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

Rick Russell

Materials Technical Fellow

NASA Engineering and Safety Center

Made For Space

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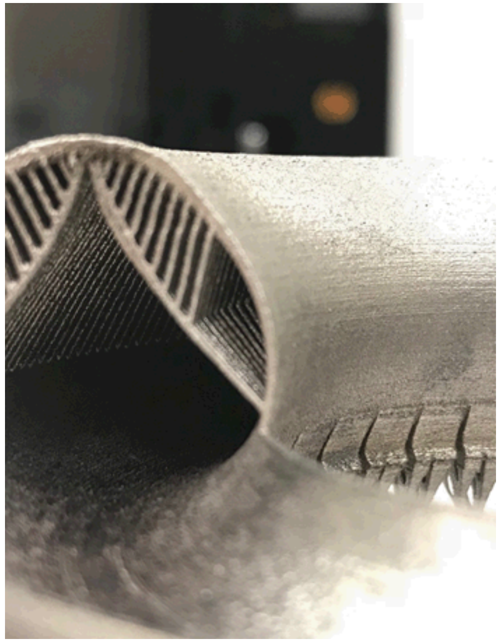
NASA's use of Additive Manufacturing

- Additive Manufacturing (AM) is rapidly becoming more attractive
- Therefore there is a critical need to increase NASA's knowledge and understanding of the materials, processes, analysis, inspection and validation methods for AM Parts
  - Standardization
  - Property validation
  - Specification development
  - Computational materials
  - NDE
  - Process monitoring – (in-situ NDE)
  - More

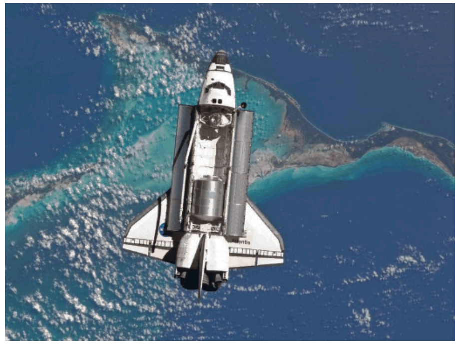


Toroidal Tank Development part

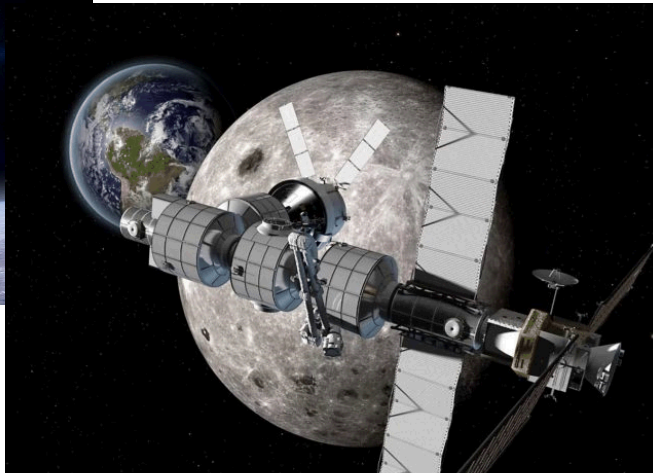
NASA’s motivation for AM Standard development

- AM parts are already being use for NASA programs in critical applications
- Human exploration of space, especially deep space, requires <u>extreme</u> reliability

Low Earth Paradigm



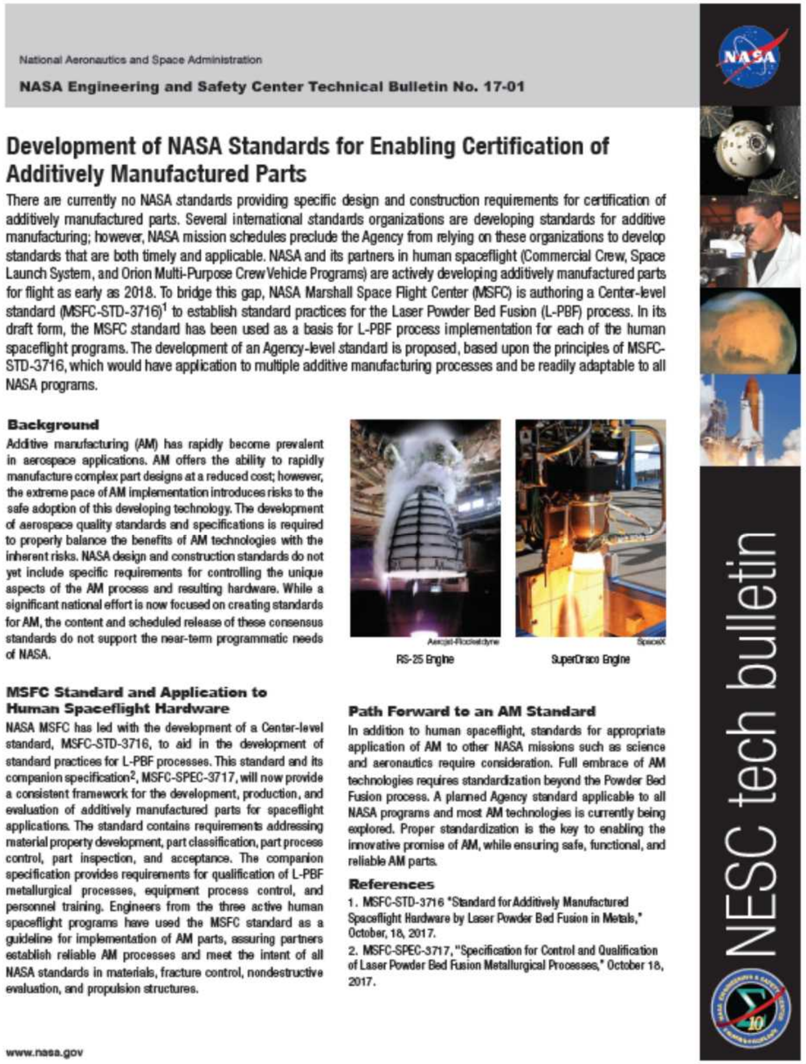
Deep Space Paradigm



250 miles vs 83,000,000+ miles
15-30 year life vs 50 to 100+ years
Replacement parts vs Limited replacement parts
Safe haven of earth vs no safe haven

Motivation for NASA Agency Standard Development

- Program partners in manned space flight programs (Commercial Crew, SLS, ISS and Orion) are actively developing AM parts
  - AM parts currently in use for commercial space flight
- NASA is unable to wait for industry Standards Development Organizations (SDOs) to develop mature, applicable AM standards
- NASA is currently using MSFC-STD-3716 and MSFC-SPEC-3717 as the basis of tailoring for all flight programs
  - MSFC documents written for SLS RS-25 restart and cover Laser Powder Bed fusion of metallic powders only
  - The parts that have seen this tailoring range from safety-critical to benign
  - Interim guidance has been released via NESC Technical Bulletin No. 17-01



National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 17-01

Development of NASA Standards for Enabling Certification of Additively Manufactured Parts

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

Background

Additive manufacturing (AM) has rapidly become prevalent in aerospace applications. AM offers the ability to rapidly manufacture complex part designs at a reduced cost; however, the extreme pace of AM implementation introduces risks to the safe adoption of this developing technology. The development of aerospace quality standards and specifications is required to properly balance the benefits of AM technologies with the inherent risks. NASA design and construction standards do not yet include specific requirements for controlling the unique aspects of the AM process and resulting hardware. While a significant national effort is now focused on creating standards for AM, the content and scheduled release of these consensus standards do not support the near-term programmatic needs of NASA.

Aerojet-Rocketdyne

RS-25 Engine

SpaceX

SuperDraco Engine

MSFC Standard and Application to Human Spaceflight Hardware

NASA MSFC has led with the development of a Center-level standard, MSFC-STD-3716, to aid in the development of standard practices for L-PBF processes. This standard and its companion specification[2], MSFC-SPEC-3717, will now provide a consistent framework for the development, production, and evaluation of additively manufactured parts for spaceflight applications. The standard contains requirements addressing material property development, part classification, part process control, part inspection, and acceptance. The companion specification provides requirements for qualification of L-PBF metallurgical processes, equipment process control, and personnel training. Engineers from the three active human spaceflight programs have used the MSFC standard as a guideline for implementation of AM parts, assuring partners establish reliable AM processes and meet the intent of all NASA standards in materials, fracture control, nondestructive evaluation, and propulsion structures.

Path Forward to an AM Standard

In addition to human spaceflight, standards for appropriate application of AM to other NASA missions such as science and aeronautics require consideration. Full embrace of AM technologies requires standardization beyond the Powder Bed Fusion process. A planned Agency standard applicable to all NASA programs and most AM technologies is currently being explored. Proper standardization is the key to enabling the innovative promise of AM, while ensuring safe, functional, and reliable AM parts.

References

1. MSFC-STD-3716 "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals," October, 18, 2017.
2. MSFC-SPEC-3717, "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes," October 18, 2017.

www.nasa.gov

NESC tech bulletin

Active AM Standards at NASA

Center-level Documents (as opposed to Agency-level) at MSFC, released October, 2017

MSFC-STD-3716

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-STD-3716
BASELINE
EFFECTIVE DATE: October 18, 2017

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

STANDARD FOR ADDITIVELY MANUFACTURED SPACEFLIGHT HARDWARE BY LASER POWDER BED FUSION IN METALS

Approved for Public Release; Distribution is Unlimited

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

MSFC-SPEC-3717

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-SPEC-3717
BASELINE
EFFECTIVE DATE: October 18, 2017

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES

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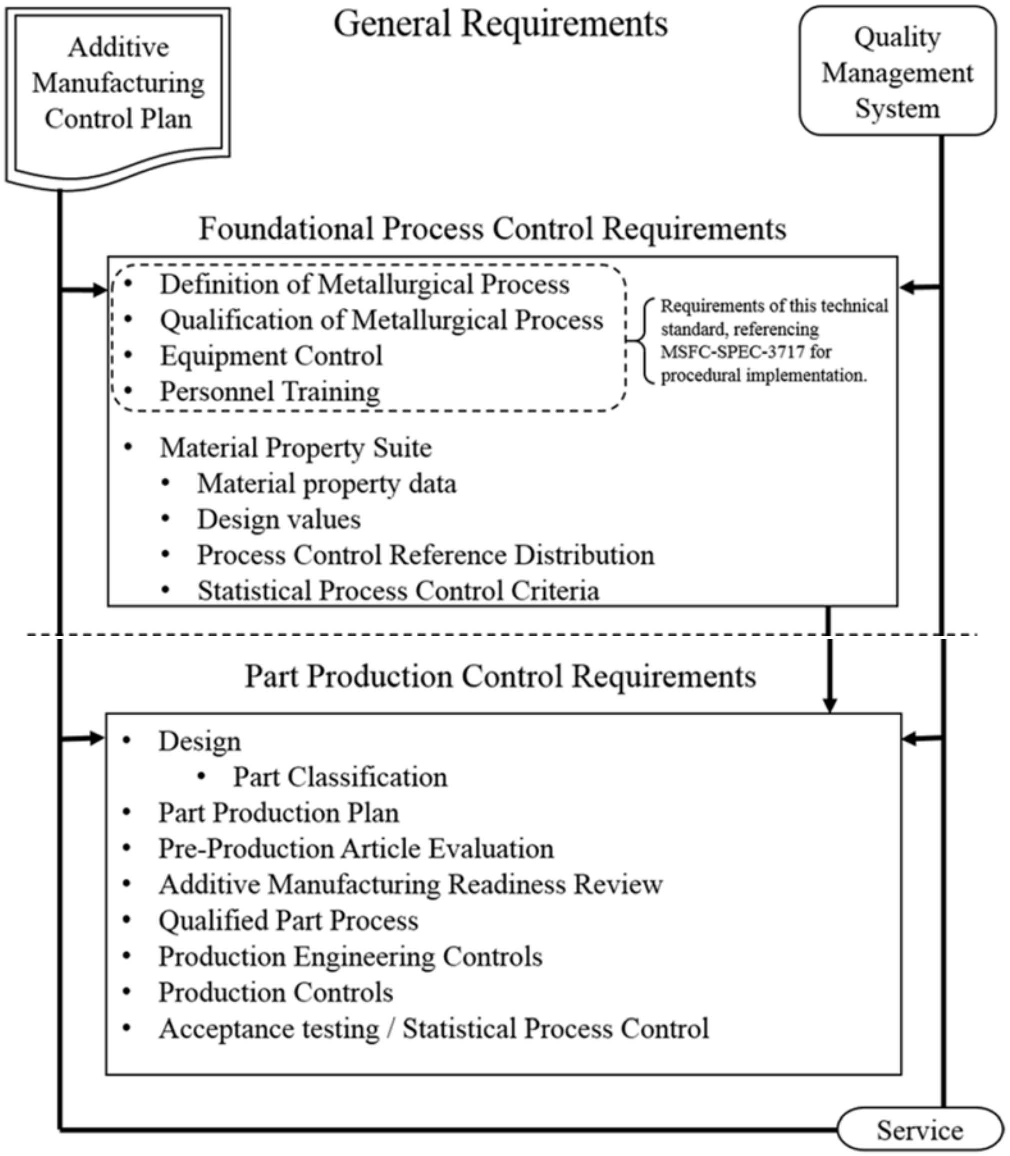
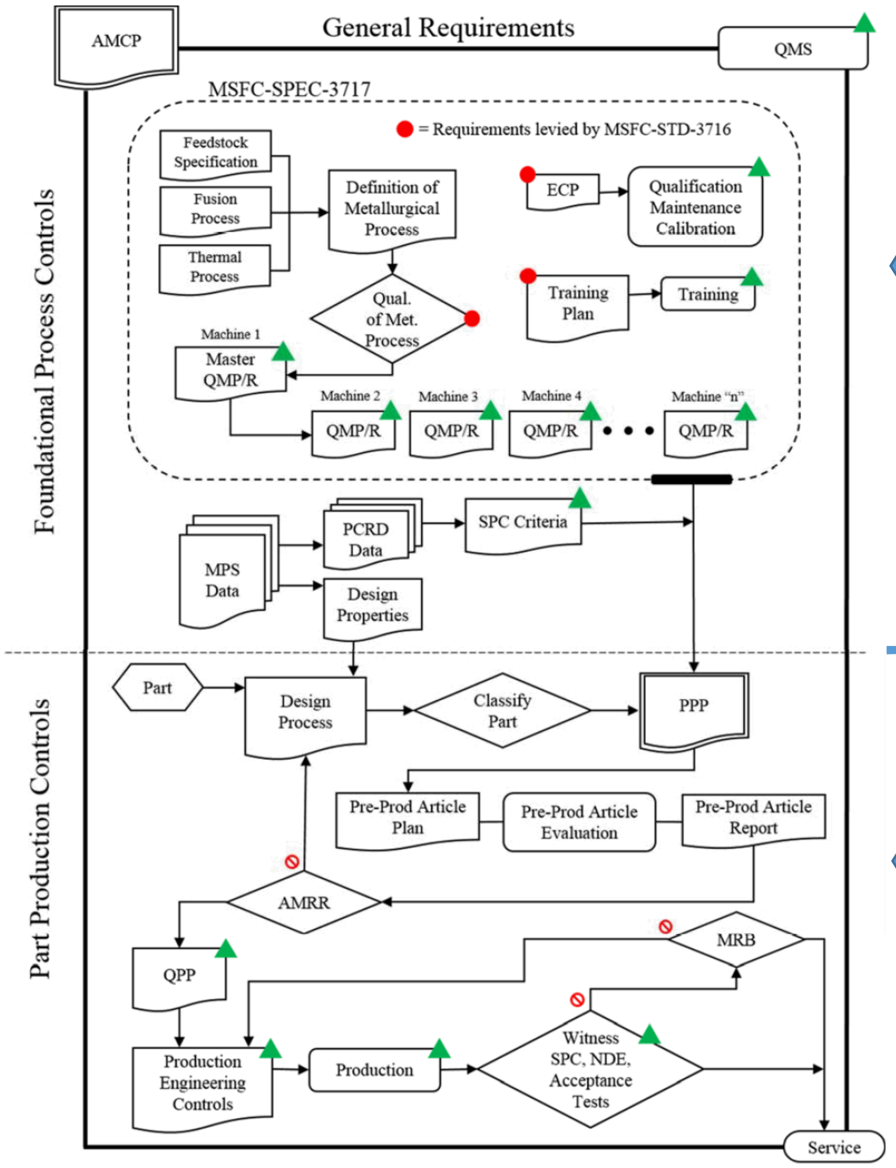
Outline of MSFC-STD-3716

- Covers ONLY Laser Powder Bed Fusion
- General requirements govern the engineering and production practice and are paralleled by a Quality Management System (QMS).
- Process control requirements provide the basis for reliable part design and production and include:
  - Qualified Metallurgical Processes (QMPs)
  - Equipment controls (ECP)
  - Personnel training
  - Material property development
- Part Production Control requirements are typical of aerospace operations and must be met before placing a part into service.



MSFC-STD-3716 / MSFC-SPEC-3717



Foundational Process Controls provide the basis for reliable part design and production

- ▲ Identifies key points of QMS involvement.
- ● Identifies PBF requirements levied by MSFC-STD-3716 with procedures in MSFC-SPEC-3717
- ⊘ Negative outcome of decisional action

Part Production Controls are typical of aerospace operations and include design, part classification, pre-production and production controls

Key Products for AM Integration

- **AMCP** Additive Manufacturing Control Plan
  - Similar function as a Materials and Process Control Plan (per NASA-STD-6016)
- **QMS** Quality Management System (Requirements)
  - Required at AS9100 level with associated audits
  - Applies to both Design Entities and Manufacturing Entities
- **EFCP** Equipment and Facilities Control Plans
  - Machine maintenance and qualification, contamination control, personnel training, etc.
- **QMP** Qualified Metallurgical Process (foundational control)
  - Analogous to a very detailed weld schedule
  - Feedstock definition, fusion parameters, and post processing that effect materials properties

Controlled through MSFC-SPEC-3717

- **MPS** Material Property Suite (properties database)
  - Owned by Design Entity with input from Manufacturing Entity
- **PPP** Part Production Plans (Overview and implementation)
- **PPA** Pre-Production Article (Part evaluations, dimensional, metallographic, mechanical)
- **MRR** Manufacturing Readiness Review
- **QPP** Qualified Part Process
  - Finalized “frozen” part process
- **PER/ADP** Production Engineering Record and Part Acceptance Data Package
  - Contains all documentation for a delivered part

Creation of a NASA Standard

- The NESC has formed a team to explore the creation of Agency Standards and Specifications for Additive Manufactured (AM) components.
  - This team includes representatives from nine NASA centers along with representatives from the FAA, Air Force, and Army.
- The intent is that these documents will be Agency Policy for AM
- The standards will create requirements with tailoring guidance that can be used to develop process specifications and manufacturing plans for both general and specific applications
- The standards will <u>not</u> specifically state how to manufacture or certify a component
- Standards will identify factors that need to be addressed for all phases of design, manufacture, and qualification.

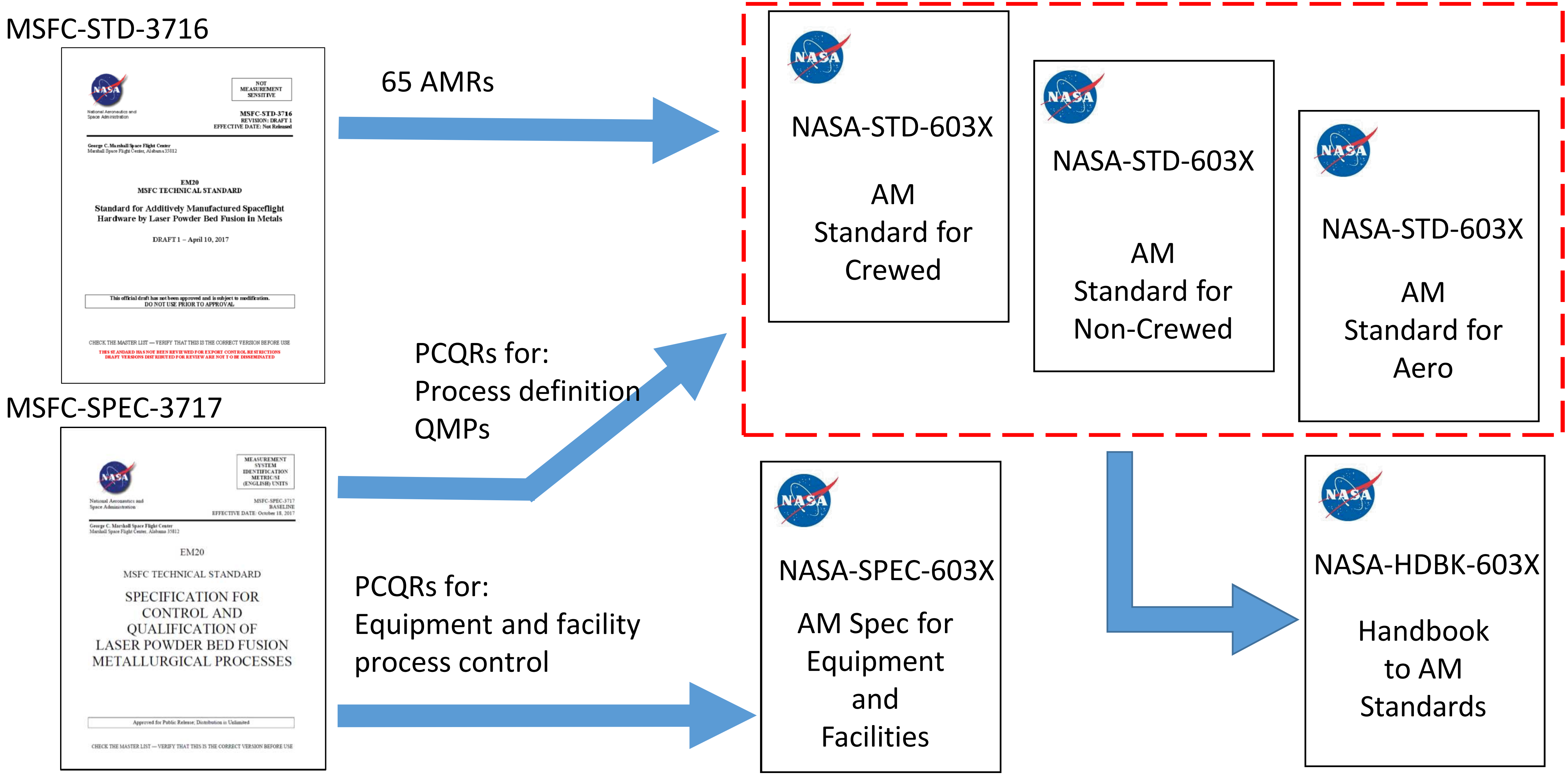
Broader Applicability to AM Processes

- Agency standards to encompass range of <u>mature</u> AM materials and technologies (not limited to L-PBF)
- Scope
  - Specific AM technologies will be included, but explicitly <u>not</u> limited
  - Specific materials type to be included are:
    - Metals
    - Polymers
    - Composites
    - Ceramics
  - Materials determined to be out of scope are:
    - Regolith
    - Printed Circuits

Proposed Document Structure

- Documents will be based on the principles of MSFC-STD-3716
  - The requirements summary as listed in Appendix F, Table VIII will be utilized and modified as appropriate.
  - Portions of MSFC-SPEC-3717 will be pulled into the NASA standards and generalized
    - *Metallurgical* Process definitions
    - Qualification of *metallurgical* processes
- A separate specification will be written to cover Equipment and Facility Process Control
- A NASA Handbook will be written to provide additional guidance and expanded commentary

Agency Document Structure



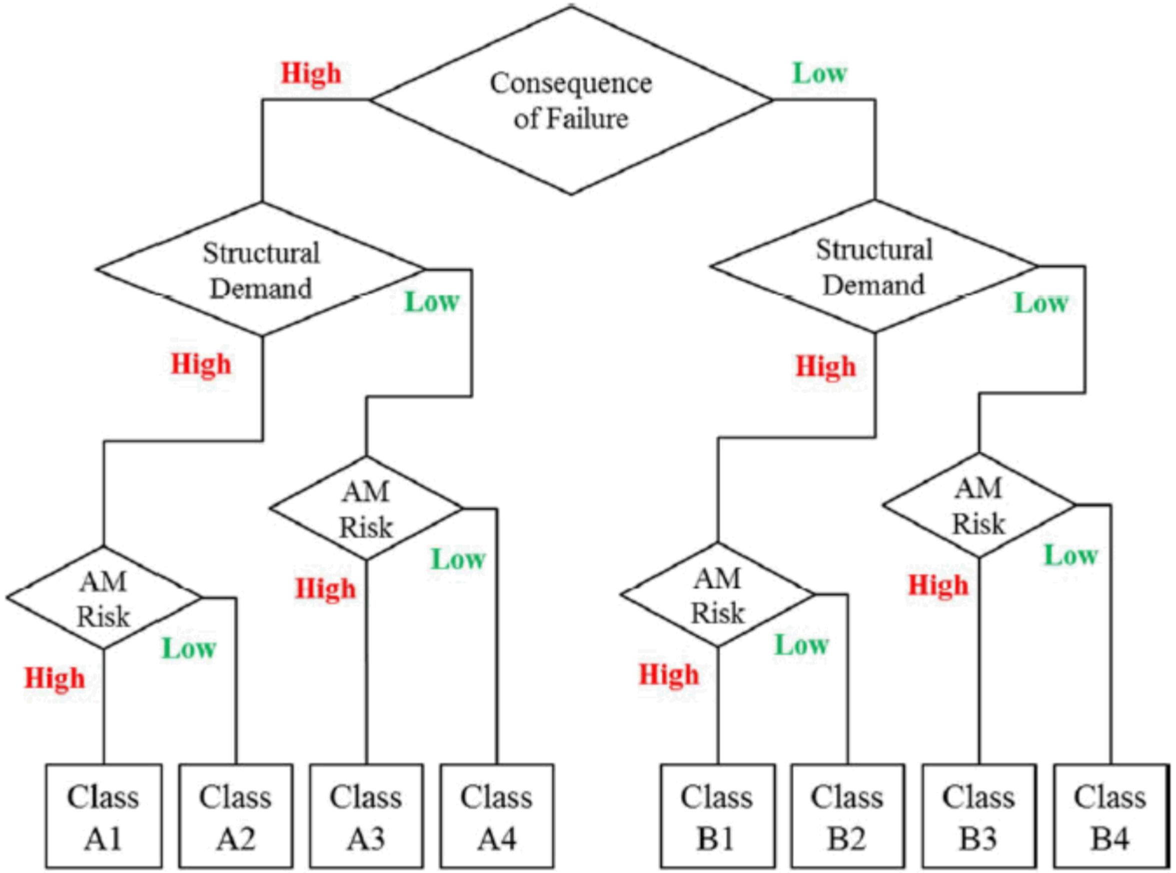
Rearranging of Requirements and Additions

- A decision was made to rearrange the order of the AMRs and PCQRs to create a document that is more product oriented
  - Gearing towards the Materials or Quality Engineer whose goal is AM part certification
- Additional requirements not in MSFC documents to be added:
  - Sub-contractors and partner requirements (AMCP)
  - Part drawing requirements
  - Non-metallic material properties

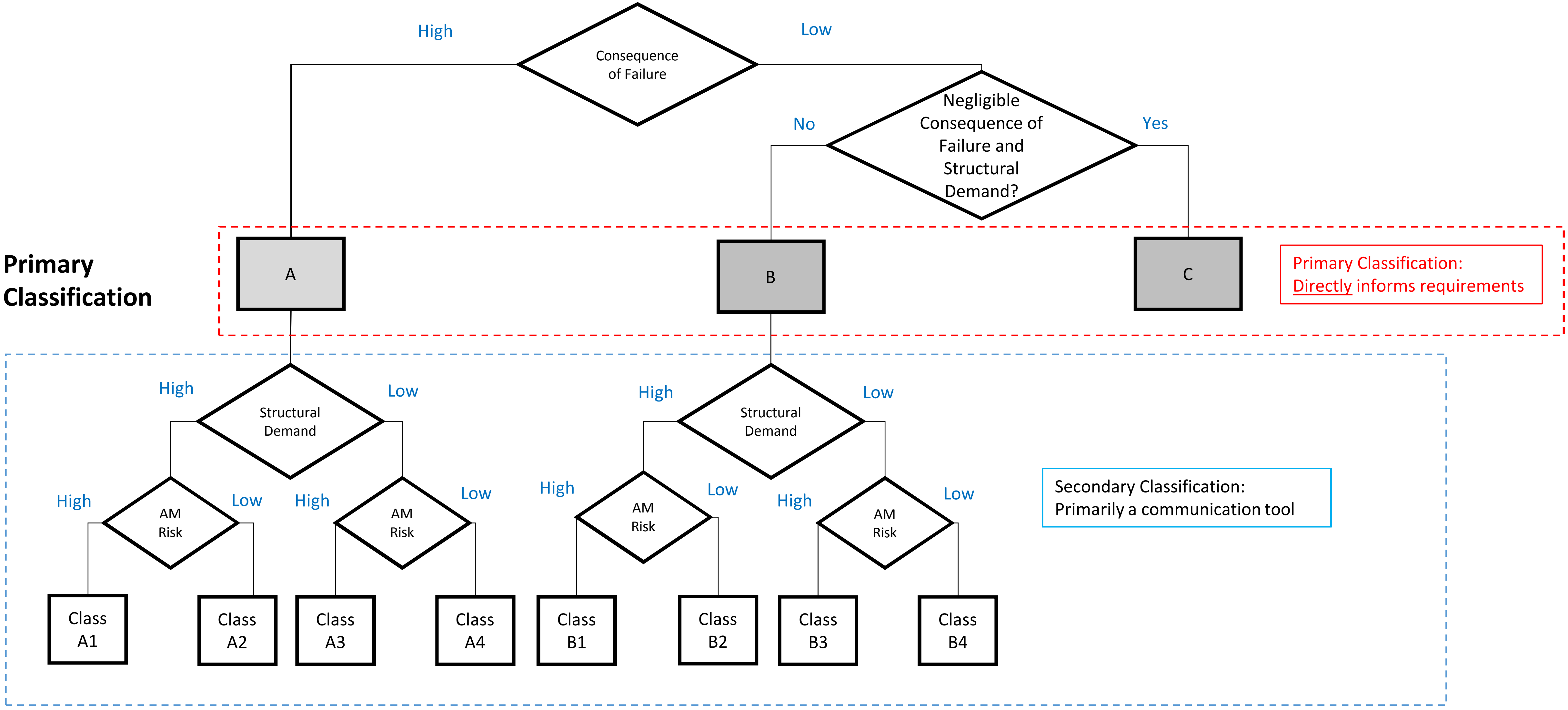
- Document outline
  - AM Control Plan (AMCP)
  - Quality Management System (QMS)
  - Equipment and Facility Control Plan (EFCP)
  - Qualified Material Process (QMP)
  - Material Property Suite (MPS)
  - Part Drawing
  - Part Production Plan (PPP)
  - Qualified Part Process (QPP)
  - AM Manufacturing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

Part Classification

- The MSFC-STD-3716 classification system was used as the starting point
- This system is risk-based and stems from the three primary questions typically asked when evaluating part risk:
  - Consequence of failure (What happens if the part fails?)
  - Structural demand (How severe is the stress environment?)
  - AM Risk (How challenging is part design and can the part be reliably inspected?)
- Part Classification in 3716 is primarily a communication tool, and does <u>not</u> directly inform most M&P requirements



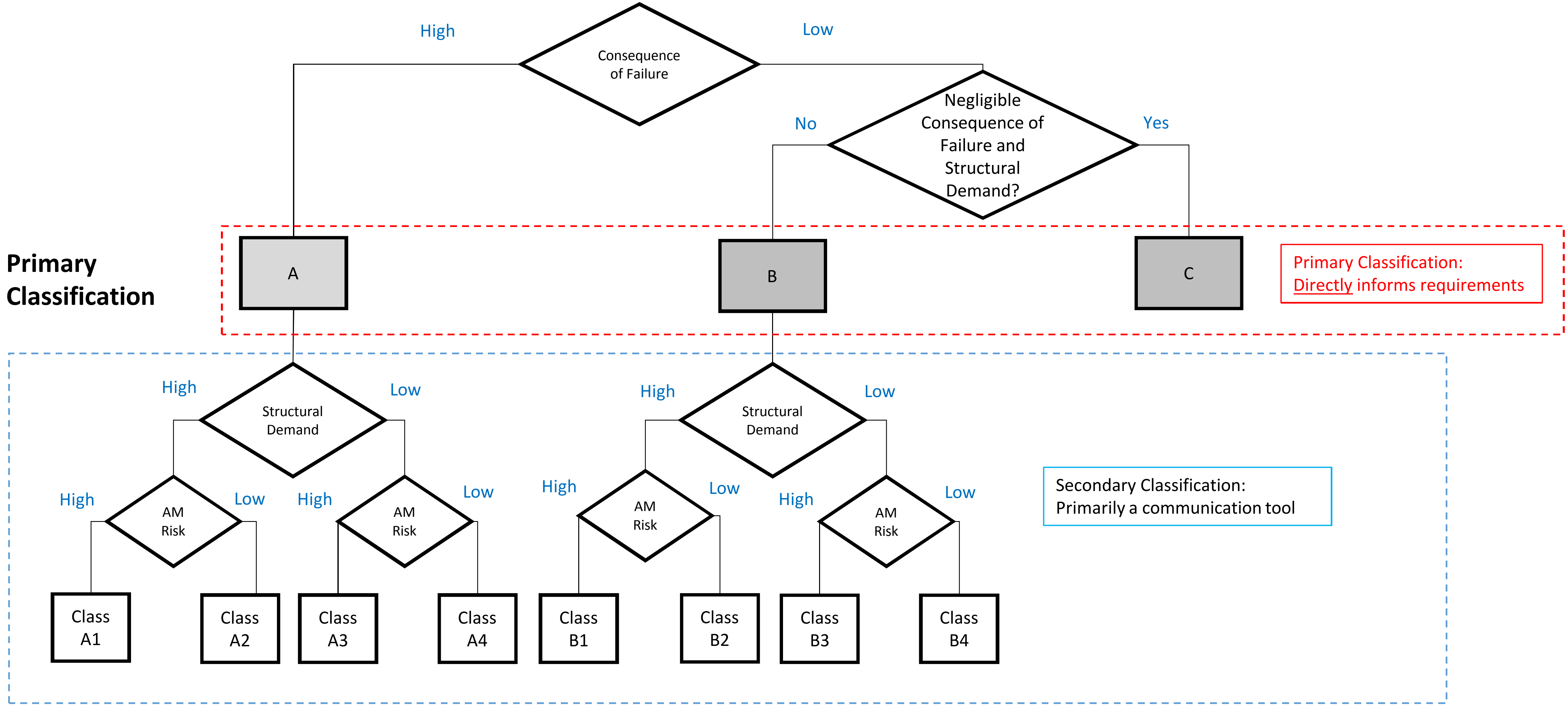
Revised Classification system



Consequence of Failure

- A part will be designated as Class A (High Consequence of Failure) if one or more of these criteria are applicable:
  - Fracture Critical per NASA-STD-5019A
    - For the Aeronautic Standard this will be replaced with a “Fatigue Critical” Criteria
  - If failure would lead to a catastrophic hazard (loss of life, disabling injury or loss of a major national asset)
  - If failure would lead to the loss of one or more primary/minimum mission objectives
    - For the Aeronautics Standard this criteria will be rewritten to allow tailoring for aircraft with a high risk tolerance

Revised Classification system



Negligible Consequence of Failure

- Philosophy: Parts warrant reduced quality assurance and material performance controls due to near zero (negligible) consequence of failure of the part. Consideration of consequence must include all possible end-uses of the part, including protoflight scenarios, or development hardware that may transition to actual flight hardware.

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

<u>The part must satisfy each of the following criteria:</u>

- ❑ Failure of part does not lead to any form of hazardous or unsafe condition
- ❑ Failure of part does not adversely affect mission objectives
- ❑ Failure of part does not adversely affect other systems or operations
- ❑ Failure of part does not alter structural margins or related evaluations on other hardware
- ❑ Failure of part causes only minor inconvenience to crew or operations
- ❑ Failure of part does not cause debris, FOD, or contamination concerns
- ❑ Failed part would not require repair or replacement is available and trivial

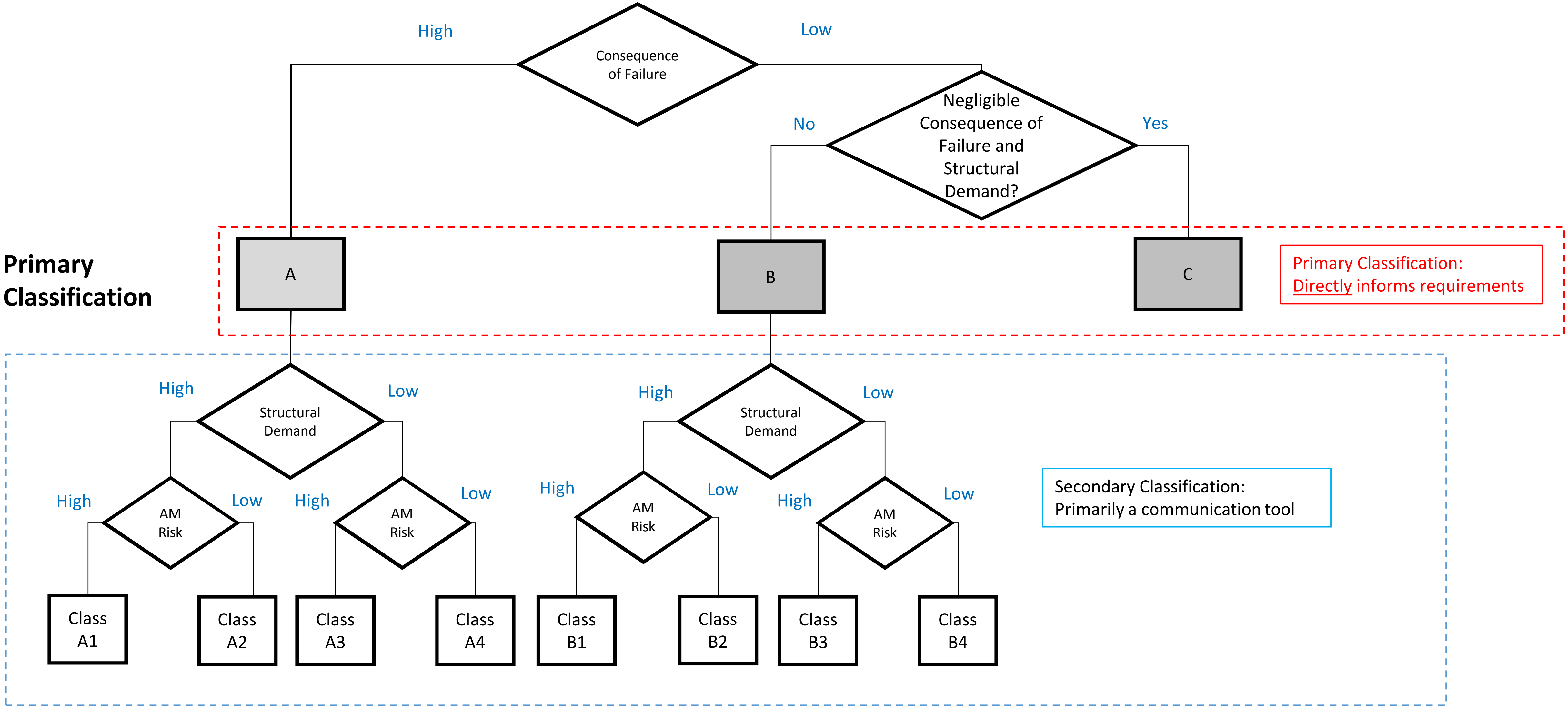
Negligible Structural Demand

- Philosophy: Parts warrant reduced quality assurance and material performance controls due to exceedingly low (negligible) structural demand on the part due to imposed loads and environment

The part must satisfy each of the following criteria:

- ❑ Loads environment is well defined
- ❑ Part is not exposed to environment with potential for material degradation
- ❑ Part is not primary structure
- ❑ Does not serve as redundant structure for fail-safe criteria
- ❑ Part is not designated Non-Hazardous Leak Before Burst
- ❑ Part does not contain, or serve as secondary containment, for a hazardous material
- ❑ Part is not subjected to impact loads
- ❑ Part has no threaded holes
- ❑ Part is not a fastener nor does it serve the purpose of a fastener
- ❑ MS UTS > 6 on local maximum principal tensile stress
- ❑ MS UTS > 4 on local maximum principal compressive stress
- ❑ MS Compression/bearing YS > 2 under fasteners

Revised Classification system



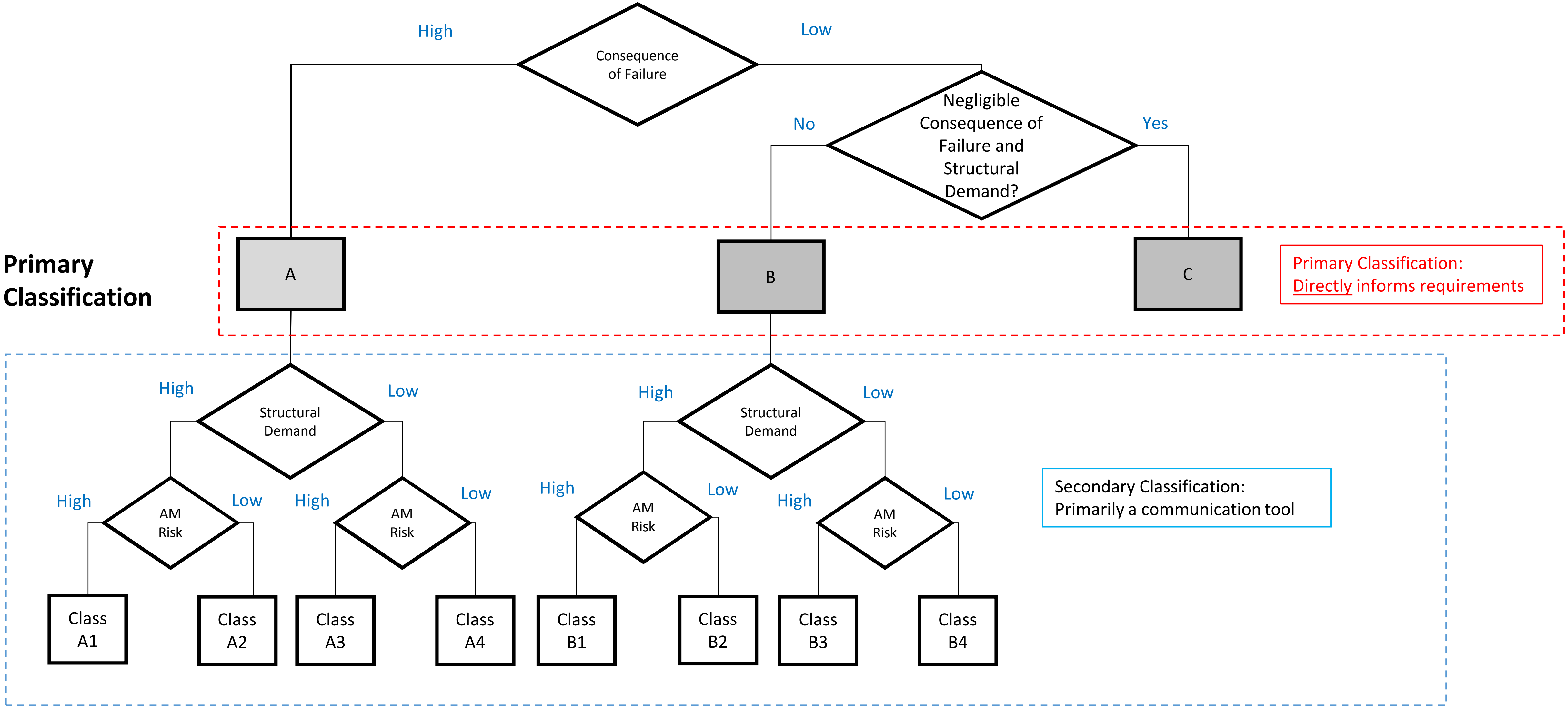
Structural Demand per MSFC-STD-3716

Material Property	Criteria for Low Structural Demand
Loads Environment	Well defined or bounded loads environment
Environmental Degradation	Only due to temperature
Ultimate Strength	Minimum margin* ≥ 0.3
Yield Strength	Minimum margin* ≥ 0.2
Point Strain	Local plastic strain < 0.005
High Cycle Fatigue, Improved Surfaces	Cyclic stress range (including any required factors) ≤ 80% of applicable fatigue limit
High Cycle Fatigue, As-built Surfaces	Cyclic stress range (including any required factors) ≤ 60% of applicable fatigue limit
Low Cycle Fatigue	No predicted cyclic plastic strain
Fracture Mechanics Life	20x life factor
Creep Strain	No predicted creep strain

NOTE: This table is specific to metals. Separate tables under development for polymers and ceramics

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

Revised Classification system



AM Risk Criteria per MSFC-STD-3716

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

AM risk = HIGH, if cumulative AM Risk score >=5

Tailoring approach

- The AMRs from MSFC-STD-3716 and the appropriate PCQRs from MSFC-SPEC-3717 will be used as the basis for tailoring
  - For each of the NASA standards a requirements matrix will be created
  - The AMRs and PCQRs will be revised to make more generic and applicable to all AM processes currently in scope
  - Matrixes will designate the intended use of each AMRs and PCQR based on part classification and mission classification/criticality
    - AW = As-written
    - T = Tailorable
    - D = Delete
  - Tailoring guidelines will be in the handbook

Requirements Matrix

Reqmt	3316/ 3317 Section Title	NASA-STD (proposed language)	Primary Author	Other Authors	A	B	C	
AMR-59	7.2 Tensile Properties	[AMR-59] Statistical assessment of AM material properties to derive design values for ultimate strength, yield strength, and elongation shall be governed the following: a. Design values are bounded by the 99% probability at 95% confidence one-sided tolerance limit estimated for the population. b. Lot variability requirements are defined by Section 5.4.2.1. c. A minimum of 100 degrees of freedom (specimens and lots) are required to initially establish design values. d. Design values supported by fewer than 300 degrees of freedom utilize a Design Value Margin greater than or equal to the estimated coefficient of variation (CV) of the available data; thus, Design Value ≤ (99/95 one-sided tolerance limit) * (1 - CV). See Figure 5, Substantiation of design value from MPS data, in Appendix C. e. The tensile property database is maintained by the CEO and updated on a periodic basis as additional data become available from process control-related activities, including witness sampling, pre-production article evaluations, QMP development, and machine qualification. f. Test and data analysis methodologies, except as noted in this requirement, following the intent of the MMPDS guidelines for static tensile property development.	Sarah	Jay, Bryan, Alex, JJ, Daniel Kim, Brian, Doug	AW	T	T	Section to be re-written with more specificity to AM and delinated by Part Class For Metals... Class A Parts: MMPDS, A-Basis Class B Parts: MMPDS, B-Basis Class C Parts: MMPDS, S-Basis (or tailor) Brian: Action to Work with Sam Cornder For Plastics, we need to bring in Alex, Daniel Kim, Jeremy Jacobs

Summary

- MSFC AM standards were developed out of necessity of timing and scope to provide a framework for negotiations of near-term AM policy in flight vehicles
- MSFC-STD-3716 and MSFC-SPEC-3717 have been implemented, in tailored form, for a range of projects across NASA (safety-critical to benign)
- MSFC-STD-3716 remains the only openly available standard that integrates requirements across all aspects of AM part production
- Agency-level AM standards are currently under development
    - Based on MSFC document philosophy
    - Developed for crewed, non-crewed, and aeronautics applications
    - Intended to be applicable to a broad range of AM processes and materials