

White Paper Discussion on Potential Approaches for Augmenting NASA-STD- 6030 Framework for In-Space Manufacturing

ISM-ASTRO

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List of Abbreviations

AM	Additive Manufacturing
ASTRO	Advanced Space Technologies for Resilient Operations
BOM	Bill of Materials
CM4QC	Computational Materials for Qualification and Certification
CMP	Candidate Material Process
D&C	Design and Construction
DfAM	Design for Additive Manufacturing
EDM	Electrical Discharge Machine
ESA	European Space Agency
ICME	Integrated Computational Materials Engineering
IMQCAM	Institute for Model-based Q&C of Additive Manufacturing
IPM	In-Situ Process Monitoring
IQ	Installation Qualification
ISM	In Space Manufacturing, referring to both manufacturing in microgravity environments (such as ISS) as well as on-surface environments (such as the lunar surface)
ISS	International Space Station
LEO	Low Earth Orbit
MSFC	Marshall Spaceflight Center
NDE	Non-Destructive Evaluation
NPR	NASA Procedural Requirement
NTRS	NASA Technical Reports Server
OQ	Operation Qualification
OWI	Operator Work Instructions
PCRD	Process Control Reference Distribution
PFMEA	Process Failure Modes and Effects Analysis
PPE	Personal Protective Equipment
PPP	Part Production Plan
PQ	Performance Qualification
QMP	Qualified Material Process
SMEs	Subject Matter Experts
SPC	Statistical Process Control
STRI	Science Technology Research Institute
TRL	Technology Readiness Level
AMF	Additive Manufacturing Facility
CT	Computed Tomography
DED	Directed Energy Deposition
ECLSS	Environmental Control and Life Support Systems
ECT	Eddy Current Testing
FAA	Federal Aviation Administration
LxC	Likelihood vs Consequence
ManD	Manufacturing Device
POD	Probability of Detection
PSPP VVUQ	Process-Structure-Property-Performance Verification, Validation, and Uncertainty Quantification

I. Disclaimer

This white paper is not written to be nor carries the authority to act as tailoring for NASA AM Technical Standards. Concepts discussed in this paper are to be taken as a philosophical approach to maturing in-space additive manufacturing methods for primarily metal parts, remaining largely process agnostic. Discussion is focused on core concepts and does not adjudicate specific design, metallurgical, or inspection techniques.

II. Introduction

The NASA Artemis Program depends on the development, production, and integration of many complex systems such as advanced propulsion, crew environment control and life support, landing systems, avionics, and cryogenic fluid management among others. Early demonstration missions are planned and underway to provide confidence in these newly developed systems needed to reliably and affordably return humans to the moon. The long-term Artemis, Moon Base, and future Mars objectives of establishing a permanent human presence on the moon through a sustained lunar base, long transit missions to Mars, and ultimately Mars surface missions, creates a new set of technical challenges not previously encountered in Low Earth Orbit (LEO) space missions. The feasibility of long-term missions will rely on the implementation of new technologies and capabilities to reduce logistical and resupply costs¹.

One technology that will be paramount to ongoing success is on-demand manufacturing at the point of need. There are economic and scheduling benefits of In-Space Manufacturing (ISM), but the ultimate driver and catalyst will be mission necessity. As missions become increasingly complex, manufacturing at the point of need will be critical to the survivability of the crew and the success of the mission. Cost savings and logistics reduction will certainly be the first gains realized as the lunar outpost is being established, but manufacturing capability will eventually evolve into a subsystem required within mission architecture. When this event horizon is reached, ISM becomes a necessity rather than an opportunity. As mission objectives and concepts of operations become more complex, the system designed for the mission must also increase in complexity. Planning and simulations will attempt to predict all possible issues that may arise, but there will be unforeseen events, especially during long duration missions. The crew must be equipped with the means to resolve these issues, which may involve modifying a design or designing new part entirely in-mission.

Manufacturing in space environments is a technical gap that spans across numerous disciplines such as design and construction (D&C) processes, materials, and quality assurance standards and specifications. Significant advancements for In-Space Manufacturing (ISM) technologies have proven successful to date, such as the commercially available polymer 3D printer installed on the ISS called the Manufacturing Device (ManD). Formerly known as the Additive Manufacturing Facility (AMF), the machine has produced over 115 end-use parts either in use on the ISS or returned to the Earth.^{2,3,4,5} Another breakthrough is ESA and Airbus Defense

and Space's Metal 3D printer technology demonstrator, installed in the ISS in 2024. Using the laser-wire directed energy deposition process with 316L stainless steel, the machine has printed tensile and bending fatigue specimens.⁶ These efforts, although breakthroughs in the field, have been primarily focused on science, demonstration, and low-risk parts.⁷ Further technology and process maturation is needed to advance AM for ISM applications to produce reliable, high-precision, fine-detail resolution metallic components for missions in space.⁸

To ensure the safety of crew and mission, ISM technology development efforts must be paralleled with efforts to evolve NASA's underlying approach and requirements. The current framework and methodologies described in NASA-STD-6030⁹ and NASA-STD-6033¹⁰ are challenged by in-space manufacturing environments. Manufacturing components in-mission rather than pre-mission requires significant tailoring approaches to the existing framework and the inclusion of new requirements not needed for terrestrial manufacturing. Note that tailoring of NASA technical standards is providing a revised "shall" statement that meets the intent to the original requirement. Tailoring is the process used to adjust or seek relief from a prescribed requirement to meet the needs of a specific program or project. Tailoring is both an expected and accepted part of establishing proper requirements. This paper discusses some of the challenges specifically pertaining to utilizing AM technologies for in space applications, along with suggested guidance for the closure of the technical gaps. A qualification architecture definition is required to be established alongside technology development efforts to enable the successful implementation of AM technologies in space.

III. High-Level Philosophical Differences

On-demand manufacturing in space will require a shift from a pre-flight qualification approach to an in-mission qualification approach. As the environment, available material, available equipment, and available operator time are substantially different, implementation of NASA-STD-6030 and NASA-STD-6033 for on-demand manufacturing in-space or on the lunar surface will require fundamental tailoring of the standards. Currently, the standards assume production environments are tightly controlled, and extensive pre-flight qualification and verification activities are conducted to demonstrate confidence that components will perform as intended. Capabilities in ISM environments are currently uncertain, with minimal infrastructure in place for verification testing and analysis. The standards are built on rigorous foundational process control informed by deep understanding of material state from analyzing and testing large sample quantities to confidently understand the inherent defect state of the materials. The foundational process controls are demonstrated to be repeatable through qualified material process (QMP) testing and are continually verified throughout part production via testing and analysis compared back to ground truth part-agnostic data. Stated simply, the process is fully qualified before and independently from part production, which allows for clear acceptance criteria and the predictable performance of parts in-service. In this state, designs are locked down and hardware is produced before launch. Production infrastructure is stable and well equipped

with instrumentation and inspection capability, and parts can be tested destructively to verify component life. However, currently there is minimal infrastructure in space regarding verification, inspection, and testing capabilities to align with the existing philosophy, both at the coupon and component level. Furthermore, the validation methods that are available in-space will be employed at a far lower level of rigor due to resources and crew time alone. This challenges some of the foundational process control concepts and subsequently many of the part verification concepts, which are heavily relied upon for acceptance rationale under the current paradigm.

The in-mission qualification methodology will likely evolve over time as technology and verification methods mature. Initially, on-demand manufacturing capability will likely outstrip capability for on-demand verification. As the effects of microgravity and radiation on manufacturing processes remain largely unknown, this early phase will require accepting higher uncertainty in material properties. To mitigate this risk, the initial paradigm will shift away from relying on exact material properties and instead depend heavily on terrestrial manufacturing comparisons, conservative safety margins, and system architecture. Consequently, early advantages for in-space additive manufacturing would trade on mission flexibility, agility, and longevity rather than lightweighting of components. In addition to designing conservatively, there will be a strong reliance on system redundancy; for example, highly accessible in-habitat parts can be accepted with a higher risk of failure because redundancy offsets the uncertain quality. Eventually, with further maturation, part qualification will evolve to utilize advanced in-space verification methods and alternative approaches, such as in-situ monitoring and Computational Materials-informed Qualification and Certification (CM4QC).

While redundancy and conservative design margins are necessary near-term mitigations for these unknowns, In-Situ Process Monitoring (IPM) is emerging as a critical qualification support tool.¹¹ Terrestrial AM industries are increasingly looking toward IPM to provide greater confidence in part quality and reduce reliance on traditional ex-situ non-destructive evaluation (NDE). IPM primarily helps establish process stability and flag anomalies as they occur by capturing layer-wise data. While there is not yet a standalone replacement for post-build inspection, integrating IPM data with statistical process control (SPC) and defect mapping frameworks can heavily supplement the limited qualification data available in-space. As this technology matures, it offers a pathway to gradually shift the paradigm away from strict physical over-engineering toward real-time digital process assurance.

In the near term, for LEO destinations and the early phases of Moon Base, it is therefore likely that safety- and mission-critical parts will continue to be manufactured on Earth and launched in payload stowage. Lower risk and certification components are expected to trade better in the short-term given the lack of infrastructure, verification methods, and the process uncertainty that currently exists. However, further development of the processes and technologies described in this paper will allow for increasingly critical parts to be manufactured

in space and for the long-term advantages of ISM to be realized. A vision for such a stepwise increase in criticality is described below in Figure 1.

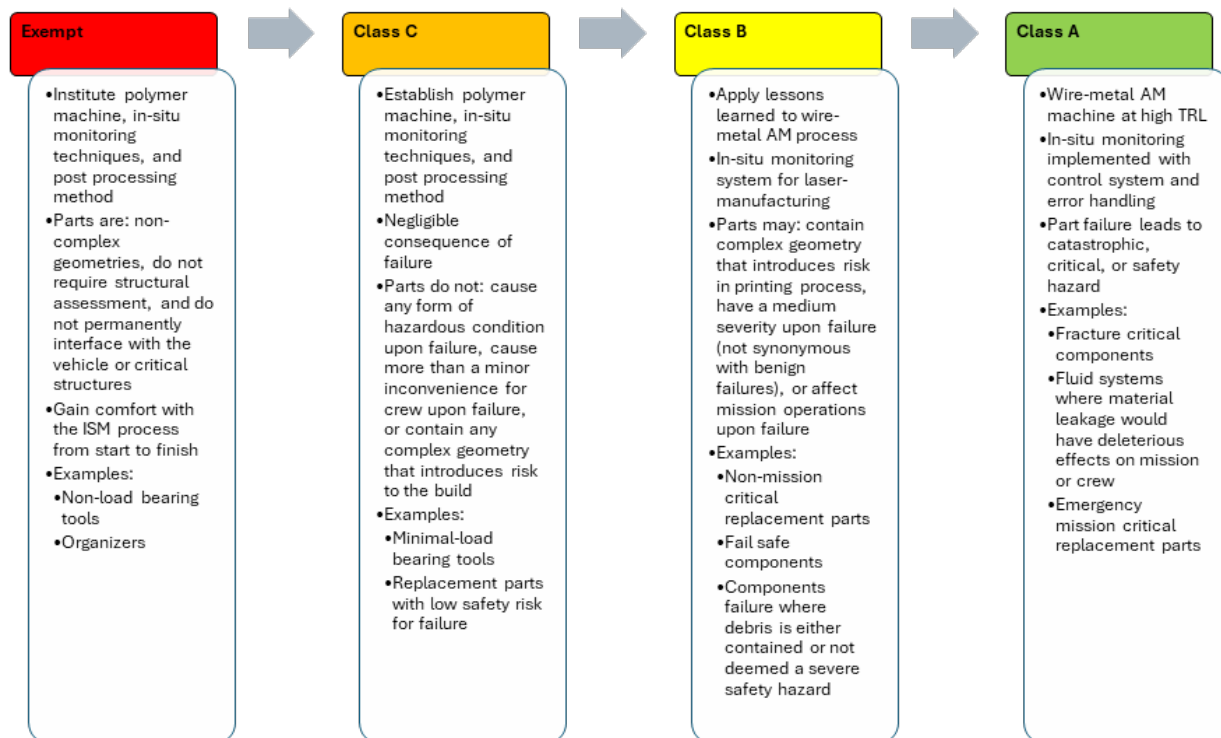


Figure 1: In-space Additive Manufacturing Qualification Vision

Figure 1 Note: This is the vision NASA hopes for ISM. It is recognized that this vision does not reflect the current industry.

IV. Risk Posture and Risk Assessment

Each of NASA's Exploration programs operates on a risk-based system with a unique risk posture. NASA AM Subject Matter Experts (SMEs) work to classify AM hardware in accordance with the NASA-STD-6030 part-classification architecture. Understanding NASA-STD-6030 hazard definitions (NPR 8715.3D) will assist in part classification and risk assessment.

The current approach for using AM flight hardware is to understand the failure probability and to have mitigations in place. The decision to fly a component requires a significant amount of data and analysis to inform this decision. AM part classification is a critical part of the risk analysis and determines how NASA Technical Standards are applied to each component. A critical best practice is to engage with NASA AM SMEs during the design and part classification phase to avoid potential misclassification of AM components. When each AM component is classified, it is done through the lens of that program's risk posture.

When using NASA-STD-6030 AM Part Classification Flow Chart (Figure 2) the first question that is asked is, "What is the consequence of failure?" NASA-STD-6030 requirements are broken out by part classification, where stringency of requirements apply to "Class A", "Class B", and "Class C" AM components in descending order. Rapid determination of part classification would be required to effectively levy requirements on new components built on a mission. Additionally, in an off-nominal situation, this decision might need to be made with less information, resources, and time than available in some cases (e.g. in the event of a known replacement component). However, in that scenario, it would be likely that high level of risk would need to be accepted.

NASA-STD-6030 states that AM components may not be classified as "low risk" per NASA-STD-5019, requiring fracture analysis to be performed.¹² In fracture analysis, if an AM component is found to be "fracture critical" it would be classified as "Class A", meaning failure of the part would produce a catastrophic, critical, or safety hazard, and/or the part is defined as mission critical by the program or project. However, applying this strict terrestrial standard 'as-is' to ISM is currently impractical due to the lack of on-orbit infrastructure for rigorous fracture analysis, post-processing, and traditional NDE.

The vast majority of components to be considered for on-mission production would therefore need to fall under Class B/C hardware to have a chance of meeting the imposed fracture control requirements, at least in the near term. Applications would be limited to such items as mounting brackets, component covers, enclosed static parts, and handheld tools. Consequently, to realize the full value of ISM, the requirements of NASA-STD-6030 and NASA-STD-5019 will ultimately need to be tailored, waived, or heavily modified, potentially relying on conservative design margins, system redundancy, and In-Situ Process Monitoring (IPM) to accommodate the constraints of on-mission production.

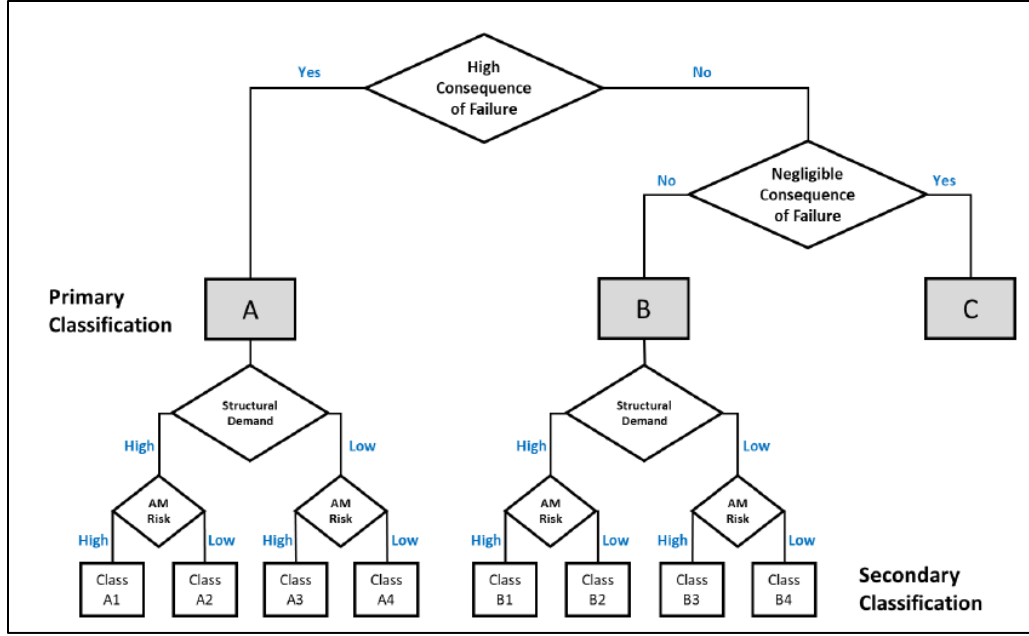


Figure 2: NASA-STD-6030 AM Part Classification Flow Chart

V. AM Qualification

Since AM material and process qualification (which inherently includes machine qualification) are critical to produce quality AM components, it is important to address how AM industry terminology relates to NASA-STD-6030 and NASA-STD-6033. The AM industry commonly uses the terms Installation Qualification (IQ), Operational Qualification (OQ), and Performance Qualification (PQ),¹³ as found in AMS 7032. While NASA-STD-6030 and NASA-STD-6033 do not call these out specifically, the concepts are incorporated in Figure 3, where orange represents IQ, blue represents OQ, and grey represents PQ.

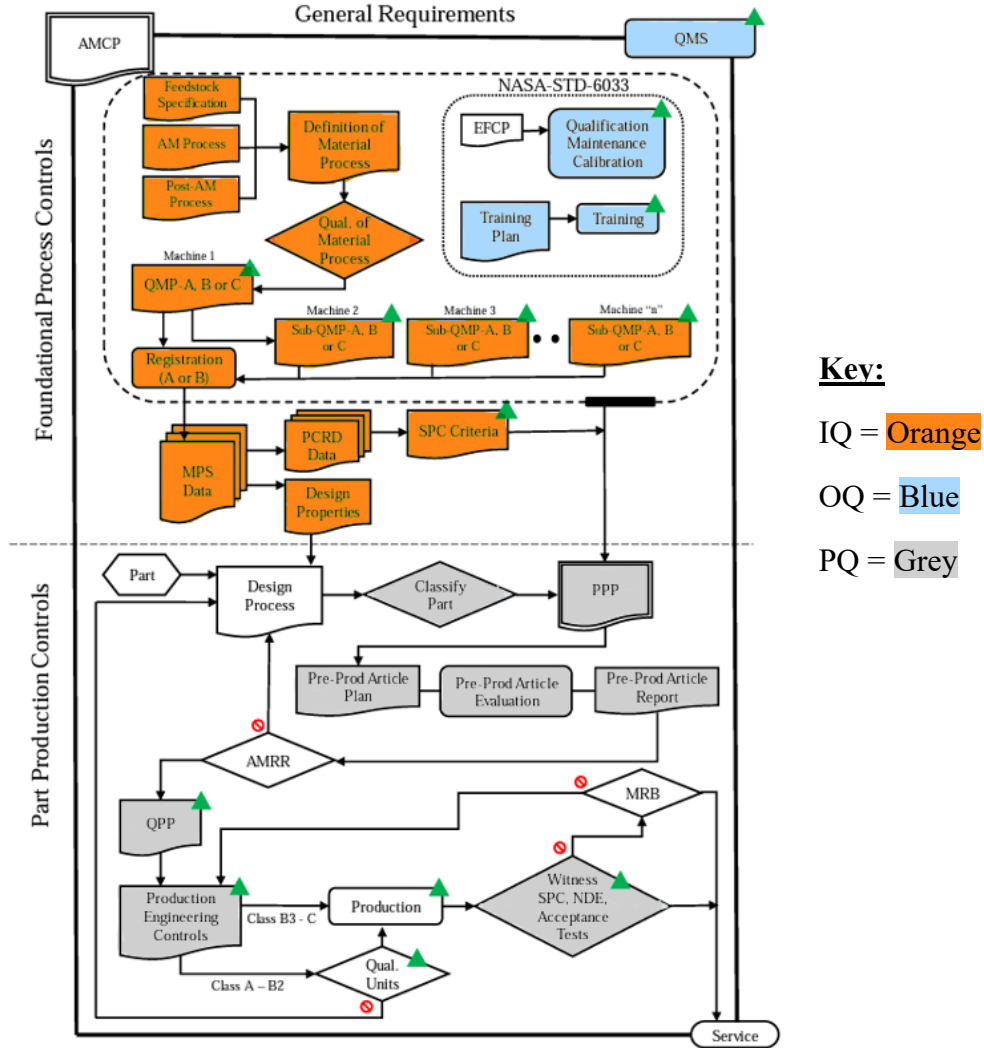


Figure 3: Key Products and Processes for NASA-STD-6030 (Figure 2)

VI. Material Properties and Selection

Presently, material allowables for nearly all metallic materials manufacturing techniques come from databases consisting of large sample quantities with statistical significance that account for inherent variation from feedstock lots, processing variability, in-use environments, etc. The leap to manufacturing in space introduces new environmental variables that are not currently well understood with respect to their impact on material quality. In addition, the ability to control process variables may be more difficult in off-world environments. Data generated in-space will be heavily scrutinized until the process can be fully matured. The approach to developing terrestrial AM material properties relies on repeatability. An entirely new approach will be required for material properties of ISM AM properties. This new tactic will have to consider the lack of comparative data and ability to perform the current required amount of material testing.

Because microgravity fundamentally alters melt-pool dynamics and thermal gradients—leading to differences in porosity and solidification compared to terrestrial baselines^{14,15,16} —space-built material properties will inherently differ. Furthermore, performing traditional physical property testing (e.g., tensile or fatigue testing) off-world is logistically prohibitive due to equipment mass and volume constraints^{17,18}. Consequently, the expectation for ISM is a paradigm shift away from physical materials test laboratories. Instead, the generation of material allowables and part acceptance will rely heavily on 'digital certification' driven by In-Situ Process Monitoring (IPM), physics-informed predictive models, and the generation of digital twins to certify part quality in real-time.

VII. Feedstock Considerations

Feedstock material selection is critical for crew safety and utilization in specific applications, and a separate white paper is in-work on the metals manufacturing technologies most suited for ISM. In the current state of AM in space, off-Earth environmental and safety factors limit the use of powder materials (metal, regolith, polymer) for several reasons. First, loose powder leads to inhalation and contamination risks, which are catastrophic hazards to astronauts and Environmental Control and Life Support Systems (ECLSS). Terrestrially, workers are required to wear personal protective equipment (PPE) such as a respirator with certification, gloves, and protective clothing when handling powders. Furthermore, the suspension of fine powders within the cabin atmosphere would only be heightened by lower gravity environments. Additionally, powders such as aluminum and titanium come with explosion risk with exposure to low amounts of energy. Instead, metal, regolith, and polymers are preferentially considered in a wire form, as currently used for wire-based directed energy deposition (DED) processes. The safe handling of the AM material must be at the forefront with these analyses performed at minimum for feedstock selection: off-gassing analysis, recyclability, fracture analysis, fluid compatibility analysis, and support removal. The first batch of material that will be used during the mission will be terrestrial, virgin feedstock. In-situ harvested materials or recycled materials to generate additional feedstock may need to be considered to reduce resupply costs. Missions must launch the correct amount of material with additional amounts for conservatism, re-use the material, and/or create new feedstock from what is available to the crew.

The role of feedstock specification and its integration into the qualification of a material process under NASA-STD-6030 is highlighted in Figure 4.

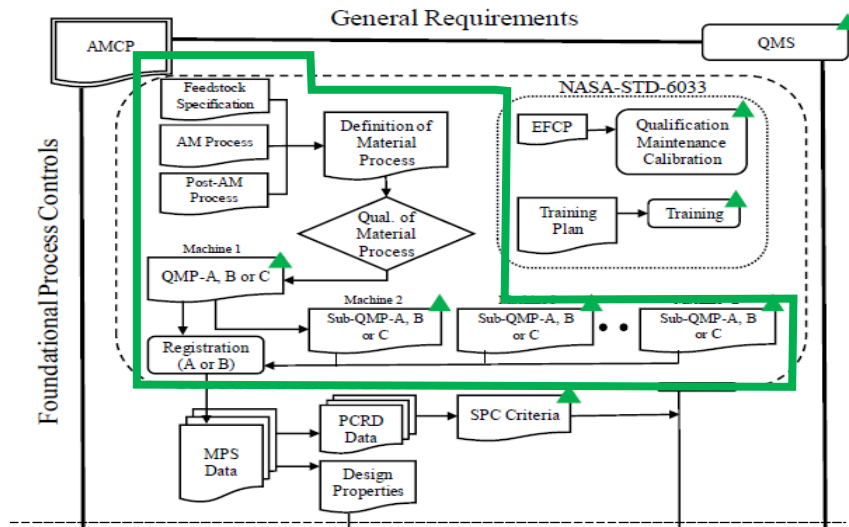


Figure 4: Foundation Process Principles of NASA-STD-6030

VIII. Material and Machine Qualification

Machine qualification and material qualification are coupled together as presented in NASA-STD-6030 and NASA-STD-6033.

A. Developing a QMP

A QMP has three primary control elements: feedstock controls, fusion controls (e.g., laser power, wire feed rate, and thermal management), and post processing controls. A single combination, or recipe, is developed through rigorous characterization and sensitivity trials to understand susceptibility to process variation and to determine the process window. With space environments, fusion controls are particularly vulnerable to environmental shifts, such as thermal radiation differences in a vacuum or microgravity affecting melt pool dynamics. Once a candidate material process (CMP) is achieved, it can then be qualified as a resulting QMP. The combination is locked down completely at this point, and through the extensive prework phase upfront, the locked down QMP should yield predictable microstructure and mechanical performance. As the ability to tightly control key aspects of a material process in-space is currently unknown, this gives an unstable foundation and calls into question the validity of an in-space QMP. The initial phases of ISM certification may present challenges to navigate, until modern techniques are matured to develop reliable and repeatable data for an in-space QMP.

One such method to consider for development is verifying prints with Earth-based machine replicas and known parameter sets before printing in space. Although the environment is not the same, running the process on the ground first establishes an essential terrestrial baseline. This allows engineers to generate "ideal" test specimens, perform extensive destructive and non-destructive material characterization (such as detailed microstructural and tensile analysis), and develop comprehensive troubleshooting models. By comparing the robust terrestrial data against the limited telemetry and telemetry-based monitoring available from the flight system, researchers could quantitatively analyze environmental differences and actively mitigate risks. Another precaution would be to verify successes on low criticality hardware first. This practice would prevent a process with a low technology readiness level (TRL) from being used to manufacture parts for applications outside of its capability limits. The near-term reality of in-space AM would prohibit the production of AM parts for Class A applications until lower criticality parts can be made safely and reliably.

B. Machine Qualification and Maintaining Qualification

In addition to machine material qualification, an understanding of how the AM machine is set up, calibrated, and maintained is critical for upholding a healthy machine. NASA-STD-6033 requirements revolve around equipment and facility requirements. The AM machine that would be used for ISM would be required to comply with those requirements. The first topic to address is operator training, as having a trained team to operate the AM machine during mission operations will be a critical step for mission success. This training must include machine capabilities and constraints, safety hazards, preventive maintenance on the machine, machine

operations, and material handling (storage, scrap material disposal, etc.). Pre-mission training will be necessary for crew members, with an OWI physically and digitally kept with the machine for reference. While on-mission, setup and build-removal will need to be completed by the crew while monitoring the build and addressing errors could likely be done by remote operators on Earth. This strategy aligns with the 2026 NASA Civil Space Shortfalls related to developing Moon Base.¹⁹

Selecting the AM machine must include careful analysis in the ease of use (printing components, maintenance, and repair) of the system. Ease-of-use case considerations are important to avoid a complex system that requires extended crew bandwidth for operations. Maintaining a qualified machine state in-space will be highly difficult if relying solely on traditional terrestrial maintenance intervals and repetitive test prints. To support this, IPM systems such as melt pool monitoring are being evaluated as continuous machine health diagnostics. By establishing a digital 'machine fingerprint' during initial qualification, subsequent production runs can be monitored against this baseline. If the in-situ data shows a drift in parameters, the system can flag the machine for targeted recalibration rather than relying on fixed calendar maintenance schedules. In terrestrial environments, using IPM to establish machine equivalency and baseline signatures has demonstrated the potential to reduce the requalification burden. Adopting similar guidance for in-space operations positions IPM as a valuable support tool to help minimize machine downtime and significantly reduce the crew bandwidth required for maintenance.

IX. Post-Processing

There are many on-Earth post-processing steps that need to be developed for in-space metal AM. First, metal AM parts naturally build up residual thermal stresses. These residual stresses can cause warping or cracking if the component is not heat-treated or stress-relieved prior to baseplate removal. Post-processing requirements must be carefully considered while trading an AM process and material. For a detailed analysis on selecting manufacturing processes that minimize post-processing dependencies in space, see the upcoming *Strategic Pathways for Advancing In-Space Manufacturing of Metal Parts* white paper.

In addition, a machine capable of removing prints from the build plate and preparing a flat surface for the next print could be required, such as a wire Electrical Discharge Machine (EDM) or a band saw. Furthermore, the removal of support material may be required, depending on the geometry of the part. It is recommended that design for additive manufacturing (DfAM) principles, such as cone supports and snap-off teeth with lattice support structures, should be applied to facilitate support and build plate removal. Cone supports are sacrificial material connecting parts with the baseplate to absorb residual stresses and minimize the contact area between the build and build plate. However, the intentional creation of this sacrificial support material consequently increases the necessity for a robust, closed-loop recycling process to

reclaim the wasted feedstock. If necessary, an air chisel could be used for manual support/build plate removal, but it would not resurface the build plate.

Both heat-treatment and post-process machining may be required if a replacement part requires a tight-tolerance mating surface, O-ring groove, or threaded hole. The current in-space heat-treatment and machining capabilities are minimal and limit what kind of parts can be produced.

X. Part Planning and Acceptance

NASA-STD-6030 employs numerous planning, verification, and risk reduction tactics to develop part acceptance rationale. Process verification testing is performed via witness coupons (of which full height contingency samples are often printed alongside production parts to aid in anomaly investigations), extensive NDE inspections take place, pre-production articles are destructively tested, components are proof tested, and in some cases subjected to system level qualification testing. The current approach fully documents all requirements for component acceptance in the Part Production Plan (PPP), which includes verification steps that are largely unavailable for ISM components. This required part acceptance rationale and pre-production planning loop is highlighted in Figure 5. With the verification steps for ISM at a low TRL, there is a need for heavily conservative safety design and part application restrictions for certain hardware criticalities. The current NASA methodology is that all AM part class components require verification steps, just at varying amounts. Therefore, specific class components shall not be manufactured until development of repeatable verification steps are in place for the class's requirements. The methodology includes starting with Class C parts of well-known processes such as polymer AM, then working towards wire-based metal AM at Class B.

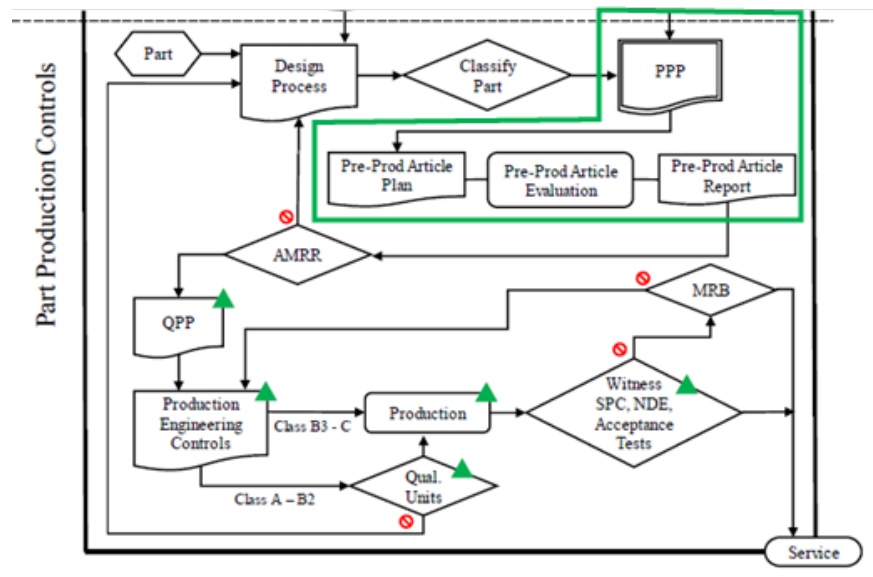


Figure 5: The Part Production Plan (PPP) of NASA-STD-6030

Recent development efforts have demonstrated that in-space ex-situ NDE for verifying surface and volumetric integrity is feasible by utilizing technologies such as X-ray computed tomography (exemplified by the GSFC Voxel CT system²⁰) and eddy current testing (ECT). However, standard ex-situ NDE methods introduce significant logistical challenges when applied to ISM, specifically regarding severe power limitations and heat dissipation constraints in a vacuum or microgravity environment. Under NASA-STD-6030, critical AM parts are generally evaluated using the Special NDE protocols defined in NASA-STD-5009²¹. Demonstrating compliance with these protocols typically requires energy-intensive inspection equipment, physical Probability of Detection (POD) test articles, and Earth-based personnel to perform and interpret the evaluations. This reliance on Earth support is difficult to sustain in deep-space operations, where communication bandwidth is limited and mission architectures prioritizing autonomous troubleshooting are becoming essential.

Beyond these logistical constraints, the physical characteristics of printed parts present additional challenges. AM components often cannot be fully evaluated using standard ex-situ NDE methods governed by standards such as NASA-STD-5009. These conventional methods are frequently limited by complex geometries and lack the capability to reliably detect AM-specific internal flaws, including lack of fusion, keyhole porosity, and micro-cracking.

Consequently, because conventional 5009 inspection methods are not easily scaled for in space manufacturing environments or for complex AM components, IPM offers a valuable pathway to reduce dependence on ex-situ inspections and support more Earth-independent operations. IPM can track process stability, identify thermal deviations, and detect immediate layer-wise anomalies. Nevertheless, its limitations must also be acknowledged, as most IPM modalities capture transient process signatures rather than the final solidified material state. As a result, definitively correlating a sensed anomaly to a specific structural defect remains challenging and prone to false indications.

To bridge this gap, engineers are working to correlate process-induced defects with in-situ sensor signatures during terrestrial baseline testing, enabling the establishment of statistical thresholds for real-time anomaly detection. Although IPM is not currently a standalone replacement for post-build inspection, maturing these capabilities gradually shifts the manufacturing process toward one that integrates fabrication and active inspection. Over time, this growing support capability offers a realistic pathway to develop part-acceptance rationale and maintain structural-integrity requirements for components manufactured in-mission.

Another consideration needed is how the configuration of the end-item will be managed as replacement parts are made in space. The framework needs a requirement for updating the system's as-built Bill of Materials (BOM) and system-level digital twins. Mission control must always know exactly which parts on the end-item are original and which are AM replacements for understanding the system's health and capabilities.

XI. Design Approach

The ability to additively manufacture in-space opens design opportunities while bringing some process considerations. Parts made in space have less environmental loads to endure such as launch loads, meaning they may be able to lower their structural requirements depending on the application. Parts can also be designed with modularity and repairability in mind since the capability to replace highly fatigued sections would exist. Additionally, ISM parts bring the opportunity to lower system failure modes, such as lowering the number of mechanisms, since parts no longer need to constrain to a launch volume and mass^{Error! Bookmark not defined.}. The component's risks of failure must still be kept in mind though. NASA recommends performing fault tree analysis to understand the risk of the component's failure in use, especially for new designs developed in-space. NASA utilizes risk matrices with a Likelihood vs Consequence (LxC) score to evaluate each risk.

However, any part would need to include Design for Additive Manufacturing (DfAM) principles. The current AM design for space-applications approach requires locked down designs far before manufacturing occurs. The methodology falls apart when material properties are less predictable and needs become more rapid. One replacement approach could be to bound a worst-case scenario property, with designs specifying an envelope and heavily conservative design margin rather than locked down requirements. This presents a need for rapid verification workflows. Even though these parts will be heavier, larger, and require more feedstock, the choice would increase reliability. Note, for replacement parts, a trade will need to be done on a part-to-part basis whether to bring a replacement part or manufacture in-space due to this process using more material. Lastly, it must be kept in mind that metal AM parts have rough as-printed surfaces, which contributes to a decrease in fatigue properties.

Another consideration is the data integrity of the print file used by the in-space AM machine. Transmitting the file over radio to the spacecraft introduces the risk of corruption and will necessitate packet protection like protocols already in place. The increased radiation environment increases the risk of a bit flip error, both on the main computer and while printing. Before executing a build, a verification step will be necessary to simulate and ensure the tool-pathing is as intended. Programming in fail-safes will be critical to the safety of the system to prevent hazardous failure states. Shielding components with circuitry (such as laser, actuator, gantry/robotic, etc. control systems) will be required for high radiation environments.

XII. Production Control

Production control is the bedrock of all modern manufacturing processes. AS9100²² and ISO9001²³ are a must-have for any manufacturer providing aerospace grade hardware. This is enabled by appropriate staffing and division of responsibilities to hold all parties accountable. Clearly, an analog for this structure in space is not practical due to crew and time limits. Additionally, training programs and operator certifications for sensitive processes typically

require significant training hours and on the job experience to obtain higher echelon certification levels. Astronauts would be trained in operating the machine before flight but will likely not have time to develop the deep subject matter expertise in-mission to troubleshoot and resolve rare machine errors or complex material science issues. For example, root cause and corrective action investigations of production anomalies/failures will require tailored approaches. Remote support will certainly be available; however, a gap still exists in evaluating the physical material itself. Crew time and crew permanence are two new constraints that must be accounted for in tailoring approaches. However, as ISM matures into an integral component of lunar and Martian mission architectures with a sustained surface presence, it is anticipated that mission planners will allocate a higher priority—and consequently more dedicated crew time—to these manufacturing and maintenance tasks.

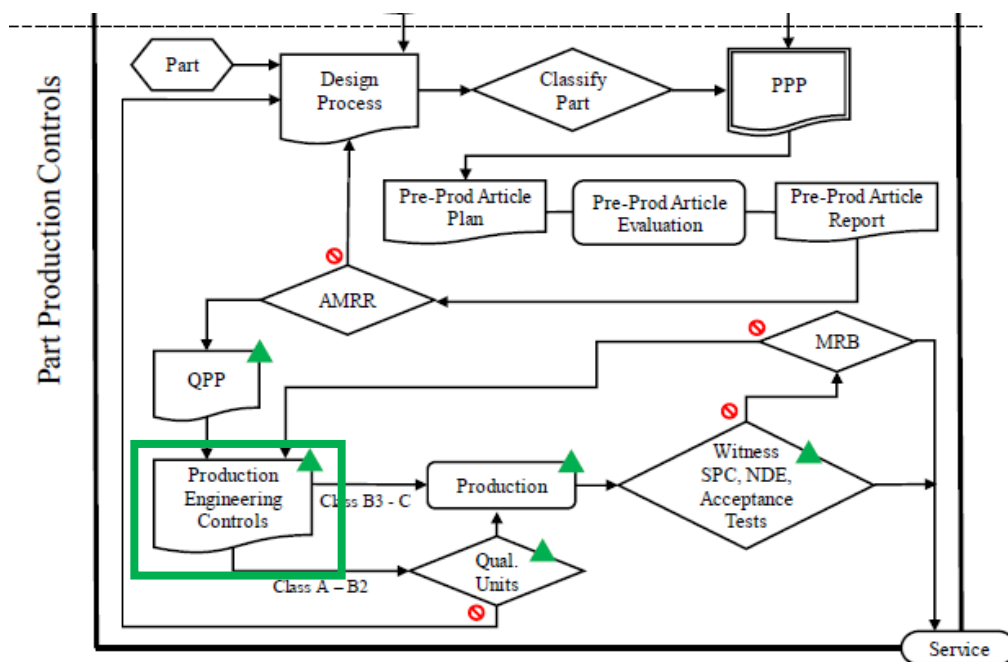


Figure 6: Production Controls of NASA-STD-6030

As builds are accumulated, under the production engineering controls highlighted in Figure 6, continual statistical analysis establishes design values and part acceptance criteria. In the standard terrestrial process, this data is used to establish an A-basis value that 99% of the specimens exceed, allowing a design value to be picked, including a margin (5.9% for example) as illustrated in Figure 7. This conservatism allows the design to capture all statistically likely forms of potential variation, with the mean and standard deviation values then used to establish acceptance criteria (Figure 8). However, it is highly unlikely that an A-basis will be established for specimens manufactured in space—at least in the near term—due to the massive volume of physical testing required. Until the level of part criticality demands such rigorous statistical

validation, off-world manufacturing will likely rely on alternative mitigation strategies, such as digital certification or conservative, B-basis equivalent safety margins.

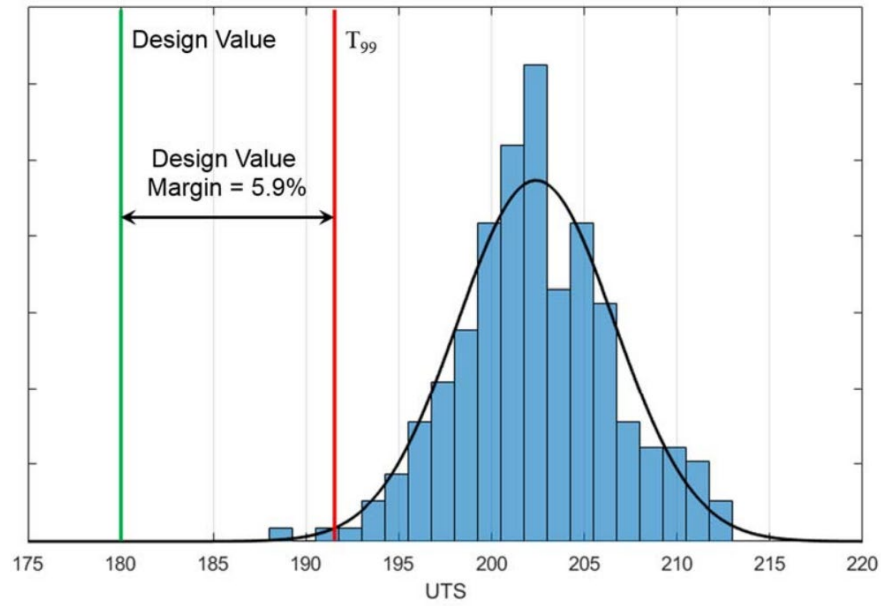


Figure 7: Substantiation of design value from MPS data from MSFC-STD-3716²⁴

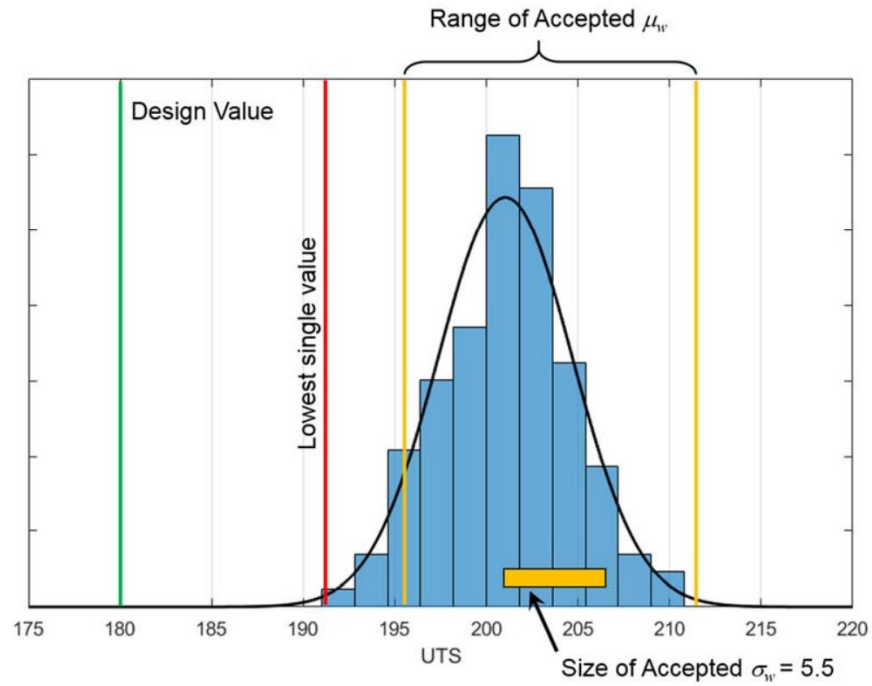


Figure 8: PCRD from witness data with defined witness acceptance criteria from MSFC-STD-3716

XIII. The Future - Data Driven Qualification

Future framework for qualification may look quite different once in-situ process monitoring and ICME models mature, especially for lunar or Martian destinations where the safety of Earth is unavailable and resupply mission cadences are drastically slower compared with LEO. Data-driven qualification approaches will be needed. This could entail automatic generation of complete cradle-to-grave digital records with the ability to reliably predict material state through real-time correlation of sophisticated IPM sensor data with advanced predictive physics modeling tools. The lack of traditional verification methods would be supplemented by digital verification, which would consist of a complete digital twin for every component produced and a digital thread for all aspects of the manufacturing lifecycle. A capability such as this would require very little intervention from the crew, as machine and process health diagnostics would be captured and potentially corrected real-time via closed loop control.

Transitioning from passive observation to this future data-driven state will likely require a structured architecture built on three growing capabilities: (1) multi-modal anomaly detection via sensor fusion, (2) probabilistic quantification to map observed indications to potential failure risks, and (3) smart disposition logic. By leveraging this structured in-process data, raw sensor outputs can eventually be transformed into a comprehensive digital twin for every component. While certifying parts purely from a digital thread requires immense development in physics modeling and efficient data management, maturing these data-driven support tools is the critical first step toward generating the reliable, cradle-to-grave digital records needed to supplement physical verification in-space. When this digital certification technology exists, the qualification framework will look drastically different from that of today and will not be exclusive to off-world manufacturing.

NASA is advancing a computational materials-informed approach to qualification and certification, supported by new initiatives designed to accelerate development, maturation, and regulatory acceptance across industry, government, and academia. Central to this effort is the Computational Materials for Qualification and Certification²⁵ (CM4QC) initiative, led jointly with the FAA, which focuses on maturing computational methods capable of predicting process–structure–property–performance (PSPP) relationships. Through the establishment of rigorous Verification, Validation, and Uncertainty Quantification (VVUQ) frameworks, CM4QC directly addresses challenges associated with off-world manufacturing, where executing large physical test matrices is infeasible. This approach provides a structured pathway for safely reducing physical testing by augmenting it with validated computational models.

Building on this foundation, NASA sponsors the Institute for Model-based Qualification and Certification of Additive Manufacturing (IMQCAM), a Science Technology Research Institute established in 2023. IMQCAM aims to develop a comprehensive digital twin of the additive manufacturing process, extending from feedstock characteristics to the resulting microstructure and predicted component fatigue performance. Collectively, these programs help

mitigate the extreme resource constraints of in-mission qualification by enabling engineers to incorporate material-property uncertainties through high-fidelity simulations. Together, they represent a significant step toward broad adoption of Computational Materials-informed qualification approaches that enhance the safety and reliability of end-use AM components.

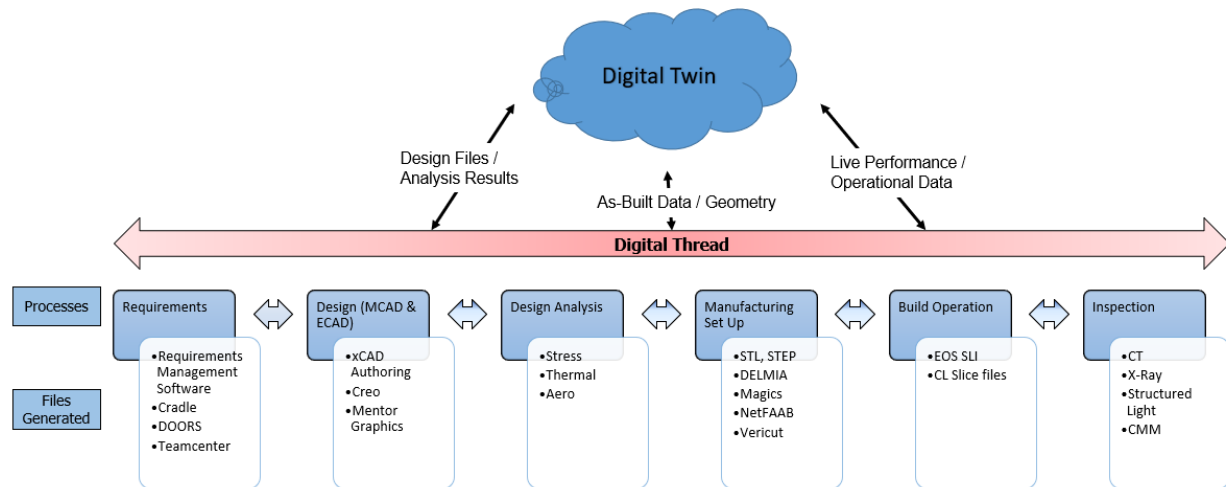


Figure 9: Digital Thread Diagram

XIV. Summary

There are numerous considerations for qualifying in-space AM processes stemming from the differences in resources, infrastructure, and environment where the machine is operating. While developing a QMP, one must consider process, material, loads, and environment—including crew bandwidth, crew training, micro/low gravity, increased radiation, pre- and post-processing equipment, and materials testing instruments. Furthermore, while much of the current discussion heavily emphasizes metallic systems, these same qualification frameworks and feedstock considerations must also be carefully tailored and applied to polymer and composite manufacturing. As the manufacturing system is developed, the certification path must be defined in tandem to account for tailoring of NASA-STD-6030 and NASA-STD-6033, as each machine type and mission will have different resources available and risks based on application.

As off-world testing and verification resources are more limited than terrestrial alternatives—primarily due to the strict mass, volume, power and safety constraints of launching and operating dedicated diagnostic equipment in space—developments are underway to allow for a more digital qualification process. This includes creating a complete digital twin for every manufactured component and a digital history of its manufacturing lifecycle to better understand the material quality on a layer-wise basis. By implementing more sensors and a control system, the machine could become more autonomous, lowering crew-time requirements. The system would output a build quality report for crew and mission control to evaluate the defect-likelihood associated with the as-built part and determine acceptability. In the interim, component designs must account for uncertainty in material properties and tolerances until manufacturing and verification technologies mature.

Establishing the infrastructure and machines for in-space AM will require substantial effort from a variety of disciplines. As confidence in machines and in-situ technologies grows, on-mission AM will be vital for augmenting and enhancing off-Earth crewed missions, directly supporting the logistical independence required for NASA's Artemis, Moon Base, and future Mars missions.

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