposure are acceptable approaches. The rationale behind the acceleration/extrapolation parameters needs to be explained in the MUA.

NASA-STD-6001B, Supplemental Test A.7, identifies changes resulting from incidental exposure (minor amounts, such as a splash) to fuels or oxidizers.

c. [MPR 49] Materials degradation in long-term tests shall be characterized by post-test analyses of the material and fluid to determine the extent of changes in chemical and physical characteristics, including mechanical properties.

d. [MPR 50] The effect of material condition (for example, parent versus weld metal or heat-affected zone) shall be addressed in the compatibility determination.

e. [MPR 210] Materials used in nitrogen tetroxide systems shall be evaluated for flammability in nitrogen tetroxide using promoted combustion tests similar to NASA-STD-6001B, Test 17, for metallic materials used in oxygen systems and Test 1 for polymeric materials.

(1) [MPR 211] When materials are determined to be flammable, a nitrogen tetroxide compatibility assessment shall be conducted using the methodology described for oxygen systems in NASA-STD-6001B and the system safety rationale of this assessment documented in an MUA.

f. [MPR 212] Materials used in other oxidizer systems shall be evaluated for potential ignition.

4.2.1.4 Oxygen Compatibility

a. [MPR 51] Materials and components, and systems used in liquid oxygen (LOX) and gaseous oxygen (GOX) environments, compressed air systems, and pressurized systems containing enriched oxygen shall be evaluated for oxygen compatibility in accordance with NASA-STD-6001B.

Material flammability ratings and tests based on NASA-STD-6001B for many materials are found in the MAPTIS database.

b. [MPR 52] When materials in such systems are determined to be flammable, an oxygen compatibility assessment shall be conducted as described in NASA-STD-6001B and the system safety rationale of this assessment documented in an MUA.

As described in NASA-STD-6001B, material/component configurational testing may be required to support the compatibility assessment.

Compressed air systems and pressurized systems containing enriched oxygen are inherently less hazardous than systems containing pure oxygen; the hazard increases with oxygen concentration and pressure.

Guidelines on the design of safe oxygen systems are contained in ASTM MNL 36, Safe Use of Oxygen and Oxygen Systems: Handbook for Design, Operation, and Maintenance; ASTM G88, Standard Guide for Designing Systems for Oxygen Service; ASTM G63, Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service; ASTM G94, Standard Guide for Evaluating Metals for Oxygen Service; and NASA/TM-2007-213740, Guide for Oxygen Compatibility Assessments on Oxygen Components and Systems.

4.2.1.4.1 Oxygen Component Acceptance Test

[MPR 53] GOX and enriched air system components that operate at pressures above 1.83 MPa (265 psia), with the exception of metallic components, such as hard lines (rigid metallic tubing), metallic flex hoses, metallic fluid fitting with all metal seals, and metallic pressure vessels (including composite overwrapped pressure vessels with metallic liners), shall undergo oxygen component acceptance testing for a minimum of ten cycles from ambient pressure to maximum design pressure within 100 milliseconds to ensure that all oxygen system spaceflight hardware is exposed to oxygen prior to launch.

This test is an acceptance test, not a qualification test, and is required for all sets of spaceflight hardware. Retesting is required if post-test actions (such as rework, repair, or interfacing with hardware having uncontrolled cleanliness) invalidate the acceptance test.

LOX system components should also be acceptance tested, but the system hardware acceptance test is normally adequate for this purpose. The number of test cycles should be as defined in the system hardware acceptance test (typically well below the ten cycles required for gaseous systems).

4.2.1.5 Electrical Wire Insulation Materials

a. [MPR 54] Electrical wire insulation materials shall be evaluated for flammability in accordance with NASA-STD-6001B, Test 4 or Test 1.

Test 4 should be used for insulation on electrical power wiring where the maximum current passing through the wiring can raise the temperature above 49 °C (120 °F). Either test can be used for signal/data wiring and other wiring where the current is too small to raise the temperature above this value.

b. [MPR 55] Arc tracking shall be evaluated in accordance with NASA-STD-6001B, Test 18, for all wire insulation constructions except polytetrafluoroethylene (PTFE), PTFE/polyimide insulation conforming to SAE AS22759C, Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy, and used in conditions bounded by the dry arc-tracking test specified by SAE AS22759C, ethylene tetrafluoroethylene (ETFE), and silicone-insulated wires (the resistance of these materials to arc tracking has already been established).

4.2.2 Metals

[MPR 56] MSFC-STD-3029A, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments, shall be used to select metallic materials to control stress corrosion cracking of metallic materials in sea and air environments, with the exception that an MUA is not required for the following conditions:

a. Parts in electrical/electronic assemblies with maximum tensile stress less than 50 percent of the yield strength.

b. Martensitic or precipitation-hardening (PH) stainless steels used in ball bearing or similar applications where the loading is compressive.

This exception cannot be used for ball-bearing races for which the primary loading is tensile.

c. Carbon and low alloy high-strength steels with strength greater than 1240 MPa (180 ksi) used in ball bearings, springs, or similar applications where the loading is compressive and there is a history of satisfactory performance.

d. Hardware provides no mission-critical functions.

Additional information regarding metallic materials can be found in MAPTIS.

4.2.2.1 Aluminum

Aluminum alloys used in structural applications should be resistant to general corrosion, pitting, intergranular corrosion, and stress corrosion cracking.

[MPR 57] The 5000-series alloys containing more than 3 percent magnesium shall not be used in spaceflight hardware that provides mission-critical functions where the temperature exceeds 66 °C (150 °F).

Grain boundary precipitation above 66 °C (150 °F) can create stress-corrosion sensitivity.

4.2.2.2 Steel

4.2.2.2.1 Drilling and Grinding of High-Strength Steel

When performing drilling, grinding, reaming, or machining of steels, low-stress machining techniques with coolant should be used. Uncontrolled high-stress machining used without coolant is detrimental to the steel microstructure. Untempered martensite is formed that leads to cracking. Overheating can soften the steel due to overtempering or decarburization. Low-stress machining practices, such as those in SAE AMS2453, Low Stress Grinding of Steel Parts Heat Treated to 180 ksi or Over, and Low Stress Grinding of Chrome Plating Applied to Steel Parts Heat Treated to 180 ksi or Over, should be used to prevent damage to the microstructure.

a. [MPR 58] When drilling, grinding, reaming, or machining is performed on high-strength steels that can form martensite and are used in spaceflight hardware that provides mission-critical functions, a validated process for machining shall be used.

b. [MPR 59] The absence of machining damage for high-strength steels used in spaceflight hardware that provides mission-critical functions shall be verified by microexamination of production parts (such as Nital etch inspection) or by a microhardness and metallurgical examination of sample parts for either of the following situations:

  (1) When the material has very low toughness (such as martensitic steel above 200 ksi) and the part has low stress margins or is fatigue driven.

  (2) When the surface condition of the part is critical to the design (such as its ability to withstand hertzian stresses or remain perfectly flat).

4.2.2.2.2 Corrosion-Resistant Steel

a. [MPR 60] Unstabilized, austenitic steels shall not be processed or used above 371 °C (700 °F) in spaceflight hardware that provides mission-critical functions.

b. [MPR 61] Welded assemblies used in spaceflight hardware that provides mission-critical functions shall be solution heat-treated and quenched after welding except for the stabilized or low carbon grades, such as 321, 347, 316L, and 304L.

c. [MPR 62] Service-related corrosion issues are common for free-machining alloys, such as 303, and these alloys shall not be used in spaceflight hardware that provides mission-critical functions when they can be exposed to moisture other than transient condensation, or to nitrogen tetroxide.

4.2.2.2.3 Ductile-Brittle Transition Temperature

[MPR 63] Steels shall not be used in tension below their ductile-brittle transition temperature.

Alloy and carbon steels, as well as ferritic, martensitic, and duplex steels tend to become brittle as the temperature is reduced. Balls in ball bearings are generally acceptable because they are in compression.

4.2.2.3 Titanium

4.2.2.3.1 Titanium Contamination

a. [MPR 64] All cleaning fluids and other chemicals used during manufacturing and processing of titanium hardware for spaceflight hardware that provides mission-critical functions shall be verified to be compatible and not detrimental to performance before use.

Hydrochloric acid, chlorinated solvents, chlorinated cutting fluids, fluorinated hydrocarbons, and anhydrous methyl alcohol can all produce stress corrosion cracking. Mercury, cadmium, silver, and gold have been shown to cause liquid-metal-induced embrittlement and/or solid-metal-induced embrittlement in titanium and its alloys. Liquid-metal-induced embrittlement of titanium alloys by cadmium can occur as low as 149 °C (300 °F), and solid-metal-induced embrittlement of titanium alloys by cadmium can occur as low as room temperature.

b. [MPR 65] The surfaces of titanium and titanium alloy mill products used for spaceflight hardware that provides mission-critical functions shall be 100 percent machined, chemically milled, or pickled to a sufficient depth to remove all contaminated zones and layers formed while the material was at elevated temperature.

Contaminated zones and layers may be formed as a result of mill processing, heat treating, and elevated temperature-forming operations.

4.2.2.3.2 Titanium Wear

Titanium and its alloys exhibit very poor resistance to wear. Fretting that occurs at interfaces with titanium and its alloys has often contributed to crack initiation, especially fatigue initiation. The preferred policy is a design that avoids fretting and/or wear with titanium and its alloys. Bolted joints are not considered to fret.

[MPR 66] All regions of titanium alloys for spaceflight hardware that provides mission-critical functions that are subject to fretting or wear shall be anodized per SAE AMS2488D, Anodic Treatment – Titanium and Titanium Alloys Solution, pH 13 or Higher, or hard-coated utilizing a wear-resistance material, such as tungsten carbide/cobalt thermal spray.

4.2.2.3.3 Titanium Flammability

a. [MPR 67] Titanium alloys shall not be used with LOX or GOX at any pressure or with air at oxygen partial pressures above 35 kPa (5 psia).

b. [MPR 68] Titanium alloys shall not be machined inside spacecraft modules during ground processing or in flight, because machining operations can ignite titanium turnings and cause fire.

4.2.2.4 Magnesium

a. [MPR 69] Magnesium alloys shall not be used in primary structure or in other areas of spaceflight hardware that provides mission-critical functions that are subject to wear, abuse, foreign object damage, abrasion, erosion, or where fluid or moisture entrapment is possible.

b. [MPR 70] Magnesium alloys shall not be machined inside spacecraft modules during ground processing or in flight because machining operations can ignite magnesium turnings and cause fire.

4.2.2.5 Beryllium

Beryllium alloys are exceptionally lightweight but are not often used because of the extreme toxicity of beryllium salts and oxides, and because it is unusually susceptible to damage. Alloys containing up to 4 percent beryllium by weight are not an issue, provided they are not machined inside spacecraft crew compartments.

a. [MPR 71] Alloys containing more than 4 percent beryllium by weight shall not be used for primary structural applications.

b. [MPR 72] Alloys containing more than 4 percent beryllium by weight shall not be used for any application within spacecraft crew compartments unless suitably protected to prevent erosion or formation of salts or oxides.

c. [MPR 73] Design of beryllium parts for spaceflight hardware that provides mission-critical functions shall address its low-impact resistance and notch sensitivity, particularly at low temperatures, and its directional material properties (anisotropy) and sensitivity to surface finish requirements.

d. [MPR 74] All beryllium parts used in spaceflight hardware that provides mission-critical functions shall be processed to ensure complete removal of the damaged layer (twins and microcracks) produced by surface-metal-working operations, such as machining and grinding.

Chemical/milling and etching are recognized successful processes for removal of the damaged layer.

e. [MPR 75] Beryllium-containing alloys (including alloys containing less than 4 percent beryllium by weight) and oxides of beryllium shall not be machined inside spacecraft crew compartments at any stage of manufacturing, assembly, testing, modification, or operation.

Stripping, crimping, and cutting electrical wire are not considered to be machining operations.

f. [MPR 76] All beryllium parts used in spaceflight hardware that provides mission-critical functions shall be penetrant-inspected for crack-like flaws with a high-sensitivity fluorescent dye penetrant in accordance with section 4.2.5.

4.2.2.6 Cadmium

Cadmium is highly toxic, can sublime and cause outgassing contamination at elevated temperatures in vacuum, and can cause liquid metal embrittlement of titanium and some steel alloys. Cadmium plating can spontaneously form cadmium whiskers.

a. [MPR 77] Cadmium shall not be used in crew or vacuum environments.

b. [MPR 78] Cadmium-plated tools and other hardware shall not be used in the manufacture or testing of spaceflight hardware that provides mission-critical functions.

4.2.2.7 Zinc

[MPR 79] Owing to zinc's ability to grow whiskers, zinc plating other than black zinc-nickel plating shall not be used in spaceflight hardware that provides mission-critical functions.

Metallic zinc is less volatile than cadmium but should not be used in vacuum environments where the temperature/pressure environment could cause contamination of optical surfaces or electrical devices.

4.2.2.8 Mercury

a. [MPR 80] Equipment containing mercury shall not be used where the mercury could come in contact with spaceflight equipment during manufacturing, assembly, test, checkout, and flight.

Mercury has the potential for causing liquid-metal embrittlement.

b. [MPR 81] Spaceflight hardware (including fluorescent lamps) containing mercury shall have three levels of containment to prevent mercury leakage.

Nonflight lamps containing mercury, such as those used in hardware ground processing and fluorescent dye penetrant inspection of flight parts, are acceptable, provided that the bulbs are protected by a non-shatterable, leak-proof outer container.

4.2.2.9 Refractory Metals

[MPR 82] For refractory alloys (alloys with a melting point above 2000 °C (3600 °F), plus osmium and iridium) used in mission-critical applications, tests shall be performed to characterize critical design properties for the intended application and the data documented in an MUA.

Engineering data on refractory alloys are limited, especially under extreme environmental conditions of spacecraft.

4.2.2.10 Superalloys (Nickel-Based and Cobalt-Based)

In these requirements, a superalloy refers to a nickel- or cobalt- based alloy that retains all or most of its strength at usage temperatures approaching 538 ºC (1000 ºF) and higher. Examples include both wrought products such as Inconel 718 and castings such as Mar-M-247 and Inconel 625.

a. [MPR 83] High-nickel content alloys are susceptible to sulfur embrittlement; therefore, for spaceflight hardware that provides mission-critical functions, any foreign material which could contain sulfur, such as oils, grease, and cutting lubricants, shall be removed by suitable means prior to heat treatment, welding, or high temperature service.

Some of the precipitation-hardening superalloys are susceptible to alloying element depletion at the surface in a high temperature, oxidizing environment. Nickel-based superalloys are susceptible to grain boundary cracking phenomena at elevated temperatures, such as Stress

Assisted Grain Boundary Oxidation Embrittlement (SAGBOE), and to stress rupture during heat treatment.

b. [MPR 84] The reduction to design properties of alloying element depletion at the surface in a high temperature, oxidizing environment shall be evaluated when a thin sheet of one of these alloys is used for spaceflight hardware that provides mission-critical functions, since a slight amount of depletion could involve a considerable proportion of the effective cross section of the material.

4.2.2.11 Tin

High-purity tin and tin plating are susceptible to two degradation phenomena: tin whisker growth and tin pest (sometimes known as tin plague). The following requirements for tin whisker mitigation may not be adequate to prevent tin pest from occurring:

a. [MPR 85] For spaceflight hardware that provides mission-critical functions, tin and tin plating shall be alloyed with at least 3 percent lead by weight or other proven alloying element(s) to prevent tin whisker growth.

b. [MPR 86] Tin and tin plating alloyed with less than 3 percent lead by weight and used in electrical/electronic applications shall comply with GEIA-STD-0005-1A, Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-Free Solder, and Control Level 2C requirements of GEIA-STD-0005-2A, Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems, with the following exceptions:

(1) Solder alloy Sn96.3Ag3.7 (Sn96) used for high-temperature applications.

(2) Solder alloy Au80Sn20 used as a die attach material or as a package sealing material.

(3) Tin alloys containing less than 20 percent tin by weight.

c. [MPR 87] When high-purity tin and tin plating are used for spaceflight hardware that provides mission-critical functions and will also be exposed to temperatures below 13 ˚C for periods longer than 6 months, the method for preventing tin pest formation shall be documented in the materials control plan.

At this time, insufficient data exist to define hard requirements for controlling tin pest. Alloying with more than 5 percent lead or smaller quantities of antimony or bismuth significantly slows tin pest formation but may not eliminate it completely. Alloying recommendations based on weight percentage are:

(1) Not less than 5 percent lead.
(2) Not less than 0.3 percent bismuth.
(3) Not less than 0.5 percent antimony.
(4) Not less than 3.5 percent silver.

d. [MPR 88] Tin plating shall not be used for contacts in electrical interconnects (connectors, sockets, switches, etc.) for spaceflight hardware that provides mission-critical functions.

Tin plating has been demonstrated to have oxidation, wear, cold-weld, fretting, and tin whisker issues that reduce performance and reliability. Tin plating may be accepted through the MUA process, provided appropriate controls (contact lubricant, stabilant, etc.) are used to mitigate the performance and/or reliability risk.

4.2.3 Nonmetallic Materials

4.2.3.1 Elastomeric Materials

a. [MPR 89] Elastomeric materials used in spaceflight hardware that provides mission-critical functions shall be selected to operate within design parameters for the useful life of the hardware.

b. [MPR 90] Elastomeric materials used in spaceflight hardware that provides mission-critical functions, other than those used in off-the-shelf parts, such as cable clamps, shall be cure-dated for tracking purposes.

c. [MPR 91] Room temperature vulcanizing (RTV) silicones that liberate acetic acid during cure shall not be used because they can cause corrosion.

d. [MPR 92] When rubbers or elastomers are used at low temperatures in spaceflight hardware that provides mission-critical functions, the ability of these materials to maintain and provide required elastomeric properties shall be verified.

Elastomers do not seal effectively below their glass-transition temperature, and the ability of elastomers to seal decreases significantly as the glass-transition temperature is approached. The high glass-transition temperature of Viton® rubbers was a major contributor to the loss of the Space Shuttle Challenger, and other elastomers may struggle to retain sealing performance at spacecraft temperatures.

4.2.3.2 Polyvinyl Chloride

[MPR 93] Use of polyvinyl chloride on spaceflight hardware shall be limited to applications in pressurized areas where temperatures do not exceed 49 °C (120 °F).

Polyvinyl chloride offgasses unacceptably at temperatures above 49 °C (120 °F). It is also normally flammable in pressurized areas of spacecraft; so, when it is used, its flammability has to be controlled in accordance with section 4.2.1.1.

Polyvinyl chloride is not vacuum-compatible.

Rigid polyvinyl chloride tubing is not acceptable for pressurized gas applications, because it can have a brittle failure when used for pressurized gas transport.

4.2.3.3 Composite Materials

Requirements and guidance on materials design values for polymer matrix, ceramic matrix, and metal matrix composites are in section 4.1.8. Requirements on sandwich assemblies are in section 4.2.6.2.

4.2.3.4 Lubricants

NASA-TM-86556, Lubrication Handbook for the Space Industry, Part A: Solid Lubricants, Part B: Liquid Lubricants, provides guidance on the evaluation and selection of lubricants for spaceflight systems and components. Guidelines on additional lubricants not listed in NASA-TM-86556 are contained in NASA/CR-2005-213424, Lubrication for Space Applications. Lubricants containing chloro-fluoro components may react with newly exposed rubbing surfaces of aluminum, magnesium or titanium alloys, especially at elevated temperatures.

4.2.3.5 Limited-Life Items

[MPR 94] All materials shall be selected to meet the useful life of the hardware with no maintenance or be identified as limited-life items requiring maintainability.

4.2.3.6 Thermal Vacuum Stability

a. [MPR 95] Nonmetallic materials that are exposed to space vacuum, with the exception of ceramics, metal oxides, inorganic glasses, and cetyl alcohol lubricants used on fasteners outside closed compartments, shall be tested using the technique of ASTM E595-15, Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment, with acceptance criteria as follows:

(1) ≤0.1 percent collected volatile condensable materials (CVCM).

(2) ≤1.0 percent total mass loss (TML) less water vapor recovery (WVR), except that a higher mass loss is permitted if this mass loss has no effect on the functionality

of the material itself and no effect on the functionality of any materials, components, or systems that could be adversely affected by the subject mass loss.

Many materials contain absorbed water, but the loss of absorbed water does not normally affect functionality; so the WVR (a measure of the total water vapor lost in the ASTM E595-15 test) is subtracted from the TML.

More stringent requirements may be needed for materials that are line of sight to contamination-sensitive surfaces on spacecraft or attached vehicles. Contamination-sensitive surfaces include windows, lenses, star trackers, solar arrays, radiators, and other surfaces with highly controlled optical properties. The approach taken depends on the specific program needs but may include lowering the CVCM requirement to ≤0.01 percent CVCM, use of optical surfaces in testing to characterize the effects of deposition, or measurement of outgassing deposition rates as functions of source and target temperature (the standard test method is ASTM E1559, Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials) and calculating deposition on critical surfaces using an integrated vehicle model. Spacecraft with cryogenic optics may be sensitive to water vapor deposition; in such cases, the WVR would not be subtracted from the TML.

b. [MPR 96] With the following exceptions, hardware items (components, assemblies, etc.) containing materials that fail the CVCM requirement and/or having unidentified materials shall be vacuum baked at the maximum tolerable temperature of the component, 10 ºC above the maximum predicted operating temperature, or an alternate temperature selected by the program/project, to meet the program/project acceptance outgassing criteria:

(1) Materials that are not near a critical surface and have a CVCM between 0.1 and 1.0 percent and an exposed surface area less than 13 cm^2 (2 in^2) are exempt.

(2) Materials with an exposed surface area less than 1.6 cm^2 (0.25 in^2) are exempt.

(3) Materials that are unexposed, overcoated, or encapsulated with approved materials are exempt.

(4) Materials enclosed in a sealed container (maximum leak rate less than 1×10^{-4} cm^3/sec) are exempt.

Determination of acceptable molecular outgassing limits, selection of the bakeout method and temperature, and determination of the specific bakeout completion criteria are the responsibility of the program/project. ASTM E2900, Standard Practice for Spacecraft Hardware Thermal Vacuum Bakeout, is recommended as a guide for performing thermal vacuum bakeout.

A vacuum-bake temperature of 125 ºC (257 ºF) (the ASTM E595-15 screening temperature) may damage some spaceflight hardware. Temperature requirements for hardware thermal vacuum *bakeout should be adjusted to prevent damage to components. Because bakeout time and efficiency are dependent on temperature, the chosen temperature should be the highest possible without damage to hardware.*

A hardware functionality bench test should be performed to re-verify performance after baking.

4.2.3.7 External Environment Survivability

[MPR 97] The critical properties of materials exposed in the spacecraft external environment shall meet operational requirements for their intended life-cycle exposure.

Applicable space environments include atomic oxygen, solar ultraviolet (UV) radiation, ionizing radiation, plasma, vacuum, thermal cycling, and contamination. Applicable planetary environments, such as dust and planetary atmospheres, may also apply. Meteoroids and orbital debris should also be considered in the analysis of long-term degradation.

4.2.3.8 Fungus Resistance

[MPR 98] Materials that are non-nutrient to fungi, as identified in MIL-HDBK-454B, General Guidelines for Electronic Equipment, Requirement 4, Fungus-Inert Materials, Table 4-I, Group I, shall be used in launch vehicles and pressurized flight compartments, except when one of the following criteria is met:

a. Materials have been tested to demonstrate acceptability per MIL-STD-810G, Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests, Method 508.

b. Materials are used in crew areas where fungus would be visible and easily removed.

c. Materials are used inside sealed containers (maximum leak rate less than 1×10^{-4} cm^3/sec) with internal container humidity less than 60 percent relative humidity (RH) at ambient conditions.

d. Materials are used inside electrical boxes where the temperature is always greater than or equal to the ambient cabin temperature.

e. Materials have edge exposure only.

f. Materials are normally stowed with no risk of condensation in stowage locations.

g. Materials are used on noncritical, off-the-shelf electrical/electronic hardware that is stowed and/or used in crew areas.

h. Materials are fluorocarbon polymers (including ETFE) or silicones.

i. Materials are used in crew clothing items.

When fungus-nutrient materials have to be used (and none of the above exception criteria are met) and an MUA is submitted for approval, supporting rationale should include how materials are treated to prevent fungus growth, using a fungus treatment that does not adversely affect unit performance or service life, does not constitute a health hazard to higher order life, and is not leached out by the use environment.

4.2.3.9 Glycols

[MPR 99] When solutions containing glycols (aliphatic dihydric alcohols) are used aboard spacecraft that have electrical or electronic circuits containing silver or silver-coated copper, a silver chelating agent, such as benzotriazole (BZT), shall be added to the solution to prevent spontaneous ignition from the reaction of silver with the glycol.

This reaction is known to occur for ethylene and propylene glycol. Solutions containing other glycols may be exempted if testing is conducted to demonstrate that the spontaneous ignition reaction does not occur.

4.2.3.10 Etching Fluorocarbons

a. [MPR 100] The etching of PTFE, perfluoroalkoxy (PFA), and fluorinated ethylene propylene (FEP) shall meet the requirements of SAE AMS2491F, Surface Treatment of Polytetrafluoroethylene, Preparation for Bonding, when adhesion to the fluorocarbon surface is required, except that for insulated wire or cable a pull test on co-produced specimens may be performed in lieu of the tensile and shear strength tests in AMS2491, section 3.5.2.

Adhesion to the fluorocarbon surface is required for electrical wire or cable insulated or coated with fluorocarbons intended for potting if mechanical bond strength and environmental sealing are a design requirement.

b. [MPR 101] Etched surfaces shall be processed within 24 hours or within 1 year if packaged per SAE AMS2491F.

The open end of the wire should not be exposed to the etchant.

4.2.4 Processes

4.2.4.1 Heat Treatment

a. [MPR 102] Heat treatment of aluminum alloys used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS2772G, Heat Treatment of Aluminum Alloy Raw Materials; SAE AMS2770N, Heat Treatment of Wrought Aluminum Alloy Parts; or SAE AMS2771E, Heat Treatment of Aluminum Alloy Castings.

b. [MPR 103] Heat treatment of steel alloys used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS-H-6875B, Heat Treatment of Steel Raw Materials, or SAE AMS2759E, Heat Treatment of Steel Parts, General Requirements.

c. [MPR 104] Heat treatment of titanium alloys used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS-H-81200D, Heat Treatment of Titanium and Titanium Alloys, for raw stock and SAE AMS2801B, Heat Treatment of Titanium Alloy Parts, for parts requiring heat treatment during fabrication.

d. [MPR 105] Heat treatment of nickel- and cobalt-based alloy parts used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS2774E, Heat Treatment, Wrought Nickel Alloy and Cobalt Alloy Parts, or SAE AMS2773E, Heat Treatment, Cast Nickel Alloy and Cobalt Alloy Parts.

Care should be taken in design of heat treatment fixturing and in heat treatment procedures for nickel- and cobalt-based alloy parts to avoid the introduction of excessive tensile stress. Inconel 718 parts have failed through SAGBOE and stress rupture from stresses induced by as little as an abrupt change in part thickness combined with introduction of a "cold" part into a hot furnace.

These AMS heat treatment specifications require hardness and/or conductivity measurements to verify the adequacy of the heat treatment process. In many cases, hardness tests are inadequate for spacecraft hardware; and testing of process-control tensile-test coupons is required.

e. [MPR 106] For spaceflight hardware that provides mission-critical functions, process-control tensile-test coupons shall be taken from the production part (or from the same material lot, having the same thickness as and processed identically to the production part) to verify the adequacy of the heat treatment process for the following conditions:

(1) Aluminum alloys are solution heat-treated.

(2) High-strength steels (>200 ksi (1380 MPa) UTS), tool steels, and maraging steel alloys are heat-treated to high strength levels.

(3) A286 or MP35N alloys (which have poor correlation between hardness and tensile strength) are heat treated.

(4) Titanium alloys are annealed or solution heat treated and aged.

(5) Nickel- and cobalt-based alloys are work strengthened before age hardening, resulting in age-hardened tensile strengths greater than 1030 MPa (150 ksi) UTS.

(6) Precipitation hardenable nickel- and cobalt-based alloys are solution heat treated.

Note: Representative tensile test coupons are preferred over hardness and conductivity measurements for aging of aluminum alloys.

f. [MPR 107] When process-control tensile-test coupons are required, the requirement for the coupons shall be specified on the engineering drawing for the part.

g. [MPR 108] If no tensile values are available in MMPDS for a specific alloy, tensile-test acceptance values shall be specified on the engineering drawing for the part.

h. [MPR 109] Materials shall not be used in spaceflight hardware that provides mission-critical functions outside the limits of their procurement specification, heat treat specification, or MMPDS specification.

Procurement specifications, heat treat specifications, and MMPDS all limit product size of metal stock to ensure full consolidation of cast structure, product uniformity, and consistent mechanical properties.

4.2.4.2 Forging

Because mechanical properties are optimum in the direction of material flow during forging, forging techniques should be used that, whenever possible, produce an internal grain-flow pattern such that the direction of flow is essentially parallel to the principal stresses. If forging techniques do not allow for an internal grain-flow pattern such that the direction of the flow is parallel to the principal stresses, parts should be designed such that the weakest grain flow direction is not in line with the principal stresses. The forging pattern should be essentially free from re-entrant and sharply folded flow lines.

a. [MPR 110] Where forgings are used in mission-critical applications, first-article (preproduction) approval shall be obtained from the procuring authority.

First article requirements apply to all forgings, including hand forging and spin forming. The first article requirements may be waived for hand forging by review of the forging plan through the MUA process.

b. [MPR 111] First-article approval and the controls to be exercised in producing subsequent production forgings shall be in accordance with SAE AMS2375D, Control of Forgings Requiring First Article Approval.

Mechanical properties testing requirements may include fracture, durability, or damage tolerance testing.

c. [MPR 112] After the forging technique, including degree of working, is established, the first production forging shall be sectioned to show the grain-flow patterns and to determine mechanical properties at control areas and the trim ring/protrusion specimens (prolongations).

d. [MPR 113] The mechanical properties of the trim ring/protrusion specimens (prolongations) for the first article shall be compared to the control coupons to show they are predictive of the properties in the body of the first article.

e. [MPR 114] Sectioning to show the grain-flow patterns and to determine mechanical properties at control areas shall be repeated after any substantive change in the forging technique, as determined by M&P analysis.

The information gained from this effort is utilized to redesign the forging as necessary.

f. [MPR 115] These data and results of tests on the redesign shall be retained and made available for review by the procuring activity.

g. [MPR 116] Trim ring or protrusion specimens (prolongations) shall be obtained for each production forging used in safety-critical applications and tested for required minimum mechanical properties.

h. [MPR 117] Surface and volumetric nondestructive inspection (NDI) shall be performed on all safety-critical forgings.

4.2.4.3 Castings

a. [MPR 118] Castings used in spaceflight hardware that provide mission-critical functions shall meet the requirements of SAE AMS2175A (2010), Castings, Classification and Inspection of.

b. [MPR 119] Where castings are used in mission-critical applications, pre-production castings shall be subjected to first-article inspection to verify proper material flow, proper material integrity, minimum required mechanical properties, proper grain size, and macro/microstructure.

c. [MPR 120] The mechanical properties in trim ring/protrusion of the first article shall be compared to the control coupons to show they are predictive of the properties in the body of the first article.

Mechanical properties testing requirements may include fracture, durability, or damage tolerance testing.

d. [MPR 121] The same casting practice and heat-treating procedure shall be used for the production castings as for the approved first-article castings.

e. [MPR 122] For Class 1 and Class 2 castings (classes as defined by SAE AMS2175A (2010)), mechanical property testing of integrally cast or excised tensile bars at critical locations shall be conducted to ensure foundry control of cast lots.

f. [MPR 123] Periodic cut-ups or functional testing shall be conducted for Class 1 and Class 2 castings (classes as defined by SAE AMS2175A (2010)).

g. [MPR 124] Surface and volumetric nondestructive inspection shall be performed on all safety-critical castings.

4.2.4.4 Formed Panels

Barrel and gore panels with complex geometries and integral stiffeners are often formed by processes such as roll forming, brake forming, peen forming, stretch forming, and explosive forming and then heat treated. The mechanical and thermal forming processes can result in strength and toughness variations across the panel.

a. [MPR 125] Where formed panels are used in mission-critical applications, pre-production panels shall be subjected to first-article inspection to verify proper material integrity, minimum required mechanical properties, proper grain size, and macro/microstructure.

b. [MPR 126] The mechanical properties of the first production article shall be compared to control coupons to show they are predictive of the properties in the body of the first article.

Mechanical properties testing requirements may include fracture, durability, or damage tolerance testing.

c. [MPR 127] The same forming practice and heat-treating procedure shall be used for the production formed panels as for the approved first-article panels.

d. [MPR 128] Sectioning to determine mechanical properties at control areas shall be repeated after any substantive change in the forming technique, as determined by M&P analysis.

e. [MPR 129] Surface and volumetric NDI shall be performed on all safety-critical formed panels.

Given the complexities of some formed panels, volumetric NDI may be performed as a raw stock inspection.

4.2.4.5 Adhesive Bonding

a. [MPR 130] Structural adhesive bonding shall meet MSFC-SPEC-445A, Adhesive Bonding, Process and Inspection, Requirements for.

The Operator Certification Plan and the Adhesive Control Plan may be described in the implementing process specification in place of submittal to NASA for approval.

Retesting of adhesives used for production parts is not required if they are within shelf life.

b. [MPR 131] Structural adhesive bonding processes shall be controlled to prevent contamination that would cause structural failure that could affect the safety of the mission, crew, or vehicle or affect mission success.

The sensitivity of structural adhesive bonds to contamination is of particular concern. Bond sensitivity studies should be conducted to verify that the required adhesive properties are maintained after exposure to potential contaminant species and concentrations, and in-process cleanliness inspections should be conducted as part of the bonding process. Silicone contamination is a particular concern because it severely degrades adhesive performance.

c. [MPR 132] Bonded primary structural joints shall demonstrate cohesive failure modes in shear.

4.2.4.6 Welding

The design selection of parent materials and weld methods should be based on consideration of the weldments, including adjacent heat-affected zones, as they affect operational capability of the parts concerned. Peaking and mismatch limits should be considered in the mechanical properties.

Welding procedures should be selected to provide the required weld quality, minimum weld energy input, and protection of the heated metal from contamination.

The suitability of the equipment, processes, welding supplies, and supplementary treatments selected should be demonstrated through qualification testing of welded specimens representing the materials and joint configuration of production parts.

Working with the delegated Technical Authority and NASA M&P organization, Programs/Projects will assess if it is more beneficial to directly use welding specifications cited in this section or develop alternatives. The requirements in this section provide compliance with NASA-STD-5006A, General Welding Requirements for Aerospace Materials. If the requirements in this section are met, no further application of NASA-STD-5006A is needed.

a. [MPR 133] If alternative specifications to those cited in this section are utilized or developed, those specifications shall meet the requirements of NASA-STD-5006A, General Welding Requirements for Aerospace Materials.

Note: NASA-STD-5006A defines weld classes in terms of weld criticality (with Class A representing safety-critical structural welds) and AWS D17.1/D17.1M AMD 1 defines weld classes in terms of inspection requirements (with Class A representing the most stringent nondestructive inspection requirements).

b. [MPR 134] Material Review Board disposition shall be required for weld repair/rework/processing activities that are not in accordance with the approved weld process specification (WPS).

Examples include:

- *Wrong filler metal used.*
- *More than two attempts performed at the same location on heat-sensitive materials.*
- *More than five attempts performed at the same location on materials that are not heat sensitive.*
- *Repair weld required after the weldment has been post-weld heat treated.*
- *Repair weld required after final machining has been completed.*
- *Repair extends outside the original weld zone.*
- *Weldment has been direct aged.*
- *Repairs following proof or leak test.*

c. [MPR 135] A weld development and certification plan shall be developed for large structural welded components such as crew modules and welded cryogenic tanks.

This plan should include full scale pathfinder weldments, tooling development, and a design values program including sensitivity testing.

4.2.4.6.1 Fusion Welding

[MPR 136] The processing and quality assurance requirements for manual, automatic, and semiautomatic welding for spaceflight applications that provide mission-critical functions shall meet the requirements of AWS D17.1/D17.1M (2010) AMD 1 (2012), Specification for Fusion Welding for Aerospace Applications, with the following modifications/additions:

Note: AWS D17.1/D17.1M (2010) AMD 1 (2012) defines weld classes in terms of inspection requirements (with Class A representing the most stringent nondestructive inspection requirements).

a. [MPR 137] Mission-critical structural welds shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012), Class A requirements.

b. [MPR 138] Other structural welds shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012), Class A or Class B requirements.

c. [MPR 139] Non-critical welds (including seal welds) shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012), Class C requirements.

d. [MPR 140] All Class A and Class B welds (including manual welds), as defined by AWS D17.1/D17.1M (2010) AMD 1 (2012), shall be qualified in accordance with AWS D17.1/D17.1M (2010) AMD 1 (2012).

AWS G2.4/G2.4M, Guide for the Fusion Welding of Titanium and Titanium Alloys, should be used for guidance on titanium welding.

e. [MPR 141] Titanium welds shall be light/dark straw or better (Ref. AWS D17.1/D17.1M (2010) AMD 1 (2012), Table 7.1).

f. [MPR 142] Titanium and its alloys shall be welded with alloy-matching or metallurgically compatible fillers or autogenously.

Ti-6Al-4V filler metal is considered to be metallurgically compatible with Ti-3Al-2.5V.

g. [MPR 143] Extra low interstitial (ELI) filler wires shall be used for titanium cryogenic applications and are preferred for general applications.

h. [MPR 144] Commercially pure (CP) titanium filler shall not be used on Ti-6Al-4V or other alloyed base material.

Hydride formation can occur in the weld, which can produce a brittle, catastrophic failure.

i. [MPR 145] Nitrogen, hydrogen, carbon dioxide, and mixtures containing these gases shall not be used in welding titanium and its alloys.

Care needs to be exercised to ensure complete inert gas (argon or helium) coverage during welding.

(1) [MPR 146] The inert gas shall have a dew point of -60º C (-76º F) or lower.

j. [MPR 147] Welded alpha and alpha plus beta titanium alloys shall be stress relieved in a vacuum or inert gas environment (Ar or He), or stress relieved in air with verification of oxide removal per SAE AMS-H-81200D or SAE AMS2801B, or certified in the as-welded condition.

k. [MPR 148] Titanium beta alloys that are welded shall be evaluated on a case-by-case basis with respect to stress relief.

Note: Stress relief of weldments does not require tensile test coupons.

l. [MPR 149] Laser welding for spaceflight hardware that provides mission-critical functions shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012) or AWS C7.4/C7.4M (2008), Process Specification and Operator Qualification for Laser Beam Welding.

m. [MPR 150] Electron beam welding for spaceflight hardware that provides mission-critical functions shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012) or SAE AMS2680C, Electron-Beam Welding for Fatigue Critical Applications.

Compliance with SAE AMS2680C is preferred but compliance with AWS D17.1/D17.1M (2010) AMD 1 (2012) is acceptable.

n. [MPR 151] The following welding practices permitted by AWS D17.1/D17.1M (2010) AMD 1 (2012) shall not be used without an approved MUA to document the acceptance rationale:

(1) Welding from both sides if full penetration of the first pass is not verified (either by inspection of the back side or by grinding prior to welding on the opposite side).

(2) Partial weld penetration in structural welds.

(3) Straightening operation after welding.

(4) Lap welds in structural applications.

o. [MPR 152] The Welding Procedure Specification (WPS) shall include the following content in addition to that required by AWS D17.1/D17.1M (2010) AMD 1 (2012):

(1) Prequalified rework welds in accordance with AWS D17.1/D17.1M (2010) AMD 1 (2012).

(2) Testing and documentation of allowable parameter variations for automatic and semi-automatic welds.

(3) Manual welding parameters.

(4) An associated Procedure Qualification Record (PQR) with tension testing and macro-examination results as part of weld qualification requirements.

Qualification strength requirements should be included in weld qualification test acceptance. Qualification strength values are not the same as materials design values.

4.2.4.6.2 Resistance Welding

[MPR 153] Resistance welding for spaceflight hardware that provides mission-critical functions, including resistance spot welding (RSW), shall meet the requirements of AWS D17.2/D17.2M (2013), Specification for Resistance Welding for Aerospace Applications.

4.2.4.6.3 Friction-Stir Welding of Aluminum Alloys

[MPR 154] Friction-stir welding of aluminum alloys for spaceflight hardware that provides mission-critical functions shall meet the requirements of AWS D17.3/D17.3M (2016), Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications.

4.2.4.6.4 Inertia Welding

[MPR 155] Inertia welding for spaceflight hardware that provides mission-critical functions shall meet the requirements of MIL-STD-1252 (1975), Inertia Friction Welding Process, Procedure and Performance Qualification.

a. [MPR 156] Surface inspection (penetrant) and volumetric inspection (radiography) shall be performed.

b. [MPR 157] All welds shall be proof tested.

c. [MPR 158] Inertia welds used in fluid systems shall be helium leak tested.

Acceptable helium leak rates should be defined by the system.

4.2.4.7 Brazing

a. [MPR 159] Brazing for spaceflight hardware that provides mission-critical functions shall be conducted in accordance with AWS C3.3 (2008), Recommended Practices for Design, Manufacture, and Examination of Critical Brazed Components.

b. [MPR 160] Brazing of aluminum alloys for spaceflight hardware that provides mission-critical functions shall meet the requirements of AWS C3.7M/C3.7 (2011), Specification for Aluminum Brazing.

c. [MPR 161] Torch, induction, and furnace brazing for spaceflight hardware that provides mission-critical functions shall meet the requirements of AWS C3.4M/C3.4 (2016), Specification for Torch Brazing; AWS C3.5M/C3.5 (2016), Specification for Induction Brazing; and AWS C3.6M/C3.6 (2016), Specification for Furnace Brazing, respectively.

d. [MPR 162] Subsequent fusion-welding operations in the vicinity of brazed joints or other operations involving high temperatures that might affect the brazed joint shall be prohibited for spaceflight hardware that provides mission-critical functions unless it can be demonstrated that the fixturing, processes, methods, and/or procedures employed will preclude degradation of the brazed joint.

e. [MPR 163] Brazed joints used in spaceflight hardware that provides mission-critical functions shall be designed for shear loading and not be relied upon for strength in axial loading for structural parts.

f. [MPR 164] The shear strength of brazed joints used in spaceflight hardware that provides mission-critical functions shall be evaluated in accordance with AWS C3.2M/C3.2 (2008), Standard Method for Evaluating the Strength of Brazed Joints.

g. [MPR 165] For furnace brazing of complex configurations of spaceflight hardware that provides mission-critical functions, such as heat exchangers and cold plates, destructive testing shall be conducted on pre-production brazed joints to verify that the braze layer that extends beyond the fillet area is continuous and forms a uniform phase.

4.2.4.8 Structural Soldering

[MPR 166] Soldering shall not be used for structural applications.

4.2.4.9 Electrical Discharge Machining and Laser Machining

a. [MPR 167] Electrical-discharge machining (EDM) and laser machining (LM) processes for spaceflight hardware that provides mission-critical functions shall be controlled to limit the depth of the oxide layer, the recast layer, and the heat-affected zone.

(1) [MPR 168] The oxide layer shall be removed from the surface.

(2) [MPR 169] In addition, the recast layer and the heat-affected zone shall be removed from bearing, wear, fatigue or fracture-critical surfaces, and from crack- or notch-sensitive materials.

The recast layer and heat-affected zone may be left on a part if an engineering evaluation shows that they are not of consequence to the required performance of the part.

b. [MPR 170] EDM/LM schedules for spaceflight hardware that provides mission-critical functions shall be qualified to determine the maximum thickness of the affected layers when the depth of the affected material must be known for removal or analysis.

4.2.4.10 Nickel Plating

a. [MPR 171] Electrodeposited nickel plating for spaceflight hardware that provides mission-critical functions shall be applied according to the requirements of SAE AMS2403N, Plating, Nickel General Purpose; SAE AMS2423E, Plating, Nickel Hard Deposit; or ASTM B689-97, Standard Specification for Electroplated Engineering Nickel Coatings.

b. [MPR 172] Electroless nickel plate for spaceflight hardware that provides mission-critical functions shall be applied per SAE AMS2404G, Plating, Electroless Nickel, or ASTM B733-15, Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal.

c. [MPR 173] The nickel-aluminum interface in nickel-plated aluminum used in spaceflight hardware that provides mission-critical functions shall be protected from exposure to corrosive environments.

Nickel and aluminum form a strong galvanic cell at the nickel-aluminum interface, and exposure of the aluminum alloy to a corrosive environment can produce rapid disbonding of the nickel plate.

4.2.4.11 Additive Manufacturing

[MPR 174] Spaceflight hardware manufactured by additive manufacturing techniques shall be designed, produced, and documented in compliance with NASA-STD-6030.

NOTE: The requirements of NASA-STD-6030 do not encompass all requirements for an AM part (flammability, toxic offgassing, vacuum outgassing, etc. also apply).

Additive Manufacturing Control Plans are reviewed and approved by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization per section 4.2 of NASA-STD-6030.

An Equipment and Facilities Control Plan per NASA-STD-6033, Additive Manufacturing Requirements for Equipment and Facility Control, is developed by the AM part producer and approved by the cognizant engineering organization per section 4.5 of NASA-STD-6030.

Material Property Suites used to design Class A and B additively manufactured parts are reviewed and approved by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization per section 6 of NASA-STD-6030.

Part Production Plans are reviewed and approved by the responsible NASA program or project, with concurrence from the responsible NASA M&P organization per section 7 of NASA-STD-6030.

4.2.5 Material Nondestructive Evaluation (NDE)

4.2.5.1 Nondestructive Evaluation (NDE) Plan

a. [MPR 175] The NDE Plan shall address the process for establishment, implementation, execution, and control of NDE through design, manufacturing, operations, and maintenance of spaceflight hardware.

b. [MPR 176] The Plan shall meet the intent of MIL-HDBK-6870B, Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts, and, when fracture control is applicable, the requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components.

In case of conflict between the requirements of the two standards, the requirements of NASA-STD-5009 are applicable. It is expected that fracture-critical and safety-critical parts have surface and volumetric inspections unless there is rationale that it is not necessary. The need for internal (volumetric) inspection depends on the application and on materials characteristics such as thickness, product form, and other factors. Internal inspection requirements and methods should be determined early in the design process so that proper flaw screening is accomplished.

c. [MPR 213] NDE acceptance criteria and requirements for qualification of NDE procedures used on all (metallic, non-metallic and composite) hardware shall be addressed in the NDE Plan.

The MUA process is used to accept qualification of specific NDE procedures not covered by the NDE Plan.

d. [MPR 177] Qualification and certification of personnel involved in nondestructive testing shall comply with NAS 410 (Revision 4), NAS Certification and Qualification of Nondestructive Test Personnel.

4.2.5.2 NDE Etching

a. [MPR 178] All machined or otherwise mechanically disturbed surfaces on metallic parts that are to be fluorescent dye-penetrant inspected shall be adequately etched to assure removal of smeared, masking material prior to penetrant application, with the following exceptions:

(1) Previously etched parts do not need etching if the surface has not been smeared since the last etching.

(2) When supporting rationale is provided, close tolerance parts may be machined near-final and etched and penetrant inspected before final machining in lieu of etching and penetrant inspecting after final machining.

b. [MPR 179] The etching procedure shall specify the minimum amount of material to be removed to ensure that smeared metal does not mask cracks.

Minimum material removal requirements for fracture-critical hardware are identified in NASA-STD-5009.

c. [MPR 180] If etching is not feasible, it shall be demonstrated that the required flaw size can be reliably detected.

4.2.6 Special Materials Requirements

4.2.6.1 Residual Stresses

Residual tensile stresses are induced into manufactured parts as a result of forming, machining, heat treating, welding, special metal-removal processes, or the straightening of warped parts. Residual stresses may be harmful in structural applications when the part is subjected to fatigue loading, operation stresses, or corrosive environments. Special consideration should be given to *the possibility of high residual stresses that might develop during off-nominal processing, such as repeated weld repairs in the same location. Residual stresses should be controlled or minimized during the fabrication sequence by special treatments, such as annealing and stress relieving. Bending and forming of tubing (for example, stainless steel and titanium tubing) is typically not stress relieved.*

a. [MPR 181] Estimates of residual stresses in structural or stress-corrosion-sensitive hardware shall be considered in structural analyses and corrosion/stress-corrosion assessments.

Residual stresses should be quantified by an appropriate technique (such as x-ray diffraction).

b. [MPR 182] The straightening of warped parts in structural hardware shall require an approved MUA.

4.2.6.2 Sandwich Assemblies

Many spaceflight hardware failures have been attributed to both vented and non-vented sandwich assemblies (using either perforated or non-perforated honeycomb core) that were compromised by the expansion of trapped gas and/or water vapor in-flight, causing internal pressure build-up and subsequent face sheet separation. Structural sandwich assemblies using honeycomb or open-cell core constructions that are exposed to ascent-aerodynamic heating and/or vacuum exposure may be either vented to relieve internal pressure or sealed and protected to preclude accumulation of water or other contaminants inside the sandwich structure.

a. [MPR 183] For vented sandwich architectures, the differential pressure on ascent shall be adequately relieved to preclude core-to-face sheet bond line “peel” failure modes that could result in face sheet separation.

Venting analysis methods are complex and may be difficult to verify. Testing should be conducted to verify that the venting architectures selected perform as intended in the as-built flight structures. “Peel” failure modes at the core-to-face sheet bondline should be characterized with expected defects (damage tolerance) and evaluated against the expected combined loading environments associated with internal pressure, temperature, absorbed water/humidity, and externally applied loads.

b. [MPR 184] Sandwich architectures that are not vented shall be capable of withstanding pressure buildup without violating strength and stability requirements.

Sandwich assemblies that are not vented may result in higher internal design pressures during flight. As for vented sandwich architectures, verification of non-vented sandwich assemblies should include evaluation of credible “peel” failure modes when exposed to all expected combined loading environments. Additionally, fatigue performance should be interrogated to *evaluate the effects of thermal cycling and the associated variation in internal gas pressure and to evaluate load cycles that can allow moisture contamination.*

c. [MPR 185] Structural sandwich assemblies shall be designed to prevent the entrance and entrapment of water vapor or other contaminants into the core structure.

Regardless of the venting architecture, careful consideration of water intrusion pathways at both the part fabrication and assembly level is necessary. Sources of water intrusion include absorption, diffusion, condensation, cryo-pumping, rain/wind-driven rainwater prior to launch, and water landing.

NASA-STD-6012, Corrosion Protection for Space Flight Hardware, requires contacts between graphite-based composites and metallic materials to be treated as dissimilar metal couples. To meet this requirement, composite sandwich assemblies that utilize aluminum honeycomb core and which may be exposed to condensed moisture/water should be electrically isolated from carbon/graphite face sheets to limit the potential for galvanic corrosion to compromise the honeycomb sandwich assembly. Alternate approaches should be identified in the corrosion control plan. The method(s) selected to prevent galvanic corrosion should be evaluated against all relevant design environments throughout the life cycle of the part.

d. [MPR 186] Structural honeycomb sandwich assemblies that will be subjected to heating shall be tested for the expected environments to show that the construction can withstand them.

Catastrophic spacecraft structural failures have been associated with ascent-aerodynamic heating (including the effects of water/water vapor), or on-orbit thermal cycling. Polymer matrix materials are affected by both water/moisture absorption and temperature. Water absorption/intrusion can be affected by mechanical and/or thermal cycling (e.g. matrix microcracking). Panel heating can soften adhesives while simultaneously driving absorbed or trapped water into steam, resulting in a dramatic rise in internal pressure. Testing should evaluate these effects for sandwich design features and potential repairs, while concurrently addressing the expected defects commensurate with damage tolerance requirements. Acceptance / proof testing of each flight article should address the combined loading environment, including effects from internal pressurization.

e. [MPR 187] Sandwich assemblies using perforated and moisture-absorbing cores shall be protected from water intrusion during assembly and prelaunch activities.

Certain sandwich core materials, e.g., Nomex® and Kevlar® aramids or foam core, are capable of absorbing significant amounts of moisture. Selection of such materials may require environmental conditioning prior to launch in addition to discrete water intrusion protections.

f. [MPR 188] Structural sandwich constructions and core materials shall be designed, evaluated, and tested in accordance with the requirements of CMH-17, Volume 6: Structural Sandwich Composites.

Because the ability of NDE to detect core-to-face sheet bond line defects is limited, the potential presence of defects makes it necessary to address both the static strength and cyclic loading capability under combined loading environments. Such environments can include pressure, temperature, and externally applied loads. Elevated temperatures from panel heating can soften adhesives and cause failure.

Acceptance / proof testing of each flight article should address the critical combined loading environment, including rapid decompression.

4.2.6.3 Corrosion Prevention and Control

[MPR 189] All parts, assemblies, and equipment used in spaceflight hardware that provides mission-critical functions, including spares, shall be finished to provide protection from corrosion in accordance with the requirements of NASA-STD-6012, with the following exceptions:

a. SAE AMS2404G is permitted for electroless nickel plating as an alternative to ASTM B733-15.

b. Titanium fasteners may be used in contact with graphite composites, provided that they are wet installed with sealant or primer materials.

4.2.6.3.1 Passivation

[MPR 190] Corrosion-resistant steels used in spaceflight hardware that provides mission-critical functions shall be passivated after machining.

4.2.6.3.2 Sealing

[MPR 191] Removable panels and access doors in exterior or interior corrosive environments shall be sealed either by mechanical seals or by separable, faying-surface sealing.

4.2.6.4 Hydrogen Embrittlement

Hydrogen embrittlement through hydrogen-metals interactions can be classified into three broad categories: hydrogen environmental embrittlement (HEE), internal hydrogen embrittlement (IHE), and hydrogen reaction embrittlement (HRE). In general, hydrogen environmental embrittlement represents the condition where the materials are exposed to a high-pressure gaseous hydrogen environment. The hydrogen for internal hydrogen embrittlement is usually not from a high-pressure gaseous system, but from an electrochemical process such as electroplating, corrosion, cathodic charging, and even from thermal charging. The hydrogen for internal hydrogen embrittlement can also come from moisture and enter the metals during welding, casting, and solidification processes from the foundry.

The hydrogen environmental embrittlement and internal hydrogen embrittlement effects are similar in many instances and they both require an external applied stress in order for the hydrogen embrittlement effects to occur. In contrast, hydrogen reaction embrittlement is usually irreversible hydrogen damage caused by a chemical reaction with hydrogen and such damage can occur without an external applied stress. This form of hydrogen damage can occur in materials such as titanium, zirconium, and some types of iron or steel-based alloys.

Overall, hydrogen embrittlement of materials is not very well understood and only limited materials property data have been generated. NASA/TM-2016-218602, Hydrogen Embrittlement, provides a detailed description of hydrogen embrittlement mechanisms, a comprehensive summary of existing hydrogen embrittlement data, and guidance on selection of materials and control of processes to prevent hydrogen embrittlement. It is a companion document to ANSI/AIAA G-095, Guide to Safety of Hydrogen and Hydrogen Systems.

a. [MPR 192] When designing liquid or gaseous hydrogen systems, the degradation of metallic materials properties by hydrogen embrittlement shall be addressed in the Materials and Processes Selection, Control, and Implementation Plan.

b. [MPR 193] An MUA shall be written rationalizing the selection of metallic materials for liquid or gaseous hydrogen systems to preclude cracking and to ensure system reliability and safety.

Test data may have to be generated in a simulated environment to support the rationale.

c. [MPR 194] Electrochemical processes or exposure to acids or bases during manufacturing or processing of spaceflight hardware that provides mission-critical functions shall be controlled to prevent hydrogen embrittlement, or embrittlement relief treatment shall be performed promptly after processing.

(1) [MPR 195] When acid cleaning baths or plating processes are used on steel parts for spaceflight hardware that provides mission-critical functions, the part shall be baked in accordance with SAE AMS2759/9D, Hydrogen Embrittlement Relief (Baking) of Steel Parts, to alleviate potential hydrogen embrittlement problems.

4.2.6.5 Intermetallic Compounds

When joining two or more metals together (soldering, wire bonding, etc.), intermetallic compounds can form that are problematic to the metal joint, leading to a weakened mechanical or electrical connection. Problems can arise from embrittlement, changes in density, or conductivity of the intermetallic compound. Gold-indium and gold-tin are two of the more common systems that form intermetallic compounds that will degrade a metal joint.

4.2.6.5.1 Gold-Indium Intermetallic Formation

Indium reacts with gold to form a succession of gold-indium intermetallic compounds. The gold-indium intermetallic compounds occupy a volume approximately four times the original volume of the consumed gold and are brittle. The original mechanical and thermal properties of gold are degraded by this intermetallic reaction possibly resulting in unreliable electrical interconnections. The gold-indium intermetallic formation progresses significantly even at room temperature and accelerates at elevated temperatures.

[MPR 196] Gold shall not be used in contact with indium or an indium alloy (such as indium solder) for spaceflight hardware that provides mission-critical functions.

4.2.6.5.2 Gold-Tin Intermetallic Formation

The combination of gold and tin is subject to two distinct degradation mechanisms: gold embrittlement of tin-based solder joints and fretting corrosion of gold-coated contacts when mated with tin or tin alloy-coated contacts.

When tin-based solder is used to join gold-plated surfaces, the gold coatings will dissolve into the final solder joint. If the concentration of gold in the tin-based solder joint exceeds approximately 3 percent by weight, then a brittle gold-tin intermetallic compound may form within the joint that can impact the long-term reliability of the solder joint.

a. [MPR 197] When used with tin-based solder joints in mission-critical hardware, gold shall be removed from at least 95 percent of the surface to be soldered of all component leads, component terminations, and solder terminals.

A double tinning process or dynamic solder wave may be used for gold removal prior to mounting the component on the assembly.

The combination of one gold-coated surface and one tin-coated or tin-alloy-coated surface for separable contact interfaces (e.g., electrical connector contact pairs) is highly prone to fretting corrosion, which can build up an electrically insulating tin-oxide film at the contact interface, resulting in increased contact resistance.

b. [MPR 198] Gold-coated contacts shall not be mated with tin or tin alloy-coated contacts for separable contact interfaces in mission-critical hardware.

4.2.6.5.3 Gold-Aluminum Intermetallic Formation

An aluminum-rich intermetallic phase, the $AuAl_2$ *intermetallic known as "Purple Plague," is inherent (and not necessarily harmful) to gold-aluminum brazing; however, if excessive heat is applied too much of the intermetallic can form at the braze/part interface, causing joint failure. A gold-rich phase, the* Au_5Al_2 *intermetallic known as "White Plague," is always detrimental. Its formation is catalyzed by silicon, so care should be taken to keep the braze joint zone free of contamination.*

a. [MPR 199] Gold-aluminum brazing processes shall be controlled to minimize formation of the $AuAl_2$ intermetallic known as "Purple Plague" and prevent formation of the Au_5Al_2 intermetallic known as "White Plague."

Purple Plague is a significant problem in microelectronic applications, because as purple plague forms, it reduces in volume. This creates cavities in the metal surrounding the purple plague, which increases electrical resistance and structurally weakens the wire bonding. White plague is worse, because it has low electrical conductivity and, if enough of it forms, the resulting electrical resistance can cause a total failure of the component.

b. [MPR 200] Gold-aluminum bonding processes shall be controlled to prevent the formation of the $AuAl_2$ intermetallic known as "Purple Plague" and the Au_5Al_2 intermetallic known as "White Plague."

4.2.6.6 Fastener Installation

4.2.6.6.1 Liquid Locking Compounds

[MPR 201] If a liquid-locking compound is used as a locking feature where rotational loosening or disengagement would result in a critical or catastrophic hazard, its use shall comply with the design and quality requirements and best practices in NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware, sections 5.5 and 7.6 and Appendix C.

4.2.6.6.2 Silver-Plated Fasteners

Silver reacts rapidly with atomic oxygen to generate a loose, friable, black oxide that can cause contamination and affect the operation of mechanisms.

[MPR 202] Silver-plated fasteners shall not be used in external applications where the silver plating is directly exposed to atomic oxygen for a period longer than 2 weeks.

4.2.6.7 Contamination Control

Contamination, if not adequately anticipated and controlled, can result in loss of spacecraft, performance degradation, mission degradation, and/or loss or injury of flight crew. Examples of contamination sources and mechanisms include:

- *Particulate and molecular contamination from both ground processing and on-orbit migration may degrade the performance of optical devices, thermal control surfaces, and solar arrays.*
- *Particulate contamination accumulated during ground processing or generated during operations may interfere with mechanisms, bearings, and seals; may plug or restrict fluid orifices or filters; and may pose a hazard to the crew.*
- *Particulate and nonvolatile residues pose an ignition hazard within systems containing oxidizers, such as oxygen or nitrogen tetroxide. Cleaning agents intended to remove contaminants from these systems may leave reactive residues if not adequately controlled and removed.*
- *Microbial contamination within life support systems and ultrapure water systems may degrade these systems.*
- *Control of terrestrial microbial contamination and extraterrestrial material may be required in accordance with NASA Procedural Requirements (NPR) 8020.12 on Planetary Protection Provisions for Robotic Extraterrestrial Missions.*

a. [MPR 203] A Contamination Control Plan shall be generated in accordance with the guidelines of ASTM E1548 (2009), Standard Practice for Preparation of Aerospace Contamination Control Plans.

b. [MPR 204] The Contamination Control Plan shall include controls on contamination-sensitive manufacturing processes, such as adhesive bonding, controls on packaging for shipment and storage, and a foreign object damage/debris (FOD) prevention program.

c. [MPR 205] The FOD prevention program shall be established for all ground operations of mechanical and electrical systems of spaceflight hardware, including the design, development, manufacturing, assembly, repair, processing, testing, maintenance, operation, and checkout of the equipment to ensure the highest practical level of cleanliness.

d. [MPR 206] The FOD prevention program shall conform to NAS 412 (Revision 1), Foreign Object Damage/Foreign Object Debris (FOD) Prevention.

e. [MPR 207] Cleanliness levels for assembly- and subassembly-level hardware shall be identified on the engineering drawings.

4.2.6.8 Packaging

[MPR 208] Packaging shall protect spaceflight hardware from corrosion and contamination during shipping and storage.

4.3 Verification

[MPR 209] Verification of compliance with the requirements of this NASA Technical Standard shall consist of the following steps, as a minimum:

a. NASA approval of the contractor Materials and Processes Selection, Control, and Implementation Plan and other applicable materials data requirements documents, such as the Contamination Control Plan and NDE Plan.

b. Contractor M&P signature on engineering drawings to verify compliance with the requirements of this NASA Technical Standard or the Materials and Processes Selection, Control, and Implementation Plan.

c. NASA audits of contractor M&P activities relating to hardware design and manufacturing.

d. Establishment and operation of the M&P control panel in accordance with section 4.1.4 of this NASA Technical Standard.

e. NASA approval of MUAs.

f. NASA approval of MIULs.

Additional aspects of the verification process should be documented in the Materials and Processes Selection, Control, and Implementation Plan.

APPENDIX A

STANDARD MATERIALS AND PROCESSES REQUIREMENTS FOR SPACECRAFT

REQUIREMENTS COMPLIANCE MATRIX WITH REQUIREMENTS JUSTIFICATIONS

A.1 PURPOSE

NASA-STD-6016A defines the minimum requirements for Materials and Processes (M&P) and provides a general control specification for incorporation in NASA program/project hardware procurements and technical programs. Incorporating a general control specification provides procedural requirements for programmatic and M&P oversight to ensure that the M&P minimum requirements are implemented, controlled, and verified. These M&P minimum requirements are derived mostly from a history of successful use by NASA and the aerospace industry of best practices and lessons learned; their imposition better ensures uniformity, interoperability, a high likelihood of reliable hardware, and ultimately, mission success.

The purpose of this appendix is to provide the justification for each of the mandatory minimum requirements that are imposed by NASA-STD-6016A. Requirement (“shall”) statements indicate contractually binding requirements that have to be implemented and their implementation verified. In some cases, the justification is obvious in the requirement statement itself. In many others, the justification results from prior failures or successes with a material or a material process, i.e., lessons learned, or based on a best practice. The section/paragraph numbers and titles are also presented for easy reference. NASA-STD-6016A has a significant amount of italicized text that provides additional requirements-related guidance and information in many of the sections.

(Note: Enter “Yes” to describe the requirement’s applicability to the program or project; or enter “No” if the intent is to tailor and enter how tailoring is to be applied in the “Rationale” column.)

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
1.2a	Scope, Applicability	[MPR 1] Programs shall apply these controls to program/project hardware.	It is NASA policy to provide clear, concise, verifiable requirements for processes, products, and components; and it is NASA policy to track and implement requirements using requirements management and configuration management control processes.		
1.2b	Scope, Applicability	[MPR 2] Programs shall be responsible for demonstrating compliance with these requirements.	It is NASA policy to implement and track requirements.		
1.3a	Scope, Tailoring	[MPR 3] Tailoring of this NASA Technical Standard's requirements in the Materials and Processes Selection, Control, and Implementation Plan for specific programs/projects shall be formally documented as part of program or project requirements and approved by the responsible program/project NASA 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.	Requirements management processes require that M&P requirement modifications be tracked and approved by responsible and knowledgeable M&P personnel and program organizations.		
2.1.1	Applicable Documents, General	[MPR 4] The latest issuances of cited documents shall apply unless specific versions are designated.	Current NASA Office of the Chief Engineer policy is to include this statement in all NASA standards.		

NOTE: Per section 4.1.6: The use of M&P that do not comply with the technical requirements of this NASA Technical Standard may be acceptable in the actual hardware applications. MUAs are required for all M&P that are technically acceptable but do not meet the technical requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
2.1.2	Applicable Documents, General	[MPR 5] Non-use of specifically designated versions shall be approved by the delegated Technical Authority.	Current NASA Office of the Chief Engineer policy is to include this statement in all NASA standards.		
2.4.2	Applicable Documents, Order of Precedence	[MPR 6] Conflict between this NASA Technical Standard and other requirements documents shall be resolved by the delegated Technical Authority.	Current NASA Office of the Chief Engineer policy is to include this statement in all NASA standards.		
4a	Requirements	[MPR 7] Materials shall meet the worst-case useful-life requirements for the particular application.	Common sense requirement that materials used in an application be assessed for all of the environmental extremes that the materials will encounter during the life cycle.		
4b	Requirements	[MPR 8] M&P used in interfacing GSE, test equipment, hardware processing equipment, hardware packaging, and hardware shipment shall be controlled to prevent damage to or contamination of spaceflight hardware.	Ensures spaceflight hardware will not be damaged or contaminated by GSE, test equipment, or other M&P that comes in contact with the spaceflight hardware.		
4.1.1a	Materials and Processes Selection, Control, and Implementation Plan	[MPR 9] Each organization that is responsible for the design and fabrication of spaceflight hardware shall provide a Materials and Processes Selection, Control, and Implementation Plan.	The Materials and Processes Selection, Control, and Implementation Plan represents a best practice for implementing, controlling, and verifying that the M&P requirements of this NASA Technical Standard are imposed and tracked through the program/project/element life cycle.		
4.1.1b	Materials and Processes Selection, Control, and Implementation Plan	[MPR 10] The Materials and Processes Selection, Control, and Implementation Plan shall also describe the methods used to control compliance with these requirements by subcontractors and	The Materials and Processes Selection, Control, and Implementation Plan needs to provide to NASA insight into how the M&P requirements are imposed		

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		vendors.	and controlled at the subcontractor and vendor level.		
4.1.1c	Materials and Processes Selection, Control, and Implementation Plan	[MPR 11] Upon approval by the procuring activity, the Materials and Processes Selection, Control, and Implementation Plan shall become the M&P implementation document used for verification.	Since the Materials and Processes Selection, Control, and Implementation Plan contains the details of how a company implements and controls the requirements imposed by this NASA Technical Standard, it follows that the Plan is the document to be used to verify that the requirements have been met.		
4.1.1.1	Coordination, Approval, and Tracking	[MPR 12] The Materials and Processes Selection, Control, and Implementation Plan shall identify the method of coordinating, approving, and tracking all engineering drawings, engineering orders, and other documents that establish or modify materials and/or processes usage.	A process needs to be in place for coordinating, approving, and tracking all M&P usage and M&P changes. The Materials and Processes Selection, Control, and Implementation Plan is the logical place for such a process to be identified.		
4.1.1.2	Approval Signature	[MPR 13] The Materials and Processes Selection, Control, and Implementation Plan shall include a requirement that all hardware design drawings and revisions for spaceflight hardware that provides mission-critical functions contain an M&P approval block, or equivalent, to ensure that the design has been reviewed by the responsible M&P authority and complies with that document.	The M&P signature block on spaceflight hardware drawings ensures that M&P called out on drawings, and changes thereto, have been approved by M&P knowledgeable personnel.		
4.1.1.3	Manufacturing Planning	[MPR 14] The Materials and Processes Selection, Control, and Implementation Plan shall identify how the responsible	M&P expertise is required in the selection and processing of materials during manufacturing.		

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		M&P organization participates in manufacturing and inspection/verification planning to ensure compliance with M&P requirements.	How that expertise is applied and utilized needs to be described in the Materials and Processes Selection, Control, and Implementation Plan.		
4.1.2a	M&P Controls	[MPR 15] All M&P for spaceflight hardware that provides mission-critical functions shall be defined by standards and specifications selected from government, industry, and company specifications and standards.	Manufacturing spaceflight hardware to consensus, Government, or company M&P standards and specifications ensures reliable, repeatable, and trackable processes and spaceflight hardware. Manufacturing spaceflight hardware to standards and specifications has been a mandatory practice for a long time.		
4.1.2b	M&P Controls	[MPR 16] All M&P for spaceflight hardware that provides mission-critical functions shall be identified directly on the appropriate engineering drawing.	Identifying all M&P directly on the drawing ensures that the M&P usage has been reviewed and approved. It also ensures that manufacturing follows the correct M&P processes, and that hardware built to print is repeatable.		
4.1.2c	M&P Controls	[MPR 17] Company M&P specifications shall be identified by document number in the Materials and Processes Selection, Control, and Implementation Plan.	Ensures that NASA's oversight responsibility has complete insight into all of the M&P that will be used to manufacture the spaceflight hardware.		
4.1.2d	M&P Controls	[MPR 18] All M&P specifications used to produce spaceflight hardware that provides mission-critical functions shall be made available to the responsible NASA Program or Project Office and M&P organization.	NASA's oversight role of approving and verifying M&P usage on mission-critical spaceflight hardware requires that all standards and specifications be available for review.		

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4.1.2e	M&P Controls	[MPR 19] Process specifications for spaceflight hardware that provides mission-critical functions shall define process steps at a level of detail that ensures a repeatable/controlled process that produces a consistent and reliable product.	Necessary to ensure a consistent and reliable product.		
4.1.2f	M&P Controls	[MPR 20] Process qualification shall be conducted to demonstrate the repeatability of all processes for spaceflight hardware that provides mission-critical functions where the quality of the product cannot be directly verified by subsequent monitoring or measurement.	Necessary to ensure a consistent and reliable product.		
4.1.2.1	Standard and Specification Obsolescence	[MPR 21] A process shall be established for ensuring that updated, alternate, or new material or process standards or specifications from those identified in the Materials and Processes Selection, Control, and Implementation Plan meet or exceed the technical requirements identified in the original material or process standards or specifications.	The use of new material or material process standards or specifications in ongoing programs requires that the changes be reviewed and approved by the M&P and program authorities. A process for ensuring such a review and approval occurs needs to be identified in the Materials and Processes Selection, Control, and Implementation Plan. Also, engineering drawings do not call out company specifications by revision; so changes to such specifications can affect the repeatability of hardware built to print.		
4.1.3	Commercial Off-The-Shelf (COTS) Hardware	[MPR 22] A procedure shall be established to ensure that all vendor-	COTS hardware can present or contain unknown hazards unless the		

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		designed, off-the-shelf, and vendor-furnished items are covered by the M&P requirements of this document, with the exception that M&P requirements for off-the-shelf hardware and other spaceflight hardware that do not provide mission-critical functions may be limited to those required to ensure safety of flight (for example, flammability, toxic offgassing) and vehicle compatibility (for example, vacuum outgassing).	M&P used to manufacture such hardware meets the requirements of this NASA Technical Standard, or the COTS M&P usage is reviewed and approved by the responsible NASA M&P and program authorities. A process needs to be established to ensure that COTS hardware is properly reviewed.		
4.1.4a	M&P Control Panel	[MPR 23] An M&P control panel shall be established by each contractor hardware provider (excluding subcontractors).	Each hardware provider needs to establish a material control panel to provide quick M&P expertise, review, and approval for hardware manufacturing problems and M&P changes. In addition, the panel provides the NASA M&P oversight responsibility with insight into company M&P implementation and control issues.		
4.1.4b	M&P Control Panel	[MPR 24] The M&P control panel's scope and membership shall be described in the Materials and Processes Selection, Control, and Implementation Plan.	The NASA M&P oversight responsibility requires understanding of who and how the contractor implements and controls requirements.		
4.1.5a	M&P Usage Documentation	[MPR 25] M&P usage shall be documented in an electronic, searchable parts list or separate electronic searchable Materials Identification and Usage List (MIUL) with the following exceptions:	The MIUL is a best practice that has a long history of use in NASA that provides a quick, reliable, and easy review process for tracking and verifying M&P usage for both NASA and the contractors.		

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		(1) Electrical, electronic, and electromechanical (EEE) parts other than wire, cable, and exposed surfaces of connectors. (2) Materials used in hermetically sealed electronic containers (maximum leak rate less than 1 x 10^{-4} cm^3/sec).			
4.1.5b	M&P Usage Documentation	[MPR 26] The documentation of M&P usage shall cover the final design as delivered.	Common sense requirement that the end product reflects the actual M&P utilized in the as-built hardware (including M&P changes resulting from repairs to nonconforming hardware).		
4.1.5c	M&P Usage Documentation	[MPR 27] The documentation approach shall be defined in the Materials and Processes Selection, Control, and Implementation Plan.	Ensures documentation of M&P usage and allows organizations to use their own documentation system.		
4.1.6a	Material Usage Agreements (MUAs)	[MPR 28] MUAs containing sufficient information to demonstrate that the application is acceptable shall be submitted by the responsible M&P organization for all M&P that are technically acceptable but do not meet the requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.	The MUA process is a long used NASA M&P best practice that enables acceptance of materials and material processes that do not meet the requirements of this NASA Technical Standard but, through the MUA review process, are determined to be acceptable. The MUA process also provides the benefit of satisfactorily resolving design non-conformances at the engineering level as opposed to the program level.		

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4.1.6b	Material Usage Agreements (MUAs)	[MPR 29] MUAs shall not be used to change the M&P requirements for a nonconforming product.	The purpose of the MUA process is to justify the acceptance of specific material or material process design non-conformances, not the acceptance of a nonconforming product.		
4.1.7a	Materials Certification and Traceability	[MPR 30] All parts or materials for spaceflight hardware that provides mission-critical functions shall be certified as to composition, properties, and requirements as identified by the procuring document.	Ensures that consistent and reliable materials are used in spaceflight hardware and further ensures that materials and their properties can be repeated from program to program and from company to company.		
4.1.7b	Materials Certification and Traceability	[MPR 31] With the exception of off-the-shelf parts, parts and materials used in critical applications, such as life-limited materials and/or safety- and fracture-critical parts, shall be traceable through all processing steps defined in the engineering drawing to the end-item application.	M&P traceability to the end item of critical parts ensures that each processing step was accomplished and that a processing record exists which often aids in understanding a problem or failure.		
4.1.7c	Materials Certification and Traceability	[MPR 32] Distributors or other processors shall not heat treat, hot work, or cold work metal stock unless they take the responsibilities as the producer of the metal and produce a new certification.	Required to control procurement of raw metallic materials. The processing changes the material properties and invalidates the original vendor's certification.		
4.1.8.1a	Requirements for Design Values	[MPR 33] A, B, or S-basis statistical values for mechanical properties of materials shall be utilized for the design and analysis of hardware for all applications where structural analysis is required.	To ensure structural integrity of spacecraft parts and structures, materials with statistically based minimum mechanical properties are required.		

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4.1.8.1b	Requirements for Design Values	[MPR 34] The sampling for other mechanical properties, such as dynamic properties like fatigue and fracture, and verification of design values shall be representative of the material, product form, and state used in the design.	Needed to ensure design values for other required mechanical properties are representative of the material, product form, and state used in the design.		
4.1.8.1c	Requirements for Design Values	[MPR 35] A, B, or S-basis statistical methods shall be defined by, and values for mechanical properties in their design environment taken from MMPDS, Metallic Materials Properties Development and Standardization, or SAE CMH-17, Composite Materials Handbook.	The handbooks imposed here have long been NASA's and the aerospace industries' most trusted and reliable sources of statistically derived mechanical design properties. MMPDS is the replacement for the old MIL-HDBK-5 and SAE CMH-17 is the replacement for the old MIL-HDBK-17.		
4.1.8.1d	Requirements for Design Values	[MPR 36] For metallic materials, the alloy, heat treatment, product specification, product form, and thickness shall match the alloy, heat treatment, product specification, product form, and thickness in MMPDS.	Since the testing to develop design values is specific to alloy, heat treatment, specification and form, the statistical relationship is relevant only to that same combination. Thickness affects strength of metal because of metallurgical factors that influence strength, like heat transfer during heat treatment and variability of reduction during metal working. This requirement is stated in MMPDS but frequently ignored.		
4.1.8.1e	Requirements for Design Values	[MPR 37] When statistical design values for new or existing structural materials are not available, they shall be determined	The statistical methods used in these handbooks are the NASA- and aerospace industry-accepted		

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		by methods described in MMPDS or SAE CMH-17 and a report documenting the derivation of the new design values be made available to NASA for review.	standard for determining mechanical design properties.		
4.1.8.1f	Requirements for Design Values	[MPR 38] The implementation of an approach for generating statistical design values that deviates from the sampling methodology and statistical methods in MMPDS or SAE CMH-17 and the use of design values that deviate from those published in MMPDS or SAE CMH-17 shall be approved with an MUA.	Not all materials, product forms, and sizes are available in the cited handbooks. Development of design values by the analytical methods described in MMPDS or SAE CMH-17 is sometimes prohibitively expensive for the application. When the test approach deviates from the published values in MMPDS or the guidance in SAE CMH-17, the MUA review process by responsible and competent M&P engineering personnel assures that acceptable minimum design properties will be derived and verified.		
4.1.8.1g	Requirements for Design Values	[MPR 39] All contractor-developed mechanical and physical property data shall be made available to the responsible NASA M&P organization.	NASA needs to have the capability to verify that contractor-developed mechanical and physical property data have been developed adequately and determine when an MUA is required per 4.1.8.1 g. NASA recognizes that such data may be proprietary and that the contractor can place limitations on how the data are made available.		
4.1.8.2a	Design Value Implementation in Design	[MPR 40] Material "B" design values shall not be used except in redundant structure in which the failure of a	"B" design values are designed for use in redundant structure. They have a less statistically significant		

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		component would result in a safe redistribution of applied loads to other load-carrying members.	minimum design value than “A” design values and are, therefore, less reliable and not to be used in single load path critical structure.		
4.1.8.2b	Design Value Implementation in Design	[MPR 41] Minimum property acceptance values in material specifications (specification minimums) not explicitly published as “S” design values in MMPDS shall require an approved MUA for use as design values.	Not all materials, product forms, and sizes are available in the cited handbooks. In some cases, specification minimums or “S” design values published in other sources are not properly derived in accordance with MMPDS. Therefore, the MUA review process by responsible and competent M&P engineering personnel assures that acceptable minimum design properties will be derived and verified.		
4.1.8.3	Structural Fastener Design Values	[MPR 42] Structural fastener design values shall be defined by minimum load test requirements in the applicable part and/or procurement specification (government, aerospace industry consensus, company-specific, or custom specification).	MMPDS design values are not transferrable to fasteners, because raw material used to make fasteners is reprocessed using various metallurgical practices, such as hot heading, thread rolling, and heat treating. These processes change the strength of the metal from the original bar stock. NASA has chosen to adopt lot tested design strength defined in the specific fastener part and procurement specifications as the design value instead of the certifications of the original bar stock.		

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4.2.1	Flammability, Offgassing, and Compatibility Requirements	[MPR 43] Materials shall meet the requirements of NASA-STD-6001B, Flammability, Offgassing, and Compatibility Requirements and Test Procedures, as described below.	Ensures that the NASA-required tests and evaluations of materials for flammability, offgassing, and compatibility are imposed.		
4.2.1.1	Flammability Control	[MPR 44] Materials that are nonflammable or self-extinguishing in their use configuration as defined by NASA-STD-6001B, Test 1 or an appropriate configurational flammability test per NASA-STD-6001B, shall be used for flammability control with the following exceptions: a. Ceramics, metal oxides, and inorganic glasses are exempt. b. Materials that are designed to ignite and burn in their use application (for example, pyrotechnic materials) are exempted from flammability requirements, provided that systems/experiments using such materials are designed so that the burning materials cannot act as an ignition source for other hardware. c. Materials used in minor quantities (dimensions controlled so the potential fire propagation path is less than 15 linear cm (6 linear in) and the surface area is no more than 80 cm^2 (12 square in)) in crew environments and 30 linear cm (12 linear	The lessons learned from the Apollo 1 fire regarding the use of flammable materials in an oxygen-rich environment makes it mandatory that special control and testing be exercised by M&P engineering to ensure that flammable materials are minimized and controlled in spacecraft environments.		

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		in) for external materials) with no propagation path or ignition source. d. Materials used in sealed containers are exempt because insufficient oxygen is available to maintain combustion. e. Materials within vented electronics packages with metallic cases and no forced air convection are exempt because of the self-extinguishing effect of expanding combustion gases in a constrained volume. f. Materials that have been shown by test to meet the requirements of NASA-STD-6001B may be used in an environment with an oxygen concentration lower than the test level without further testing (provided that the oxygen partial pressure is no greater than the partial pressure at the test level or general test data exist to demonstrate that the higher oxygen partial pressure is outweighed by the lower percentage concentration for the environments in question). g. Materials are acceptable when used on a metal substrate that provides an adequate heat sink. A heat sink is considered adequate in the use configuration by test or analysis. When			

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		testing is conducted, materials passing the flammability test on a metal substrate are acceptable on metal substrates of the same thickness or greater. Materials that are flammable but have a thickness less than 0.25 mm (0.010 in) and are attached to a metallic surface greater than 1.6 mm (0.062 in) thick are acceptable by analysis. h. Materials are unexposed, overcoated with a verified fire-blocking material, or no more than 1/4 inch thick and sandwiched between nonflammable materials with only the edges exposed. i. Flammability configuration analysis in accordance with JSC 29353 shows hardware configuration to be self-extinguishing.			
4.2.1.2a	Toxic Offgassing	[MPR 45] All nonmetallic materials used in habitable flight compartments, with the exception of ceramics, metal oxides, inorganic glasses, and materials used in sealed container (maximum leak rate less than 1 x 10^{-4} cm^3/sec), shall meet the offgassing requirements of Test 7 of NASA-STD-6001B.	All materials offgas small quantities of trace gas contaminants. Materials that release toxic gases must be controlled in closed spacecraft-habitable compartments. The required testing ensures that the materials used are safe from a toxicity standpoint.		
4.2.1.2b	Toxic Offgassing	[MPR 46] Spacecraft maximum allowable concentration (SMAC) values shall be obtained from JSC 20584 (2008), Spacecraft Maximum Allowable Concentrations for Airborne	Industrial maximum concentrations of airborne contaminants are based on an 8-hour workday exposure and are not appropriate for the continuous exposure that applies in		

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		Contaminants, or from MAPTIS for compounds for which no SMAC values are found in JSC 20584.	spacecraft environments. The SMAC values in JSC 20584 are set by the NASA/JSC Toxicology Group in cooperation with the National Research Council Committee on Toxicology. Supplementary values in MAPTIS are set by the NASA/JSC Toxicology Group only for evaluation of offgassing test data.		
4.2.1.3a	Fluid Compatibility (Fluids Other Than Oxygen)	[MPR 47] An MUA shall be written rationalizing the selection of materials if any of the following conditions apply: (1) If a material is exposed directly to a hazardous fluid[1]. (2) If a material is exposed directly to a hazardous fluid vapor. (3) If a material is exposed to a hazardous fluid liquid or a vapor by failure of a single barrier seal. (4) If a material is exposed to a hazardous fluid liquid or a vapor by leakage or permeation through a single or multiple seals. [1] For the purpose of this NASA Technical Standard, the definition of hazardous fluids includes gaseous oxygen (GOX), liquid oxygen (LOX), fuels, oxidizers, and other fluids that are critical or catastrophic hazards due to chemical or physical degradation of the materials in the system, corrosion (with the exception of general corrosion covered by NASA-STD-6012), or cause an exothermic reaction.	It is necessary to ensure that materials are compatible with the hazardous fluids with which they are in contact or will come in contact. An MUA is required to document the rationale for accepting the materials.		
4.2.1.3b	Fluid Compatibility	[MPR 48] Appropriate long-term tests to	Since some incompatible		

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	(Fluids Other Than Oxygen)	simulate the worst-case use environment and operational conditions that would enhance reactions or degradation shall be conducted for materials with long-term exposure to liquid fuels, oxidizers, and other hazardous liquids.	material/fluid combinations only manifest themselves after long-term exposure, it is necessary to conduct long-term exposure testing.		
4.2.1.3c	Fluid Compatibility (Fluids Other Than Oxygen)	[MPR 49] Materials degradation in long-term tests shall be characterized by post-test analyses of the material and fluid to determine the extent of changes in chemical and physical characteristics, including mechanical properties.	To determine in long- or short-term tests if material degradation has occurred, post-test analyses must be performed to determine, e.g., if mechanical properties have changed or if unacceptable levels of the test material have been dissolved into the test fluid.		
4.2.1.3d	Fluid Compatibility (Fluids Other Than Oxygen)	[MPR 50] The effect of material condition (for example, parent versus weld metal or heat-affected zone) shall be addressed in the compatibility determination.	It has long been known that a material’s condition, such as a weld, its heat-affected zone, and the parent metal, can have significantly different outcomes in corrosion/compatibility testing which needs to be addressed when determining compatibility and any necessary testing.		
4.2.1.3e	Fluid Compatibility (Fluids Other Than Oxygen)	[MPR 210] Materials used in nitrogen tetroxide systems shall be evaluated for flammability in nitrogen tetroxide using promoted combustion tests similar to NASA-STD-6001B, Test 17, for metallic materials used in oxygen systems and Test 1 for polymeric materials.	Nitrogen tetroxide is a powerful oxidizer, and flight hardware failures have been caused by ignition of metallic materials (notably titanium).		
4.2.1.3(1)	Fluid Compatibility (Fluids Other Than	[MPR 211] When materials are determined to be flammable, a nitrogen	The rigorous Oxygen Compatibility Assessment (OCA) methodology		

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	Oxygen)	tetroxide compatibility assessment shall be conducted using the methodology described for oxygen systems in NASA-STD-6001B and the system safety rationale of this assessment documented in an MUA.	described in NASA-STD-6001 for evaluating potential materials ignition in oxygen systems is also the most effective methodology for evaluating ignition in nitrogen tetroxide systems.		
4.2.1.3f	Fluid Compatibility (Fluids Other Than Oxygen)	[MPR 212] Materials used in other oxidizer systems shall be evaluated for potential ignition.	The possibility of similar ignition issues occurring in systems containing oxidizers other than oxygen and nitrogen tetroxide needs to be addressed.		
4.2.1.4a	Oxygen Compatibility	[MPR 51] Materials and components, and systems used in liquid oxygen (LOX) and gaseous oxygen (GOX) environments, compressed air systems, and pressurized systems containing enriched oxygen shall be evaluated for oxygen compatibility in accordance with NASA-STD-6001B.	Because of the highly reactive nature of oxygen with metals and nonmetals, it is necessary that all materials that are in contact with or will come in contact with oxygen must be evaluated for compatibility with oxygen. NASA-STD-6001B governs how such evaluation is to be accomplished.		
4.2.1.4b	Oxygen Compatibility	[MPR 52] When materials in such systems are determined to be flammable, an oxygen compatibility assessment shall be conducted as described in NASA-STD-6001B and the system safety rationale of this assessment documented in an MUA.	Materials are commonly found to be flammable in standard flammability tests but can often be found not to be a flammability hazard in their use configuration. Such a determination is made by conducting an oxygen compatibility assessment and documenting the acceptance rationale in an MUA.		
4.2.1.4.1	Oxygen Component Acceptance Test	[MPR 53] GOX and enriched air system components that operate at pressures above 1.83 MPa (265 psia), with the exception of metallic components, such as	Ensures that material surfaces that can react with oxygen at relatively high pressures have been thoroughly exposed and		

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		hard lines (rigid metallic tubing), metallic flex hoses, metallic fluid fitting with all metal seals, and metallic pressure vessels (including composite overwrapped pressure vessels with metallic liners), shall undergo oxygen component acceptance testing for a minimum of ten cycles from ambient pressure to maximum design pressure within 100 milliseconds to ensure that all oxygen system spaceflight hardware is exposed to oxygen prior to launch.	conditioned to the system oxygen pressure and will be nonreactive to oxygen during use.		
4.2.1.5a	Electrical Wire Insulation Materials	[MPR 54] Electrical wire insulation materials shall be evaluated for flammability in accordance with NASA-STD-6001B, Test 4 or Test 1.	The lessons learned from the Apollo 1 fire and the Apollo 13 oxygen tank explosion make it imperative that the flammability of wire insulation be evaluated. NASA-STD-6001 specifies how to conduct such tests.		
4.2.1.5b	Electrical Wire Insulation Materials	[MPR 55] Arc tracking shall be evaluated in accordance with NASA-STD-6001B, Test 18, for all wire insulation constructions except polytetrafluoroethylene (PTFE), PTFE/polyimide insulation conforming to SAE AS22759C, Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy, and used in conditions bounded by the dry arc-tracking test specified by SAE AS22759C, ethylene tetrafluoroethylene (ETFE), and silicone-insulated wires (the resistance of these materials to arc tracking has already been	Since arc tracking is a problem that is due to a breakdown of a wire's insulating material that results in uncontrolled arcing to other wires and components, it is necessary to test wire insulating materials for their susceptibility to arc tracking.		

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		established).			
4.2.2	Metals	[MPR 56] MSFC-STD-3029A, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments, shall be used to select metallic materials to control stress corrosion cracking of metallic materials in sea and air environments, with the exception that an MUA is not required for the following conditions: a. Parts in electrical/electronic assemblies with maximum tensile stress less than 50 percent of the yield strength. b. Martensitic or precipitation-hardening (PH) stainless steels used in ball bearing or similar applications where the loading is compressive. c. Carbon and low alloy high-strength steels with strength greater than 1240 MPa (180 ksi) used in ball bearings, springs, or similar applications where the loading is compressive and there is a history of satisfactory performance. d. Hardware provides no mission-critical functions	Stress corrosion cracking in seacoast and air environments is a potential problem for the high-strength alloys typically used in spacecraft structures. MSFC-STD-3029 provides data on the stress-corrosion sensitivity of most structural alloys and contains requirements to eliminate the potential for stress-corrosion cracking when stress-corrosion-sensitive materials are used. The standard also contains test methods for evaluating stress-corrosion sensitivity of alloys without existing data and defines stress corrosion cracking threshold values for many of the alloys used in spacecraft structures.		
4.2.2.1	Aluminum	[MPR 57] The 5000-series alloys containing more than 3 percent magnesium shall not be used in	Under certain conditions, an intergranular aluminum-magnesium grain boundary precipitate can		

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		spaceflight hardware that provides mission-critical functions where the temperature exceeds 66 °C (150 °F).	occur rendering such alloys susceptible to exfoliation corrosion or stress corrosion.		
4.2.2.2.1a	Drilling and Grinding of High-Strength Steel	[MPR 58] When drilling, grinding, reaming, or machining is performed on high-strength steels that can form martensite and are used in spaceflight hardware that provides mission-critical functions, a validated process for machining shall be used.	A well-known lesson learned is that some metal removal processes, particularly aggressive ones, cause surface overheating in high-strength steels that produces the undesirable crack-prone condition of untempered martensite.		
4.2.2.2.1b	Drilling and Grinding of High Strength Steel	[MPR 59] The absence of machining damage for high-strength steels used in spaceflight hardware that provides mission-critical functions shall be verified by microexamination of production parts (such as Nital etch inspection) or by a microhardness and metallurgical examination of sample parts for either of the following situations: (1) When the material has very low toughness (such as martensitic steel above 200 ksi) and the part has low stress margins or is fatigue driven. (2) When the surface condition of the part is critical to the design (such as its ability to withstand hertzian stresses or remain perfectly flat).	Tests and examinations cited are best practices for identifying the presence of untempered martensite.		
4.2.2.2.2a	Corrosion-Resistant Steel	[MPR 60] Unstabilized, austenitic steels shall not be processed or used above 371 °C (700 °F) in spaceflight hardware that	Eliminates the potential of a corrosion-susceptible condition due to grain boundary precipitation of		

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		provides mission-critical functions.	chromium carbide.		
4.2.2.2.2b	Corrosion-Resistant Steel	[MPR 61] Welded assemblies used in spaceflight hardware that provides mission-critical functions shall be solution heat-treated and quenched after welding except for the stabilized or low carbon grades, such as 321, 347, 316L, and 304L.	Eliminates the potential of a corrosion-susceptible condition of weld heat-affected zone grain boundary precipitation of chromium carbide.		
4.2.2.2.2c	Corrosion-Resistant Steel	[MPR 62] Service-related corrosion issues are common for free-machining alloys, such as 303, and these alloys shall not be used in spaceflight hardware that provides mission-critical functions when they can be exposed to moisture other than transient condensation, or to nitrogen tetroxide	Eliminates the exposure of the more corrosion-susceptible stainless steel alloys to moisture or to nitrogen tetroxide, for which corrosion of these alloys has also been observed.		
4.2.2.2.3	Ductile-Brittle Transition Temperature	[MPR 63] Steels shall not be used in tension below their ductile-brittle transition temperature.	Prevents the use of alloys that are too impact- and crack-sensitive and prone to unexpected failure at low temperature.		
4.2.2.3.1a	Titanium Contamination	[MPR 64] All cleaning fluids and other chemicals used during manufacturing and processing of titanium hardware for spaceflight hardware that provides mission-critical functions shall be verified to be compatible and not detrimental to performance before use.	An Apollo Program lesson learned occurred when a titanium pressure vessel failed due to stress corrosion in anhydrous methanol that was used as a substitute pressurant for Aerozine-50 in a ground test. Methanol, a commonly used solvent for cleaning metals, was considered benign to titanium.		
4.2.2.3.1b	Titanium Contamination	[MPR 65] The surfaces of titanium and titanium alloy mill products used for spaceflight hardware that provides mission-critical functions shall be 100	A lesson learned from a titanium pressure vessel that was severely cracked from an alpha case that formed during heat treatment.		

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		percent machined, chemically milled, or pickled to a sufficient depth to remove all contaminated zones and layers formed while the material was at elevated temperature.			
4.2.2.3.2	Titanium Wear	[MPR 66] All regions of titanium alloys for spaceflight hardware that provides mission-critical functions that are subject to fretting or wear shall be anodized per SAE AMS2488D, Anodic Treatment – Titanium and Titanium Alloys Solution, pH 13 or Higher, or hard-coated utilizing a wear-resistance material, such as tungsten carbide/cobalt thermal spray.	Since titanium is subject to wear and fretting which can lead to crack initiation, it is necessary to harden the titanium surfaces by anodizing per the cited specification or per a hard-coating process.		
4.2.2.3.3a	Titanium Flammability	[MPR 67] Titanium alloys shall not be used with LOX or GOX at any pressure or with air at oxygen partial pressures above 35 kPa (5 psia).	Titanium is highly flammable in oxygen-rich environments, and its use in such environments must be avoided.		
4.2.2.3.3b	Titanium Flammability	[MPR 68] Titanium alloys shall not be machined inside spacecraft modules during ground processing or in flight, because machining operations can ignite titanium turnings and cause fire.	Because of titanium's sensitivity to ignition in oxygen-containing environments, fine turnings and particles with large surface areas from machining and grinding processes can even ignite in air. Obviously, such fires in a spacecraft must be prevented.		
4.2.2.4a	Magnesium	[MPR 69] Magnesium alloys shall not be used in primary structure or in other areas of spaceflight hardware that provides mission-critical functions that are subject to wear, abuse, foreign object damage,	Magnesium's low strength and hardness renders it relatively sensitive to mechanical damage and abuse and is relatively corrosion sensitive. Therefore, its use in		

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		abrasion, erosion, or where fluid or moisture entrapment is possible.	primary structure needs to be avoided.		
4.2.2.4b	Magnesium	[MPR 70] Magnesium alloys shall not be machined inside spacecraft modules during ground processing or in flight, because machining operations can ignite magnesium turnings and cause fire.	Magnesium can be ignited in air at room temperature from machining operations. Obviously, such fires in a spacecraft must be prevented.		
4.2.2.5a	Beryllium	[MPR 71] Alloys containing more than 4 percent beryllium by weight shall not be used for primary structural applications.	Beryllium alloys have an inherent low ductility and brittle nature, and their use in primary structure needs to be avoided.		
4.2.2.5b	Beryllium	[MPR 72] Alloys containing more than 4 percent beryllium by weight shall not be used for any application within spacecraft crew compartments unless suitably protected to prevent erosion or formation of salts or oxides.	Beryllium containing alloys, even those containing as little as 4 percent beryllium, present a problem in that oxides and salts of beryllium are highly toxic and the use thereof requires that the metal be protected from abrasion or conditions that could form beryllium particles, beryllium oxides, or salts.		
4.2.2.5c	Beryllium	[MPR 73] Design of beryllium parts for spaceflight hardware that provides mission-critical functions shall address its low-impact resistance and notch sensitivity, particularly at low temperatures, and its directional material properties (anisotropy) and sensitivity to surface finish requirements.	When beryllium is required to be used in mission-critical spaceflight hardware, it is important that the low ductility and brittle nature of beryllium be critically reviewed. When analyzing the stress state in beryllium, it is important to recognize the low Poisson's Ratio of beryllium. This low Poisson's Ratio can lead to very high stresses.		
4.2.2.5d	Beryllium	[MPR 74] All beryllium parts used in spaceflight hardware that provides	When beryllium is required to be used in mission-critical hardware,		

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		mission-critical functions shall be processed to ensure complete removal of the damaged layer (twins and microcracks) produced by surface-metal-working operations, such as machining and grinding.	the detrimental surface damage that occurs in beryllium from mechanical metal removal methods, such as machining and grinding, must be removed. The damage removal must be by chemical etch to remove the surface damage. The technique of removing successively shallower cuts will reduce the depth of the damage but will never completely eliminate the damage. The nature of the damage is a crystal twinning in the grains which pins dislocations and subsequently reduces material ductility.		
4.2.2.5e	Beryllium	[MPR 75] Beryllium-containing alloys (including alloys containing less than 4 percent beryllium by weight) and oxides of beryllium shall not be machined inside spacecraft crew compartments at any stage of manufacturing, assembly, testing, modification, or operation.	Due to the highly toxic nature of beryllium dust and oxides formed during machining or grinding, such operations must be highly controlled and never allowed to occur in spacecraft crew compartments.		
4.2.2.5f	Beryllium	[MPR 76] All beryllium parts used in spaceflight hardware that provides mission-critical functions shall be penetrant-inspected for crack-like flaws with a high-sensitivity fluorescent dye penetrant in accordance with section 4.2.5.	Ensures that the crack-sensitive beryllium parts are crack free.		
4.2.2.6a	Cadmium	[MPR 77] Cadmium shall not be used in crew or vacuum environments.	Because of its toxic nature and relatively high vapor pressure, the use of cadmium in spacecraft crew compartments and in the space		

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			vacuum environment needs to be prevented.		
4.2.2.6b	Cadmium	[MPR 78] Cadmium-plated tools and other hardware shall not be used in the manufacture or testing of spaceflight hardware that provides mission-critical functions.	Cadmium is relatively soft and could be readily transferred to spacecraft parts through contact between the parts and cadmium-plated tools. Therefore, the use of such tools must be prevented.		
4.2.2.7	Zinc	[MPR 79] Owing to zinc’s ability to grow whiskers, zinc plating other than black zinc-nickel plating shall not be used in spaceflight hardware that provides mission-critical functions.	The use of zinc-plated parts in spaceflight hardware needs to be prevented because zinc has a tendency to grow whiskers that cause electrical shorts and are also a source of contamination. Zinc also has a relatively high vapor pressure and, in the vacuum of space, it presents the risk of volatilizing and redepositing on critical surfaces.		
4.2.2.8a	Mercury	[MPR 80] Equipment containing mercury shall not be used where the mercury could come in contact with spaceflight equipment during manufacturing, assembly, test, checkout, and flight.	Mercury in contact with some metals can result in severe embrittlement; therefore, such contact must be prevented.		
4.2.2.8b	Mercury	[MPR 81] Spaceflight hardware (including fluorescent lamps) containing mercury shall have three levels of containment to prevent mercury leakage.	Because of the high toxicity of mercury vapor and liquid mercury’s potential for causing embrittlement of other metals, its safe containment in a spacecraft environment must be extraordinarily redundant.		
4.2.2.9	Refractory Metals	[MPR 82] For refractory alloys (alloys with a melting point above 2000 °C (3600	Refractory metals are used in high-temperature applications where the		

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		°F), plus osmium and iridium) used in mission-critical applications, tests shall be performed to characterize critical design properties for the intended application and the data documented in an MUA.	material properties at the intended use-temperature are lacking or limited. Testing must be performed to obtain the necessary design properties for the application. Documentation of the design properties is also required.		
4.2.2.10a	Superalloys (Nickel-Based and Cobalt-Based)	[MPR 83] High-nickel content alloys are susceptible to sulfur embrittlement; therefore, for spaceflight hardware that provides mission-critical functions, any foreign material which could contain sulfur, such as oils, grease, and cutting lubricants, shall be removed by suitable means prior to heat treatment, welding, or high temperature service.	Since superalloys are susceptible to sulfur embrittlement from contact with sulfur containing materials at elevated temperatures, it is mandatory that such materials be removed from the surface of the superalloys before they are exposed to high temperatures.		
4.2.2.10b	Superalloys (Nickel-Based and Cobalt-Based)	[MPR 84] The reduction to design properties of alloying element depletion at the surface in a high temperature, oxidizing environment shall be evaluated when a thin sheet of one of these alloys is used for spaceflight hardware that provides mission-critical functions, since a slight amount of depletion could involve a considerable proportion of the effective cross section of the material.	Since superalloys experience alloy depletion at elevated temperatures, it is mandatory that the depth of such depletion on a superalloy's design properties be assessed, particularly in the case of thin sheets.		
4.2.2.11a	Tin	[MPR 85] For spaceflight hardware that provides mission-critical functions, tin and tin plating shall be alloyed with at least 3 percent lead by weight or other proven alloying element(s) to prevent tin whisker growth.	Self-explanatory, in that 3 percent lead in tin and tin plating is necessary to prevent tin-whisker growth. Several other alloying elements in tin and tin plating have also been shown to prevent tin whiskers.		

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4.2.2.11b	Tin	[MPR 86] Tin and tin plating alloyed with less than 3 percent lead by weight and used in electrical/electronic applications shall comply with GEIA-STD-0005-1A, Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-Free Solder, and Control Level 2C requirements of GEIA-STD-0005-2A, Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems, with the following exceptions: (1) Solder alloy Sn96.3Ag3.7 (Sn96) used for high-temperature applications. (2) Solder alloy Au80Sn20 used as a die attach material or as a package sealing material. (3) Tin alloys containing less than 20 percent tin by weight.	Since the cited standards specifically address how to mitigate the tin whisker problems for tin and tin-plating containing less than 3 percent lead, it is necessary that they be used for applications that use tin and tin-plating with less than 3 percent lead.		
4.2.2.11c	Tin	[MPR 87] When high-purity tin and tin plating are used for spaceflight hardware that provides mission-critical functions and will also be exposed to temperatures below 13 ˚C for periods longer than 6 months, the method for preventing tin pest formation shall be documented in the materials control plan.	Since tin pest is a problem that results from tin and tin plating being exposed to a low temperature for a long period of time (as can occur for spacecraft external materials), it is necessary to address how the tin pest problem will be controlled. Tin pest has been observed on ISS external hardware.		
4.2.2.11d	Tin	[MPR 88] Tin plating shall not be used for contacts in electrical interconnects (connectors, sockets, switches, etc.) for	Because of the many problems that have been encountered with tin plating, such as oxidation, wear,		

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		spaceflight hardware that provides mission-critical functions.	fretting, and whiskers, it is necessary to limit the use of tin plating in spaceflight hardware unless the potential problems are suitably mitigated and its use approved through an MUA review process.		
4.2.3.1a	Elastomeric Materials	[MPR 89] Elastomeric materials used in spaceflight hardware that provides mission-critical functions shall be selected to operate within design parameters for the useful life of the hardware.	Since elastomers have age-life limitations, it is necessary to select elastomeric materials that can function and endure the space environment for the expected life of the hardware.		
4.2.3.1b	Elastomeric Materials	[MPR 90] Elastomeric materials used in spaceflight hardware that provides mission-critical functions, other than those used in off-the-shelf parts, such as cable clamps, shall be cure-dated for tracking purposes.	The age-life of elastomers begin when they are cured; therefore, because of age-life limitations, their cure dates need to be recorded so the ages of the elastomers can be tracked.		
4.2.3.1c	Elastomeric Materials	[MPR 91] Room temperature vulcanizing (RTV) silicones that liberate acetic acid during cure shall not be used because they can cause corrosion.	Requirement justifies itself, in that the release of a corrosive acid is unacceptable.		
4.2.3.1d	Elastomeric Materials	[MPR 92] When rubbers or elastomers are used at low temperatures in spaceflight hardware that provides mission-critical functions, the ability of these materials to maintain and provide required elastomeric properties shall be verified.	The lesson learned from the Challenger O-ring failure due to its inelastic behavior at a moderately cold temperature strongly emphasizes the need to verify the low temperature elastic properties of rubbers and elastomers. Fluorocarbon elastomers are particularly susceptible to embrittlement.		

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4.2.3.2	Polyvinyl Chloride	[MPR 93] Use of polyvinyl chloride on spaceflight hardware shall be limited to applications in pressurized areas where temperatures do not exceed 49 °C (120 °F).	Polyvinyl chloride (PVC) cannot be used in space vacuum because it contains large quantities of plasticizers that outgas in space vacuum, making the PVC brittle and acting as a source of contamination. PVC also offgasses excessively above 120 ºF, so its use in hardware that experiences such temperatures must be restricted. PVC is flammable in spacecraft cabin environments, and its use is subject to the same controls as other flammable materials.		
4.2.3.5	Limited-Life Items	[MPR 94] All materials shall be selected to meet the useful life of the hardware with no maintenance or be identified as limited-life items requiring maintainability.	If a material cannot meet the useful life requirements of the hardware of which it is a part, then it must be identified as having limited-life and a maintenance plan identified to address its limited-life.		
4.2.3.6a	Thermal Vacuum Stability	[MPR 95] Nonmetallic materials that are exposed to space vacuum, with the exception of ceramics, metal oxides, inorganic glasses, and cetyl alcohol lubricants used on fasteners outside closed compartments, shall be tested using the technique of ASTM E595-15, Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment, with acceptance criteria as follows:	Since nonmetallic materials outgas in the vacuum of space, it is necessary to quantify the nature and amount of outgassing that can occur. ASTM E595 is the consensus standard for conducting such tests and quantifying mass loss and CVCM. The traditional ≤1.0 percent total mass loss (TML) spacecraft requirement is relaxed in this standard. Vacuum outgassing		

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		(1) ≤0.1 percent collected volatile condensable materials (CVCM). (2) ≤1.0 percent total mass loss (TML) less water vapor recovery (WVR), except that a higher mass loss is permitted if this mass loss has no effect on the functionality of the material itself and no effect on the functionality of any materials, components, or systems that could be adversely affected by the subject mass loss.	causes contamination only from condensable materials and the TML is unimportant except in special cases where cryogenic surfaces are present and in cases where the mass loss causes unacceptable degradation of the material. The vast majority of materials with a TML ≤5 percent are acceptable for normal spacecraft applications, provided the ≤0.1 percent CVCM requirement is met.		
4.2.3.6b	Thermal Vacuum Stability	[MPR 96] With the following exceptions, hardware items (components, assemblies, etc.) containing materials that fail the CVCM requirement and/or having unidentified materials shall be vacuum baked at the maximum tolerable temperature of the component, 10 ºC above the maximum predicted operating temperature, or an alternate temperature selected by the program/project, to meet the program/project acceptance outgassing criteria: (1) Materials that are not near a critical surface and have a CVCM between 0.1 and 1.0 percent and an exposed surface area less than 13 cm^2 (2 in^2) are exempt. (2) Materials with an exposed	Since vacuum baking can sufficiently outgas materials that fail the CVCM requirements established by this NASA Technical Standard, it is necessary to vacuum bake hardware items that contain materials that do not meet the CVCM requirements.		

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		surface area less than 1.6 cm^2 (0.25 in^2) are exempt. (3) Materials that are unexposed, overcoated, or encapsulated with approved materials are exempt. (4) Materials enclosed in a sealed container (maximum leak rate less than 1 x 10^{-4} cm^3/sec) are exempt.			
4.2.3.7	External Environment Survivability	[MPR 97] The critical properties of materials exposed in the spacecraft external environment shall meet operational requirements for their intended life-cycle exposure.	The spacecraft external environment includes ultraviolet radiation, atomic oxygen in low-Earth orbit, plasma, and high-energy radiation, all of which can cause materials degradation. For example, ultraviolet radiation causes darkening of many materials, leading to loss of thermal control, and atomic oxygen erodes most polymeric materials, causing physical degradation. Since repair capabilities are very limited or nonexistent, it is imperative that materials so exposed meet their operational life cycle.		
4.2.3.8	Fungus Resistance	[MPR 98] Materials that are non-nutrient to fungi, as identified in MIL-HDBK-454B, General Guidelines for Electronic Equipment, Requirement 4, Fungus-Inert Materials, Table 4-I, Group I, shall be used in launch vehicles and pressurized	Materials that resist the growth of fungus are required in launch vehicles that are exposed to weather environments and in pressurized habitable compartments. The requirement statement identifies		

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		flight compartments, except when one of the following criteria is met: a. Materials have been tested to demonstrate acceptability per MIL-STD-810G, Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests, Method 508. b. Materials are used in crew areas where fungus would be visible and easily removed. c. Materials are used inside sealed containers (maximum leak rate less than 1 x 10^{-4} cm^3/sec) with internal container humidity less than 60 percent relative humidity (RH) at ambient conditions. d. Materials are used inside electrical boxes where the temperature is always greater than or equal to the ambient cabin temperature. e. Materials have edge exposure only. f. Materials are normally stowed with no risk of condensation in stowage locations. g. Materials are used on noncritical,	many exceptions where such controls are unnecessary.		

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		off-the-shelf electrical/electronic hardware that is stowed and/or used in crew areas. h. Materials are fluorocarbon polymers (including ETFE) or silicones. i. Materials are used in crew clothing items.			
4.2.3.9	Glycols	[MPR 99] When solutions containing glycols (aliphatic dihydric alcohols) are used aboard spacecraft that have electrical or electronic circuits containing silver or silver-coated copper, a silver chelating agent, such as benzotriazole (BZT), shall be added to the solution to prevent spontaneous ignition from the reaction of silver with the glycol.	Required to prevent this unusual spontaneous ignition reaction.		
4.2.3.10a	Etching Fluorocarbons	[MPR 100] The etching of PTFE, perfluoroalkoxy (PFA), and fluorinated ethylene propylene (FEP) shall meet the requirements of SAE AMS2491F, Surface Treatment of Polytetrafluoroethylene, Preparation for Bonding, when adhesion to the fluorocarbon surface is required, except that for insulated wire or cable a pull test on co-produced specimens may be performed in lieu of the tensile and shear strength tests in AMS2491, section 3.5.2.	It is NASA policy to use voluntary consensus standards where possible. The cited specification is the industry standard for preparing polytetrafluoroethylene for bonding and has been reviewed and approved for use by NASA.		
4.2.3.10b	Etching Fluorocarbons	[MPR 101] Etched surfaces shall be processed within 24 hours or within 1 year if packaged per SAE AMS2491F.	Ensures that the etched surface remains active and ready for bonding.		

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4.2.4.1a	Heat Treatment	[MPR 102] Heat treatment of aluminum alloys used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS2772G, Heat Treatment of Aluminum Alloy Raw Materials; SAE AMS2770N, Heat Treatment of Wrought Aluminum Alloy Parts; or SAE AMS2771E, Heat Treatment of Aluminum Alloy Castings.	It is NASA policy to use voluntary consensus standards where possible. The cited standards are the widely accepted consensus standards for heat treating aluminum alloys, and they have been reviewed and approved for use by NASA.		
4.2.4.1b	Heat Treatment	[MPR 103] Heat treatment of steel alloys used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS-H-6875B, Heat Treatment of Steel Raw Materials, or SAE AMS2759E, Heat Treatment of Steel Parts, General Requirements.	It is NASA policy to use voluntary consensus standards where possible. The cited standards are the widely accepted consensus standards for heat treating steel alloys, and they have been reviewed and approved for use by NASA.		
4.2.4.1c	Heat Treatment	[MPR 104] Heat treatment of titanium alloys used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS-H-81200D, Heat Treatment of Titanium and Titanium Alloys, for raw stock and SAE AMS2801B, Heat Treatment of Titanium Alloy Parts, for parts requiring heat treatment during fabrication.	It is NASA policy to use voluntary consensus standards where possible. The cited standards are the widely accepted consensus standards for heat treating titanium alloys, and they have been reviewed and approved for use by NASA.		
4.2.4.1d	Heat Treatment	[MPR 105] Heat treatment of nickel- and cobalt-based alloy parts used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS2774E, Heat Treatment, Wrought Nickel Alloy and	It is NASA policy to use voluntary consensus standards where possible. The cited standards are the widely accepted consensus standards for heat treating nickel- and cobalt-based alloys and have		

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		Cobalt Alloy Parts, or SAE AMS2773E, Heat Treatment, Cast Nickel Alloy and Cobalt Alloy Parts.	been reviewed and approved for use by NASA.		
4.2.4.1e	Heat Treatment	[MPR 106] For spaceflight hardware that provides mission-critical functions, process-control tensile-test coupons shall be taken from the production part (or from the same material lot, having the same thickness as and processed identically to the production part) to verify the adequacy of the heat treatment process for the following conditions: (1) Aluminum alloys are solution heat-treated. (2) High-strength steels (>200 ksi (1380 MPa) UTS), tool steels, and maraging steel alloys are heat-treated to high strength levels. (3) A286 or MP35N alloys (which have poor correlation between hardness and tensile strength) are heat treated. (4) Titanium alloys are annealed or solution heat treated and aged. (5) Nickel- and cobalt-based alloys are work strengthened before age hardening resulting in age-hardened tensile strengths greater than 1030 MPa (150 ksi) UTS. (6) Precipitation hardenable nickel-	Heat treat variations can compromise the strength and ductility of the alloys for the heat-treat conditions cited. In addition, the commonly used hardness test to verify the adequacy of the heat treat process is not a good predictor of strength and ductility.		

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		and cobalt-based alloys are solution heat treated.			
4.2.4.1f	Heat Treatment	[MPR 107] When process-control tensile-test coupons are required, the requirement for the coupons shall be specified on the engineering drawing for the part.	Ensures compliance.		
4.2.4.1g	Heat Treatment	[MPR 108] If no tensile values are available in MMPDS for a specific alloy, tensile-test acceptance values shall be specified on the engineering drawing for the part.	Ensures that accept/reject criteria are established.		
4.2.4.1h	Heat Treatment	[MPR 109] Materials shall not be used in spaceflight hardware that provides mission-critical functions outside the limits of their procurement specification, heat treat specification, or MMPDS specification.	Ensures that the materials that are used have defined and dependable design properties.		
4.2.4.2a	Forging	[MPR 110] Where forgings are used in mission-critical applications, first-article (preproduction) approval shall be obtained from the procuring authority.	Ensures that a NASA M&P technical expert(s) has reviewed and approved the first-article cut-up process.		
4.2.4.2b	Forging	[MPR 111] First-article approval and the controls to be exercised in producing subsequent production forgings shall be in accordance with SAE AMS2375D, Control of Forgings Requiring First Article Approval.	It is NASA policy to use voluntary consensus standards where possible. The cited standard is the widely accepted consensus standard for control of the first-article forging cut-up and has been reviewed and approved for use by NASA.		
4.2.4.2c	Forging	[MPR 112] After the forging technique, including degree of working, is established, the first production forging	Ensures that the forging process has broken up the cast structure and that expected microstructure and		

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		shall be sectioned to show the grain-flow patterns and to determine mechanical properties at control areas and the trim ring/protrusion specimens (prolongations).	mechanical properties are produced by the forging process.		
4.2.4.2d	Forging	[MPR 113] The mechanical properties of the trim ring/protrusion specimens (prolongations) for the first article shall be compared to the control coupons to show they are predictive of the properties in the body of the first article.	The mechanical properties of the trim ring/protrusion specimens (prolongations) for subsequent articles will be used to verify that the mechanical properties of subsequent articles are acceptable. As such, they have to be representative of the properties in the body of each subsequent article. For the first article, they are compared with the mechanical properties of the control coupons from the body of the article to verify that they are truly representative.		
4.2.4.2e	Forging	[MPR 114] Sectioning to show the grain-flow patterns and to determine mechanical properties at control areas shall be repeated after any substantive change in the forging technique, as determined by M&P analysis.	Since any changes in the forging process can significantly alter the grain flow, microstructure, and mechanical properties, it is necessary to conduct a first-article-like cut-up to ensure the resulting properties are acceptable.		
4.2.4.2f	Forging	[MPR 115] These data and results of tests on the redesign shall be retained and made available for review by the procuring activity.	Since forging process changes can significantly alter the mechanical and metallurgical properties of the forging, it is necessary to conduct a first-article-like cut-up and have the		

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			results reviewed and approved by NASA M&P engineering.		
4.2.4.2g	Forging	[MPR 116] Trim ring or protrusion specimens (prolongations) shall be obtained for each production forging used in safety-critical applications and tested for required minimum mechanical properties.	It is standard practice in the forging industry to obtain and test trim ring or protrusion specimens to ensure that the mechanical properties of each forging are achieved.		
4.2.4.2h	Forging	[MPR 117] Surface and volumetric nondestructive inspection (NDI) shall be performed on all safety-critical forgings.	Obviously, the severe plastic deformation involved in a forging process can introduce both surface and internal defects for which inspection is needed.		
4.2.4.3a	Castings	[MPR 118] Castings used in spaceflight hardware that provides mission-critical functions shall meet the requirements of SAE AMS2175A (2010), Castings, Classification and Inspection of.	It is NASA policy to use voluntary consensus standards. SAE AMS2175 is the industry specification for classifying and inspecting castings and has been reviewed and approved for use by NASA.		
4.2.4.3b	Castings	[MPR 119] Where castings are used in mission-critical applications, pre-production castings shall be subjected to first-article inspection to verify proper material flow, proper material integrity, minimum required mechanical properties, proper grain size, and macro/microstructure.	For mission-critical castings, it is considered mandatory to subject the first casting(s) to destructive testing to verify the mechanical properties and metallurgical characteristics of the casting process.		
4.2.4.3c	Castings	[MPR 120] The mechanical properties in trim ring/protrusion of the first article shall be compared to the control coupons	Trim rings/protrusions will be obtained for all production castings so the first article testing needs to		

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		to show they are predictive of the properties in the body of the first article.	verify that they are representative of the cast parts.		
4.2.4.3d	Castings	[MPR 121] The same casting practice and heat-treating procedure shall be used for the production castings as for the approved first-article castings.	Ensures to a reasonable degree that the production castings will have the same mechanical properties and metallurgical characteristics as the first-article casting(s) that validated the casting process.		
4.2.4.3e	Castings	[MPR 122] For Class 1 and Class 2 castings (classes as defined by SAE AMS2175A (2010)), mechanical property testing of integrally cast or excised tensile bars at critical locations shall be conducted to ensure foundry control of cast lots.	Tensile bars cast at the same time as the production casting(s) ensure that the casting process is reproducing the same mechanical properties. Integrally casting tensile bars with each production lot is a standard practice in the casting industry.		
4.2.4.3f	Castings	[MPR 123] Periodic cut-ups or functional testing shall be conducted for Class 1 and Class 2 castings (classes as defined by SAE AMS2175A (2010)).	For the most critical castings, periodic cut-ups or functional testing ensures that the casting process is under control and is reproducible.		
4.2.4.3g	Castings	[MPR 124] Surface and volumetric nondestructive inspection shall be performed on all safety-critical castings.	Castings frequently contain unacceptable defects that cannot be detected except by these NDE techniques.		
4.2.4.4a	Formed Panels	[MPR 125] Where formed panels are used in mission-critical applications, pre-production panels shall be subjected to first-article inspection to verify proper material integrity, minimum required mechanical properties, proper grain size, and macro/microstructure.	The process for forming panels needs to be verified as producing panels with proper material integrity, mechanical properties, grain size, and macro/microstructure.		
4.2.4.4b	Formed Panels	[MPR 126] The mechanical properties of	Control coupons will be used for		

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		the first production article shall be compared to control coupons to show they are predictive of the properties in the body of the first article.	verification of the properties of each production formed panel, so the first article testing needs to verify that they are representative of the formed panels.		
4.2.4.4c	Formed Panels	[MPR 127] The same forming practice and heat-treating procedure shall be used for the production formed panels as for the approved first-article panels.	Ensures to a reasonable degree that the production formed panels will have the same mechanical properties and metallurgical characteristics as the first-article formed panel that validated the process.		
4.2.4.4d	Formed Panels	[MPR 128] Sectioning to determine mechanical properties at control areas shall be repeated after any substantive change in the forming technique, as determined by M&P analysis.	Since any changes in the forming process can significantly alter the grain flow, microstructure, and mechanical properties of the panel, it is necessary to conduct a first-article-like cut-up to ensure the resulting properties are still acceptable.		
4.2.4.4e	Formed Panels	[MPR 129] Surface and volumetric NDI shall be performed on all safety-critical formed panels.	Formed panels may contain unacceptable defects that cannot be detected except by these NDE techniques.		
4.2.4.5a	Adhesive Bonding	[MPR 130] Structural adhesive bonding shall meet MSFC-SPEC-445A, Adhesive Bonding, Process and Inspection, Requirements for.	MSFC-SPEC-445 is the NASA-wide, accepted specification for adhesive bonding and inspection.		
4.2.4.5b	Adhesive Bonding	[MPR 131] Structural adhesive bonding processes shall be controlled to prevent contamination that would cause structural failure that could affect the safety of the mission, crew, or vehicle or affect	The strength of a structural adhesive bond can be significantly degraded by bond surface contamination, particularly from silicones. Therefore, it is imperative		

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		mission success.	that bond surface cleanliness be maintained and verified.		
4.2.4.5c	Adhesive Bonding	[MPR 132] Bonded primary structural joints shall demonstrate cohesive failure modes in shear.	In bonded joints, cohesive failure is the desired failure mode that best ensures a reliable and repeatable shear strength design value, whereas an adhesive failure is almost always the result of inadequate surface preparation and is indicative of an improper bonding process.		
4.2.4.6a	Welding	[MPR 133] If alternative specifications to those cited in this section are utilized or developed, those specifications shall meet the requirements of NASA-STD-5006A, General Welding Requirements for Aerospace Materials.	The AWS D17 welding requirements are commonly used by aerospace companies but are far more detailed than is required by NASA and also have some deficiencies. If an aerospace company chooses to not follow the AWS D17 requirements, plus the supplemental requirements identified in this document, they may develop their own standard, provided that it complies with the less detailed but more stringent requirements in NASA-STD-5006.		
4.2.4.6b	Welding	[MPR 134] Material Review Board disposition shall be required for weld repair/rework/processing activities that are not in accordance with the approved weld process specification (WPS).	Weld procedure variances that have not been qualified by prior test or experience need to be reviewed and approved by a Material Review Board and/or M&P knowledgeable personnel.		
4.2.4.6c	Welding	[MPR 135] A weld development and	The welding of large structural		

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		certification plan shall be developed for large structural welded components such as crew modules and welded cryogenic tanks.	welded components can have major problems if the weld development and certification plan isn't established well before welding flight hardware. The plan is expected to include full scale pathfinder weldments, tooling development, and a design values program including sensitivity testing.		
4.2.4.6.1	Fusion Welding	[MPR 136] The processing and quality assurance requirements for manual, automatic, and semiautomatic welding for spaceflight applications that provide mission-critical functions shall meet the requirements of AWS D17.1/D17.1M (2010) AMD 1 (2012), Specification for Fusion Welding for Aerospace Applications, with the following modifications/additions:	It is NASA policy to use voluntary consensus standards where possible. The cited specification is the aerospace industry specification for fusion welding of aerospace structures and components and has been reviewed and approved for use by NASA with modifications/additions to address minor deficiencies in the baseline standard.		
4.2.4.6.1a	Fusion Welding	[MPR 137] Mission-critical structural welds shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012), Class A requirements.	Structural welds that are safety-critical are required to meet the most stringent set of requirements, as is the case for the cited Class A requirements. Note that the weld classes in AWS D17.1 are based on nondestructive inspection requirements (with the most stringent inspection requirements for Class A welds), whereas traditional NASA weld classes were based on weld criticality (with		

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			Class A welds being the highest criticality level).		
4.2.4.6.1b	Fusion Welding	[MPR 138] Other structural welds shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012), Class A or Class B requirements.	Structural welds that are not safety-critical are allowed to meet a less stringent set of requirements, as is the case for the cited Class B requirements. The more stringent Class A requirements may also be used.		
4.2.4.6.1c	Fusion Welding	[MPR 139] Non-critical welds (including seal welds) shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012), Class C requirements.	Non-structural, non-safety-critical welds are allowed to meet the least stringent set of requirements, as is the case for the cited Class C requirements.		
4.2.4.6.1d	Fusion Welding	[MPR 140] All Class A and Class B welds (including manual welds), as defined by AWS D17.1/D17.1M (2010) AMD 1 (2012), shall be qualified in accordance with AWS D17.1/D17.1M (2010) AMD 1 (2012).	Ensures that Class A and B manual weld processes are also qualified, not just the operators who perform the welds.		
4.2.4.6.1e	Fusion Welding	[MPR 141] Titanium welds shall be light/dark straw or better (Ref. AWS D17.1/D17.1M (2010) AMD 1 (2012), Table 7.1).	Titanium welds with worse coloration than light/dark straw (as listed in AWS D17.1, Table 7.1) indicate improper inert gas control during welding and presents the possibility that weld contamination/oxidation occurred.		
4.2.4.6.1f	Fusion Welding	[MPR 142] Titanium and its alloys shall be welded with alloy-matching or metallurgically compatible fillers or autogenously.	Prevents the creation of a completely unknown titanium alloy in the weldment by welding together, for example, an alpha alloy and an alpha-beta alloy or		

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			other incompatible combinations of titanium alloys.		
4.2.4.6.1g	Fusion Welding	[MPR 143] Extra low interstitial (ELI) filler wires shall be used for titanium cryogenic applications and are preferred for general applications.	ELI weld wire produces a more ductile weld at cryogenic temperatures.		
4.2.4.6.1h	Fusion Welding	[MPR 144] Commercially pure (CP) titanium filler shall not be used on Ti-6Al-4V or other alloyed base material.	Welding Ti-6Al-4V with CP weld wire results in a significant alloy content and interstitial solubility difference between the parent metal and the weld metal, which can lead to interstitial migration and precipitation of embrittling species, such as titanium hydride, at the weld fusion line. An Apollo SIV-B stage was destroyed due to inadvertently welding a Ti-6Al-4V pressure vessel with CP weld wire.		
4.2.4.6.1i	Fusion Welding	[MPR 145] Nitrogen, hydrogen, carbon dioxide, and mixtures containing these gases shall not be used in welding titanium and its alloys.	Titanium welding needs to be performed in an inert gas environment. The cited gases are not considered inert to titanium and can react with titanium alloys at weld temperatures.		
4.2.4.6.1i(1)	Fusion Welding	[MPR 146] The inert gas shall have a dew point of -60º C (-76º F) or lower.	Ensures that the water content in the inert gas is low enough that the potential reaction of water with titanium at the welding temperature is not a problem.		
4.2.4.6.1j	Fusion Welding	[MPR 147] Welded alpha and alpha plus beta titanium alloys shall be stress relieved in a vacuum or inert gas environment (Ar or He), or stress relieved	Welding of titanium alloys may produce residual stresses that are high enough that the weld needs to be stress relieved. Such stress relief		

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		in air with verification of oxide removal per SAE AMS-H-81200D or SAE AMS 2801B, or certified in the as-welded condition.	treatments are done at high enough temperatures that precautions against oxidation of the titanium must be exercised.		
4.2.4.6.1k	Fusion Welding	[MPR 148] Titanium beta alloys that are welded shall be evaluated on a case-by-case basis with respect to stress relief.	Titanium beta alloys are less prone to residual stress during welding, but stress relieving of beta welds still needs to be considered.		
4.2.4.6.1l	Fusion Welding	[MPR 149] Laser welding for spaceflight hardware that provides mission-critical functions shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012) or AWS C7.4/C7.4M (2008), Process Specification and Operator Qualification for Laser Beam Welding.	It is NASA policy to use voluntary consensus standards where possible. The cited specifications are industry standards for laser welding that have been reviewed and approved for use by NASA.		
4.2.4.6.1m	Fusion Welding	[MPR 150] Electron beam welding for spaceflight hardware that provides mission-critical functions shall comply with AWS D17.1/D17.1M (2010) AMD 1 (2012) or SAE AMS2680C, Electron-Beam Welding for Fatigue Critical Applications.	It is NASA policy to use voluntary consensus standards where possible. The cited specifications are industry standards for electron beam welding that have been reviewed and approved for use by NASA, whereas SAE AMS2681 is another common industry standard for electron beam welding but is not considered adequate.		
4.2.4.6.1n	Fusion Welding	[MPR 151] The following welding practices permitted by AWS D17.1/D17.1M (2010) AMD 1 (2012) shall not be used without an approved MUA to document the acceptance rationale: (1) Welding from both sides if full	Although permitted by AWS D17.1/D17.1M (2010) AMD 1 (2012), these practices have been determined to be unacceptable for NASA Program hardware unless approved through an MUA review process.		

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		penetration of the first pass is not verified (either by inspection of the back side or by grinding prior to welding on the opposite side). (2) Partial weld penetration in structural welds. (3) Straightening operation after welding. (4) Lap welds in structural applications.			
4.2.4.6.1o	Fusion Welding	[MPR 152] The Welding Procedure Specification (WPS) shall include the following content in addition to that required by AWS D17.1/D17.1M (2010) AMD 1 (2012): (1) Prequalified rework welds in accordance with AWS D17.1/D17.1M (2010) AMD 1 (2012). (2) Testing and documentation of allowable parameter variations for automatic and semi-automatic welds. (3) Manual welding parameters. (4) An associated Procedure Qualification Record (PQR) with tension testing and macro-examination results as part of weld qualification requirements.	NASA review of the cited AWS specification has determined that these additional requirements need to be included in the WPS to ensure the adequacy and completeness of the welding process.		
4.2.4.6.2	Resistance Welding	[MPR 153] Resistance welding for spaceflight hardware that provides	It is NASA policy to use voluntary consensus standards where		

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		mission-critical functions, including resistance spot welding (RSW), shall meet the requirements of AWS D17.2/D17.2M (2013), Specification for Resistance Welding for Aerospace Applications.	possible. The cited specification is an industry standard for resistance welding that has been reviewed and approved for use by NASA. Resistance welding is not used frequently in NASA programs and then primarily for spot welding of batteries.		
4.2.4.6.3	Friction-Stir Welding of Aluminum Alloys	[MPR 154] Friction-stir welding of aluminum alloys for spaceflight hardware that provides mission-critical functions shall meet the requirements of AWS D17.3/D17.3M (2016), Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications.	It is NASA policy to use voluntary consensus standards where possible. The cited specification is an industry standard for friction-stir welding that has been reviewed and approved for use by NASA.		
4.2.4.6.4	Inertia Welding	[MPR 155] Inertia welding for spaceflight hardware that provides mission-critical functions shall meet the requirements of MIL-STD-1252 (1975), Inertia Friction Welding Process, Procedure and Performance Qualification.	Although this standard is no longer active, it has been determined by NASA that it is the best standard existing for establishing and controlling the inertia welding process. Other active inertia friction welding specifications were reviewed and found to be inadequate for NASA's use or were only recommended practices, not requirements.		
4.2.4.6.4a	Inertia Welding	[MPR 156] Surface inspection (penetrant) and volumetric inspection (radiography) shall be performed.	Generally, inertia welds are performed on pressure-containing tube and valve components that require inspection for surface and subsurface defects that could develop into leaks.		
4.2.4.6.4b	Inertia Welding	[MPR 157] All welds shall be proof	Generally, inertia welds are		

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		tested.	performed on pressure-containing tube and valve components that need to be proof tested.		
4.2.4.6.4c	Inertia Welding	[MPR 158] Inertia welds used in fluid systems shall be helium leak tested.	Generally, inertia welds are performed on pressure-containing tube and valve components that need to be helium leak tested.		
4.2.4.7a	Brazing	[MPR 159] Brazing for spaceflight hardware that provides mission-critical functions shall be conducted in accordance with AWS C3.3 (2008), Recommended Practices for Design, Manufacture, and Examination of Critical Brazed Components.	It is NASA policy to use voluntary consensus standards where possible. The cited specification is the industry specification for the design, manufacture, and examination of critical brazed components and has been reviewed and approved for use by NASA.		
4.2.4.7b	Brazing	[MPR 160] Brazing of aluminum alloys for spaceflight hardware that provides mission-critical functions shall meet the requirements of AWS C3.7M/C3.7 (2011), Specification for Aluminum Brazing.	It is NASA policy to use voluntary consensus standards where possible. The cited specification is an industry specification for brazing of aluminum that has been reviewed and approved for use by NASA.		
4.2.4.7c	Brazing	[MPR 161] Torch, induction, and furnace brazing for spaceflight hardware that provides mission-critical functions shall meet the requirements of AWS C3.4M/C3.4 (2016), Specification for Torch Brazing; AWS C3.5M/C3.5 (2016), Specification for Induction Brazing; and AWS C3.6M/C3.6 (2016), Specification for Furnace Brazing, respectively.	It is NASA policy to use voluntary consensus standards where possible. The cited specifications are the industry specifications for the types of brazing cited, and they have been reviewed and approved for use by NASA.		
4.2.4.7d	Brazing	[MPR 162] Subsequent fusion-welding	Need to ensure that high-		

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		operations in the vicinity of brazed joints or other operations involving high temperatures that might affect the brazed joint shall be prohibited for spaceflight hardware that provides mission-critical functions unless it can be demonstrated that the fixturing, processes, methods, and/or procedures employed will preclude degradation of the brazed joint.	temperature processing near existing braze joints does not degrade the joint by re-melting and reflowing the braze metal.		
4.2.4.7e	Brazing	[MPR 163] Brazed joints used in spaceflight hardware that provides mission-critical functions shall be designed for shear loading and not be relied upon for strength in axial loading for structural parts.	Since transferring all of the load in a structural braze joint by tension through the braze material is not considered as reliable as transferring the load by shear through the braze material, tension loaded braze material has to be avoided. This is accomplished by using lap joint designs versus butt joints, where the large brazed surface area in a lap joint results in a relatively low shear stress in the braze material.		
4.2.4.7f	Brazing	[MPR 164] The shear strength of brazed joints used in spaceflight hardware that provides mission-critical functions shall be evaluated in accordance with AWS C3.2M/C3.2 (2008), Standard Method for Evaluating the Strength of Brazed Joints.	It is NASA policy to use voluntary consensus standards where possible. The cited standard is an industry standard for how to evaluate the strength of brazed joints and has been reviewed and approved for use by NASA.		
4.2.4.7g	Brazing	[MPR 165] For furnace brazing of complex configurations of spaceflight hardware that provides mission-critical functions, such as heat exchangers and	Destructive testing ensures the adequacy of the braze flow and that the braze alloy and its adhesion to the brazed surfaces are continuous		

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		cold plates, destructive testing shall be conducted on pre-production brazed joints to verify that the braze layer that extends beyond the fillet area is continuous and forms a uniform phase.	and metallurgically acceptable.		
4.2.4.8	Structural Soldering	[MPR 166] Soldering shall not be used for structural applications.	The low strength and poor creep resistance of solders means soldering cannot be used in structural applications.		
4.2.4.9a	Electrical Discharge Machining and Laser Machining	[MPR 167] Electrical-discharge machining (EDM) and laser machining (LM) processes for spaceflight hardware that provides mission-critical functions shall be controlled to limit the depth of the oxide layer, the recast layer, and the heat-affected zone.	Since the high surface temperature associated with the EDM and LM machining processes causes undesirable surface damage, it is necessary to control the processes to ensure the depth of damage is predictable and manageable.		
4.2.4.9a(1)	Electrical Discharge Machining and Laser Machining	[MPR 168] The oxide layer shall be removed from the surface.	The oxide layer that is produced by the EDM and LM machining processes is generally brittle and crack-prone and must be removed.		
4.2.4.9a(2)	Electrical Discharge Machining and Laser Machining	[MPR 169] In addition, the recast layer and the heat-affected zone shall be removed from bearing, wear, fatigue or fracture-critical surfaces, and from crack- or notch-sensitive materials.	The recast layer and the heat-affected zone produced by the EDM and LM machining processes are generally undesirable conditions and need to be removed from wear surfaces and fracture-critical surfaces.		
4.2.4.9b	Electrical Discharge Machining and Laser Machining	[MPR 170] EDM/LM schedules for spaceflight hardware that provides mission-critical functions shall be qualified to determine the maximum thickness of the affected layers when the depth of the affected material must be	Qualification of the EDM and LM machining processes ensures that the depth of the detrimental surface conditions is predictable and the amount of material that must be removed is known.		

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		known for removal or analysis.			
4.2.4.10a	Nickel Plating	[MPR 171] Electrodeposited nickel plating for spaceflight hardware that provides mission-critical functions shall be applied according to the requirements of SAE AMS2403N, Plating, Nickel General Purpose; SAE AMS2423E, Plating, Nickel Hard Deposit; or ASTM B689-97, Standard Specification for Electroplated Engineering Nickel Coatings.	It is NASA policy to use voluntary consensus standards where possible. The cited specifications are industry standards for electroplating nickel that have been reviewed and approved for use by NASA.		
4.2.4.10b	Nickel Plating	[MPR 172] Electroless nickel plate for spaceflight hardware that provides mission-critical functions shall be applied per SAE AMS2404G, Plating, Electroless Nickel, or ASTM B733-15, Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal.	It is NASA policy to use voluntary consensus standards where possible. The cited specifications are industry standards for electroless nickel plating that have been reviewed and approved for use by NASA.		
4.2.4.10c	Nickel Plating	[MPR 173] The nickel-aluminum interface in nickel-plated aluminum used in spaceflight hardware that provides mission-critical functions shall be protected from exposure to corrosive environments.	Since there is a strong galvanic couple between nickel and aluminum, the interface between them must be protected in corrosive environments.		
4.2.4.11	Additive Manufacturing	[MPR 174] Spaceflight hardware manufactured by additive manufacturing techniques shall be designed, produced, and documented in compliance with NASA-STD-6030.	Imposes NASA-STD-6030 additive manufacturing requirements on NASA space programs.		
4.2.5.1a	Nondestructive Evaluation (NDE) Plan	[MPR 175] The NDE Plan shall address the process for establishment,	Since there are many NDE techniques that are available to		

NOTE: Per section 4.1.6: The use of M&P that do not comply with the technical requirements of this NASA Technical Standard may be acceptable in the actual hardware applications. MUAs are required for all M&P that are technically acceptable but do not meet the technical requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		implementation, execution, and control of NDE through design, manufacturing, operations, and maintenance of spaceflight hardware.	inspect spaceflight hardware and such inspections are performed throughout the life cycle of the hardware, a Plan is needed to ensure that the application and sequence of the inspections are proper and efficient.		
4.2.5.1b	Nondestructive Evaluation (NDE) Plan	[MPR 176] The Plan shall meet the intent of MIL-HDBK-6870B, Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts, and, when fracture control is applicable, the requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components.	Obviously, since NASA-STD-5009 sets NDE requirements for fracture-critical components, it has to be included in the NDE Plan for spaceflight hardware. Although MIL-HDBK-6870 states that it is for guidance only, it is to be treated as a requirements document for non-fracture-critical components in the NDE Plan.		
4.2.5.1c		[MPR 213] NDE acceptance criteria and requirements for qualification of NDE procedures used on all (metallic, non-metallic and composite) hardware shall be addressed in the NDE Plan.	NDE acceptance criteria and qualification requirements are crucial for composite and other structural nonmetallic materials, not just metallic materials.		
4.2.5.1d	Nondestructive Evaluation (NDE) Plan	[MPR 177] Qualification and certification of personnel involved in nondestructive testing shall comply with NAS 410 (Revision 4), NAS Certification and Qualification of Nondestructive Test Personnel.	NAS-410 has long been the aerospace industry and NASA standard for certifying and qualifying NDE personnel. Although ASNT-TC-1A is also widely used for certifying and qualifying nondestructive test personnel, it is a recommended practice only.		
4.2.5.2a	NDE Etching	[MPR 178] All machined or otherwise	Machining metal surfaces causes a		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		mechanically disturbed surfaces on metallic parts that are to be fluorescent dye-penetrant inspected shall be adequately etched to assure removal of smeared, masking material prior to penetrant application, with the following exceptions: (1) Previously etched parts do not need etching if the surface has not been smeared since the last etching. (2) When supporting rationale is provided, close tolerance parts may be machined near-final and etched and penetrant inspected before final machining in lieu of etching and penetrant inspecting after final machining.	disturbed, smeared thin layer of metal that masks cracks, and the disturbed layer must be removed by etching prior to penetrant inspection.		
4.2.5.2b	NDE Etching	[MPR 179] The etching procedure shall specify the minimum amount of material to be removed to ensure that smeared metal does not mask cracks.	Since the disturbed metal layer has a certain depth, it is required that at least an amount of metal equal to the thickness of the disturbed layer be removed to have an effective penetrant inspection.		
4.2.5.2c	NDE Etching	[MPR 180] If etching is not feasible, it shall be demonstrated that the required flaw size can be reliably detected.	Since not being able to etch means that the penetrant inspection process would be ineffective, it is necessary to employ other NDE methods, such as eddy current or ultrasonics that can detect the critical flaw size.		
4.2.6.1a	Residual Stresses	[MPR 181] Estimates of residual stresses	Many metal processes produce		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		in structural or stress-corrosion-sensitive hardware shall be considered in structural analyses and corrosion/stress-corrosion assessments.	residual stresses that can add to the stresses from the normally applied service stresses resulting in a higher stress state that needs to be addressed and accounted for in the analyses. An important lesson was learned in repair welding of 2195 Aluminum Lithium. The repair weld material was very low strength compared to the parent material (it was 4043 weld wire in 2195 parent material), so the effect of the residual stress was not apparent (i.e., there wasn't much warpage). However, when wide specimens containing only a short repair-welded area were tensile tested, the residual stress added to the discontinuity shear stress at the weld/parent metal interface, causing early failure.		
4.2.6.1b	Residual Stresses	[MPR 182] The straightening of warped parts in structural hardware shall require an approved MUA.	Since straightening of a warped part requires plastic deformation and creates the potential for mechanical damage and high residual stresses, it is necessary for M&P engineering to review and approve the process.		
4.2.6.2a	Sandwich Assemblies	[MPR 183] For vented sandwich architectures, the differential pressure on ascent shall be adequately relieved to preclude core-to-face sheet bond line "peel" failure modes that could result in	Vents on vented sandwich constructions must be large enough to prevent the pressure differential between the sandwich interior and the external environment during		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		face sheet separation.	launch becoming large enough to cause face sheet separation.		
4.2.6.2b	Sandwich Assemblies	[MPR 184] Sandwich architectures that are not vented shall be capable of withstanding pressure buildup without violating strength and stability requirements.	Non-vented sandwich structure will develop a pressure differential during ascent of one atmosphere (14.7 psia) between the sandwich interior and space vacuum. The structure must be verified to withstand this pressure differential without causing face sheet separation.		
4.2.6.2c	Sandwich Assemblies	[MPR 185] Structural sandwich assemblies shall be designed to prevent the entrance and entrapment of water vapor or other contaminants into the core structure.	Since moisture can accumulate in vented core sandwich assemblies and can migrate from cell to cell presenting a corrosion problem, and since it can also cause structural failure in a launch environment where the exterior pressure decrease and the rapid temperature increase can flash the water to vapor causing over pressurization of the face sheet, it is necessary to prevent such water entrapment and migration in sandwich assemblies. An Apollo lesson learned occurred when a vented core honeycomb interstage tank structure failed due to moisture accumulation and flash evaporation during launch. Water intrusion can occur from condensation / exposure of sandwich constructions to humid		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
			air below the dew point, "cryo-pumping" where sandwich structures are exposed to large thermal / humidity gradients induced by cryogenic fluid storage, gravitational migration of rain water, forced penetration of wind-driven rain, etc.		
4.2.6.2d	Sandwich Assemblies	[MPR 186] Structural honeycomb sandwich assemblies that will be subjected to heating shall be tested for the expected environments to show that the construction can withstand them.	The use of metallic or glass-reinforced cores to minimize intrusion of moisture intrusion into the sandwich core and can result in vapor build-up over-pressurizing the sandwich assembly when it is heated by the launch environment.		
4.2.6.2e	Sandwich Assemblies	[MPR 187] Sandwich assemblies using perforated and moisture-absorbing cores shall be protected from water intrusion during assembly and prelaunch activities.	To prevent moisture accumulation that can cause internal corrosion and structural failure, sandwich assemblies need to be protected from water intrusion prior to launch in addition to their being designed to prevent moisture intrusion.		
4.2.6.2f	Sandwich Assemblies	[MPR 188] Structural sandwich constructions and core materials shall be designed, evaluated, and tested in accordance with the requirements of CMH-17, Volume 6: Structural Sandwich Composites.	It is NASA policy to use voluntary consensus standards where possible. The cited standard is an industry-accepted standard for sandwich construction and core materials that has been reviewed and approved for use by NASA.		
4.2.6.3	Corrosion Prevention and Control	[MPR 189] All parts, assemblies, and equipment used in spaceflight hardware that provides mission-critical functions, including spares, shall be finished to	Ensures that corrosion of space spaceflight hardware will be addressed and eliminated to the extent possible.		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		provide protection from corrosion in accordance with the requirements of NASA-STD-6012, Corrosion Protection for Space Flight Hardware, with the following exceptions: a. SAE AMS2404G is permitted for electroless nickel plating as an alternative to ASTM B733-15. b. Titanium fasteners may be used in contact with graphite composites, provided that they are wet installed with sealant or primer materials.			
4.2.6.3.1	Passivation	[MPR 190] Corrosion-resistant steels used in spaceflight hardware that provides mission-critical functions shall be passivated after machining.	Ensures that the normally present passive layer that provides corrosion resistance is restored.		
4.2.6.3.2	Sealing	[MPR 191] Removable panels and access doors in exterior or interior corrosive environments shall be sealed either by mechanical seals or by separable, faying-surface sealing.	Ensures that corrosive environments cannot intrude into sealed compartments.		
4.2.6.4a	Hydrogen Embrittlement	[MPR 192] When designing liquid or gaseous hydrogen systems, the degradation of metallic materials properties by hydrogen embrittlement shall be addressed in the Materials and Processes Selection, Control, and Implementation Plan.	Ensures that the potential for hydrogen embrittlement of metallic structures containing hydrogen will be evaluated.		
4.2.6.4b	Hydrogen Embrittlement	[MPR 193] An MUA shall be written rationalizing the selection of metallic materials for liquid or gaseous hydrogen	Ensures that the potential for hydrogen embrittlement of metallic structures containing hydrogen has		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		systems to preclude cracking and to ensure system reliability and safety.	been evaluated.		
4.2.6.4c	Hydrogen Embrittlement	[MPR 194] Electrochemical processes or exposure to acids or bases during manufacturing or processing of spaceflight hardware that provides mission-critical functions shall be controlled to prevent hydrogen embrittlement, or embrittlement relief treatment shall be performed promptly after processing.	Ensures that the potential for hydrogen embrittlement is minimized by controlling the time of exposure to electrochemical processes and to acids and bases or that the embrittlement relief treatments are carried out soon after exposure to such processes and fluids.		
4.2.6.4c(1)	Hydrogen Embrittlement	[MPR 195] When acid cleaning baths or plating processes are used on steel parts for spaceflight hardware that provides mission-critical functions, the part shall be baked in accordance with SAE AMS2759/9D, Hydrogen Embrittlement Relief (Baking) of Steel Parts, to alleviate potential hydrogen embrittlement problems.	Baking ensures relief of the potential for hydrogen embrittlement in steels after exposure to acids or plating processes. The baking process in SAE AMS2759/9D has a long history and is the accepted way to relieve the potential for hydrogen embrittlement in steels.		
4.2.6.5.1	Gold-Indium Intermetallic Formation	[MPR 196] Gold shall not be used in contact with indium or an indium alloy (such as indium solder) for spaceflight hardware that provides mission-critical functions.	A lesson learned when indium solder in a Goddard satellite contacted gold wires and the resulting gold-indium intermetallic resulted in severe embrittlement and failure of the gold wires.		
4.2.6.5.2a	Gold-Tin Intermetallic Formation	[MPR 197] When used with tin-based solder joints in mission-critical hardware, gold shall be removed from at least 95 percent of the surface to be soldered of all component leads, component terminations, and solder terminals.	Ensures that the dissolution of gold into tin-based solder will be minimized, thereby minimizing the formation of brittle gold-tin intermetallic compounds.		
4.2.6.5.2b	Gold-Tin Intermetallic	[MPR 198] Gold-coated contacts shall not	Ensures that the propensity for		

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Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
	Formation	be mated with tin or tin alloy-coated contacts for separable contact interfaces in mission-critical hardware.	fretting corrosion between gold-coated contacts and mating tin-coated contacts will be avoided.		
4.2.6.5.3a	Gold-Aluminum Intermetallic Formation	[MPR 199] Gold-aluminum brazing processes shall be controlled to minimize formation of the $AuAl_2$ intermetallic known as “Purple Plague” and prevent formation of the Au_5Al_2 intermetallic known as “White Plague.”	An aluminum-rich intermetallic phase, the $AuAl_2$ intermetallic known as “Purple Plague,” is inherent (and not necessarily harmful) to gold-aluminum brazing; however, if excessive heat is applied, too much of the intermetallic can form at the braze/part interface, causing joint failure. A gold-rich phase, the Au_5Al_2 intermetallic known as “White Plague,” is always detrimental. Its formation is catalyzed by silicon, so care should be taken to keep the braze joint zone free of contamination.		
4.2.6.5.3b	Gold-Aluminum Intermetallic Formation	[MPR 200] Gold-aluminum bonding processes shall be controlled to prevent the formation of the $AuAl_2$ intermetallic known as “Purple Plague” and the Au_5Al_2 intermetallic known as “White Plague.”	Purple Plague is a significant problem in microelectronic applications, because as purple plague forms, it reduces in volume. This creates cavities in the metal surrounding the purple plague, which increases electrical resistance and structurally weakens the wire bonding. White plague is worse, because it has low electrical conductivity and, if enough of it forms, the resulting electrical resistance can cause a total failure of the component. Whereas some		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
			amount of purple plague is expected and acceptable for gold-aluminum brazing processes, it is never acceptable in electrical bonding processes.		
4.2.6.6.1	Liquid Locking Compounds	[MPR 201] If a liquid-locking compound is used as a locking feature where rotational loosening or disengagement would result in a critical or catastrophic hazard, its use shall comply with the design and quality requirements and best practices in NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware, sections 5.5 and 7.6 and Appendix C.	Imposing NASA-STD-5020 ensures that issues and problems associated with the use of liquid-locking compounds will be avoided.		
4.2.6.6.2	Silver-Plated Fasteners	[MPR 202] Silver-plated fasteners shall not be used in external applications where the silver plating is directly exposed to atomic oxygen for a period longer than 2 weeks.	Ensures that the friable black oxide that forms on silver exposed to atomic oxygen will not contaminate other components or mechanisms or contaminate astronaut suits and gloves during EVAs.		
4.2.6.7a	Contamination Control	[MPR 203] A Contamination Control Plan shall be generated in accordance with the guidelines of ASTM E1548 (2009), Standard Practice for Preparation of Aerospace Contamination Control Plans.	Spacecraft performance can be severely degraded by the presence of excessive contamination, leading to loss of mission or mission objectives. A Contamination Control Plan covering the entire hardware life cycle is necessary to ensure that a “build clean” approach is properly implemented. The cited ASTM standard is a voluntary consensus standard that		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
			has been reviewed and approved for use by NASA.		
4.2.6.7b	Contamination Control	[MPR 204] The Contamination Control Plan shall include controls on contamination-sensitive manufacturing processes, such as adhesive bonding, controls on packaging for shipment and storage, and a foreign object damage/debris (FOD) prevention program.	The cited areas of material processing, hardware packaging, and FOD prevention are the most important types of contamination that need to be controlled and addressed in the Contamination Control Plan.		
4.2.6.7c	Contamination Control	[MPR 205] The FOD prevention program shall be established for all ground operations of mechanical and electrical systems of spaceflight hardware, including the design, development, manufacturing, assembly, repair, processing, testing, maintenance, operation, and checkout of the equipment to ensure the highest practical level of cleanliness.	Since damage to spaceflight hardware from FOD can be very expensive and impact schedules, it is mandatory that a FOD prevention program be established that addresses all sources and means of preventing FOD damage throughout the hardware’s life cycle.		
4.2.6.7d	Contamination Control	[MPR 206] The FOD prevention program shall conform to NAS 412 (Revision 1), Foreign Object Damage/Foreign Object Debris (FOD) Prevention.	It is NASA policy to use voluntary consensus standards where possible. NAS 412 is the aerospace industry standard for FOD prevention and has been reviewed and approved for use by NASA.		
4.2.6.7e	Contamination Control	[MPR 207] Cleanliness levels for assembly- and subassembly-level hardware shall be identified on the engineering drawings.	Ensures that the cleanliness level of each hardware item has been specified.		
4.2.6.8	Packaging	[MPR 208] Packaging shall protect spaceflight hardware from corrosion and contamination during shipping and	Obviously, spaceflight hardware needs to be protected during shipment and storage.		

Section	Section Title	NASA-STD-6016C Imp Requirement Statement	Justification	Applicable (Yes or No)	If No, Enter Rationale
		storage.			
4.3	Verification	[MPR 209] Verification of compliance with the requirements of this NASA Technical Standard shall consist of the following steps as a minimum: a. NASA approval of the contractor Materials and Processes Selection, Control, and Implementation Plan and other applicable materials data requirements documents, such as the Contamination Control Plan and NDE Plan. b. Contractor M&P signature on engineering drawings to verify compliance with the requirements of this NASA Technical Standard or the Materials and Processes Selection, Control, and Implementation Plan. c. NASA audits of contractor M&P activities relating to hardware design and manufacturing. d. Establishment and operation of the M&P control panel in accordance with section 4.1.4 of this NASA Technical Standard. e. NASA approval of MUAs. f. NASA approval of MIULs.	Since it is NASA policy to provide clear, concise, verifiable requirements, it is necessary for NASA M&P to have oversight and insight into how the contractors and their subs and vendors implement and control spaceflight hardware M&P. The cited steps of reviewing and approving the contractors' M&P plans, requiring M&P drawing signature approval, conducting audits, membership on the materials control panel, and approval of MUAs and MIULs provide NASA M&P with the oversight and insight necessary to verify that the requirements of NASA-STD-6016 have been met.		

NOTE: Per section 4.1.6: The use of M&P that do not comply with the technical requirements of this NASA Technical Standard may be acceptable in the actual hardware applications. MUAs are required for all M&P that are technically acceptable but do not meet the technical requirements of this NASA Technical Standard, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan.

APPENDIX B

TYPICAL MUA FORM

MATERIAL USAGE AGREEMENT	C	USAGE AGREEMENT NO.	REV	PAGE OF

PROJECT:	SYSTEM:	CATEGORY:	ORIGINATOR:	ORGANIZATION/CONTRACTOR:

PART NUMBER(S):	USING ASSEMBLY(S):	ITEM DESCRIPTION:	ISSUE:
MATERIAL DESIGNATION:	MANUFACTURER:	SPECIFICATION:	PROPOSED EFFECTIVITY:

MATERIAL CODE:			LOCATION:	ENVIRONMENT:		
THICKNESS:	WEIGHT:	EXPOSED AREA	HABITABLE ☐	PRESSURE PSIA:	TEMP.F:	MEDIA:
			NONHABITABLE ☐			

APPLICATION:

RATIONALE: (use second page if required.)

MATERIAL USAGE AGREEMENT DISPOSITION

CONTRACTOR TIER 1	CONTRACTOR PRIME	NASA PROJECT MGR.	NASA M & P

	DATE	APPROVE	REJECT	DEFER	MEMO NO.:
					EFFECTIVITY:
					ORIGINATING CONTRACTOR

STRESS CORROSION EVALUATION FORM

1. Part Number ____________________
2. Part Name ____________________
3. Next Assembly Number ____________________
4. Manufacturer ____________________
5. Material ____________________
6. Heat Treatment ____________________
7. Size and Form ____________________
8. Sustained Tensile Stresses-Magnitude and Direction
    a. Process Residual ____________________
    b. Assembly ____________________
    c. Design, Static ____________________
9. Special Processing ____________________
10. Weldments
    a. Alloy Form, Temper of Parent Metal ____________________
    b. Filler Alloy, if none, indicate ____________________
    c. Welding Process ____________________
    d. Weld Bead Removed - Yes ( ), No ( ) ____________________
    e. Post-Weld Thermal Treatment ____________________
    f. Post-Weld Stress Relief ____________________
11. Environment ____________________
12. Protective Finish ____________________
13. Function of Part ____________________
____
14. Effect of Failure ____________________
____
15. Evaluation of Stress Corrosion Susceptibility ____________________
____
16. Remarks: ____________________
____

APPENDIX C

RETIRED CATEGORY III MUA RATIONALE CODES

The Category III MUA rationale codes in the interim and baseline release of NASA-STD-6016 have been incorporated (with modifications) into the body of this NASA Technical Standard as exceptions to the requirements or have been eliminated. Category III MUAs are no longer required for codes that were incorporated as exceptions. Codes were eliminated when the rationales were no longer applicable or a full MUA was considered appropriate for the deviation. The retired codes are listed here for continuity with programs working to the earlier releases. As described in section 4.1.6.1.3, contractors who want to use Category III rationale codes may do so through their approved Materials and Processes Selection, Control, and Implementation Plan.

RETIRED FLAMMABILITY RATIONALE CODES

CODE	RATIONALE
101	Approved Materials Usage Agreement (MUA) Category I.
102	Approved Materials Usage Agreement (MUA) Category II.
103	Materials passed requirements when tested in configuration.
104	Unexposed, overcoated, or sandwiched between nonflammable materials and no ignition source or propagation path.
105	Minor usage (less than 45 g (0.1 lb) mass and 13 cm^2 (2 in^2) surface area); no propagation path or ignition source.
107	Passes test No. 10 of NASA-STD-6001, Flammability Test for Materials in Vented Containers, by test or analysis.
108	Off-the-shelf equipment having material acceptable in configuration; no ignition source or propagation path.
109	Material not exposed; totally immersed in fluid; evaluated for fluid compatibility only.
110	Material is acceptable when used on a metal substrate that provides a good heat sink. Material considered noncombustible in this configuration by test or analysis.
111	Material is flammable but is sandwiched between nonflammable materials with edges only exposed and is more than 5 cm (2 in) from an ignition source or more than 30 cm (12 in) from other flammable materials.
112	Material is flammable but is unexposed or is overcoated with a nonflammable material.
113	Material is flammable but has a thickness less than 0.25 mm (0.010 in) and is sprayed or bonded to a metallic surface greater than 1.6 mm (0.062 in) thick.
114	Material is flammable but is used in "small amounts" and is more than 5 cm (2 in) from an ignition source or more than 30.5 cm (12 in) from other flammable materials. "Small amounts" for flammability may be quantified as follows: total weight less than 45 g (0.1 lb) and less than 13 cm^2 (2.0 in^2) surface area.

RETIRED TOXICITY (OFFGASSING) RATIONALE CODES

CODE	RATIONALE
201	Approved Material Usage Agreement (MUA) Category I.
202	Meets toxicity requirements with performed cure.
203	T value for material/component in usage weight is <0.5 for manned flight compartment volume.
204	Materials usage in hermetically sealed container.

RETIRED FLUID SYSTEM COMPATIBILITY RATIONALE CODES

CODE	RATIONALE
301	Approved Material Usage Agreement (MUA) Category I.
302	Passes requirements in configuration.
303	Material is B-rated in MAPTIS (batch/lot testing required) but batch/lot used in hardware passed test.
304	Approved Material Usage Agreement (MUA) Category II.

RETIRED THERMAL VACUUM STABILITY RATIONALE CODES

CODE	RATIONALE
401	Approved Material Usage Agreement (MUA) Category I.
402	Approved Material Usage Agreement (MUA) Category II.
403	VCM between 0.1 and 1.0 percent; exposed area is less than 13 cm^2 (2 in^2) and not near a critical surface.
404	VCM >1.0 percent; exposed area is less than 1.6 cm^2 (0.25 in^2).
405	Unexposed, overcoated, or encapsulated with approved material.
406	Material is B-rated in MAPTIS (batch/lot testing required) but batch/lot used in hardware cured to meet requirements.
407	Meets thermal vacuum stability requirements in configuration.
408	Materials usage in hermetically sealed container.
409	Material has VCM >0.1 percent but is enclosed in a sealed container (maximum leak rate less than 1×10^{-4} cm^3/sec).

RETIRED STRESS CORROSION CRACKING RATIONALE CODES

CODE	RATIONALE
501	Approved Material Usage Agreement (MUA) Category I.
502	Approved Material Usage Agreement (MUA) Category II.
503	Maximum tensile stress <50 percent of yield strength for part on electrical/electronic assemblies.
504	Martensitic or PH stainless steels used in ball bearing, race, or similar applications where the primary loading is compressive.
505	Metal not listed in table 1 of MSFC-STD-3029 for stress corrosion cracking is not exposed to a corrosive environment after final assembly through end-item use.
506	Carbon and low alloy high strength steels greater than 1240 MPa (180 ksi) used in ball bearings, springs, or similar applications where primary loading is compressive, low tensile stresses, or history of satisfactory performance.

RETIRED CORROSION RATIONALE CODES

CODE	RATIONALE
601	Approved Material Usage Agreement (MUA) Category I.
602	Approved Material Usage Agreement (MUA) Category II.
603	Adequately finished for corrosion protection.
604	Acceptable in use environment.
606	Electrical grounding required, cladding plus conversion coating adequate.
607	Thermal conductance and electrical bonding requirements preclude painting. Conversion coating is adequate (for aluminum only).
608	Finished on a higher assembly.
609	Laminated shim - minimum exposure of corrosion resistant material.
610	Material does not meet the requirements of MSFC-SPEC-250, Class II, but is treated or coated in a manner which meets or exceeds the requirements of MSFC-SPEC-250. Actual surface treatment shall be listed.
611	Material does not meet the requirements of MSFC-SPEC-250, Class II, but is not exposed to a corrosive environment after final assembly through end-item use.
612	Welding of titanium alloy-to-alloy or commercially pure-to-alloy using commercially pure filler metal in mixed alloy welds where hydrogen embrittlement is not predicted in service.

RETIRED GENERAL CODES

CODE	RATIONALE
702	Generic materials controlled by military or industry specification using MAPTIS averages for ratings or test results. Material codes for generic material shall be used.
703	Military specification or industry specification allowing several material options where all options have acceptable ratings.

APPENDIX D

RECOMMENDED DATA REQUIREMENTS DOCUMENTS

D.1 Recommended Data Requirements

The purpose of this appendix is to provide recommended Data Requirements Documents (DRDs) as follows:

- Materials and Processes Selection, Control, and Implementation Plan.
- Materials Usage Agreements (MUAs).
- Materials Identification and Usage List (MIUL).
- Contamination Control Plan (CCP).
- Nondestructive Evaluation (NDE) Plan.
- Additive Manufacturing Control Plan (AMCP)
- Corrosion Prevention and Control Plan.

Examples of DRD content for the first five recommended DRDs are provided on the following pages. An example of DRD content for the Corrosion Prevention and Control Plan is provided in NASA-STD-6012. Additional information regarding the AMCP can be found in NASA-STD-6030. The specific DRDs and the content of those DRDs should be tailored to each spacecraft program and additional DRDs may be appropriate.

DATA REQUIREMENTS DESCRIPTION (DRD)

1. **PROGRAM**:
2. **DRD NO.**: XXXX
3. **DATA TYPE**: 1
4. **DATE REVISED**:
5. **PAGE**: 1
6. **TITLE**: Materials and Processes Selection, Control, and Implementation Plan

7. **DESCRIPTION/USE**:
This Plan shall document the degree of conformance and method of implementation for each requirement in this standard, identifying applicable in-house specifications used to comply with the requirement. It shall also describe the methods used to control compliance with these requirements by subcontractors and vendors. The Materials and Processes Selection, Control, and Implementation Plan, upon approval by the procuring activity, shall become the Materials and Processes implementation document used for verification.

8. **DISTRIBUTION**: As determined by the Contracting Officer.

9. **INITIAL SUBMISSION**: SRR

10. **SUBMISSION FREQUENCY**: Final at SDR

11. **REMARKS**:

12. **INTERRELATIONSHIP**: Parent SOW Paragraph: XXXX

13. **DATA PREPARATION INFORMATION**:

13.1 **SCOPE**:
The Materials and Processes Selection, Control, and Implementation Plan shall describe the hardware developer’s activities involved in the identification, evaluation, documentation, and reporting of materials and processes usage in space spaceflight hardware, support hardware, and ground support equipment.

13.2 **APPLICABLE DOCUMENTS**:
NASA-STD-6016A, Standard Materials and Processes Requirements for Spacecraft

13.3 **CONTENTS**:
The necessary interfaces with procuring activity in the operation of this Plan shall be defined. The method for materials control and verification of subcontractors and vendors shall be included in the hardware developer's plan. As a minimum and as applicable, the Plan shall address the following:

Conformance – The Plan shall address each applicable paragraph of NASA-STD-6016A and describe the method of implementation and degree of conformance for each applicable requirement. If tailoring of the requirements is planned or necessary, alternate approaches to NASA-STD-6016A may be submitted in this Plan, which meet or exceed the stated requirements. This tailoring approach will allow for NASA approval of alternate requirements.

Hardware Developer's Organization – Authority shall be assigned to an individual or group who shall be responsible for review and approval of all M&P specified prior to release of engineering documentation.

Materials and Processes Identification – Identification and documentation of the M&P used, both in the original design and in any changes, shall be contained in the Materials Identification and Usage List (MIUL) DRD.

Testing – Logic, procedures, and data documentation for any proposed test program to support materials screening and verification testing. Any material/process testing to be performed by the hardware developer shall require prior NASA approval.

Materials Usage Agreement (MUA) Procedures – Logic, procedures, and documentation involved in documenting and approving materials/processes as indicated in NASA-STD-6016A shall be defined, including those that do not meet the established requirements but are proposed for use due to lack of replacement materials/processes or other considerations, and shall be contained in the Materials Usage Agreement (MUA) DRD.

Material Design Properties – The Plan shall contain the philosophy describing how material properties will be determined, and if those properties do not exist, how the material properties will be developed, including, but not limited to, the statistical approaches to be employed.

Process Controls – The Plan shall identify all process specifications used to implement specific requirements in NASA-STD-6016A. All materials processes used in manufacturing shall be documented in process specifications, and all applicable process specifications shall be identified on the engineering drawing. Each processing step in the process specification shall be identified in a level of detail that ensures the process is repeatable.

13.4 **FORMAT**: Electronic, Word®-compatible document or Adobe® PDF. For each paragraph in section 4 of NASA-STD-6016A, the Plan shall state the requirement from NASA-STD-6016A, identify the degree of conformance under the subheading “Degree of Conformance,” and identify the method of implementation under the subheading “Method of Implementation.”

13.5 **MAINTENANCE**: Contractor-proposed changes to document shall be submitted to NASA for approval. Complete reissue of the document is required.

DATA REQUIREMENTS DESCRIPTION (DRD)

1.	**PROGRAM**:	2. **DRD NO.**: XXXX
3.	**DATA TYPE**: 1 (Category I and II MUAs)	4. **DATE REVISED**:
	2 (Category III MUAs)	5. **PAGE**: 1
6.	**TITLE**: Materials Usage Agreements (MUAs)	

7. **DESCRIPTION/USE**:
MUAs shall be submitted for all materials and processes that are technically acceptable but do not meet the technical requirements of NASA-STD-6016A, as implemented by the approved Materials and Processes Selection, Control, and Implementation Plan. [The use of materials and processes that do not comply with the technical requirements of this standard may be technically acceptable if hardware reliability and vehicle safety are not affected.]

8. **DISTRIBUTION**: As determined by the Contracting Officer.

9. **INITIAL SUBMISSION**: PDR.

10. **SUBMISSION FREQUENCY**: At PDR and as the need for new MUAs is identified during the detailed design process. MUAs shall be revised and resubmitted whenever design modifications affect the part numbers or the environment or loads change to more severe than identified on the MUA or the MUA rationale.

11. **REMARKS**:

12. **INTERRELATIONSHIP**: Parent SOW Paragraph: XXXX

13. **DATA PREPARATION INFORMATION**:
13.1 **<u>SCOPE</u>**:
MUAs shall be submitted as described below.

Category I MUAs – Category I MUAs are those that involve material/processes usage that could affect the safety of the mission, crew, or vehicle or affect the mission success, but **must** be used for functional reasons. Approval by the responsible NASA Materials and Processes organization and the NASA Program/Project Office shall be required.

Category II MUAs - Category II MUAs are those that involve material/processes usage that fails a screening of Materials and Processes requirements and is not considered a hazard in its use application but for which no Category III rationale code exists. Approval by the responsible NASA Materials and Processes organization shall be required.

Category III MUAs – Category III MUAs are those that involve materials or processes that have not been shown to meet these requirements but have an approved rationale code listed in the hardware developer-approved Materials and Processes Selection, Control, and Implementation Plan. They are evaluated and determined to be acceptable at the configuration/part level. Category III MUAs shall be reported in the Materials Identification and Usage List (MIUL) system or electronic data system utilizing the approved rationale codes in the Materials and Processes Selection, Control, and Implementation Plan. No MUA form is submitted. [Category III MUAs are identified here for completeness but are not required until after PDR.]

13.2 **APPLICABLE DOCUMENTS**:
NASA-STD-6016A, Standard Materials and Processes Requirements for Spacecraft
MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments

13.3 **CONTENTS**:
The MUA package shall include all technical information required to justify the application. MUAs for stress corrosion shall include a Stress Corrosion Cracking Evaluation per MSFC-STD-3029, section 5.4.

13.4 **FORMAT**: Electronic. A sample MUA form is provided in NASA-STD-6016A; however, Contractor format is acceptable. The complete MUA package shall be provided in Adobe® PDF format; the MUA form shall also be provided in a format that is compatible with the NASA Materials and Processes Technical Information System (MAPTIS) database.

13.5 **MAINTENANCE**: Contractor updates to the Category I and Category II MUAs shall be submitted to NASA for approval. Complete reissue of the MUA is required.

DATA REQUIREMENTS DESCRIPTION (DRD)

1. **PROGRAM**:
2. **DRD NO.**: XXXX
3. **DATA TYPE**: 2
4. **DATE REVISED**:
5. **PAGE**: 1
6. **TITLE**: Materials Identification and Usage List (MIUL)

7. **DESCRIPTION/USE**:
The MIUL is an electronic searchable parts list or separate electronic searchable materials identification and usage list. The MIUL identifies all Materials and Processes (M&P) usages contained in the end item, excluding piece part electronics and materials in sealed containers (maximum leak rate less than 1 x 10^{-4} cm^3/sec), for evaluation of the acceptability of M&P selected and utilized.

8. **DISTRIBUTION**: As determined by the Contracting Officer.

9. **INITIAL SUBMISSION**: PDR

10. **SUBMISSION FREQUENCY**: As-designed MIUL – at Hardware Acceptance Review
As-built MIUL updates – prior to FRR

11. **REMARKS**:

12. **INTERRELATIONSHIP**: Parent SOW Paragraph: XXXX

13. **DATA PREPARATION INFORMATION**:

13.1 **SCOPE**:

Materials and processes usage shall be documented in an electronic searchable parts list or separate electronic searchable Materials Identification and Usage List (MIUL). The procedures and formats for documentation of materials and processes usage will depend upon specific hardware but shall cover the as-built hardware. The system used shall be an integral part of the engineering configuration control/release system. A copy of the stored data shall be provided to NASA in a form compatible with the Materials and Processes Technical Information System (MAPTIS).

Wire, cable, and exposed surfaces of connectors shall be reported on the MIUL. All other standard and nonstandard electrical, electronic, and electromechanical (EEE) parts are exempt from reporting on the MIUL. Materials used in hermetically sealed electronic containers (maximum leak rate less than 1 x 10^{-4} cm^3/sec) are also exempt from inclusion in the MIUL.

13.2 **APPLICABLE DOCUMENTS**:
NASA-STD-6016A, Standard Materials and Processes Requirements for Spacecraft

13.3 **CONTENTS**:
The parts list or MIUL shall identify the following applicable information:

- Detail drawing and dash number
- Next assembly and dash number
- Change letter designation
- Drawing source
- Material form
- Material manufacturer
- Material manufacturer's designation
- Material specification
- Process specification
- Environment
- Weight (nonmetallic materials)
- MAPTIS Material Code (if data are to be provided in a form compatible with MAPTIS)
- Standard/commercial part number
- Contractor
- System
- Subsystem
- Maximum operating temperature
- Minimum operating temperature
- Fluid type
- Surface area (nonmetallic materials)
- Associate contractor number
- Project
- Document title
- Criticality
- Line number
- Overall evaluation
- Overall configuration test
- Maximum operating pressure
- Minimum operating pressure
- MUA number or rationale code
- Cure codes
- Materials rating
- Remarks (comments field)

13.4 **FORMAT**: Contractor format is acceptable. However, Contractor format for electronic submittal of MIUL data shall be compatible with the NASA Materials and Processes Technical Information System (MAPTIS) database.

13.5 **MAINTENANCE**: Contractor updates to the MIUL shall be submitted to NASA for approval. Complete reissue of the document is not required.

DATA REQUIREMENTS DESCRIPTION (DRD)

1. **PROGRAM**: 2. **DRD NO.**: XXXX
3. **DATA TYPE**: 2 4. **DATE REVISED**:
5. **PAGE**: 1
6. **TITLE**: Contamination Control Plan (CCP)

7. **DESCRIPTION/USE**:
The Contamination Control Plan defines implementation measures to control contamination of spaceflight hardware and fluid systems during manufacturing, assembly, test, transportation, storage, launch site processing, and post-flight refurbishment.

8. **DISTRIBUTION**: As determined by the Contracting Officer.

9. **INITIAL SUBMISSION**: PDR

10. **SUBMISSION FREQUENCY**: The contractor may submit updates/revisions at any time. Final submission shall be at CDR.

11. **REMARKS**:

12. **INTERRELATIONSHIP**: Parent SOW Paragraph: XXXX

13. **DATA PREPARATION INFORMATION**:
13.1 **SCOPE**:
The Contamination Control Plan shall be generated in accordance with the guidelines of ASTM E1548, Standard Practice for Preparation of Aerospace Contamination Control Plans (as specified by NASA-STD-6016A) and shall include:

a. A Foreign Object Debris (FOD) Control Plan to prevent damage to spaceflight hardware and injury to the flight crew by FOD during manufacture, assembly, test, transportation, storage, launch site processing, operation, repair, modification, refurbishment, and maintenance. The FOD prevention program shall conform to NAS 412, Foreign Object Damage/Foreign Object Debris (FOD) Prevention, as specified by NASA-STD-6016A.

b. Definition of cleanliness level acceptance limits and verification methods for fluid systems, and for general spaceflight hardware internal and external surfaces. The Plan shall also contain a list identifying all system fluids, together with the fluid specifications (for procurement or custom mixing) and the required cleanliness levels for the fluid system.

13.2 **APPLICABLE DOCUMENTS**:
NASA-STD-6016A, Standard Materials and Processes Requirements for Spacecraft
NAS 412, Foreign Object Damage/Foreign Object Debris (FOD) Prevention

13.3 **CONTENTS**:
The FOD Control Plan shall address the following elements:

a. Identification of probable FOD sources.
b. Early design considerations for FOD prevention, resistance to damage, foreign object entrapment, etc.
c. Manufacturing planning for minimizing FOD generation and cleaning up whatever FOD is generated.
d. FOD control methods.
e. FOD Awareness and Prevention Training.
f. Metrics - Measuring techniques for analysis, trending, and feedback.
g. Incident investigation/reporting, "lessons learned."
h. Awareness/Employee Feedback.

The contractor shall define cleanliness level acceptance limits and verification methods for fluid systems and for general spaceflight hardware internal and external surfaces. The contractor shall also provide a list identifying all system fluids, together with the fluid specifications (for procurement or custom mixing) and the required cleanliness levels for the fluid system.

13.4 **FORMAT**: Electronic, Word®-compatible document or Adobe® PDF.

13.5 **MAINTENANCE**: Changes to the document proposed by the contractor shall be submitted to NASA for approval. Complete reissue of the document is required.

DATA REQUIREMENTS DESCRIPTION (DRD)

1. **PROGRAM:**
2. **DRD NO.:** XXXX
3. **DATA TYPE:**
4. **DATE REVISED:**
5. **PAGE:** 1
6. **TITLE:** Nondestructive Evaluation (NDE) Plan

7. **DESCRIPTION/USE:**
The Nondestructive Evaluation (NDE) Plan shall address the NDE requirements necessary to assure the health and integrity of the spaceflight hardware throughout its life cycle. This Plan shall identify all Nondestructive Evaluation (NDE) standards employed in the inspection of materials.

8. **DISTRIBUTION:** As determined by the Contracting Officer.

9. **INITIAL SUBMISSION:** PDR

10. **SUBMISSION FREQUENCY:** The contractor may submit updates/revisions at any time.

11. **REMARKS:**

12. **INTERRELATIONSHIP:**

13. **DATA PREPARATION INFORMATION:**

13.1 **SCOPE:**
The NDE Plan shall address the process for establishment, implementation, execution, and control of NDE. The Plan shall meet the intent of MIL-HDBK-6870, Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts, and the requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components as specified by NASA-STD-6016A, Standard Materials and Processes Requirements for Spacecraft.

13.2 **APPLICABLE DOCUMENTS:**
NASA-STD-6016A, Standard Materials and Processes Requirements for Spacecraft
MIL-HDBK-6870, Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts
NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
NAS 410, NAS Certification and Qualification of Nondestructive Test Personnel

13.3 CONTENTS:

NDE Specifications and Standards – The NDE Plan shall address the selection and the order of precedence of applicable government, industry, and prime contractor NDE specifications and standards and how the requirements contained therein are implemented through internal procedures and how-to documents. The oversight of subcontractor implementation and flow down of the NDE requirements shall also be addressed. The Plan shall address commonly used aerospace industry NDE methods including, but not limited to, fluorescent dye penetrant, radiographic (film radiography, digital radiography, computed tomography), ultrasonic, neutron radiography, magnetic particle, eddy current, infrared thermography, and visual inspection. The Plan shall address how all NDE specifications and standards will be approved by the appropriate Government authority.

NDE Requirements During Hardware Design – The NDE Plan shall address how the processes are implemented to ensure that all designs are reviewed to establish NDE inspection requirements and to ensure that the parts are inspectable. The Plan shall address how the areas or zones of the part to be inspected are identified on the drawing. The Plan shall address how the operations and maintenance NDE requirements will be integrated in the design of the hardware.

Part Classification – The Plan shall address appropriate spaceflight hardware and GSE part classification in accordance with MIL-HDBK-6870.

NDE Sensitivity Levels – NDE sensitivity levels shall be classified as Standard NDE, Special NDE, Custom NDE, and Visual Inspection in the NDE Plan. The Plan shall address minimum detectable flaw size for Standard NDE for each material group of spaceflight hardware in compliance with NASA-STD-5009 where applicable. The Plan shall address procedures for defining NDE acceptance criteria for each of the sensitivity levels and identify organizations and their responsibilities in establishing NDE acceptance criteria, NDE drawing call outs, and NDE Operations and Maintenance criteria. Note: Custom sensitivity level refers to an NDE sensitivity level that is not covered under the other three NDE sensitivity levels and is applicable to non-fracture-critical parts.

NDE Acceptance Criteria – The Plan shall address how NDE acceptance criteria are determined and implemented for each sensitivity level. For spaceflight hardware, the Plan shall require rejection of any crack-like flaw irrespective of the sensitivity level of the inspection. The Plan shall address how significant flaw indications, irrespective of the acceptance criteria, will be dispositioned.

NDE During Manufacturing –The Plan shall address establishment of minimum NDE acceptance requirements in terms of NDE sensitivity level, methods of inspection (fluorescent dye penetrant, ultrasonic, etc.), sampling frequency, and NDE inspection coverage (e.g., 100 percent surface area or selected area) for manufactured hardware as grouped by classification of the part, material type, and form. The NDE Plan shall address how NDE is sequenced such that inspection reliability is optimized by performing NDE before manufacturing processes that may significantly reduce flaw detection capability. The requirements for etching of metal parts prior to penetrant inspection shall be specifically addressed in the Plan.

NDE Material Compatibility – The Plan shall address compatibility of NDE materials and processes with the hardware.

Fracture-Critical Parts – The Plan shall address how the listing of all Fracture-Critical parts, created according to the Fracture Control Plan, will be integrated with NDE requirements. The Plan shall address Special NDE and Standard NDE methods in accordance with NASA-STD-5009.

NDE During Operations and Maintenance – The NDE Plan shall address the NDE requirements necessary to assure the health and integrity of the hardware throughout its life cycle. The NDE Plan shall address NDE requirements during operations and maintenance of those parts that are susceptible to damage, such as impact, corrosion, material degradation and wear, etc. The NDE Plan shall address NDE requirements for inspecting repaired parts. The Plan shall address the NDE procedures and physical standards required to perform the operations and maintenance NDE inspections.

NDE Reporting and Record Retention – The NDE Plan shall describe the NDE nonconformance reporting system, record retention, and traceability.

Process Audit – The Plan shall address periodic auditing of NDE processes at prime contractor, vendors, and subcontractors to verify compliance with the NDE requirements established in the Plan.

Personnel Training – The NDE Plan shall identify formal training and certification requirements for NDE Inspection in accordance with NAS 410, NAS Certification and Qualification of Nondestructive Test Personnel.

13.4 **FORMAT:** Electronic, Word®-compatible document or Adobe® PDF.

13.5 **MAINTENANCE**: Changes to the document proposed by the contractor shall be submitted to NASA for approval. Complete reissue of the document is required.

APPENDIX E

REFERENCES

E.1 Purpose and/or Scope

The purpose of this appendix is to provide reference material for background information only. The referenced sections below refer to this NASA Technical Standard. In case of conflict, refer to paragraph 2.4.

E.2 Reference Documents

DOT/FAA/AR-03/19 (Reference Section 4.1.8.1 and 4.2.3.3)	Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure
NASA NPR 8020.12 (Reference section 4.2.6.7)	Planetary Protection Provisions for Robotic Extraterrestrial Missions
NASA-STD-5012 (Reference section 4.1.8.1)	Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines
NASA-STD-5019 (Reference sections 4.1.8.1 and 4.1.8.2)	Fracture Control Requirements for Spaceflight Hardware
NASA/CR-2005-213424 (Reference section 4.2.3.4)	Lubrication for Space Applications
NASA-STD-5005 (Revision D or later) (Reference section 4.0)	Standard for the Design and Fabrication of Ground Support Equipment
NASA-STD-6033 (Reference section 4.2.4.11)	Additive Manufacturing Requirements for Equipment and Facility Control

NASA/TM-2007-213740 (2007) (Reference section 4.2.1.4)	Guide for Oxygen Compatibility Assessments on Oxygen Components and Systems
NASA/TM-2016-218602 (2016) Reference section 4.2.6.4)	Hydrogen Embrittlement
NASA-TM-86556 (1985) (Reference section 4.2.3.4)	Lubrication Handbook for the Space Industry, Part A: Solid Lubricants, Part B: Liquid Lubricants
ANSI/AIAA G-095 (Reference section 4.2.6.4)	Guide to Safety of Hydrogen and Hydrogen Systems
ASTM E1559 (Reference section 4.2.3.6)	Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials
ASTM E2900 (Reference section 4.2.3.6)	Standard Practice for Spacecraft Hardware Thermal Vacuum Bakeout
ASTM G63 (Reference section 4.2.1.4)	Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service
ASTM G88 (Reference section 4.2.1.4)	Standard Guide for Designing Systems for Oxygen Service
ASTM G94 (Reference section 4.2.1.4)	Standard Guide for Evaluating Metals for Oxygen Service

ASTM MNL 36 (Reference section 4.2.1.4)	Safe Use of Oxygen and Oxygen Systems: Handbook for Design, Operation, and Maintenance
AWS G2.4/G2.4M (Reference section 4.2.4.6.1)	Guide for the Fusion Welding of Titanium and Titanium Alloys
SAE AMS2453 (Reference section 4.2.2.2.1)	Low Stress Grinding of Steel Parts Heat Treated to 180 ksi or Over, and Low Stress Grinding of Chrome Plating Applied to Steel Parts Heat Treated to 180 ksi or Over