GUIDANCE NOTES ON

ADDITIVE MANUFACTURING

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American Bureau of Shipping
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Foreword

As introduced in the ABS *Advisory on Additive Manufacturing*, the latest innovation in manufacturing is additive manufacturing (AM), wherein parts are fabricated by adding material layer-by-layer. AM technologies allow designers and builders to re-think the way parts are designed, constructed, and delivered. The rapid development of AM technologies has indicated that the marine and offshore industries may greatly benefit from AM's capacity to support a flexible fabrication facility.

The goal of a flexible fabrication facility based upon an AM system (machinery and software) is to enable production of a variety of qualified parts in a highly versatile manner. In this way, a single AM service provider (AMSP) can act as the equivalent of multiple qualified factories with disparate production lines under one roof, serving many different clients. A single AMSP may produce a wide range of parts, from many different materials, to meet diverse quality and critical service requirements.

These Guidance Notes introduce a qualification scheme that defines AM processes with sufficient clarity to achieve consistent, repeatable results while accommodating frequent changes to the factory configuration and product requirements.

Like traditional manufacturing, quality in AM relies on a clear understanding of the process, from design through manufacturing. Consistent quality involves an up-front understanding of the effects that the material, the process selection, and manufacturing configuration have on the specific part design, build sequence, and manufacturing parameters. Management of each of these aspects is necessary to effectively control variability and anticipate the effects of process changes.

As standardization for AM develops, it is important to understand that the definition of a "qualified" AM process changes between industries and users, and that there may be different qualification requirements, methods, and metrics. The ABS AM qualification structure outlined in these Guidance Notes represents a recommended standardized method that targets the needs of the maritime and offshore industries.

These Guidance Notes become effective on the first day of the month of publication.

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SECTION 1 General

1 Scope

These ABS *Guidance Notes on Additive Manufacturing* (AM) outline a procedure for systematically qualifying AM parts, processes, systems, and materials primarily intended for marine and offshore use. The scope of these Guidance Notes includes AM processes that are capable, either directly or indirectly, of producing metallic parts, including the following as outlined by ASTM F42: Directed Energy Deposition (DED), Powder Bed Fusion (PBF), and Binder Jetting (BJ). These Guidance Notes can be used to assess the capability of an AM process to produce an existing design, as well as new designs that may be specific to AM. These Guidance Notes follow a multi-staged approach to qualification similar to the ABS *Guidance Notes on Qualifying New Technologies* (NTQ). Each stage is designed to build upon the previous stage to develop a more complete understanding of the process.

2 Purpose

Evaluating the performance of AM parts is dependent on knowledge of the entire manufacturing process workflow including: material selection, part model design, part/build orientation, parameter selection, processing conditions, post processing, inspection, acceptance criteria, and operator knowledge. The purpose of these Guidance Notes is not to exhaustively outline the requirements and risks of using AM designs in marine and offshore applications. It is a tool to guide would-be users of AM through the process of defining an AM procedure with sufficient detail to produce parts consistently, attain the required properties, and regulate process changes for the:

- System (machinery and software)
- Process (fabrication steps, order, and parameters)
- Part (geometry, functional requirements, material)

Generally, all AM parts should meet or exceed the design requirements of their non-AM equivalents(1). Alternatively, AM parts complying with national or proprietary specifications may be accepted, provided such specifications give reasonable equivalence to these requirements and also adequately account for the unique features of AM. Typically, metal AM part properties range between those of cast and forged counterparts. However, process variation, the location and type of defects, and metallurgical anisotropy are unique to the individual processing conditions of AM and should be considered in the design of the part.

AM's value lies in its ability to produce a low number of complex parts faster than traditional manufacturing methods. Additional benefits include the ability to process high performance materials while reducing the industrial footprint and increasing the flexibility of a fabrication facility. AM gives manufacturers significant control over the build process. This amount of control has benefits and drawbacks, because as opposed to manual techniques, there is little room for human intervention once building begins. The AM system controls the designated parameters once building begins.

Note:

1 For parts required by ABS Rules to be unit certified, reference is to be made to the ABS *Rules for Materials and Welding Rules (Part 2)* and the applicable sections of Parts 3 and 4 of the ABS *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)* including manufacturer qualification and survey. ABS may identify additional survey witness/hold points, indicating requirements above and beyond unit certification. Where the ABS Rules do not require unit certification, recognized international standards should be referenced as applicable. To establish equivalency, the relevant Rules for products made by traditional (non-AM) processes apply together with the guidance herein. For additional guidance on determining the applicable requirements, refer to 2/1.4.

3 Acronyms and Definitions

3.1 Acronyms

AMSP	Additive Manufacturing Service Provider
ABS	American Bureau of Shipping
AM	Additive Manufacturing
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
AWS	American Welding Society
BJ	Binder Jetting
C2G	Cradle to Grave
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DED	Directed Energy Deposition
FAT	Factory Acceptance Testing
FDA	Food and Drug Administration
FDS	Functional Design Specifications
FEA	Finite Element Analysis
FMECA	Failure Mode Effect Criticality Analysis
GN	Guidance Notes
HIP	Hot Isostatic Pressing
ISO	International Organization for Standardization
ML	Manufacturer’s Log
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NTQ	New Technology Qualification
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PCWD	Process Configuration and Workflow Diagram
PDO	Part Design Owner
PDP	Part Design Package
PITP	Part Inspection & Testing Package
PMD	Part Manufacturing Description
PO	Purchase Order

PSD	Particle Size Distribution
QMS	Quality Management System
SAE	Society of Automotive Engineers
TDS	Technical Design Specifications
UL	Underwriters Laboratories

3.2 Definitions

Additive Manufacturing. Manufacturing technologies that fabricate parts by adding material layer by layer as opposed to removing material.

Additive Manufacturing Service Provider. The organization responsible for operating an AM system (machinery + software) to produce the design.

American Society of Mechanical Engineers. Standards development organization. Multiple committees relate to AM.

American Society for Testing and Materials. Standards development organization. Committee F42 covers AM.

American Welding Society. Standards development organization. Committee D20 covers AM.

Binder Jetting. An AM process that uses binder to bind loose powder particles into a desired shape followed by additional post-processing steps to achieve the desired part properties.

Cradle to Grave File. The data package detailing the entire design, production, inspection, and testing information for the AM part.

Computer Aided Design. Computer software and the process used to design 3D solid or surface models creating a digital definition of the part.

Computer Aided Engineering. Modeling and simulation software used to help designers and engineers analyze performance of parts and systems virtually.

Computer Aided Manufacturing. Computer software designed to control/operate tools or other manufacturing machinery such as some AM machines, lathes, mills, etc.

Computational Fluid Dynamics. Computer modeling and simulation software used to analyze the properties and performance of fluid based systems.

Computer Numerical Control. Computer-controlled machine tools that create a part or feature by following a sequence of motion and machine function commands. See CAD, CAM.

Directed Energy Deposition. An AM technology that deposits material by providing energy to a feedstock delivered by a nozzle, welding fixture, etc.

Factory Acceptance Testing. A series of tests conducted to confirm that a part or system meets the agreed functional and technical design requirements.

Feedstock Facility. The facility that will produce the material used for building the parts, reference parts, and all other items in the build volume for both the qualification and production builds.

Food and Drug Administration. Regulatory authority on AM medical devices.

Functional Design Specifications. A document or series of documents that describe the required properties and functions of the design.

Finite Element Analysis. Computer modeling and simulation software used to analyze thermal and mechanical effects, stresses and strains in materials, parts and systems.

Failure Mode Effect Criticality Analysis. Technique used for assessing the severity, frequency, effect, and mitigation for design risk.

Guidance Notes. ABS non-mandatory guidance document designed to direct users towards standards and regulatory compliance.

Hot Isostatic Pressing. A post-processing technique involving pressure and temperature used to remove or reduce stresses and porosity from AM parts.

International Organization for Standardization. An international standards development organization. Technical committee TC 261 covers AM.

Manufacturer's Log. A series of documents included in the PMD that describes the calibration, maintenance, and qualification status of AM systems and processes.

National Aeronautics and Space Administration. An organization that has published technical standards for metal powder bed fusion qualification and quality for aerospace applications.

National Institute for Occupational Safety and Health. NIOSH operates under the Centers for Disease Control and Prevention and generates knowledge and programs that improve workplace health and safety.

National Institute of Standards and Technology. US Government organization for measurement science, standards, and technology.

New Technology Qualification. An ABS five-stage procedure for qualifying new technologies using a risk-based approach.

Original Equipment Manufacturer. The organization that originally created the machine or software of interest.

Powder Bed Fusion. An AM process that uses a laser or electron beam energy source to sinter or melt loose powder particles in the desired shape.

Process Configuration and Workflow Diagram. A roadmap of a specific AM process, depicting nodes, connections, and a sequence of operations.

Part Design Owner. The organization that owns the design of the part to be built.

Part Design Package. The sum of design documents that describe the part to be built, including drawings, functional and technical design specifications, models, etc.

Part Manufacturing Description. Supplementary information for each process step indicated as a node in the PCWD. Explains "how" each procedure is conducted.

Purchase Order. AM feedstock supplier document indicating the required properties for a certain type of product. Individual feedstock orders contain certificates of compliance for the given PO.

Particle Size Distribution. A statistical representation of the range of particle sizes within a sample of metal powders used in AM.

Part Inspection and Testing Package. Describes the standards and metrics used to evaluate the design's performance, including testing and inspection results.

Quality Management System. See ISO 9001 or equivalent standard.

Society of Automotive Engineers. Standards development organization, AMS committee covers AM.

Technical Design Specifications. A document or series of documents that describe how the required properties and functions of the design are met.

Underwriters Laboratories. A standards development organization, UL has published information regarding AM facility safety.

SECTION 2 Structure of ABS AM Qualification

AM qualification relies on a clear understanding of the entire manufacturing workflow from initial digital product definition and material feedstock characterization through AM fabrication, post-processing, acceptance, and installation on the asset. This family of documents and data is referred to as the "cradle to grave" (C2G) file, and defines the qualification method, processing parameters, design requirements and material properties for the part in its intended application.

Using the same make and models of a machine, even if provided by the same AM original equipment manufacturer (OEM), does not guarantee consistent performance from machine-to-machine or build-to-build. AM processes require numerous pieces of machinery, software, material interactions, and workflow steps, each with their own performance metrics.

Therefore, it is critical to have a clear and unambiguous understanding of the AM system, process parameters, inputs, outputs, and workflow to systematically track and improve quality. The C2G file defines and constrains the AM process, material, and part to be qualified to an acceptance range in accordance with the available Rules, standards and practices.

While various OEMs, operators, and national labs may have individual resources to gauge a machine's performance, there is currently no single standardized test coupon that can validate an AM system's performance as being "in-spec". Standards for validating individual AM systems and builds are not yet available or well-developed. Interim documents and procedures may require development on a case-by-case basis until standardization matures.

To accommodate the flexibility of AM systems, processes, and parts, the C2G file is built with collaboration among the Part Design Owner (PDO), Additive Manufacturing Service Provider (AMSP), and ABS, as well as other relevant interested bodies. The ABS C2G methodology contains four sub-packages, detailed in Subsection 2/1.

1 Documentation Overview

The C2G file structure for qualifying AM processes and parts is divided into four packages, which are summarized and described in 2/1.1 through 2/1.4. The purpose of the C2G file is to develop a single source that provides a complete description of the final product, including production parts, reference parts, test samples, test artifacts, manufacturing parameters, tests, inspections, and applicable standards.

The C2G file outlined in Section 2, Table 1 is a living file; sub-packages will be referenced and updated regularly throughout the AM qualification process and during ongoing operations. Relevant information to populate the C2G should be included as linked documents with clear revision history.

TABLE 1
Documentation Structure for Qualifying AM Systems, Processes, and Parts

Name	*Acronym*	*Purpose*	*Contents*
Cradle to Grave File	C2G	A master reference file that is retained for the life of the part.	Contains the unique PCWD, PDP, PMD, PITP, and any other relevant information to the part and manufacturing process.
Process Configuration and Workflow Diagram	PCWD	Describes the order of operations for the overall AM process. An example PCWD is shown in Appendix 1.	A single workflow diagram where each major (1) manufacturing step is listed as a separate 'node', each connected by their respective inputs and outputs.
Part Design Package	PDP	Describes the design's functional and technical requirements, including the materials basis.	Contains the production part drawings, test sample and test artifact drawings, functional design specifications, technical design specifications, CAE/CAD models, etc. The PDP also contains the material basis, which provides the material selection for the design, along with the environmental conditions and feedstock requirements.
Part Manufacturing Description	PMD	Describes the process (fabrication steps, order, and parameters) used by the relevant personnel and AM system to produce the part, including the manufacturer's log (ML) (2).	The PMD contains the AM procedure specification (3), build volume model, and process monitoring and control details for all items included in each build cycle (production parts, reference parts, test samples, and test artifacts). The ML contains the relevant information and documentation for machinery calibration and maintenance and worker qualification(s).
Part Inspection & Testing Package	PITP	Describes how the parts, test specimens and artifacts are inspected and tested, what metrics will be used to gauge initial part and AM process performance, and what data will be used for maintaining a qualified process.	The PITP contains the list of Rules, codes, and standards used to evaluate parts, test specimens, and test artifacts. The PITP also includes the results and criteria for the testing and inspections, such as test reports, inspection results, or other files.

Notes:

1 Major manufacturing steps include design and CAD/CAE file creation, feedstock production, AMSP operations, heat treatment, machining, inspection, mechanical/chemical testing, and installation at end-application. Each AM process node indicated on the PCWD that includes a witness/hold point should be witnessed by ABS for each initial qualification as well as reestablishing qualification. Witness/hold points, once established, should be indicated on the PCWD for ease of reference. Ongoing process examination should be agreed upon between the PDO and AMSP, and depends on the frequency of AM part production, the size and criticality of the parts, and C2G requirements.

2 Refer to 2/1.3.5, "Process Confidentiality".

3 An AM procedure specification (AMPS) is similar to a welding procedure specification (WPS) for AM. See American Welding Society (AWS) D20.

1.1 Process Configuration and Workflow Diagram (PCWD)

The roadmap for the AM process is contained in the process configuration and workflow (PCWD) diagram. The PCWD allows the PDO, AMSP and ABS to divide an AM process into individual manufacturing steps. Each organization conducting a manufacturing step in the AM part's workflow should be identified in the PCWD as its own "node", including all suppliers and subcontractors. The PDO and AMSP should identify and agree which manufacturing capabilities are available in-house, and which are considered outsourced, such as heat treatment, hot isostatic pressing (HIP), nondestructive evaluation (NDE), and machining. An example PCWD is shown in Appendix 1 for a process where the PDO has requested an AMSP to fabricate a part, and the AMSP has then subcontracted the heat treatment, testing, and inspection.

Each manufacturing node contains six blocks: header, input, machinery, software, process information, and outputs.

i) The header block contains an outline of the general information for each organization/facility, such as name, location, applicable QMS type, and experience with similar parts and/or AM.

ii) The input block contains the raw materials or information used to produce the product. For example, a feedstock facility may use barstock to produce wire, while a PDO may use field data to design a new part.

iii) The AM system (machinery) block contains a description of the machines and other equipment used to process materials and parts, such as AM machine make, model, serial number, etc.

iv) AM system (software) block contains a description of the software programs and packages used to supply information to, or otherwise control and/or monitor the AM process.

v) The process (fabrication steps, order, and parameters) information block describes what processes are conducted at the location described in the header block to convert the inputs into outputs.

vi) Outputs provide a description of the physical and/or digital deliverables between nodes. The outputs and inputs of different PCWD nodes are connected using arrows.

The PCWD is meant to be a "living" document and will be updated as more information becomes available.

Note: The QMS may employ a different quality scheme for the PDO, AMSP, and AM feedstock provider. In general, the QMS should at least govern specific functions, including worker training for AM, process revision control, change of/new supplier, data storage/management, data security, addressing AM nonconformance, material handling, powder storage, anti-contamination procedures, and material disposal.

1.2 Part Design Package (PDP)

The first group of documents in the C2G file includes comprehensive product definition with description, functional and technical specifications, and standards that must be met according to the PDO for the design to be considered adequate.

This information is contained in the part design package (PDP), which includes the part drawing(s), models, digital design definition, functional design specifications (FDS), technical design specifications (TDS), engineering calculations, drawings, design models, examples of similar approved designs, etc.

The PDP documents should also describe the architecture and function for the system into which the AM part will be installed. Initial details about the physical and functional interface requirements, such as mechanical fit, hydraulic/pneumatic interface, and electrical continuity should be provided along with associated requirements and tolerances. The PDO should consider the effect of service environment on the part when considering system performance. AM processing may create parts with different long-term material properties such as fatigue, corrosion, creep, and wear than non-AM counterparts.

AM-produced parts may use different materials and have different/alternative geometries than parts produced by traditional manufacturing methods. The PDO should address the use of AM-specific design modifications such as topological optimization, generative design, functionally graded (strengthened, corrosion-enhanced, etc.), and combining parts in assemblies. The PDO should also indicate prior experience and/or instances of similar existing designs in other systems, regardless of whether they were produced with AM or traditionally. Examples could include prior certifications, successful applications, case studies, analyses, etc. The AMSP should also provide proof of authorization by the PDO to build the intended parts.

The design is to be initially proven by first principles, calculations, prior experience, and testing, and then checked for compliance with Rules, codes, and standards that may specify additional design features. The reason for this is that standards should not be used as a replacement for first engineering principles. Rather, they should be used to augment acceptable first principle designs.

Note: The PDP is meant to be a "living" document and will be updated as more information becomes available.

1.2.1 Material Basis

The PDO and AMSP should specify the material selection for the design, the material feedstock, and the environmental conditions to which the design will be exposed. This material basis should include the type and grade of material, final heat treated/post processed condition of part (i.e., as-built, annealed, HIP, etc.), and the material properties used in the design specifications. A description of the required mechanical properties in specific locations and directions is to be submitted. Accounting for anisotropic properties early in the design process can help designers and materials engineers build testing and inspection plans that will establish the properties that best meet the design requirements.

Note: Modeling software for mechanical properties may not adequately account for anisotropic behavior of AM–processed materials.

Note: Hotspot locations, regions of localized thermal or mechanical effect concentration, and other areas such as rapid changes in cross-section, sharp changes in deposition process parameters, deposition direction, etc., should be identified and assessed and may require additional testing, inspections, or subsequent design model modifications.

For both wire and powder manufacturers, the PDO, AMSP, and AM feedstock provider should agree on a purchase order (PO) that denotes the following:

i) Supplier name and address

ii) Feedstock product name

iii) Purchase order reference number

iv) Certificates of compliance for each order made to that PO

v) Feedstock lot number

vi) Feedstock production process

vii) Chemical composition

viii) Representative micrograph or picture of product morphology

ix) Packaging and storage requirements

x) Feedstock production date/Expiration date

Note: The feedstock should not be used if the:

- Feedstock marking is damaged such that it is unreadable.
- Feedstock packaging is damaged such that there is doubt as to whether the feedstock remains in an acceptable condition per the manufacturer’s recommendations.
- Feedstock manufacturer/OEM requirements for storage conditions and/or shelf life are not met.

Note: AM system OEMs may also prescribe OEM-sourced materials (e.g., powders for PBF machines).

Feedstock requirements may depend on the AM feedstock type (e.g., powder, wire, etc.), the AM OEM requirements, and the service criticality of the part. For both wire and powder manufacturers, the purchase order should have a unique identification number and include material grade, chemical composition, heat/lot designation, and applicable product standards. Measurement techniques and relevant measurement standards for all feedstock properties should also be listed.

Powder manufacturers should list the following, along with associated measurement techniques and standards, as applicable:

i) Production type (e.g., Plasma Atomization, Gas Atomization, Plasma Rotating Electrode Process, etc.)

ii) Particle size distribution (PSD)

iii) Powder sampling methodology

iv) Limits on the amount of particles outside the designated PSD range *v)* Density, including measurement technique (e.g., skeletal, tap, apparent, etc.)

vi) Mean particle shape (morphology), limits on satellite particles, and porosity (hollow particles) should be listed, and a representative picture provided if possible

Wire manufacturers should list the following, along with associated measurement techniques and standards, as applicable:

i) Feedstock storage conditions (e.g., atmosphere, temperature, separation, cleanliness, etc.)

ii) Coating or lubrication on wire, which may require removal prior to fabrication

iii) Wire surface roughness

The material supplier is to be included in the PCWD, as some AM requirements may entail a configuration-controlled virgin powder material specification. For wire manufacturers, the product form (e.g., diameter, coated wire, uncoated wire, etc.) and acceptable surface roughness should be provided. Additional feedstock requirements may be required by guidance documents, such as AWS A5.XX or ASME IIC. The properties listed above are minimum details. Application-specific requirements may involve additional information.

Feedstock documents should account for the unique requirements of AM processing, such as tight process configuration, high material quality, and revision control of all manufacturing processes. Currently, there is a limited selection of AM-specific material grades relative to non-AM alternatives. If the feedstock supplier has certified AM feedstock for previous processes, the details of same and any applicable previous experience can be submitted for reference.

The material basis should include, as applicable, the relevant details for the build platform or substrate material for the build process, including material thickness, grade, surface preparation, and markings. In addition, the relevant details for inert or other process gases should include vendor, type, grade, purity or other information regarding the gas supply source.

The PDO, AMSP, and feedstock supplier should agree on the feedstock properties and establish an initial purchase order certificate/template that takes into account all noted requirements and measurements. This document will be reviewed by ABS.

After the pre-production validation series of builds that includes parts, reference parts, test samples, and test artifacts, a feedstock property check should be conducted to determine if additional feedstock requirements should be specified.

1.3 Part Manufacturing Description (PMD)

The purpose of the PMD is to contain the parameters for the AM process and other associated processes in the PCWD. The PMD should include the manufacturing system capabilities, including the applicable AM category (e.g., PBF-L, PBF-Electron Beam, DED-Laser, DED-Gas Metal Arc, BJ-Direct, and BJ-Indirect), machine make and model, and basic machine details such as the technical specifications provided by the AM machine OEM (e.g., build volume, material compatibility, feature resolution capability, and surface roughness).

The PMD should describe the deposition plan, build volume model, build platform description (if applicable), support arrangement, heat treatment, machining, surface modification (e.g., peening, carburization), and other information required for manufacturing not included in the PDP. The location, orientation, and dimensions with tolerances of all production parts, reference parts, test samples, and test artifacts in the qualification, pre-production, and production build volumes should also be specified. Section 2, Figure 1 shows an initial build volume model for a PBF or BJ system. Section 2, Figure 2 shows an initial build volume model for a DED system.

FIGURE 1
Example PBF or BJ Build Volume Model, Showing Build Volume Containing One Production Part, Reference Part, Test Sample, and Test Artifact

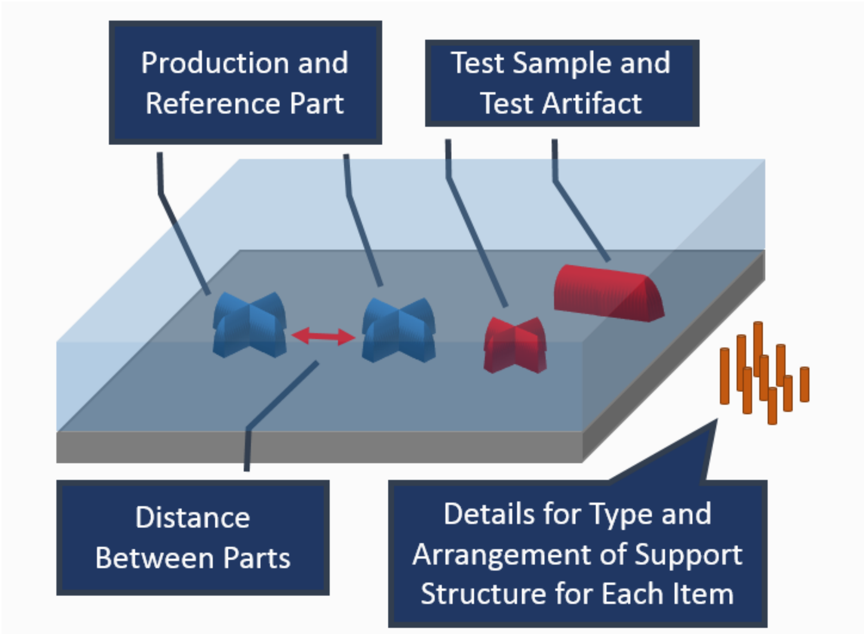
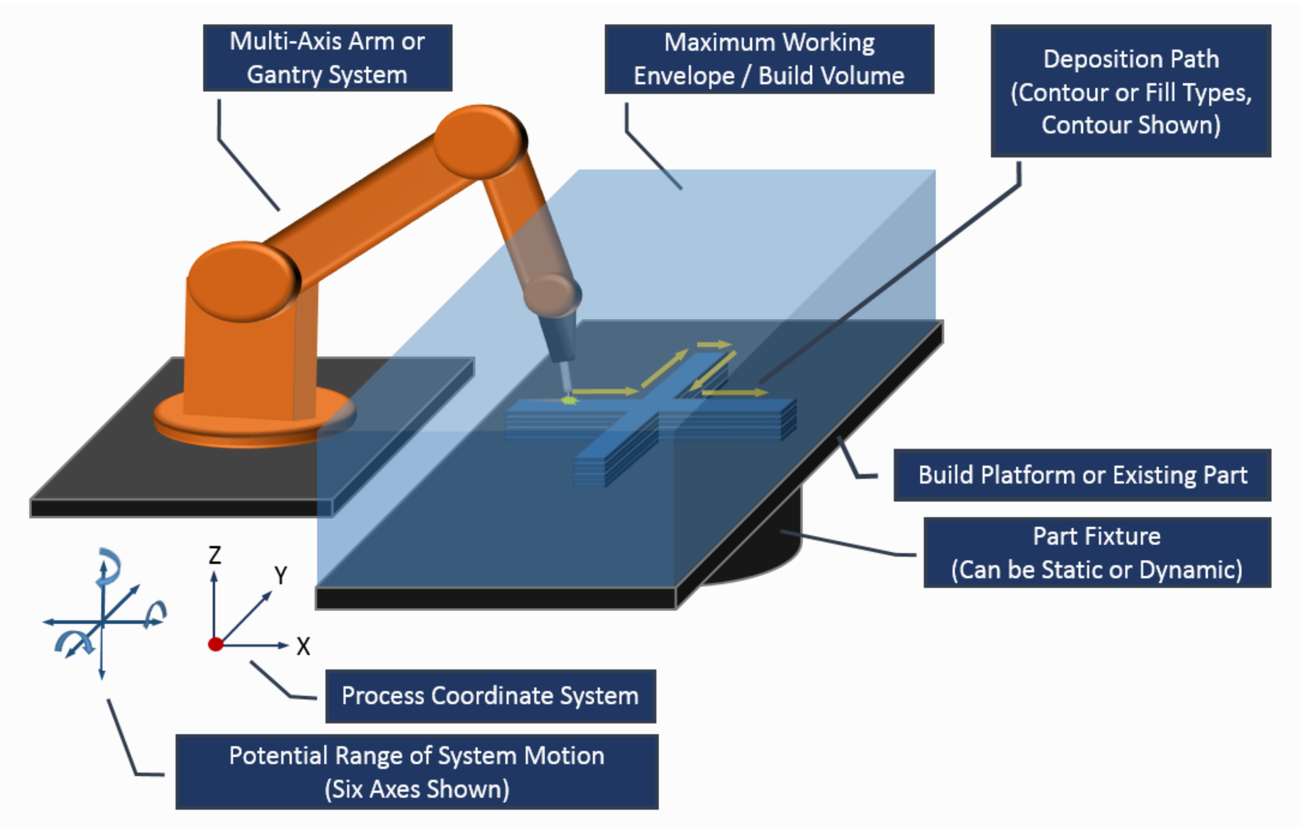


FIGURE 2
Example DED Build Volume Model, Showing Build Volume Containing One Production or Reference Part with Integral Build Platform



In general, the PMD should define the steps required to manage the physical, chemical, and microstructural property evolutions of parts from the as-built to final state. The PMD should also account for residual stresses accumulated during the build process and indicate post-processing activities required to achieve desired surface finish of final part(s).

Post processing is required to improve properties of as-built parts, which may have:

- Lower tensile elongation
- Fewer fatigue cycles to failure
- Lower creep rupture lifetime
- Less corrosion resistance
- Higher surface roughness or "near-net" shape

Note: Removing parts from support structures prior to stress relief can cause severe distortion, cracking, and premature part failure. Parts should not be removed from fixtures or build platform/support structures until the appropriate stress relief procedures have been performed. The build orientation and support structure may be designed to accommodate AM post-build operations such as heat treatment and machining.

Deposition process parameters (e.g., scan plan, deposition plan, etc.) are critical to each qualified AM process. Refer to 2/1.3.4 for process confidentiality. Changes in process parameters may require requalification and/or proof of equivalence by testing and inspection methods, as agreed among the PDO, AMSP, and ABS. As such, version control should also be specified for machine software used to run the build file. In addition to the process parameters for the production part, the PMD should include processing parameters for the items referenced in Section 2, Table 2 at a minimum.

TABLE 2
Nomenclature for Items in the Build Volume Model

Production Part	The AM part to be qualified.
Reference Part	Sacrificial part with identical geometry to the production part.
Test Samples	Material from which test specimens will be obtained, including mechanical, chemical, and microstructural properties.
Test Artifacts	Test artifacts are objects that can be fabricated either in each build cycle or during qualification builds that contain multiple features that aid in monitoring or measuring process repeatability or quality. Examples include reference geometries, NDE calibration and reference blocks, or archive samples.

Whenever possible, technical specifications and associated measurements for AM systems (machinery and software) and processes should be provided with tolerances and associated measurement techniques. The PDO and AMSP should also indicate how many units are intended to be manufactured and how many units per build cycle, for example: one-off, set number/range, or ongoing production. PMD documents may be supplied by the PDO, AMSP, or other relevant bodies indicated in the PCWD.

Note: Manufacturers new to AM may not have a well-developed, robust understanding of the intended AM process and its associated critical parameters. Therefore, information not available initially will be populated in subsequent stages. The PMD is meant to be a "living" document and will be updated as more application-specific knowledge is gained.

1.3.1 Process Monitoring and Control Criteria

AM is variable intensive, so actively tracking, testing, and inspecting for all process variables and part properties during regular build operations may be impractical due to computational limitations. The ability to detect errors early within builds is crucial. Undetected defects in the build process may cause parts to be rejected. Since it may not be possible to fully monitor and/or control all process variables in real-time, the AMSP may therefore choose to track certain part properties that are sensitive to fluctuations in critical and/or auxiliary process parameters as a way of inferring or tracking process stability. These are referred to as process stability variables.

Process control variables relating to the energy source and build environment (such as preheat and atmosphere) have a large impact on process stability. This may manifest in physical characteristics such as variable surface roughness and dimensional fluctuations, and possibly influence mechanical properties. Tracking process stability variables could provide an early indication of builds being out-of-spec by providing indicators that are sensitive to process fluctuations. Establishing a list of process variables and part properties that are process-sensitive may reduce the cost and time of production by enabling an AMSP to recognize and stop "failed" builds early in the build cycle.

The PMD should provide a description of process stability variables and artifacts used to monitor the build process, as well as the applicable measurement techniques. Examples could include measuring surface roughness or accuracy on worst-case surfaces, such as overhangs, abrupt geometrical changes, or high-aspect ratio geometries, such as posts, thin walls, or holes.

Note: Listing variables that are held constant or assumed to be constant and not under the direct control of the machine or operator may aid in analyzing and improving the stability of the AM process.

Note: Not all manufacturers may have the ability for track and/or anticipate AM process parameters with advanced algorithms or machine learning. Therefore, these capabilities are not mandatory requirements, but are intended to assist the PDO and AMSP in process design and optimization. It is anticipated that there will be significant industrial focus on developing these features.

1.3.2 Design of Test Artifacts

A valuable practice to aid in establishing, tracking, and maintaining build quality is the use of test artifacts. Test artifacts are samples that can be fabricated either in each build cycle or during qualification builds that contain multiple features that aid in monitoring or measuring process repeatability or quality. Use of test artifacts that demonstrate multiple different types of features is recommended, such as the NIST demonstration artifact for PBF, which includes numerous features and is shown in Section 2, Figure 3 and Section 2, Table 3.

Note: The use of test artifacts is also discussed in the ABS *Advisory on Additive Manufacturing*.

FIGURE 3
NIST Test Artifact for PBF

(Left: top view; right: oblique view)

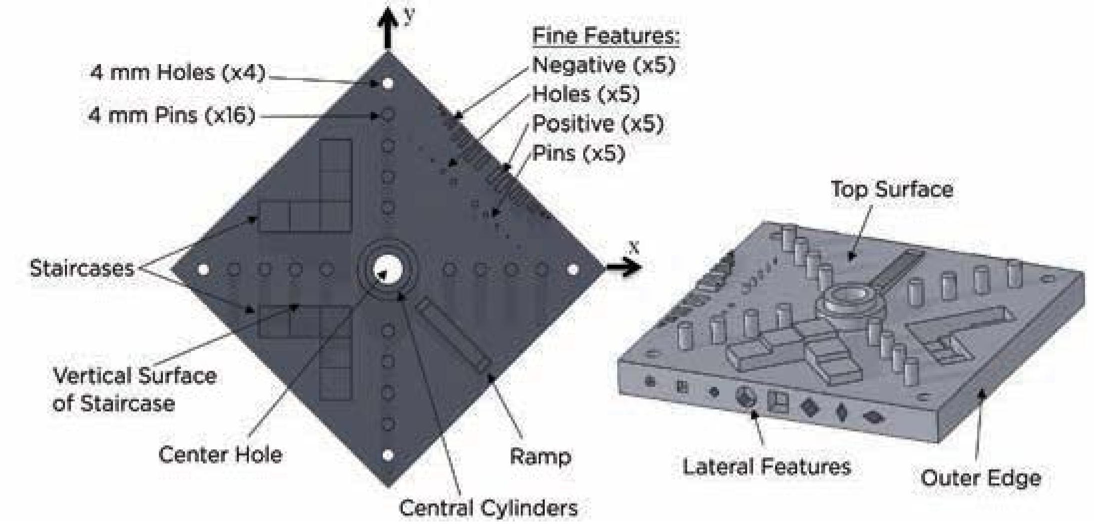


TABLE 3
Example Features/Properties for Test Artifacts

Design Features:	*Applicable AM Process Categories*
1. Minimum feature size, deposition resolution	1. PBF, DED, BJ
2. High aspect-ratio features (holes, points, cones, etc.)	2. PBF, DED, BJ
3. Thin features	3. PBF, DED, BJ
4. Internal features	4. PBF, BJ
5. Unsupported features (angles, bridges, overhangs)	5. PBF, BJ
6. Rapid changes in cross-section thickness*	6. PBF, DED
* May lead to stair-stepping or pull-in distortion.	
Build Arrangement:	
1. Orientation, location in build volume	1. PBF
2. Fixturing and support arrangement	2. PBF
3. Build volume density	3. PBF
Material Properties:	
1. Mechanical properties	1. PBF, DED, BJ
2. Chemistry	2. PBF, DED, BJ
3. Surface roughness	3. PBF, DED, BJ
4. NDE calibration blocks	4. PBF, DED, BJ
5. Heat treatment response	5. PBF, DED, BJ
6. Microstructure, esp. at critical locations such as overhanging contours, center of part, etc.	6. PBF, DED, BJ
7. Grain size, grain orientation (in-layer, through-layer), phase distribution, etc.	7. PBF, DED, BJ
8. Feedstock powder properties (powder capsule)	8. PBF, DED
Nondestructive Evaluation & Finishing:	
1. Inspectability of complex geometries	1. PBF, DED, BJ
2. Machinability/finish-ability of complex geometries	2. PBF, DED, BJ
3. Potential defects (intentionally designed, e.g., NDE calibration blocks/artifacts)	3. PBF, DED, BJ
4. Potential defects (unintentionally designed, e.g., defects generated by operating AM machines at process parameter range limits.)	4. PBF, DED, BJ

The NIST test artifact was designed for PBF. However, similar demonstration artifacts can be considered or developed as applicable. Not all applications have the same needs regarding the accuracy of critical features. Thus, the test artifact design for one industry or application may be different from another. For example, an oilfield part such as a small downhole tool may place greater emphasis on internal channel quality and surface roughness, versus a larger part intended to transfer stress. Regardless of the category of AM process or type of part produced, any proposed test artifacts should consider both the standard and unique features of the part design and also provide relevant information about the fabrication process. In addition, test artifacts may be fabricated with the intent of preserving raw material (processed or un-processed) for future reference. These samples may not be subjected to immediate destructive testing, and are referred to as archive samples.

Separate build volume models may be required when not all qualification items can fit into a single build cycle. Multiple builds may also be required by the Rules, codes, and standards referenced in the PITP. For example, conducting a machine qualification build (i.e., standard geometry) or pre-production validation build (i.e., sacrificial reference part(s)) may be necessary before production begins.

When separate build volume models are required, the same C2G file is to be used for the qualification build(s) as is intended for production. Together, the PDP and PMD should contain a description of the build volume model(s) for all production parts, reference parts, test samples, and artifacts for both qualification and production. The build volume models for both the qualification and production build cycles should be agreed upon between the PDO, AMSP, and ABS prior to beginning production.

The procedures, measurements and/or artifacts used to demonstrate ongoing process stability and qualification status should be agreed upon by the PDO, AMSP, and ABS.

1.3.3 Digital Manufacturing and Process Database

Central to the application of AM in any critical context is the use and interpretation of process data. AM processes typically begin with a digital design definition of a 3D solid or surface model for the part. This model-based approach facilitates a virtual simulation of the:

- Part performance using CAE
- Manufacturing process using CAM
- Simulation of subsequent operations such as part assembly and field performance

AM is a variable-intensive process. AM processes can have upwards of 100 quality-affecting variables in a single build. Therefore, the quality and accuracy of data recorded during each process step and the cumulative amounts that are stored and archived by various parties such as the PDO, AMSP, and AM system manufacturer play an important role in the process controls and resulting quality of builds. Many AM system manufacturers offer their own proprietary software for AM that includes process monitoring and control, and manufacturing workflows.

AM systems can run in either open or closed loop control. AM systems running under open loop control follow a prescribed sequence of motion and machine function commands relying on little or no human interaction. Some AM systems utilize closed control of main and auxiliary hardware, relying on sensors, data and software or hardware logic to control the process. Therefore, to document and control the process, attention should be given to data collection associated with each manufacturing step along with the relevant measurement and control techniques.

To aid in new process development, traceability, and quality improvement, the AMSP/PDO should maintain a database that is robust, scalable, and statistics-capable for storing material data, product definition, design information, build files, processing parameters, test/inspection results, workflow configurations, post processing, and other associated manufacturing information.

Critical aspects of AM including feedstock characterization, build orientation, build history, post processing, machine maintenance, system settings, and software compatibility require subjective reasoning from users to complete manufacturing workflows. This information is fundamental in order to produce repeatable results, regardless of the quality or expense of the AM system.

The AM feedstock supplier should be aware of the material characterization and purchase order information required by the AMSP/PDO for their process database. This will help confirm that purchase orders and feedstock lot properties are properly archived and may be readily cross-referenced with specific build cycles.

Note: These Guidance Notes do not directly address data security for ongoing digital manufacturing operations. Additional guidance on data security may be found in:

- ABS *Guidance Notes on Application of Cybersecurity Principles to Marine and Offshore Operations – ABS CyberSafety™ Volume 1*
- ABS *Guide for Cybersecurity Implementation for the Marine and Offshore Industries – ABS CyberSafety™ Volume 2*
- ABS *Guidance Notes on Data Integrity for Marine and Offshore Operations – ABS CyberSafety™ Volume 3*

1.3.4 Manufacturer's Log

The AMSP and PDO should develop and maintain a manufacturer's log that will be used to determine the current status of the AM process to produce the desired part. The manufacturer's log adds the following information to the PMD:

i) Calibration State of relevant machinery (a record of past calibration dates and future calibration schedule).

ii) Maintenance State of relevant machinery (a record of past maintenance dates, and future preventative maintenance schedule). A preventative maintenance strategy should be defined for all critical machinery listed in the PMD/PCWD.

iii) Process parameters with tolerances for the current build. Refer to 2/1.3.4 for process confidentiality.

iv) Name and version of applicable quality control software and last patch date.

v) Personnel training and suitable experience relevant to the current AM build, along with any relevant qualifications.

vi) Records of AM machine usage by different personnel.

vii) Instances of process intervention, interruption, or cancellation, with associated timestamp or other designation such that the effect can be correlated if required.

viii) Other machine usage information, such as dedication to a specific material type.

ix) Worker and manufacturing safety procedures/records applicable to AM (e.g., NIOSH, UL, etc.)

Note: Rules, codes, and standards contained within the PITP may provide or require a certain format for manufacturer log information. Due to the wide range of potentially applicable standards, the information provided by individual compliance may overlap, and therefore the manufacturer's log may contain duplicate information.

Note: Variance in powder properties should be considered prior to the manufacturing process, including aspects such as stratification, inter-batch variability of powder ordered to the same specification, and gradual reuse/mixing of powders in the AM machinery. Procedures for process restart, powder mixing, and maintaining feedstock consistency should be considered as part of the PMD/Manufacturer's Log prior to production, along with the associated testing as indicated in the part inspection and testing package.

A well-kept manufacturer log avoids costly downtime by proactively managing the downtime and reducing cost for the AM process/part. It provides quick reference to allow personnel to confirm whether a process is in-control and in a qualified status (calibrated, maintained, and within process parameter ranges) during ongoing manufacturing operations. The manufacturing log is documented as a supplement to the PMD, and its active status is reviewed as part of ABS witnessing and review activities. The manufacturer's log should be readily accessible and items *i)* through *ix)* (above) should be available in hard copy format upon request.

1.3.5 Process Confidentiality

AM process details may be considered proprietary or confidential to the PDO and/or AMSP. In these cases, locked, encrypted, and revision-controlled files may be referenced. In all cases, there must be sufficient information available to ABS to perform a qualification of the AM process.

At a minimum for such proprietary files, the following aspects are to be indicated:

- *Process/Part.* Clearly specify which processes/parts the revision-controlled file will apply.
- *Filename and Revision.* Confirm that both the filename and contents of the revision-controlled file remain constant and are consistently managed within the change management system of the AMSP.
- *Associated AM System Software Version.* Confirm that the software version used to open and employ the revision-controlled file remains constant or otherwise demonstrates continuity.

1.4 Part Inspection & Testing Package (PITP)

The PITP is a series of documents that work together to:

i) Outline the testing methodology/philosophy for producing AM parts.

ii) List the Rules, codes, and standards to which any tests or inspections are performed, including relevant qualifications.

iii) Provide the results of relevant inspections and testing.

The PDO, AMSP, and ABS should agree upon the applicable Rules, codes, and standards for the part design, manufacturing, and materials for the given application. The contents of the PITP will vary for different applications and parts. Deciding on the applicable codes and standards occurs concurrently with development of the PCWD, PDP, and PMD.

Documents indicating test samples and artifacts are to be provided, along with adequate justification for their selection. The PITP should specify the post-processed condition for each test sample (including all associated specimens) and artifact, such as "as-built" or "post-HIP". The condition of test samples, specimens, and artifacts should represent the same as production parts at the current stage of the PCWD.

The PITP should include all relevant Rules, codes, and standards as well as a description of the production NDE of AM parts, such as:

- Anticipated defect characteristics
- Likely location of defects
- Actual location of defects
- Anticipated probability of detection of known types of defects
- Pre-planned defects in artifacts such as AM NDE calibration blocks

A reporting format should be defined for AM test and inspection data, including at a minimum: microstructure, mechanical properties, porosity, chemical composition, and other relevant design properties. PITP documentation should also include factory acceptance testing and installation testing specifications such as hydrostatic or load testing.

Testing suites from multiple build cycles may be required for initial process qualification, along with justification on the amount of sampling specified. The amount and type of testing varies on a case-by-case basis and should be agreed upon between the PDO, AMSP, and ABS. Worst-case design parameters should be considered when determining the inspections, testing, and artifact design as well as process stability variables, such as those listed in 2/1.3.1. The PDO and AMSP/PDO should provide justification of the methodology used for worst-case design parameter selection.

Testing and inspections should be conducted on items in Section 2, Table 2 that have been subjected to all post-processing steps indicated in the PCWD. If items are tested in intermediate metallurgical conditions, the PDO/AMSP should provide justification as to why the final condition was not used. The PDO and AMSP should also provide an explanation of how the chosen condition is representative of the final design, along with any associated design or correction factors.

In general, AM part performance should reliably meet or exceed non-AM design equivalents. However, current Rules, codes, and standards that apply to conventional manufacturing process may not address additive manufacturing designs, materials, and processing conditions. In general, if existing guidance does not adequately address AM-specific features, then the PDO, AMSP, and ABS should agree on these discrepancies and develop a test plan that accounts for these features. Use of each reference should be evaluated on a case-by-case basis.

Deviations or modifications to existing test documents should be noted specifically in the PITP. Technical justification with supporting documentation should also be provided for testing to account for new AM design features, such as internal lattices, topology, and optimized structures.

Known limitations of Rules, codes, and standards listed in the PITP and their applicability to AM should be clearly indicated. Reference to NISTIR 8005 "Applicability of Existing Materials Testing Standards for Additive Manufacturing Materials," the ANSI Standardization Roadmap for Additive Manufacturing, or similar is recommended. Deviations applicable to AM from standard techniques should be indicated in the PITP, along with a description/justification for the change. An example could include changing standard inspection, sampling procedures, or sampling frequency because of geometric inaccessibility due to the complexity of the design.

Due to ongoing standards development in AM, any Rules, codes, and standards applicable to items or procedures may be noted as N/A or under development in the PITP (e.g., AWS D20.1, draft ASTM/ISO documents, etc.). Unpublished standards may be referred to. However, requalification of processes requires reviewing the current C2G file for compliance with respect to the most recent Rules, codes, and standards available. Therefore, awareness of upcoming documents serves to expedite process requalification.

PDO and AMSP should discuss part and build design (to include supports, orientation, etc.) and confirm that post processing and finishing is possible (i.e., AM can produce features that are difficult or impossible to finish or inspect, such as internal channels and lattices). In these cases, other process monitoring/control, post processing, inspection, and testing may be specified.

2 AM Qualification Process

ABS AM qualification is divided into four stages: feasibility, verification, pre-production validation, and production. Once the initial C2G file is populated, the qualification process can begin, as shown in Section 2, Figures 4 and 5.

ABS will review the proposed C2G file at each stage for compliance with the available Rules, codes, and standards and offer feedback on qualification.

FIGURE 4
ABS Additive Manufacturing Qualification Process

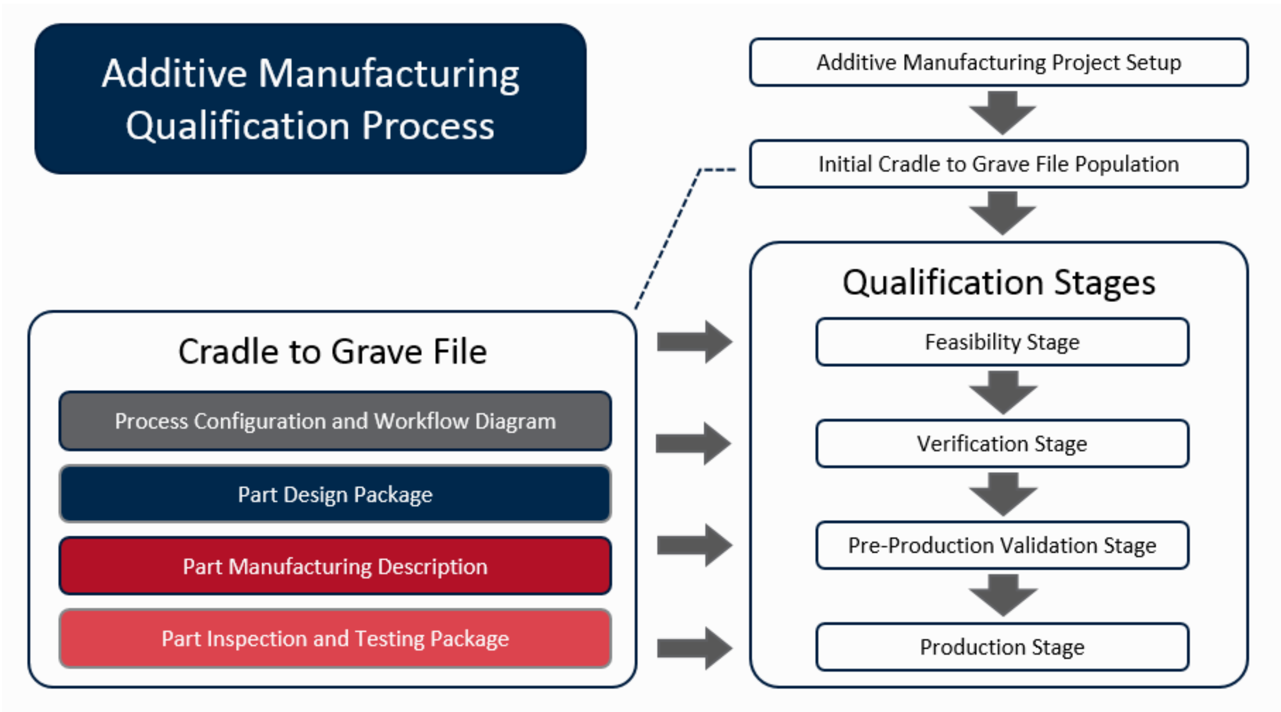
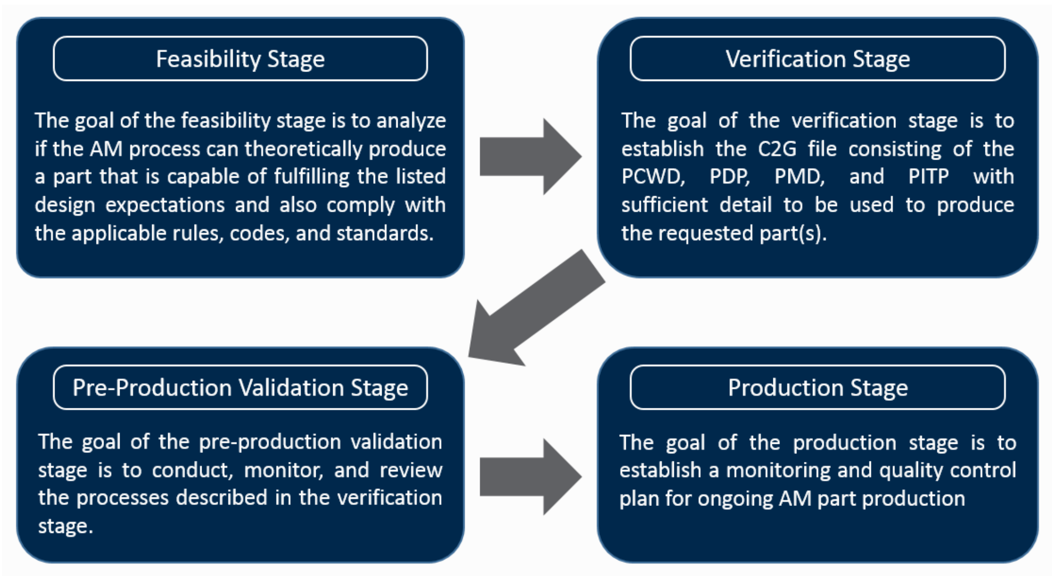


FIGURE 5
Additive Manufacturing Qualification Stage Goals



SECTION 3 Feasibility Stage

The goal of the feasibility stage is to analyze if the AM process can theoretically produce a part that is capable of meeting design requirements while also complying with the applicable Rules, codes, and standards. Therefore, during Section 3 (feasibility), the review does not delve into the details of how the part is produced, but rather the initial C2G file is populated and reviewed at a high-level. Areas anticipated to require additional detail and/or research should be noted. Deviations from existing standards or procedures should also be noted.

While an exhaustive risk analysis of AM processes may be cumbersome due to the large number of design and process parameters, a high-level risk and/or sensitivity study should be conducted for both the AM process and the part to be produced. Design properties and/or process parameters that limit or have a large influence on part life, the manufacturing process, and system function should be indicated.

1 Initial C2G Population

The PDO and AMSP should populate each node in the PCWD with all initially available documents and data necessary to conduct the complete AM process (feedstock through end use) as described in the PCWD. Information that is unavailable or missing should be marked as such and addressed later in the qualification process, as possible. Refer to 2/1.3.4 for process confidentiality.

During the Feasibility Stage, users of these Guidance Notes will build an initial:

i) Manufacturing to end-application diagram illustrating the AM material, process, part(s), and application requirements

ii) Set of design, manufacturing, testing, and inspection documents indicating the procedures to be followed

iii) Description of material, process, or end-application aspects that may require additional research/data for qualification

Upon satisfactory completion of the review, ABS will issue a Statement of Maturity for the feasibility of the AM process, indicating that overall process feasibility was evaluated based on the available information relating to the current technology.

SECTION 4 Verification Stage

The goal of the verification stage is to complete a detailed review of the C2G file contents, including part design, material properties, testing and inspection criteria, AM process details, witness/hold points, and final part application. Although a detailed analysis of the materials, part design, manufacturing process, and end application is conducted, parts are not physically produced during the verification stage.

By the end of the verification stage, the PDO, AMSP, and ABS are to share a definition of the AM process and agreed-upon metrics for gauging its performance, with tolerances. The PDO and AMSP should also assign relevant tolerances based on application requirements and experience.

To satisfy the documentation requirements of the verification stage, the C2G file contents should include a complete (i.e., no items indicated as missing from the feasibility stage review) initial version of the manufacturing process as described in Subsection 2/1 and below.

- The PCWD should encompass the entire manufacturing process from feedstock and digital file production through post processing and part installation.
- The PDP should contain the drawings, models (for both part design and AM processing, as applicable), and other design documents for all production parts, reference parts, test samples, and test artifacts. The PDP should also contain an adequate description of the required material properties for both feedstock and finished parts in the materials basis.
- The PMD should contain a comprehensive set of documents explaining how the AM process is to be conducted, from drawing development and feedstock acquisition through post processing and part installation. The PMD should also contain a current summary of the manufacturer's log.
- The PITP should include the applicable standards for each process indicated in the PCWD, along with associated inspection and measurement techniques and tolerances. The PITP should also outline the tests and inspections to be performed in the AM process, and the process monitoring and control requirements.

Upon satisfactory completion of a C2G file review, ABS will issue a Statement of Maturity for the verification of the AM process, indicating that overall process was evaluated based on the available information and the current technology and found to be satisfactory.

Note: Accommodating changes to the manufacturing workflow (PCWD) become increasingly difficult when discovered later in the AM qualification process. "Critical" parameters (discussed more in Subsection 4/1) once qualified by demonstration and satisfactory testing results in Section 5, may require process requalification if changes are outside of listed tolerances.

1 Critical and Auxiliary Parameters

Once the C2G file is populated with all primary available information, the PDO and AMSP should submit an initial PCWD to ABS for review. Each PCWD node's process parameters are to be divided into those that are critical to the node and therefore the overall process, and those that are auxiliary.

Critical parameters are essential to the AM procedure, have a direct impact on quality, and vary during the manufacturing process. Critical parameters are to be monitored and, if changed or found to be outside of tolerances, may disqualify the AM process and require requalification. Examples of critical parameters include machine (make, model, and serial number), machine location, deposition parameters, material feedstock, and heat treatment characteristics.

Auxiliary parameters can directly affect the AM process, and should be established agreed upon between the PDO, AMSP, and ABS. The auxiliary parameters' influence is less critical, and therefore a change may not necessarily mean that the process requires requalification.

Auxiliary parameters are those that typically remain constant or operate within narrow tolerances. Examples of auxiliary parameters could include the make and model of powder recycling machinery, power supply, machining/finishing equipment, or certain production sequencing software.

The influence of auxiliary parameters on the overall AM process should be tracked along with the relevant operation procedures used to conduct them. For example, cleaning and maintenance procedures should be specified if an AM system is used to process more than one type of material. One related risk of multi-material systems is cross-contamination between material types. While cleanliness is not a direct process parameter (e.g., heat input, current, travel speed, etc.), cleanliness directly affects build quality. To account for this, feedstock and part chemistry should be monitored closely in the inspection schedule, especially if materials have been changed.

Auxiliary machinery also requires regular maintenance and calibration per the relevant Rules, codes, and standards.

Tolerances for each critical and auxiliary parameter should be established.

Note: AM process parameters may not readily transfer between different makes and models of AM machinery, software, OEMs, and manufacturing configurations. Configurations of AM systems may be proprietary and as such may be reviewed on a case-by-case basis.

Process data records for all Critical and Auxiliary process parameters throughout the PWCD should be documented in the relevant database listed in Subsection 1/3 and Subsection 5/3. Refer to 2/1.3.4 for process confidentiality. Change in version of the control file or adjustments/omissions to data records may require explanation and potentially process requalification.

Note: ABS should be notified of any major facility renovations or other manufacturing changes/developments that may affect the qualification stage of the AM process.

2 Part and Process Design

Part properties may be affected by the orientation and location within the build volume. Build files for parts, reference parts, test samples, and test artifacts should include extra material (machining allowance) to account for losses due to distortion, machining, and post-processing, as applicable.

Analytical part models (e.g., finite element analysis (FEA), computational fluid dynamics (CFD), heat transfer, etc.) should consider the effect of material anisotropy, build orientation, build path, etc. The models should be used to ascertain critical design locations and identify localized undesirable thermal and mechanical effects.

The thermal history of the finished part should be specified. A record of thermal history should include the cyclic thermal effects of AM processing, heat treatment, HIP, etc. The goal is to define the temperature profile and thermal processing required to achieve the desired properties.

2.1 AM Modeling and Simulation

If CAE or FEA modeling software (e.g., ABAQUS, ANSYS, etc.) is used to determine the influence of AM process parameters on part properties, the inputs to such models should be reviewed by ABS. For example, certain software packages allow the user to input custom material feedstock properties, anticipate the stresses caused by the AM process, and modify the build geometry (e.g., shrinkage compensation) so the part “distorts” into the correct shape during processing. In these cases, the “pre-distorted” and “resulting” geometries should be reviewed, along with relevant finite element residual stress calculations. These models may be used to design the post-process stress-relief procedures.

Modeling and simulation software can be used to predict the effects of material anisotropy on material properties. However, the PITP should still include testing to validate the microstructural, mechanical, and chemical properties at critical design locations. These locations should be indicated in the PDP, and additional reference parts, test samples, or test artifacts may need to be included in the PMD for production.

Process modeling can provide an additional degree of confidence in the parts/process and save the PDO and AMSP time and money by anticipating if a build process is not capable of producing the desired results. However, modeling technologies alone are not mature enough to fully validate the quality of parts within a build, and cannot replace physical compliance verification activities or test builds.

Process modeling may serve as a tool to guide PDOs and AMSPs to optimize processes and designs. Tests and inspections conducted in the PITP should corroborate that both the AM process model and finished parts function as expected.

3 In-Process Monitoring and Control during Production

In-process monitoring systems (machinery and software) used to track process stability should be indicated when available. AM OEMs may have software and/or hardware packages that are capable of measuring different features of the AM process, such as melt pool temperature, melt-pool emission characteristics, energy input, etc. This information can be used to actively control the process, or accumulated to aid in process trending or decision-making.

Process monitoring and/or control system details (e.g., software/hardware name, revision, measurement characteristics if available, etc.) should be recorded in the C2G file for each part produced. For each process qualification or requalification, actual results of testing and inspections in the PITP should be reviewed against the in-process monitoring and/or control system to verify its accuracy. Refer to 2/1.3.4 for process confidentiality.

Relevant process deviations and relevant indications identified by the in-process monitoring system within parts should be examined. These findings may influence the required number of tests and inspections in the PITP. For example, if the in-process monitoring software captures a potential defect in a built tensile specimen within the gauge length, then the specimen should be inspected prior to testing and discarded if an actual defect is found.

In determining relevant indications, consideration is to be given to the type of in-process monitoring applied. Relevant indications measured by process monitoring software may not provide metrics that are readily comparable to design requirements (e.g., melt pool emissions versus defect size). In these cases, the in-process monitoring capabilities provide an additional layer for quality control by the AMSP/PDO. In cases where the in-process monitoring system provides metrics that are readily comparable to requirements in the PITP, relevant indications are those that exceed the applicable threshold values and as such are to be assessed.

In-process monitoring and/or control systems should not replace regular compliance verification activities or pre-production validation builds. However, they can provide an additional degree of confidence in part soundness and process stability. Therefore, it can save the AMSP time and money by identifying defects or other anomalies early in the build cycle. Currently, in-process monitoring and control techniques alone are not mature enough to fully validate the quality of parts. Generally, in-process monitoring/control systems cannot yet fully determine if a part is “good”, but they can help determine if it is “bad” or to guide inspection. Thus, while using OEM monitoring/control systems provides additional confidence in build process stability, the overall quality for the build still depends on the trained judgment of facility personnel and results of inspections and tests.

If the AMSP chooses to use in-process monitoring/control as a way of tracking process stability and verifying qualification status of builds during production, then relevant indications in parts should be recorded in the process database, reviewed in the witnessing plan, and a summary of indications included in the PITP for each build.

3.1 Process Intervention

The AMSP should indicate the acceptable degrees of intervention during the AM build process, such as cancelling builds due to in-process monitoring or process restart due to power outage, refilling feedstock or gas. The specific interventions should be listed in the PMD and potential risks addressed in Subsection 4/6 with associated tests to quantify the effect of the intervention in terms of risk for the part/process.

An artifact in each production and qualification build allows multiple properties to be monitored using a consistent reference across build cycles. The effect of process interruptions may be quantified more easily due to the availability of a pre-designed test artifact(s), see 2/1.3.2.

4 Material Reuse (Metal Powders)

If applicable to the chosen AM process, the AMSP should define the recycling and reuse protocol for powder materials, metrics for tracking powder quality, and tolerances including aspects such as:

i) Number of days the powder has been in the machine

ii) Number of hours the machine has been in operation

iii) Amount of powder used in each build cycle

iv) Number of build operations conducted using each powder batch/lot

v) Recycled powder restrictions such as reuse ratio, chemistry, etc.

vi) Powder cleanliness and contamination requirements

For additional information about suggested limits on powder recycling and on items *i)* through *vi)*, refer to NASA MSFC-STD-3716 and MSFC-SPEC-3717. The AMSP should also provide a preliminary description of the effect of recycled material on build processes. This document should be reviewed and updated as new process data, process standards and experience become available.

Procedures for process restart, powder mixing, and maintaining feedstock consistency should be considered as part of the PMD prior to production, along with the associated testing as applicable per the PITP. Powder reuse should account for mixtures of different batches or lots of powder in AM machinery.

Note: AMSP/PDO should notify ABS if it is intended to use recycled or otherwise non-virgin powder as a feedstock for the AM process. This includes all qualification as well as production cycles.

5 Witness and Hold Points in PCWD Process Nodes

The PDO/AMSP and ABS should establish and agree upon the initial set of witness/hold points during the verification stage. Each witness/hold point should be indicated on the respective AM process node on the PCWD, and may reference any appropriate PITP documents for convenience. Each process node that includes a witness/hold point should be witnessed by ABS during initial qualification as well as when re-establishing qualification. Witness/hold points, once established, should be indicated on the PCWD for ease of reference.

ABS witness/hold points for the process should be agreed upon prior to beginning production and should include an inspection and test plan that references the applicable PITP documents including:

- Material feedstock details (see 2/1.2.1)
- Process monitoring/control systems and data capture (see 2/1.3.1 and Subsection 4/3)
- Current and accurate manufacturer's log, including process set-up and initiation procedures/documents (See 2/1.3.3)
- Witnessing of testing and inspections for AM production parts, reference parts, test specimens, artifacts, etc. (see PCWD and PITP, 2/1.1 and 2/1.4)

6 Part and Process Risk Analysis

A more detailed risk analysis than performed in the feasibility stage may be necessary for certain parts, such as for those described in 4-1-1/3.5 of the *Marine Vessel Rules*. The breadth and depth of the qualification should correlate with the applicable Tiers of Approval for the part as indicated in Appendix 1-1-A4 of the ABS *Rules for Conditions of Classification*.

Worst-case operation conditions and part conditions should be specified, with associated values and tolerances. Additional items listed in Section 2, Table 2 may be added to the qualification or production build cycles, and inspected and tested to account for potential gaps.

If the PDO chooses to use AM to reduce the total number of parts in assemblies by combining parts into a single AM part, a risk analysis should consider the new level of system risk. For example, using AM to combine parts may increase system risk undesirably due to the potential of a (now) single-point failure.

The anticipated properties of AM parts identified in the PDP, and critical parameters could most affect the design properties (e.g., process sensitivity study). Upon completion of the risk study, if applicable, the C2G file contents should be revised to account for any relevant changes in design, process, inspection or testing.

SECTION 5 Pre-Production Validation Stage

The goal of the pre-production validation stage is to conduct, monitor, and review the processes described in the verification stage. The AMSP is to demonstrate that the manufacturing process can produce the desired part(s), within the given parameters, with a reasonable degree of confidence.

In order to complete the pre-production validation, the process described by the PCWD will be used to import, fabricate, and post-process a series of builds that include production parts, reference parts, test samples, and test artifacts. The builds are conducted in accordance with the agreed procedures and monitored to demonstrate repeatability within the designated values and tolerances. For qualification, requalification, or production, ABS will witness and review the applicable process steps/nodes that are identified as having witness/hold points in the PCWD, or as specifically indicated by Rules, codes, and standards contained within the C2G file.

The adequate completion of the testing and inspection regimen establishes the baseline metrics for maintaining process qualification. Upon satisfactory completion of the manufacturing, testing, and inspections, the C2G file and all its contents become locked as a "qualified" AM process. Agreed changes to the C2G file can be made during pre-production validation, but not after the pre-production validation stage has been completed. Deviations, modifications, and interventions to the proposed procedures are to be noted in the C2G file and discussed.

As introduced in Section 2, multiple build cycles and different build models may be required for initial (pre-production) process validation prior to beginning regular production. One reason for this is that various codes and standards may require separate AM system capability demonstration build cycles than those used to produce the desired parts.

ABS maturity statements are based on the production build volume model(s) submitted in the C2G file, as well as any other qualification build cycles and associated models that may be indicated per PITP requirements. Once an AM process is validated, the production build models contained within that C2G file become locked. Production continues as long as both the AM system operates within the designated tolerances and the produced parts function, inspect, and test within the designated specifications. Since build volume models become locked, it is recommended to critically consider how many of each item listed in Section 2, Table 2 are included in each production build model. Upon satisfactory completion of a C2G file review, ABS will issue a Statement of Maturity for the pre-production validation of the AM process, indicating that overall process was evaluated based on the available information and the current technology and found to be satisfactory.

Note: The pre-production validation stage is also used to identify installation practices of the part(s), and any in-service restrictions.

1 Confirmation of Manufacturing System

Prior to beginning the fabrication process, the C2G file should be re-checked for accuracy and correct revision/version number of all contents. This confirmation is critical. For example, if an AMSP accidentally produces the design using an old file revision or process control software version, then the data collected gives evidence towards qualification of that process, not the one designated in the PCWD. The PDO/AMSP may attempt to qualify the unintentionally changed process separately from the original, pending agreement among the PDO, AMSP, and ABS. Alternatively, the discrepancy can be amended, and the procedures, inspections, and tests can be conducted again to qualify the originally-intended process. In either case, the process, test, and inspection data should be stored in the process database for future reference.

It is the responsibility of the PDO and AMSP to confirm that the entire manufacturing process is conducted in accordance with the procedures and requirements listed in the C2G file.

2 Testing and Inspection Results

Results of PITP testing and inspection schedule are to comply with the agreed requirements defined in applicable documents. Additionally, the results of physical part inspections and testing should be compared against the digital part/model equivalents for the applicable properties (e.g., dimensions, mass, density, etc.). This aids in process improvement and model validation, and helps to confirm that the intended parts are produced as anticipated.

Deviation outside the agreed-upon tolerances of critical and auxiliary parameters is cause for rejection of parts. Alternatively, deviations from the approved procedures may be approved as alternative processes on a case-by-case basis, where the detail and scope of review is contingent on the similarity between the newly proposed process, part design, and the existing qualified process.

Prior to the conclusion of the pre-production validation stage, the initial witness/hold points indicated in the C2G file should be reviewed and modified if necessary to more adequately assess production.

A summary report of all inspections and testing conducted in the PITP should be provided upon part delivery and included in the C2G file. The results should be shared among the PDO, AMSP, and ABS and reviewed for compliance with PDP requirements.

Note: Depending on product manufacturing experience and in-service history, the PDO, AMSP, and ABS may need to assess if additional criteria for inspection and testing should be included in the C2G file for future AM process builds.

3 Ongoing Process Database

Each qualified process owned or managed by the PDO/AMSP should be stored in a manufacturing/process database. For more information, see Subsection 1/3, along with the necessary design, material, process, monitoring, inspection, and test data.

Data should be recorded such that previous build information can be readily compared to the current build cycle. This facilitates re-establishing process qualification status after maintenance, calibration, repair, or other process interruptions indicated in the manufacturer's log.

The database should be capable of comparing numeric process values statistically to analyze the effect of critical and auxiliary parameter changes on the process.

SECTION 6 Production Stage

The goal of the production stage is to establish a monitoring and quality control plan. Maintaining a qualified AM process involves monitoring and recording the parameters indicated in the locked C2G file and in the process database with enough detail to be able to adequately verify that process remains within limits.

Ongoing process examination should be agreed upon between the PDO, AMSP, and ABS, and depends on the frequency of AM part production, the size and criticality of the parts, and C2G file requirements.

Continued AM process qualification also depends on the AMSP maintaining a current manufacturer's log and demonstrating consistent satisfactory performance. All maintenance and calibration should be in accordance with the AM machine manufacturer's recommended schedules, including preventative maintenance requirements. Re-establishing the maturity of AM processes should be conducted in accordance with the most recent version of the applicable Rules, codes, and standards referenced in the C2G file.

Note: Depending on the process defined in the C2G file, some standards may require review and requalification of processes at specified intervals, such as annually. ABS recommends survey/audit intervals at the minimum intervals as specified in the C2G file. If satisfactory results are obtained from continuous process monitoring and statistical process control methods, requalification and review periods may be extended.

If the AM system is not adequately maintained, calibrated, and otherwise managed in accordance with the manufacturer's log, AM process Statements of Maturity are suspended until the system is satisfactorily repaired and a qualified employee demonstrates satisfactory operation within the tolerances of a maturity-evaluated process. Adequate confirmation should be given for each suspended process before resuming its maturity-evaluated status.

Note: Since it can be challenging during production to maintain a maturity-evaluated AM process, it may be useful to use planned downtime to perform repair, maintenance, and calibration on the items identified in the PCWD.

Process maturity is lost when there is a permanent change in the configuration of the maturity-evaluated process defined in the C2G file for a critical parameter, multiple auxiliary parameters, or when statistical process control indicates that the operation may be drifting outside of maturity-evaluated limits. Subsection 6/4 outlines a suggested method to anticipate changes in parameters outside of the designated tolerances and to maintain a maturity-evaluated AM process.

1 Re-Establishing AM Process Maturity

In order to re-establish AM process maturity, the C2G (PDP, PMD, PITP, PCWD) along with any other relevant information (e.g. material basis, manufacturer's log, etc.) used to produce the last maturity-evaluated build should be re-evaluated and updated with respect to any new information. Changes between the previously maturity-evaluated C2G file and the updated C2G file should be summarized in a Return to Service report that is then included in the C2G file.

The process changes listed in the Return to Service report are to be reviewed by ABS. The updated AM process should be performed, witnessed, inspected, and tested similar to the original maturity evaluation process. Depending on the type of AM process and part criticality, re-establishing or maintaining process maturity may involve producing and inspecting the relevant production parts, reference parts, test samples, and test artifacts indicated in the maturity-evaluated C2G file with each build cycle or before and after a production run, until performance can be accurately assessed.

Note: The updated process may require recording additional process data than originally designated. The new data should be recorded and be statistically comparable.

Upon successful results per the revised C2G file, the AM process becomes re-evaluated for maturity as long as the items listed in the C2G file and all dependent documents (e.g., manufacturer's log, materials basis, etc.) remain current.

2 Installation and Operation

The PDO should develop an in-service inspection and test plan for AM-parts, including activities such as defining a preliminary list of lifetime assessment variables (e.g., fatigue life, corrosion performance, etc.) and associated monitoring and inspection methods (e.g., visual inspection, nondestructive evaluation, acoustic emission, etc.).

The intent is to anticipate in-service AM part characteristics and failure mechanisms, and design inspection criteria to reduce operations risk by identifying at-risk parts and acceptable tolerances prior to potential failures. The PDP may be updated to include a place to hold relevant in-service inspection data, especially regarding requirements that are more rigorous than or different from those of a non-AM part equivalent. The PDO may also opt to implement a condition-based monitoring/maintenance system.

Part failures should be documented in the associated PDP and added into a statistics-capable process database. If possible, associated measurements of lifetime assessment variables should be included (e.g., number of fatigue cycles to failure, corrosion rate, etc.). Such in-service, field performance, and failure analysis data is critical for identifying the types, locations, and causes of critical defects.

Note: Currently, there are no standards that adequately address welding of AM parts. Post-fabrication welding to AM parts is not recommended, including auxiliary welding during manufacturing such as attaching handling devices.

3 Cybersecurity and Digital Manufacturing

The AMSP and PDO are jointly responsible for establishing and maintaining digital system security. The AMSP and PDO should demonstrate an adequate awareness of digital security for all applicable AM system components related to qualified processes. This includes a knowledge of system assets, potential faults or gaps, and data handling procedures.

The goal of these measures is to prevent situations where:

- AM system components are used as an access point for the manufacturing facility.
- Time and resources are wasted if/when a malicious body were to hack into the facility, damage machines, alter part/process files, etc.
- Individuals or software takes copies of built jobs and send files to unknown sources.
- Malicious programs add wasted time into processes and/or slow connections.
- Intellectual property is compromised.

Assets include:

- *System Assets.* AM machinery, computers, etc. for the facility. System components should be analyzed both individually and together including potential means for security or signal compromise. Components include interfaces into other systems, between segments or enclaves within the facility, and data transfer devices or methods that can carry data, including malware and similar, into otherwise pristine areas.
- *Connections Among the Assets.* Including information exchange within the facility and to the outside environment. Both physical and wireless connections among system components should be considered.
- *Identities Operating within the System.* Including people or systems that could exchange information into/out of the AM system.

The AMSP/PDO should specify procedures that maintain active digital system security, which will include necessary conditions of confidentiality, integrity, and availability. Examples include workplace procedures such as locking/logging out of computers and other relevant equipment after working hours, encrypting USB sticks, and storing all confidential documents in locked cabinets when not in use.

The PMD should also consider any applicable effects of digital file conversion and transfer, such as pixilation or unmatched surfaces, as well as data fidelity and security over time (e.g., changing file types, software version/format changes, etc.). All converted and/or transferred files should be checked for similar units of measurement, origin location, build file resolution versus machine feature resolution capability, etc. The AMSP should define a data import/export plan to consistently prepare and convert part design and manufacturing files to versions compatible with the AM system.

4 Ongoing Production Risk Assessment

Maintaining AM process qualification depends upon successful maintenance of qualified (locked) process configuration. Ongoing process qualification status is determined by referencing the PCWD, PMD, and manufacturer's log and confirming that all critical parameters are within the tolerances and versions listed.

It is recommended that the PDO/AMSP conduct an ongoing process risk/sensitivity analysis for changes that would disrupt a qualified process as well as other qualified processes by triggering the need for resubmittal and requalification. Considerations for maintaining qualified production operations include:

i) Changes to the AM system(s) defined in the PCWD and/or PMD and procedures other than predefined preventative maintenance, such as AM system upgrades or facility expansion.

ii) Changes to the PDP outside of listed tolerances, such as adding or removing design features.

iii) Changes to the PMD such as implementing new powder feedstock recycling procedures.

iv) Changes in the PITP based on new/changing regulation requirements.

v) Replacement, repair, or alteration of critical AM machinery or services. Qualified AM processes may be specific to the serial number of a particular AM machine.

vi) Changes to the AMSP facility, such as moving an AM machine.

vii) Changes or updates to software, such as process monitoring/control systems and file conversion.

viii) Process contamination risks, such as:

a) For wire-based systems, comingling elements (e.g., wire feeders, liners, etc.) that contact the feedstock of different alloy systems.

b) For powder-based systems, using different kinds of powder feedstock in a single AM machine.

c) Sharing auxiliary tools for different AM processes, such as cleaning brushes between different alloy systems.

d) Use of different types of cleaning solvents.*

** Note:* Use of chemicals to clean a powder bed fusion machine's internal or process-related areas should be discussed between the AMSP and the AM OEM prior to production, as certain cleaning agents such as chlorinated solvents, methyl alcohol, or citrus-based products may have an effect on build quality depending on the material feedstock.

APPENDIX 1 Example PCWD with Supporting Information

Appendix 1, Figures 1 through 9 provide an outline of the PCWD for a DED-GMAW (WAAM) process and part, with outsourced heat treatment, inspection, and testing, intended for a machinery application. The structure of each process node is standardized to include room for the facility, inputs, machinery, software, process details, and outputs. Below each process node is a description of how the information is sorted into the C2G file packages. The following figures are intended as generic guidance, as the actual structure of each C2G file is anticipated to be unique for each part and process.

FIGURE 1
Example Process Configuration Workflow Diagram Outline for a DED-GMAW (WAAM) Process with Outsourced Heat Treatment, Inspection, and Testing, Showing Typical Node Structure

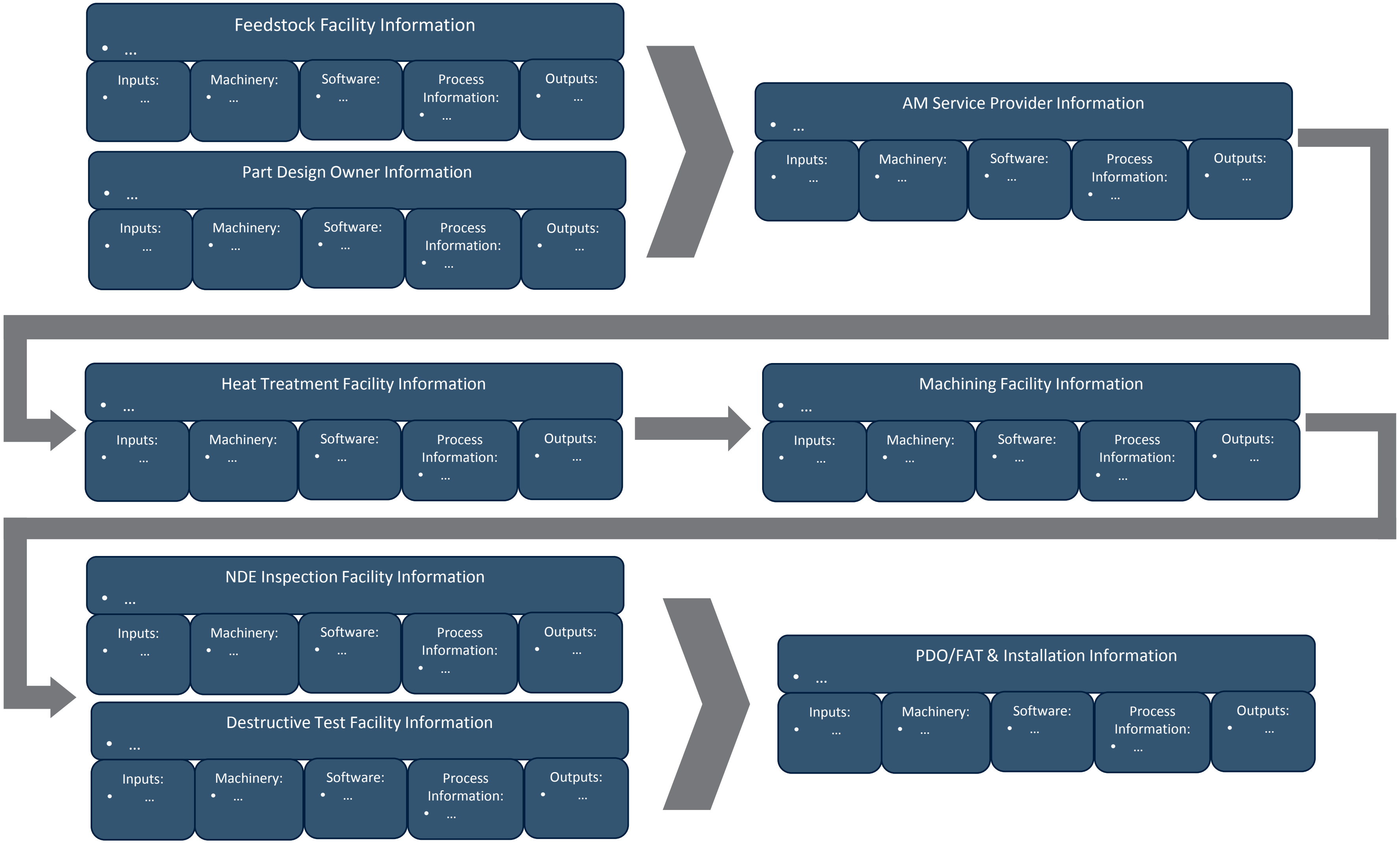


FIGURE 2A
Example Feedstock Facility Node

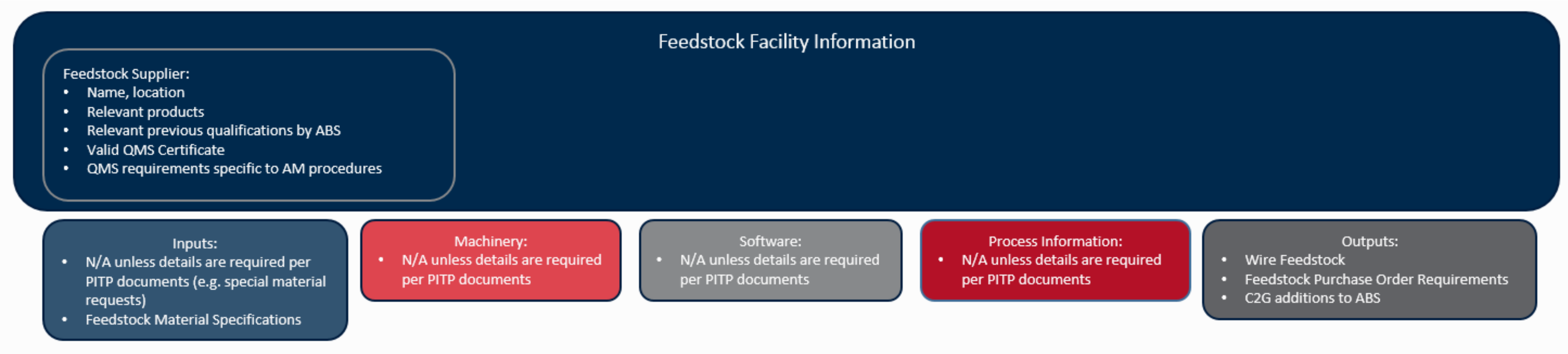


FIGURE 2B
Example Feedstock C2G Documentation

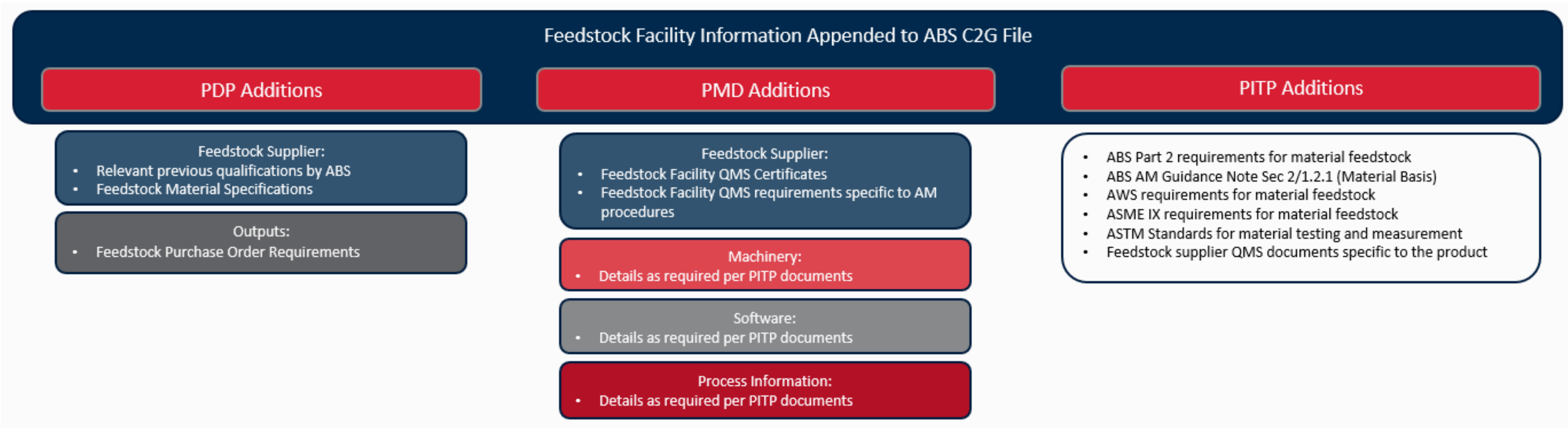


FIGURE 3A
Example Part Design Owner Node

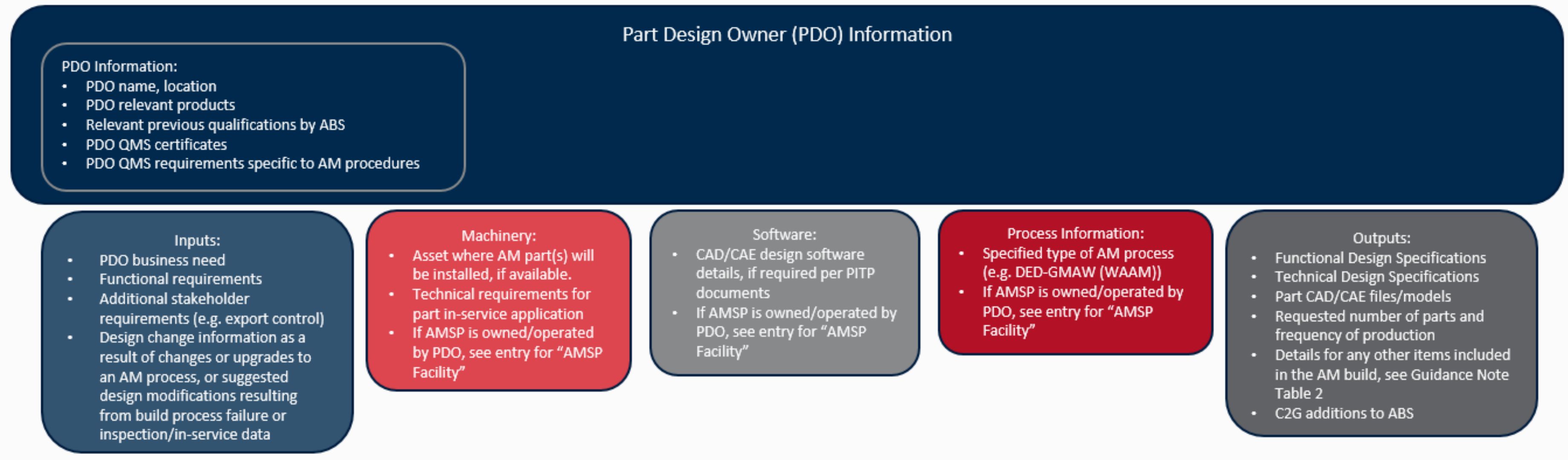


FIGURE 3B
Example Part Design Owner C2G Documentation

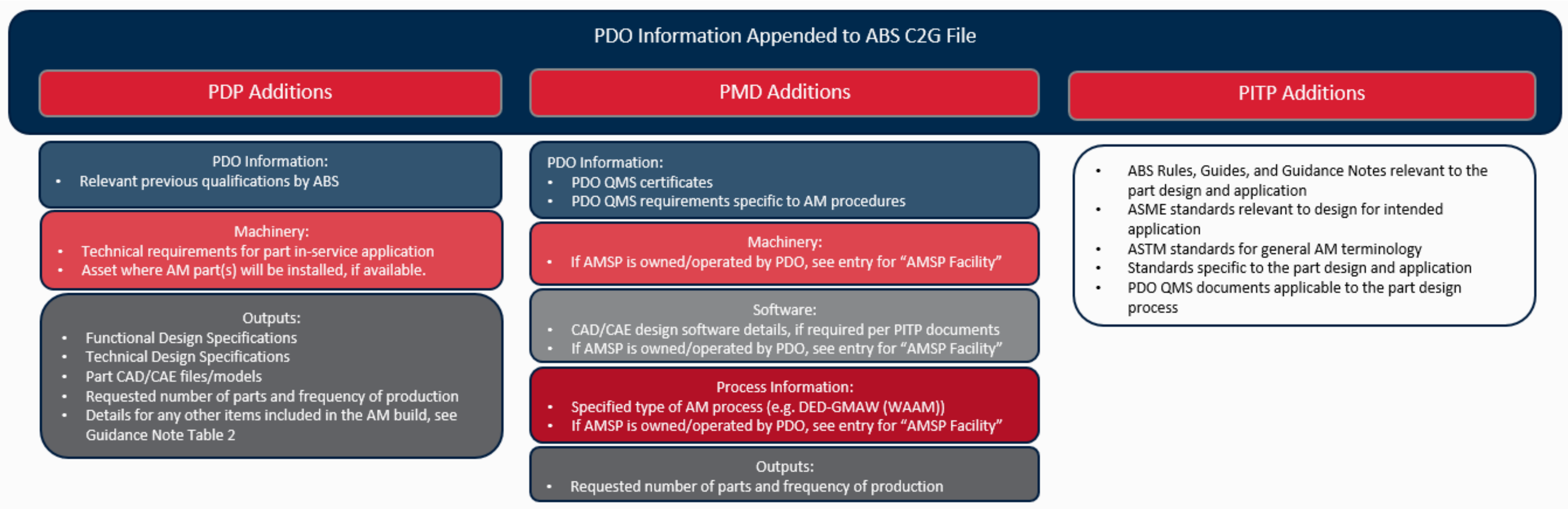


FIGURE 4A
Example AM Service Provider Node

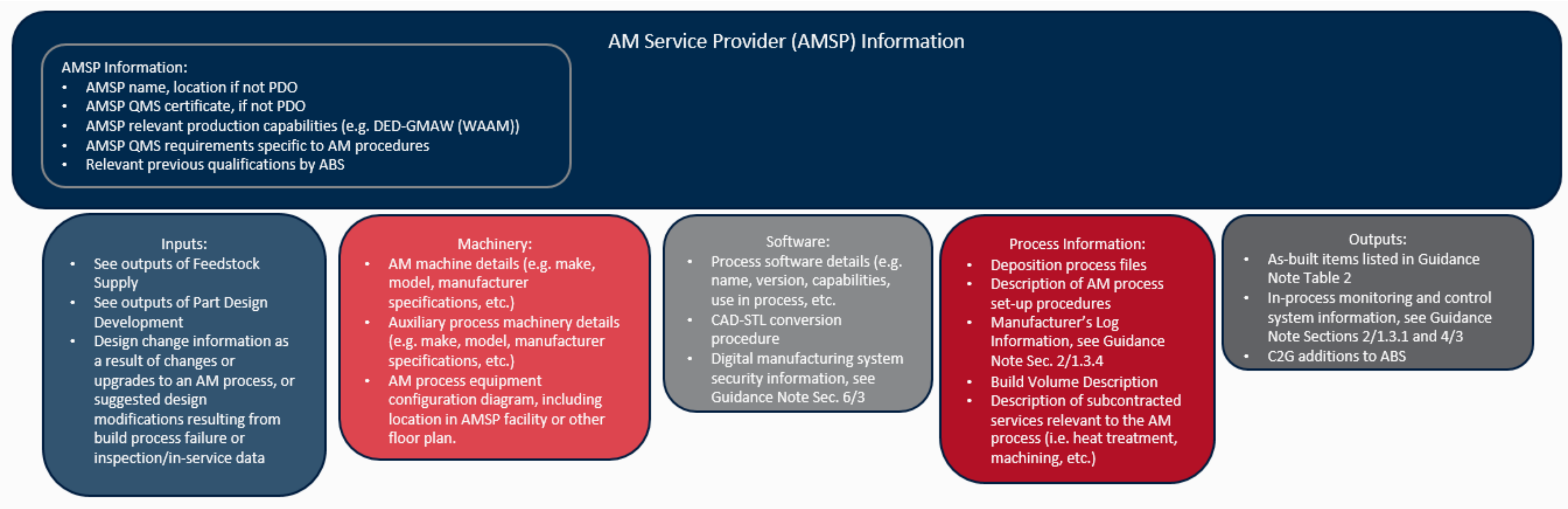


FIGURE 4B
Example AM Service Provider C2G Documentation

AMSP Information Appended to ABS C2G File

PDP Additions

- N/A

PMD Additions

AMSP Information:
- AMSP QMS certificates
- PDO QMS requirements specific to AM procedures

- Machinery:
- AM machine details (e.g. make, model, manufacturer specifications, etc.)
- Auxiliary process machinery details (e.g. make, model, manufacturer specifications, etc.)
- AM process equipment configuration diagram, including location in AMSP facility or other floor plan.

Software:
- Process software details (e.g. name, version, capabilities, use in process, etc.
- CAD-STL conversion procedure
- Digital manufacturing system security information, see Guidance Note Sec. 6.3

Process Information:
- Deposition process files
- Description of AM process set-up procedures
- Manufacturer's Log Information, see Guidance Note Sec. 2/1.3.4
- Build Volume Description
- Description of subcontracted services relevant to the AM process (i.e. heat treatment, machining, etc.)

Outputs:
- As-built items listed in Guidance Note Table 2
- In-process monitoring and control system information, see Guidance Note Sections 2/1.3.1 and 4/3

PITP Additions

- ABS Guidance Note on Additive Manufacturing
- AWS Standards relevant to AM process (e.g. filler metal, shielding gas, etc.)
- ASTM standards for AM (e.g. F2921, F3187, etc.)
- AMSP and PDO QMS documents for the AM process, including feedstock control, file transfer, fabrication, post processing, part marking and packaging, as applicable.
- Critical AM equipment (machinery and software) manufacturer specifications for calibration, maintenance, and operation.

FIGURE 5A
Example Heat Treatment Node

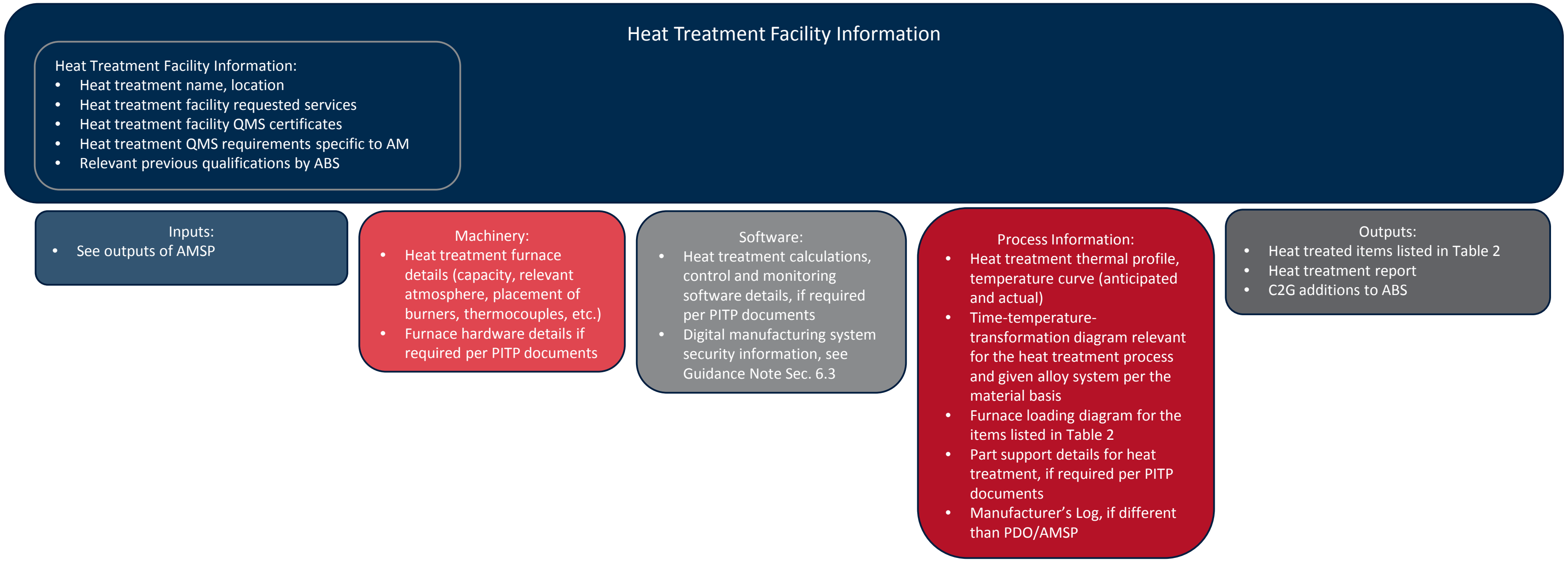


FIGURE 5B
Example Heat Treatment C2G Documentation

Heat Treatment Information Appended to ABS C2G File

PDP Additions

- N/A

PMD Additions

Heat Treatment Facility Information:
- Heat treatment facility QMS certificate
- Heat treatment QMS requirements specific to AM

Machinery:
- Heat treatment furnace details (capacity, relevant atmosphere, placement of burners, thermocouples, etc.)
- Furnace hardware details if required per PITP documents

Software:
- Heat treatment calculations, control and monitoring software details, if required per PITP documents
- Digital manufacturing system security information, see Guidance Note Sec. 6.3

Process Information:
- Heat treatment thermal profile, temperature curve (anticipated and actual)
- Time-temperature-transformation diagram relevant for the heat treatment process and given alloy system per the material basis
- Furnace loading diagram for the items listed in Table 2
- Part support details for heat treatment, if required per PITP documents
- Manufacturer's Log, if different than PDO/AMSP

Outputs:
- Heat treated items listed in Table 2
- Heat treatment report

PITP Additions

- ABS rules relevant to the heat treatment and properties of the part
- AWS standards relevant to post-weld heat treatment
- ASTM standards relevant to the heat treatment
- Heat treatment facility QMS and relevant process documents
- PDO heat treatment QMS requirements

FIGURE 6A
Example Machining Node

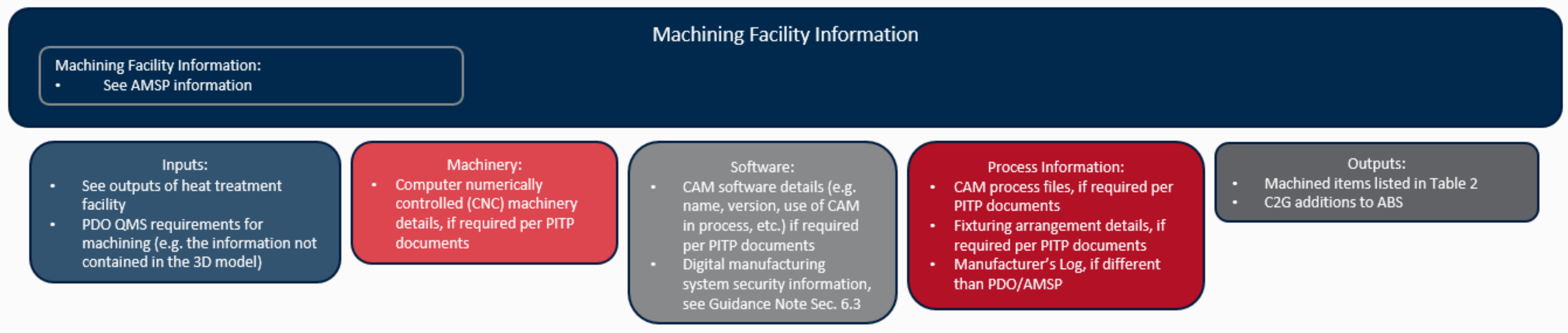


FIGURE 6B
Example Machining C2G Documentation

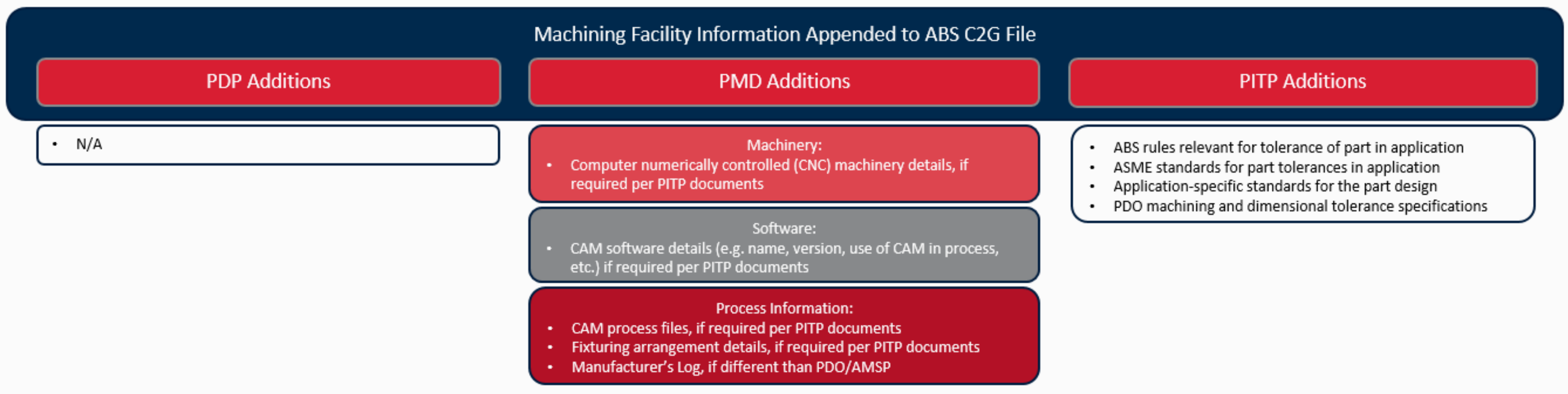


FIGURE 7A
Example Nondestructive Evaluation Node

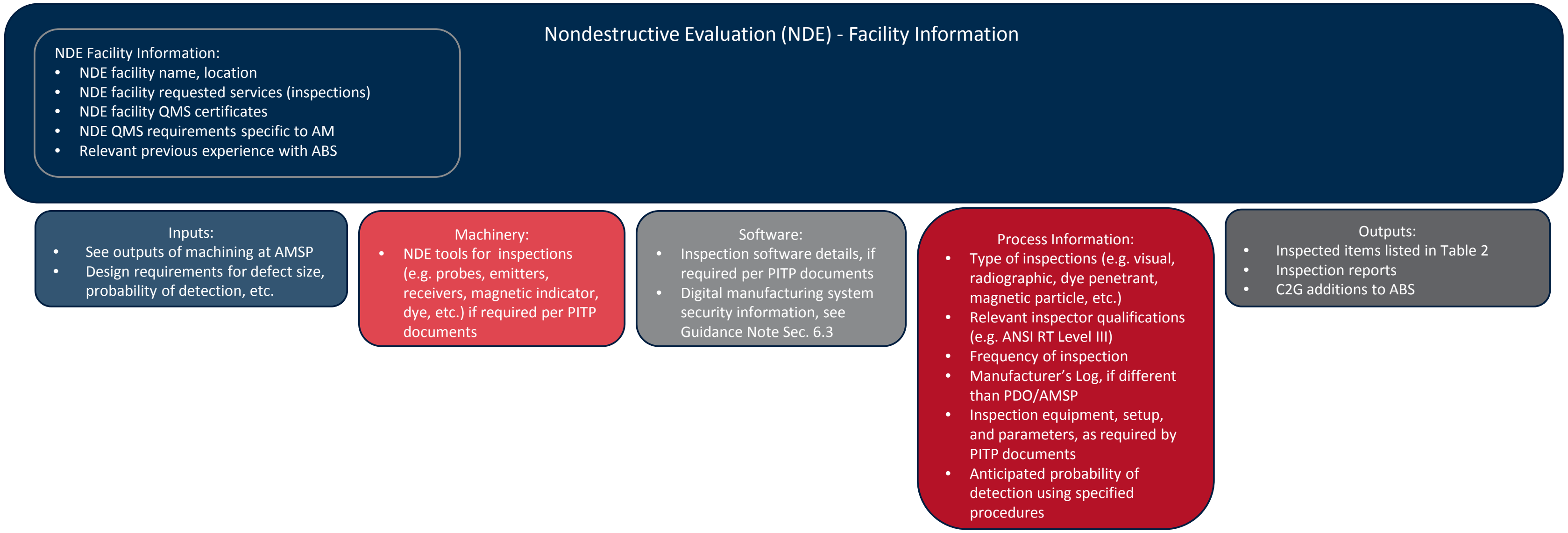


FIGURE 7B
Example Nondestructive Evaluation C2G Documentation

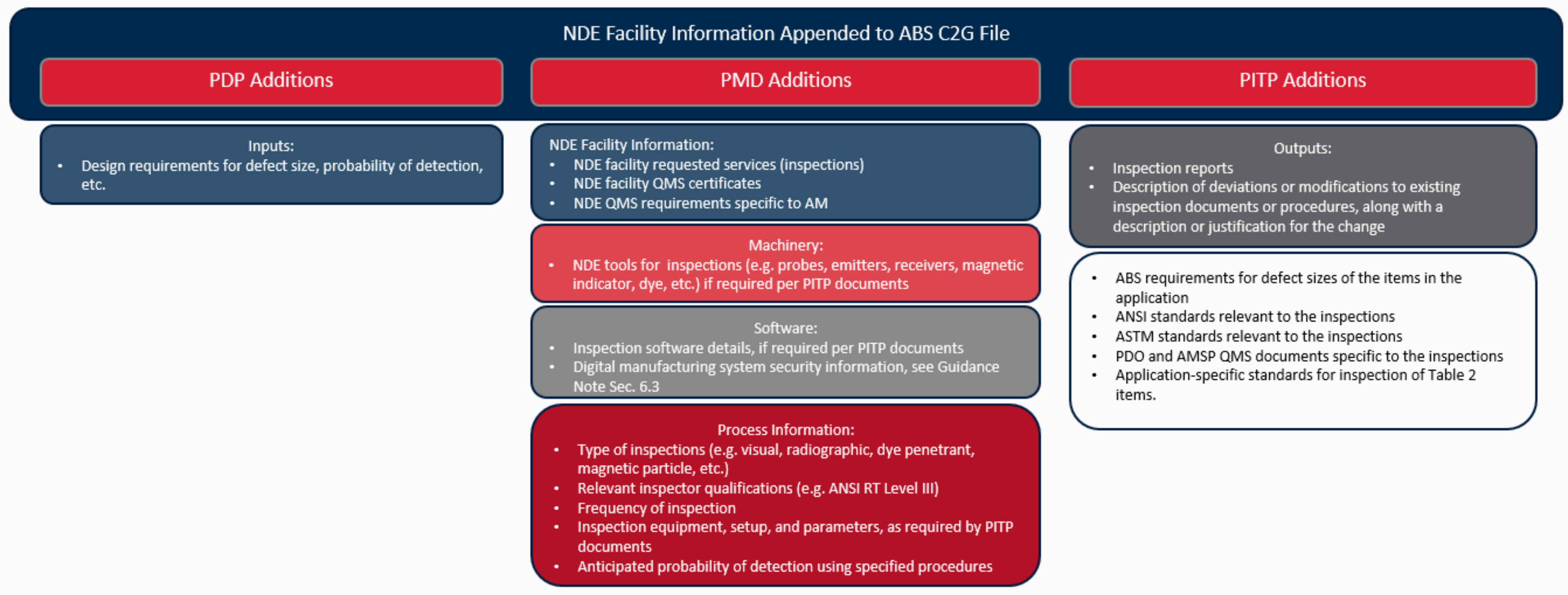


FIGURE 8A
Example Destructive Testing Node

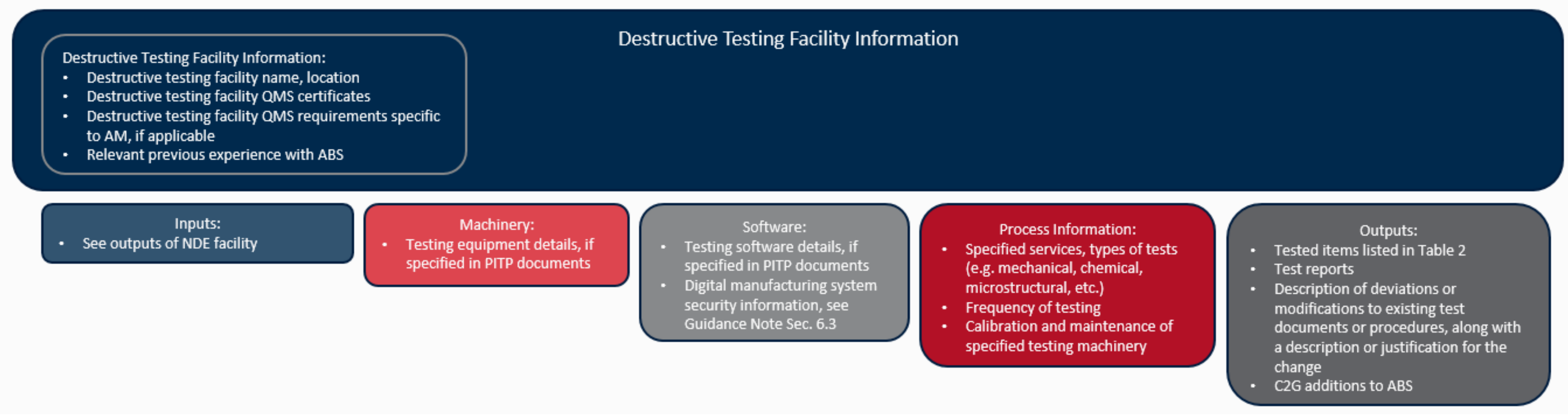


FIGURE 8B
Example Destructive Testing C2G Documentation

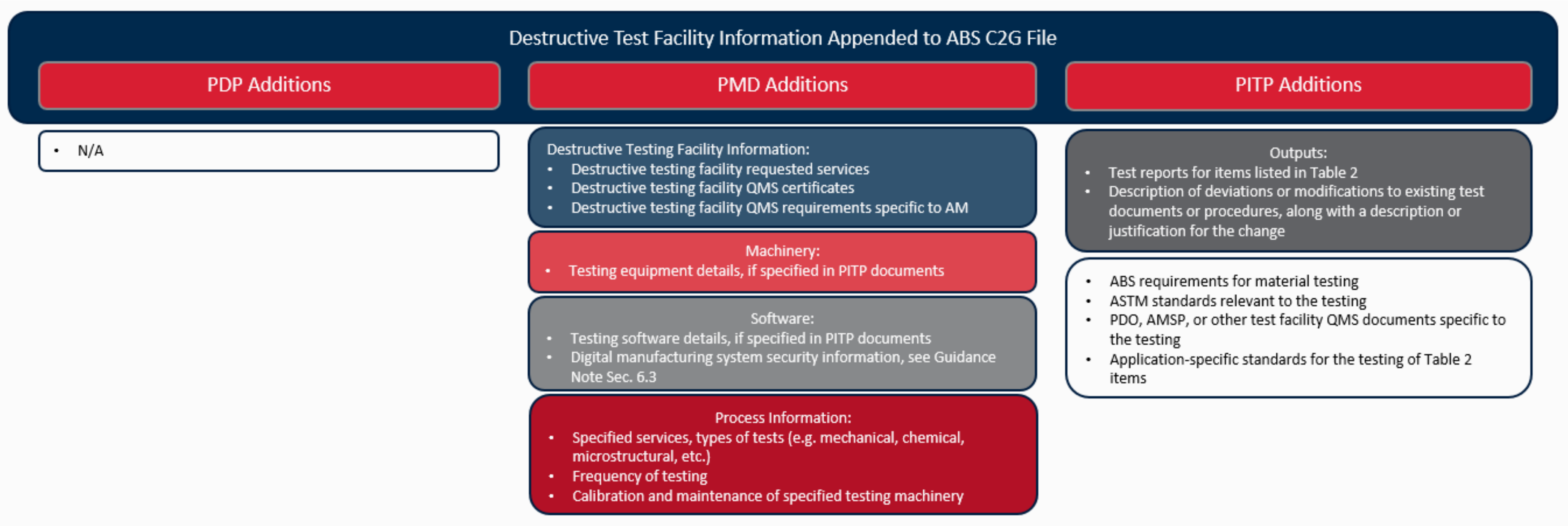


FIGURE 9A
Example Part Design Owner Acceptance and Installation Node

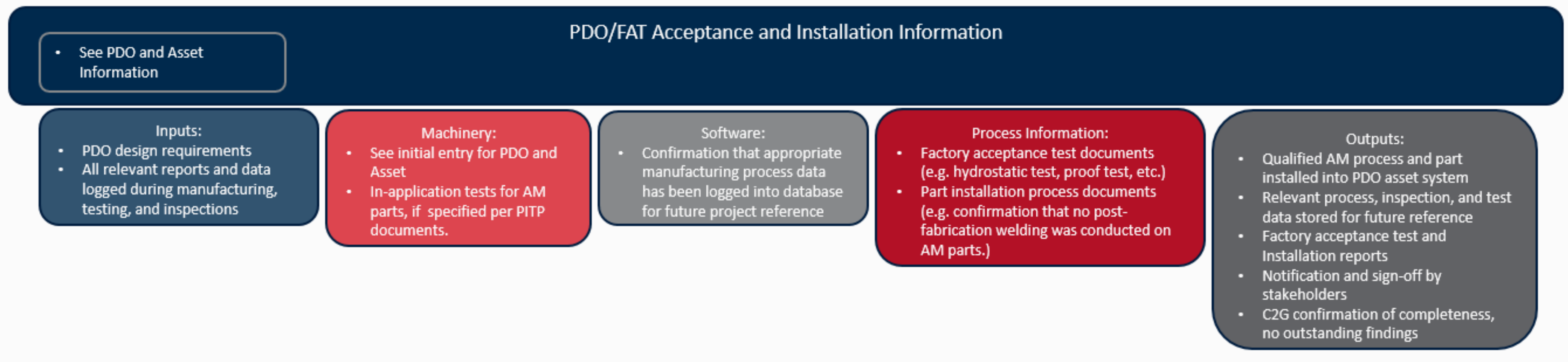
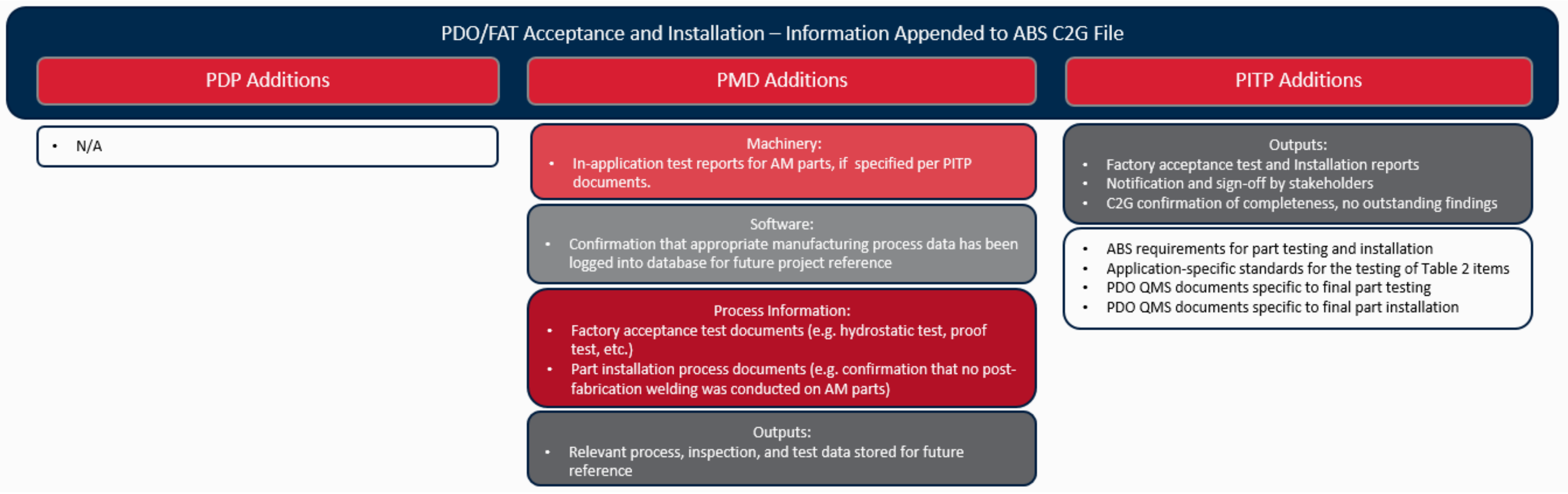


FIGURE 9B
Example Part Design Owner Acceptance and Installation C2G Documentation



APPENDIX 2 References

In addition to the regular design/code requirements to produce each part without AM (using conventional methods), other standards and guidance documents may be applied. Use of each may require additional discussion among the PDO, AMSP, feedstock provider, and ABS throughout the qualification process.

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11. ASTM International, *Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion* (ASTM F3301-18), ASTM International, West Conshohocken, 2018.
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17. ASME, *Product Definition for Additive Manufacturing* (Draft) (ASME Y14.46-2017), ASME, New York, 2017.

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22. National Aeronautics and Space Administration, *Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals* (MSFC-STD-3716 EM20), NASA, Huntsville, 2017.

23. National Aeronautics and Space Administration, *Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes* (MSFC-STD-3717 EM20), NASA, Huntsville, 2017.

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