Role of NDE and In Situ Process Monitoring in Managing Risk of AM Space Hardware

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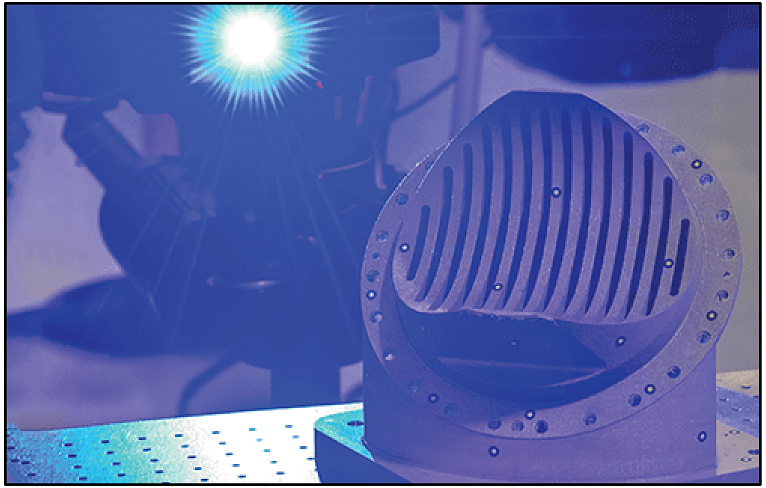

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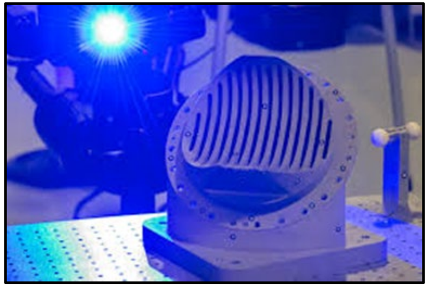
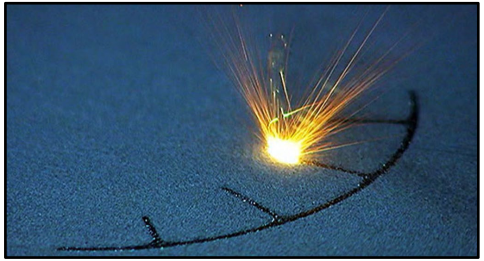
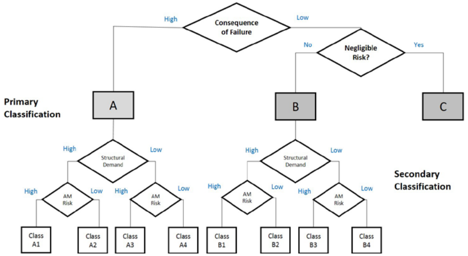
We will discuss NASA’s interest in qualifying in situ monitoring methods for certification of AM space hardware.



NASA’s involvement and approach



Qualification of in situ monitoring



Certification framework

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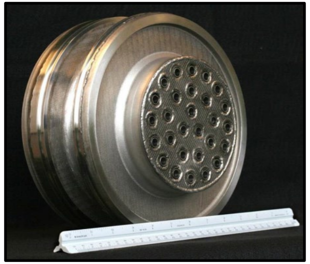
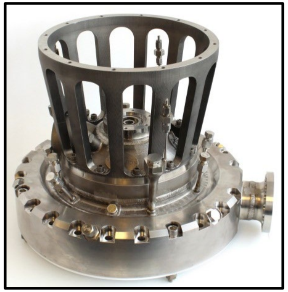
NASA is interested in qualifying in situ monitoring for complex, critical parts that are difficult to inspect using traditional NDE.

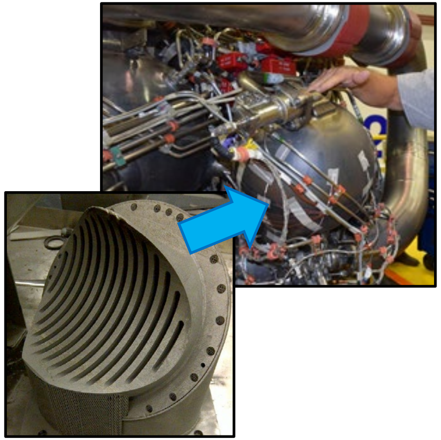
28-Element Inconel® 625 Fuel Injector
Reduced 163 parts to 2
Schedule reduced from 1 year to 4 months
70% cost reduction



Cryogenic Heat Exchanger-Injector-Condenser Demo



Injector Assembly
MSFC Project with Army Air and Missile Defense (AMD)



RS-25 Pogo Accumulator Z-Baffle
Over 100 Welds Eliminated
Nearly 35% Cost Reduction

All hardware images are in the public domain.
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MSFC has investigated in situ process monitoring through various mechanisms.

Small Business Innovation Research

SBIR·STTR
America's Seed Fund™
POWERED BY NASA

Monitoring Systems

EOS | Optical Tomography & Meltpool Monitoring

Open Additive | Thermal Tomography & High-Speed Spatter Imaging

Phase3D | Height Mapping

ASTM E3353-22

ASTM INTERNATIONAL

"Standard Guide for In-Process Monitoring Using Optical and Thermal Methods for Laser Powder Bed Fusion"

ASTM AM Center of Excellence

CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

Completed a landscape survey and workshop with road mapping session
Strategic Guide available now!

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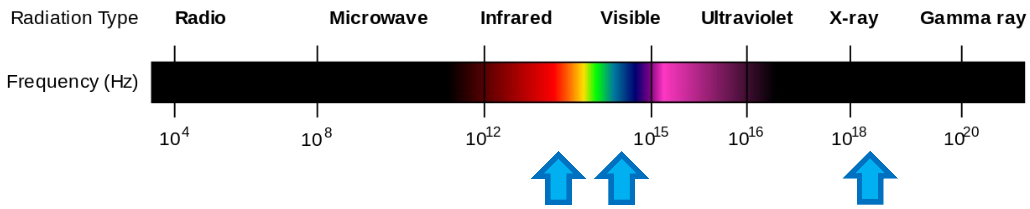
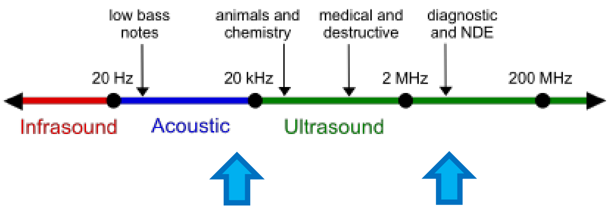
There are many different in situ process monitoring technologies which observe different physical phenomena.

Electromagnetic Frequency Spectrum



Ultrasonic Frequency Spectrum



	Monitor During Build Process	Inspection Between Build Layers
Passive (No external excitation)	Infrared/near-IR melt pool monitoring	Visual Laser profilometry
Active (Added excitation)	-	Laser ultrasonic Eddy current

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There are also different additive manufacturing technologies that can be monitored.

	Powder Bed Systems	Freeform Fabrication
Process:	Laser Powder Bed Fusion (L-PBF) Electron Beam Melting (EBM) Selective Laser Sintering (SLS)	Laser Directed Energy Deposition (DED) Electron Beam Free Form Fabrication (EBF^3) Rapid Plasma Deposition Additive Friction Stir Weld Fused Filament Fabrication (FFF)
Feedstock:	Metals: Nickel alloys, copper alloys, titanium alloys, etc. Polymers: nylon, polyamide	Metal powder/wire/chips Filament: polymer, carbon fiber, biological, etc.

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There are two main functions of in situ process monitoring:

Process Control Function

- Real-time warning of build problems
- Use to check for process drift
- Monitor effects of parameter changes, spatter, etc.

- **Not** counting on it for quantitative part quality metrics or defect detection
  - May help tell you where to look for a problem, but would require verification with NDE

vs.

Part Quality Function

- **Quantitative analysis of part quality**
- Requires a known correlation between indications, physics of the process, and actual defects in the finished part
- Need to know probability of detection
  - Extra step – verify actual size, location of created defects

- Need to **treat it like NDE** – believe and investigate every indication
  - Can’t dismiss anything as a false positive unless proven

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When considering the use of in situ process monitoring for part qualification, there are a few aspects that challenge the current paradigm.

In-process vs. post-process NDE

- Often, flaw observations are indirect
  - Directly observing process variation, inferring final flaw
  - Must understand physical basis for measured phenomena
  - Need to prove a causal correlation from measured indications to flaw state
- Probability of detection (POD) study must include secondary verification of created flaws

Closed-loop process control

- Current NASA qualification logic based on a locked process
- For real-time parameter changes, a new approach is needed

no longer nondestructive

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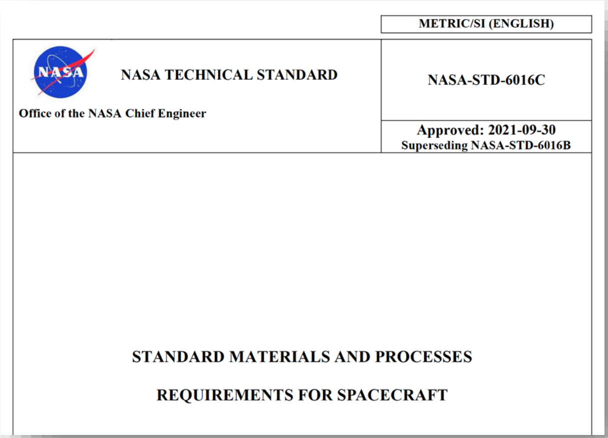
The current logic of additive manufactured part certification is outlined in NASA-STD-6016C, NASA-STD-6030, and NASA-STD-6033.


METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-6016C

Approved: 2021-09-30
Superseding NASA-STD-6016B

STANDARD MATERIALS AND PROCESSES

REQUIREMENTS FOR SPACECRAFT

NASA-STD-6016C

General M&P requirements

MSFC-STD-3716

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

MSFC-SPEC-3717

Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

NASA-STD-6030

NASA Technical Standard

Additive Manufacturing Requirements for Spaceflight Systems

NASA-STD-6033

NASA Technical Standard

Additive Manufacturing Requirements for Equipment and Facility Control

Handbook coming soon with more specifics on implementation.

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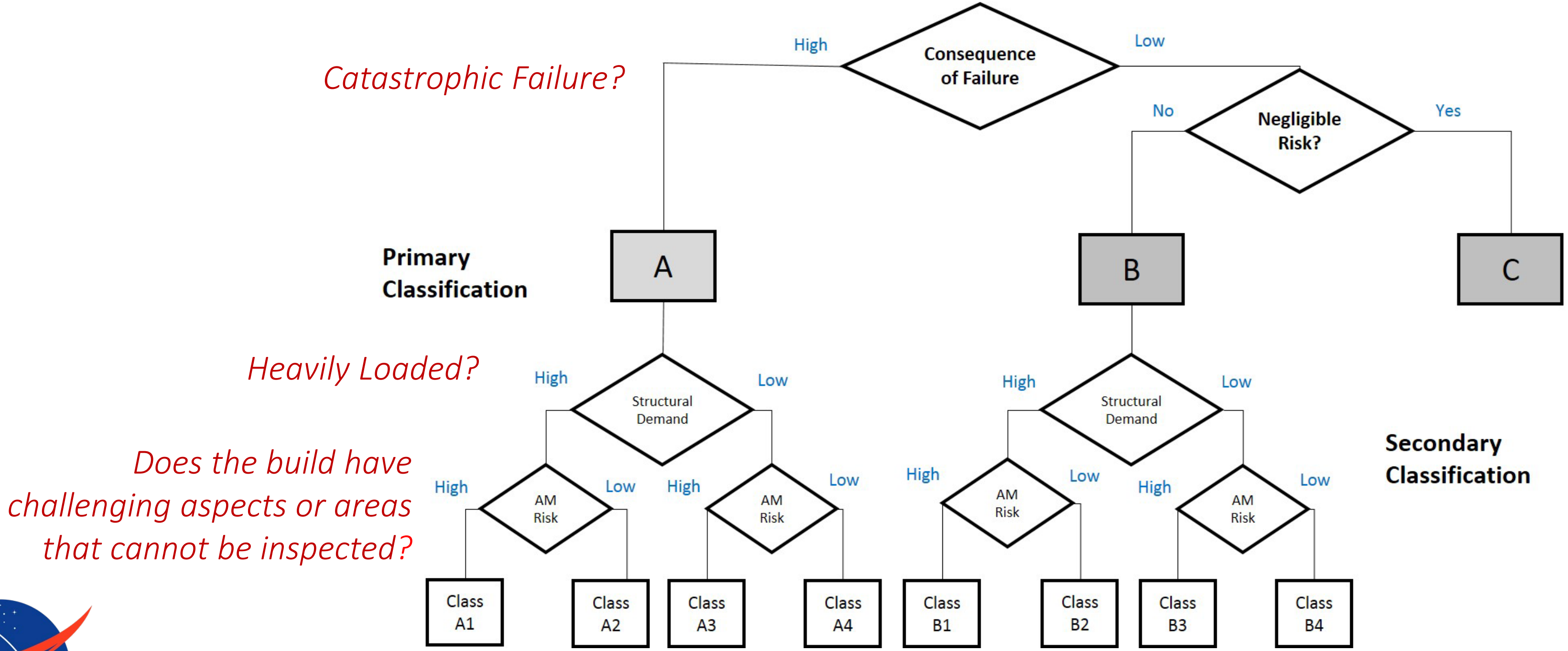
Classifications for AM parts consider the risk of AM manufacturability and inspectability.



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The NASA standard requires *quantitative* NDE with full coverage of the surface and volume for Class A Parts.

Language:

"All Class A parts **shall** receive ***quantitative NDE*** with full coverage of the surface and volume of the part, including verifiable detection of critical initial flaw size in critical damage tolerant parts, with any coverage limitations due to NDE techniques(s) and/or part geometry documented in the PPP"

Rationale:

- "NDE provides a necessary degree of quality assurance for AM parts in addition to the process controls of this NASA Technical Standard."
- "No methodology currently exists to preclude all AM process failure modes through the available manufacturing process controls."

(emphasis added)

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For Class A parts, the NDE approach must comply with the Special NDE requirements in NASA-STD-5009.

Language:

"The NDE approach for Class A parts **shall** meet the Special NDE requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components, and be documented in the PPP."

Rationale:

- "The defects of interest in AM are of a different nature than those listed in Tables 1 and 2 of NASA-STD-5009, and AM microstructures can impact the effectiveness of NDE methods. Therefore, all inspection of fracture critical AM hardware should be treated as Special NDE."
- "Alternative flaw screening methods for Class A parts (e.g., proof testing) may be feasible with full justification provided in the PPP."

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The NASA standard requires NDE *for process control* with full coverage of the surface and volume for Class B Parts.

Language:

"All Class B parts **shall** receive ***NDE for process control*** with full coverage of the surface and volume of the part, ~~including verifiable detection of critical initial flaw size in critical damage tolerant parts~~, with any coverage limitations due to NDE techniques(s) and/or part geometry documented in the PPP"

Rationale:

- "NDE for process control requires the use of physical reference standards for calibration and acceptance criteria based on the capability of the NDE technique but does not require quantitative validation of flaw detection.
- "Targeted approaches for NDE can be proposed and approved per the PPP."

(emphasis added)

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For Class B parts, the NDE approach must meet the requirements in NASA-STD-5009.

Language:

"The NDE approach for Class B parts **shall** meet the ~~Special NDE~~ requirements of NASA-STD-5009 and be documented in the PPP."

Rationale:

- "The requirements in NASA-STD-5009 establish important controls, including the definition, validation, documentation, and approval of all NDE procedures, standards, methods, and acceptance criteria […]"
- "Alternative post-build quality assurance methods for Class B parts (e.g., proof testing), as well as a reduction in NDE scope for Class B parts, may be feasible with full justification provided in the PPP."

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Passive in situ process monitoring may be used as a quantitative indicator of part quality, if qualified.

Language:

"Prior to use as a quantitative indicator of part quality for part acceptance, passive in-situ process monitoring technologies **shall** be ***qualified*** by the CEO to the satisfaction of NASA in a manner analogous to other NDE techniques."

Rationale:

- "All processes that are used to establish quantifiable quality assurance metrics are qualified against established criteria to verify detection reliability, calibration, and implementation. If in-situ monitoring techniques are employed for such purposes, the need for such qualification is unchanged."

(emphasis added)

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Passive in situ process monitoring may NOT replace NDE.

Rationale (cont.):

- "Certification of a passive in-situ monitoring technology relies upon a thorough understanding of the physical basis for the measured phenomena, a proven causal correlation of the measured phenomena to a well-defined defective process state, and a proven level of reliability for detection of the defective process state."
- "If qualified in the manner stated above, an in-situ process monitoring technique can be used to complement NDE in the Integrated Structural Integrity Rationale of the PPP. At this time, even a qualified in-situ process monitoring method cannot be considered a complete replacement for NDE."
- "Even if qualification is not desired, the use of in-situ process monitoring is encouraged as a source of process control data. This data can also be used to help guide targeted inspection."

(emphasis added)

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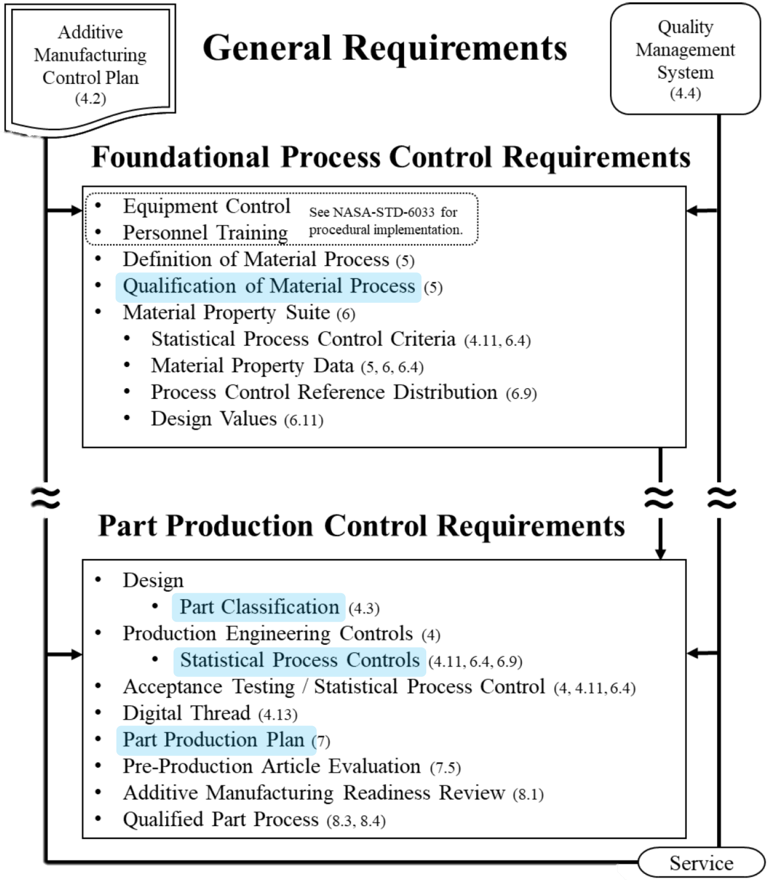
In situ monitoring can be used in several aspects of certification:



Qualification of Material Process (QMP)

- Use with process development

Part Classification

- Improve inspectability for better AM risk posture
- Inspection process must be qualified by cognizant engineering org. (CEO)

Part Production Plan

- Integrated Structural Integrity Rationale (ISIR):
  - Can be specified as a defect screening action
  - Must be qualified by CEO

Production Controls

- Could develop certain metrics to track over time

The <u>current</u> certification approach does not accommodate the use of adaptive systems.

"Closed-loop process control based on adaptive in-situ monitoring technologies that alter the defined AM process in response to monitored phenomena are not currently applicable technology per this NASA Technical Standard and cannot be used without prior approved tailoring."

Adaptive (Closed-Loop) Systems

- Monitor the process using sensors (e.g. meltpool thermal signature) and change a machine/process parameter (e.g. laser power) to optimize the response
- Currently available in many directed energy deposition (DED) systems

Two issues for verification:

1. Verify the sensor performance, algorithm and machine response ***(control system)***
2. Verify the physics – does controlling this parameter result in a good part? ***(materials)***

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For certifying closed-loop control systems, NASA can leverage the expertise of the spacecraft control systems community.

Verification of a control system:

1. Verify the accuracy of the sensor data
2. Verify the software/algorithm processing and response
3. Verify that the changed parameter responds correctly

Black box issue:

- For commercial systems, machine parameters may not be known, algorithms may not be accessible
- Ideal approach: collaborate with machine manufacturers
- Can also develop transfer function by studying inputs/outputs

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Verifying that the adaptive system results in good material is a challenge that will require further study.

What is being monitored, and to what end?

Assume you're monitoring the meltpool thermal emissions

Are you looking to keep it constant, or vary it based on part geometry?

What does it really tell you about the process and the material?

Is this a good indicator of material quality?

Is the resulting microstructure/morphology consistent and repeatable?

What parameter will you change?

More complex if monitoring multiple signals and/or changing multiple parameters

Qualify process for each different system, alloy, part?

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In summary, NASA encourages in situ monitoring for certification of AM hardware.

To use for ***quantitative part quality*** function, monitoring system must be qualified.

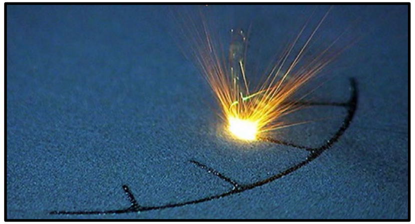
→ Main challenge: developing correlation of indication to verified defect

Qualifying ***closed-loop, adaptive*** systems will require a new approach to the QMP.

NDE is still vital for verification of post-build quality.

Thank you for your time!

Questions?



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