ICAM 2024

ASTM International Conference on Advanced Manufacturing – ICAM 2024

NASA's Office Safety Mission Assurance Efforts to improve Non-destructive Evaluation Methods for Additive Manufacturing and In-Space Inspection

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Justin Jones (GSFC)
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Eric Burke

Eric Burke is a research and development physicist at NASA Langley Research Center where he serves as the Nondestructive Evaluation (NDE) Program manager for NASA's Office of Safety and Mission Assurance.

With over 15 years of engineering experience within the NASA community, Burke focuses on the development and application of innovative materials and technologies. He is a Subject Matter Expert in the field of in-situ NDE on Additive Manufacturing (AM) parts and leads NDE activities and research on AM across all the NASA centers.

Burke also leads the Small Business Innovative Research and Development program for technologies that will apply to future inspection of the International Space Station and deep space vehicles. Recent highlights include the delivery of a single side 3D x-ray system that is being used to scan the heat shield of the Orion spacecraft currently located at Kennedy Space Center. This prototype x-ray system is proving to be a critical piece for inspection of Avcoat® joints for the Orion program.

Burke has received national recognition for excellence in the area of NDE and technology development including the NASA Early Career Achievement Medal and Launch Director's Award and a Silver Snoopy Award. Recently receiving 2 Space Flight Awareness (SFA) Flight Safety Awards.

He holds four U.S. patents and has authored or co-authored nearly 20 conference papers. Prior to joining NASA in 2010, Burke worked as a research and development engineer for United Space Alliance and the University of Dayton. Burke holds both a Bachelor of Science degree and a Master of Science degree in mechanical engineering, solid mechanics, from the University of Dayton.

Mr. Burke is an avid cyclist and 2-time Ironman Triathlete. In his spare time Mr. Burke coaches his sons and daughter soccer teams. www.linkedin.com/in/ericrburke

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NASA OFFICE of SAFTEY & MISSION ASSUREANCE (OSMA)

OSMA
OFFICE OF SAFETY & MISSION ASSURANCE

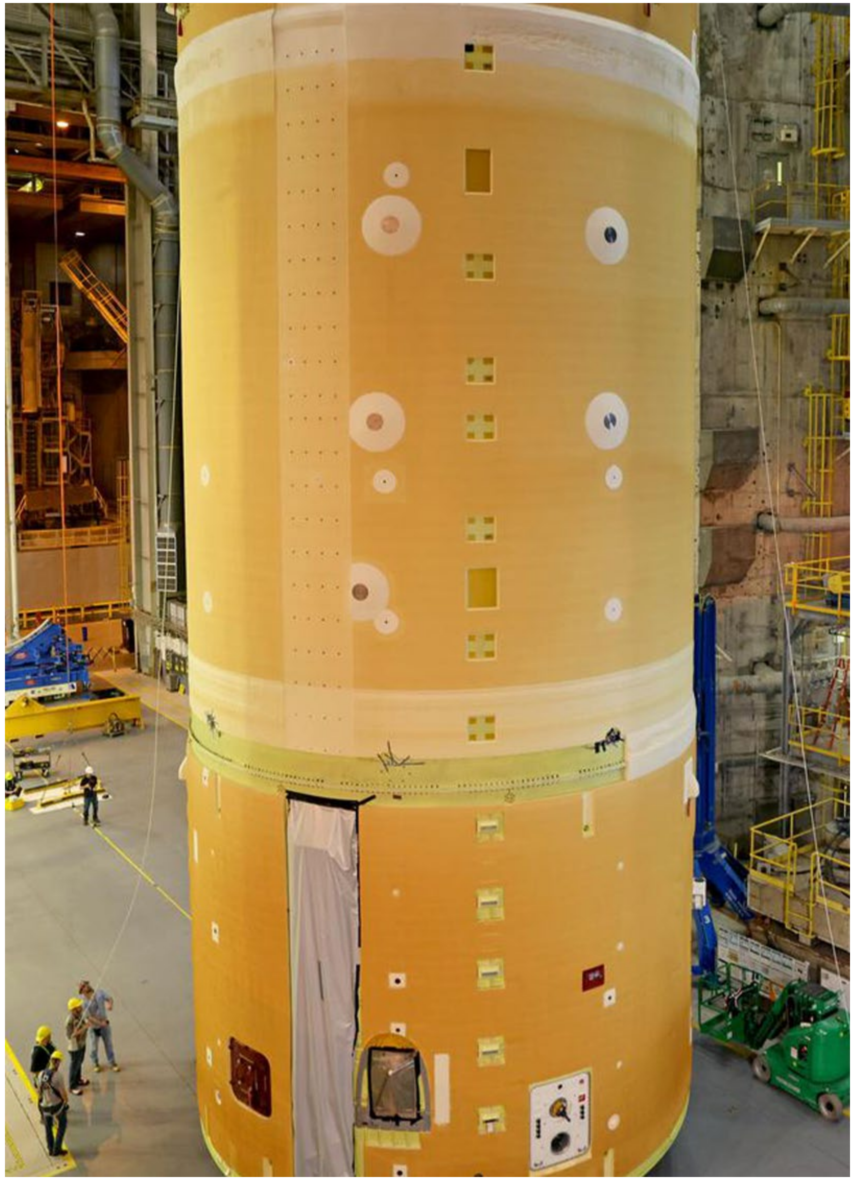
The Office of Safety and Mission Assurance (OSMA) assures the safety and enhances the success of all NASA activities through the development, implementation and oversight of agencywide safety, reliability, assurance and space environment sustainability policies and procedures. OSMA includes the Mission Assurance Standards and Capabilities Division, Missions and Programs Assessment Division, Institutional Safety Management Division, and NASA Safety Center, as well as the Independent Verification and Validation Program.

Responsible for:

- Establishing and assuring compliance with NASA Safety and Mission Assurance (SMA) strategies, policies and standards.
- Fostering early integration and life cycle implementation of Safety, Reliability, Maintainability and Quality Assurance (SRM&QA) into NASA's programs and operations.
- Improving methodologies for risk identification and assessment and providing recommendations for risk mitigation and acceptance.
- Performing independent SMA assessments and process verification reviews.
- Providing analysis and recommendations for critical agency safety decisions.
- Sponsoring the innovation and rapid transfer of SRM&QA technologies, processes and techniques to improve safety and reliability and reduce the cost of mission success.

OSMA NDE Development Program

- The OSMA NDE Development Program is structured within NASA to explore and apply advanced NDE tools across the agency.
- During each budgetary cycle, an NDE critical issues list is collected from all centers, programs and chief engineers
- NDE proposals are developed around these critical issues in the following way:
  - New starts will begin as a Phase 1. Phase 1 timeframe will be only 1 year.
  - Successful Phase 1's will be eligible for Phase 2. Phase 2 expected completion timeframe will be 1 to 2 years.
- Results and outcomes from phase 1's and 2's are presented internally and externally yearly for review.
- Prototypes, advancements and enhancements are deployed to relevant programs for immediate use.
- Subject areas include but are not limited to:
  - Application and development of State of the Art (SOA) NDE techniques.
  - Application and development of Computational NDE including modeling and automated defect recognition.
  - Application and development of NDE on Additively manufactured parts.
  - Application and development NASA Standards and Documents



Current NASA Standards for Metallic AM

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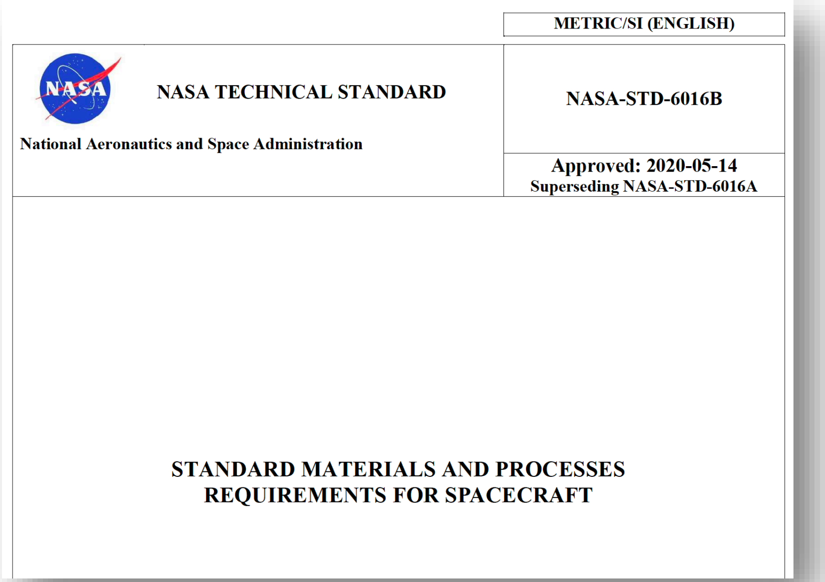
METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

National Aeronautics and Space Administration

NASA-STD-6016B

Approved: 2020-05-14
Superseding NASA-STD-6016A

STANDARD MATERIALS AND PROCESSES
REQUIREMENTS FOR SPACECRAFT

NASA-STD-6016B

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

NASA-STD-5009 NONDESTRUCTIVE EVALUATION REQUIREMENTS FOR FRACTURE-CRITICAL METALLIC COMPONENTS -> Points to the NASA-STD-6030

Handbook coming soon with more specifics on implementation.

Quality Management for AM

NASA has adopted AS9100, Quality Management Systems - Requirements for Aviation, Space, and Defense Organizations, for flowing down quality management system (QMS) requirements to its suppliers. This standard sets expectations for quality controls, process validation, control of external suppliers, and product quality assurance. While these generic requirements will readily apply to parties designing AM parts, building AM parts, supplying specialized capital equipment for manufacturing AM parts, and to raw feed stock suppliers, there remain considerations that are uniquely applicable to AM part production.

Examples are: critical attributes related to raw material production and product acceptance, material storage and handling, second-party surveillance of Statistical Process Control (SPC) methods and results, and personnel training. NASA is working with Nadcap and working internally to mature these areas of quality assurance knowledge and practice.

OSMA efforts on improvements for Ultrasonics for Additive Manufacturing:

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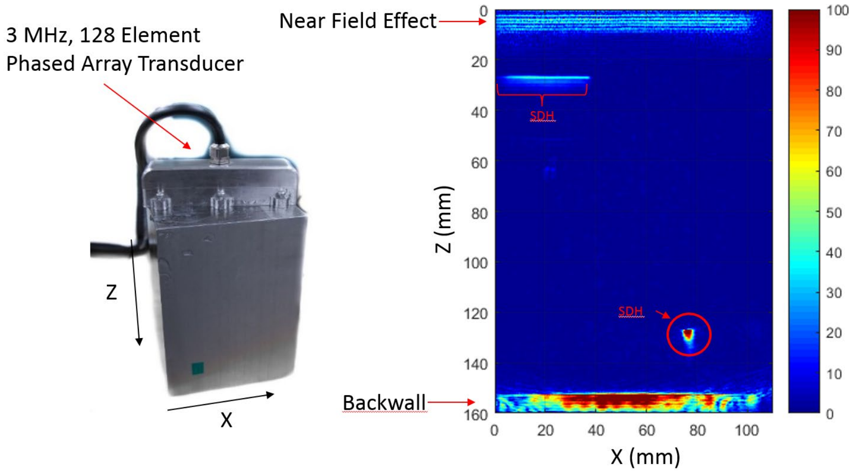
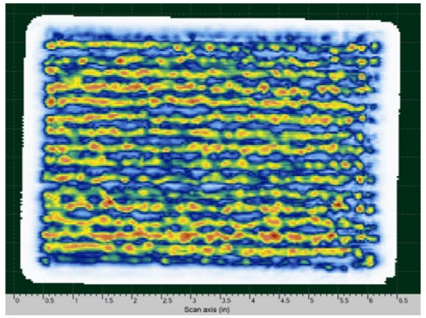
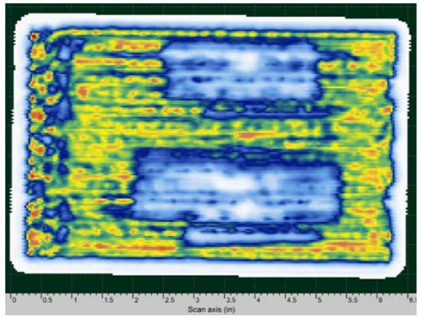
- NDE analyses of Electron Beam Freeform (EBF)[3] samples were completed using both phased array ultrasonics and Total Focusing Method (TFM) Full Matrix Capture (FMC) Inspection.
- Layering anomalies were highly visible in the phased array data.
- TFM & FMC methods preformed better on the EBF block and Signal to Noise Ratio (SNR) was significantly improved.



FMC probe and Inside-Out B-Scan



Inside-Out Block



Outside-In Block with Natural Voids

Phased Array Inside-Out (left) and Outside-IN B-Scan

First attempt “Outside-In” block with natural

As-Built

After Machining

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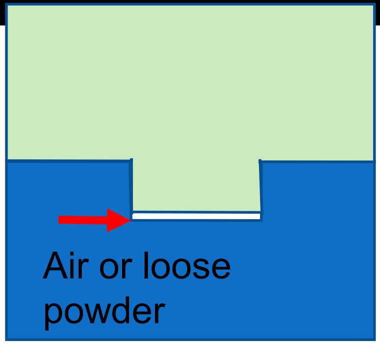
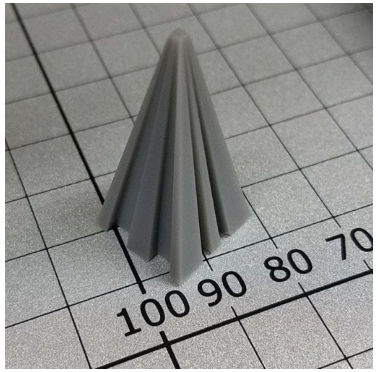
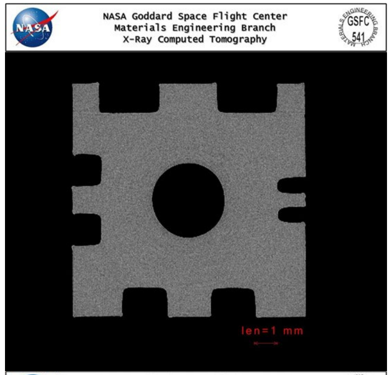
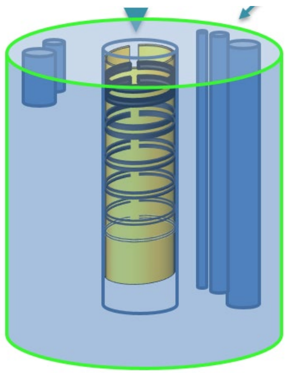
Improvements for X-Ray Tomography for Additive Manufacturing

- Image Quality Indicators (IQI) for performance assessments of tomographic system performance.
  - (“IQIs”): Develop a methodology and set of tools to ascertain Computed Tomography (CT) system performance.
  - (“Reverse Approach/Detectibility of AM Flaws”): Use CT system to characterize AM material build defects and limitations of the CT system to inspect such defects.
- Developments of nano-penetrants for improved crack detection.
  - Magnaflux P-1A filtered particle
- Probability of Detection (POD) using a tomographic system.
  - Currently in work at MSFC working on additively manufactured Inconel 718







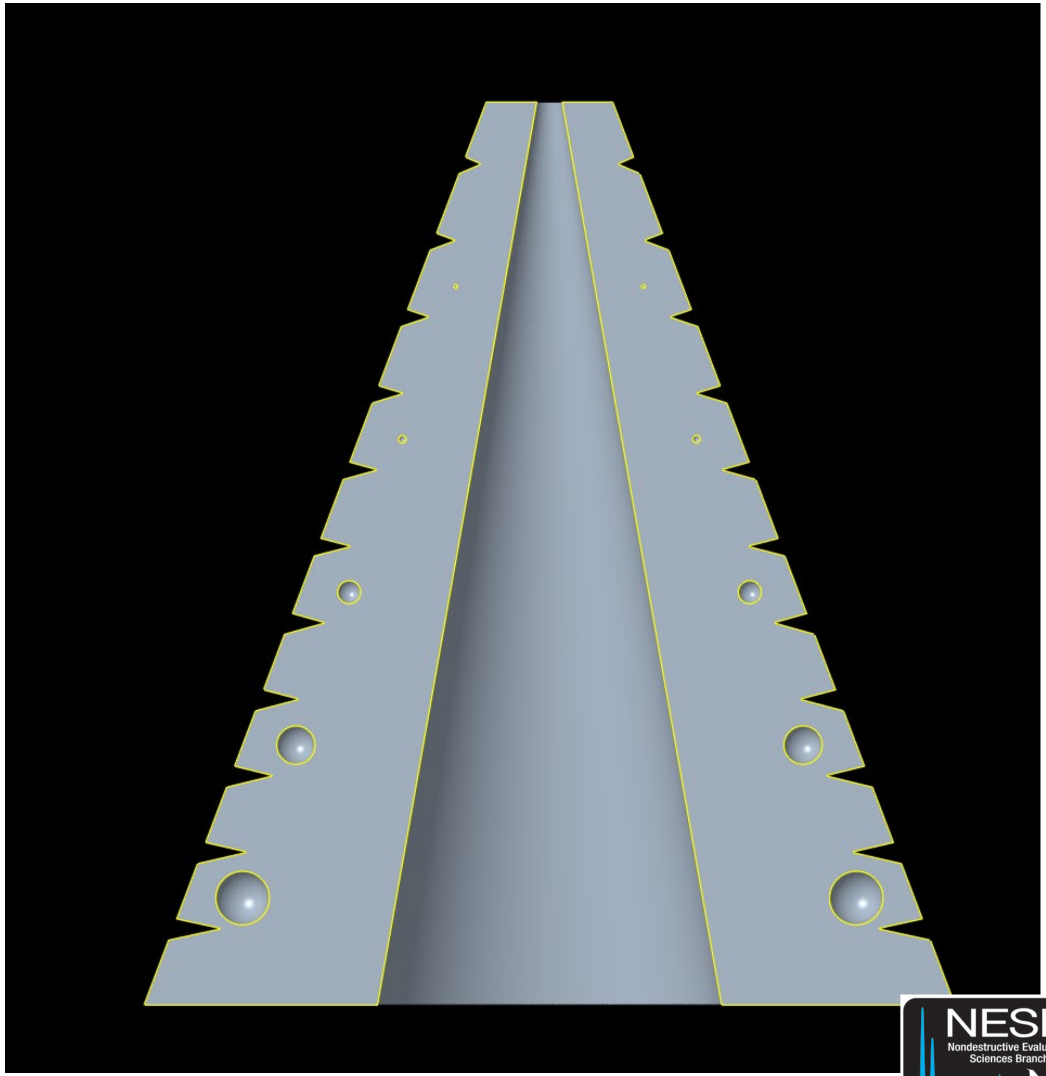


Jones, J. S. (n.d.). Additive manufacturing (AM) activities and non-destructive evaluation (NDE) at GSFC. NASA Technical Reports Server (NTRS). Retrieved July 13, 2023, from https://ntrs.nasa.gov/citations/20170001434

Variations on IQI

CT IQI are being included in AM wind tunnel model builds.

This modified version of the NDE IQI helps to ensure build quality but has built in spheres to trap powder for post build analysis.



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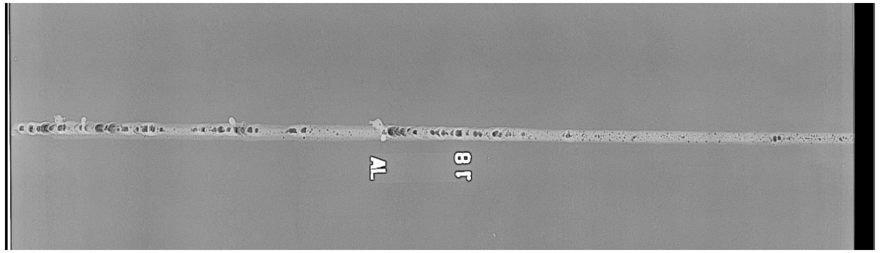
Nondestructive Evaluation Sciences Branch

Applications of EMAT in Vacuum

Electro Magnetic Acoustic Transducer (EMAT) Capability Assessment and in-line Integration (MSFC):

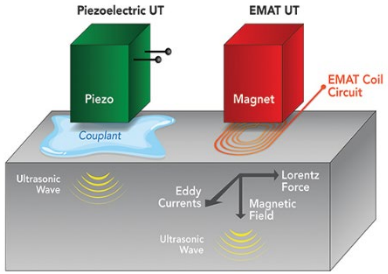
- MSFC is currently conducting sensitivity studies using EMAT as compared to conventional phased array ultrasound (PAUT). Currently within the agency we are developing EMAT capability, and it is quickly gaining hold with our commercial space flight partners.
- Eventually inclusion in future NASA-STD-5009.
- Electro magnetic acoustic transducer (EMAT) is an Ultrasonic Testing (UT) technique that generates sound waves in the part inspected instead of the transducer.
- Ultrasonic waves are induced into the test object when a relatively high frequency field generated by electric coils interacts with a low frequency or static field generated by magnets.



Weld inspection using EMAT system

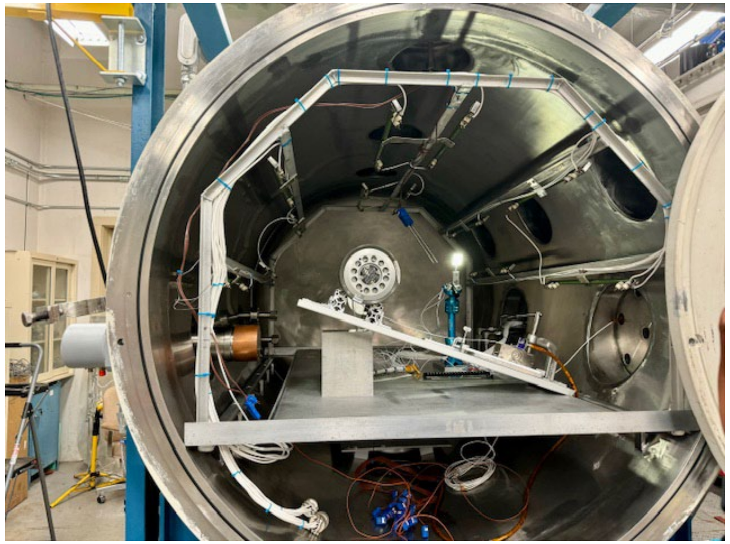
Advantages:

- Dry, non-contact inspection, vacuum capable.
- Insensitive to surface conditions & easier probe deployment
- Easy integration to automated inspection system



Current Progress:

- The fabrication of weld panels containing various weld defects is complete. These panels are currently undergoing inspection using PAUT and EMAT system, with ongoing analysis of the results.
- The integration of the EMAT system into the scanner for semi-automated inspection of weld panels has been successfully completed.
- A study to determine the probability of detection for flaw sizes specified in NASA-STD-5009 is currently in progress.
- Testing is underway for vacuum chamber test of the EMAT system.



Weld inspection using EMAT system under vacuum

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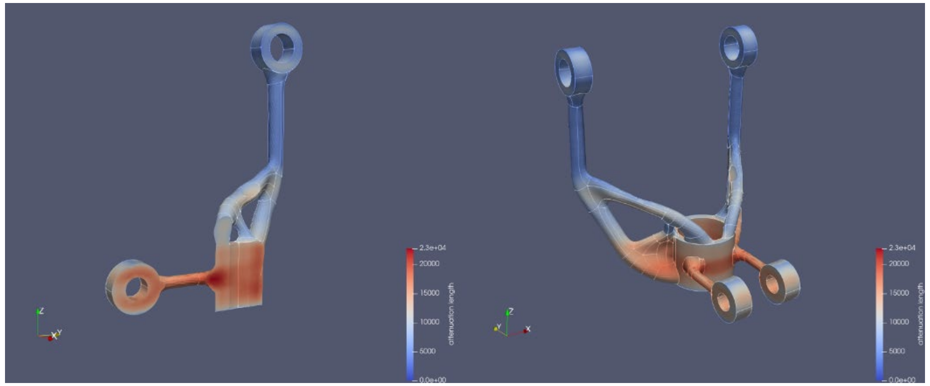
Design for Inspection (LaRC):

- Design for Inspection (DFI) is the concept of evaluating a design for it's inspectability, and feeding that measured inspectability into the design cycle so it may be considered with other design requirements.
  - We designed and prototyped an algorithm that takes in 3D CAD models of generative designed additively manufacture (GD-AM) parts
  - Algorithm considers attenuation path lengths, effects of penumbra, and beam hardening.
  - Output of algorithm is a 3D mesh where each vertex is assigned an inspectability score
  - Output can then be fed directly into generative design algorithms as another constraint in the optimization problem
  - We've been issued a provisional patent on the algorithm, and have presented work to both Autodesk Fusion 360 and Lawrence Livermore National Labs



Output of new DFI X-ray CT showing differences in inspectability.

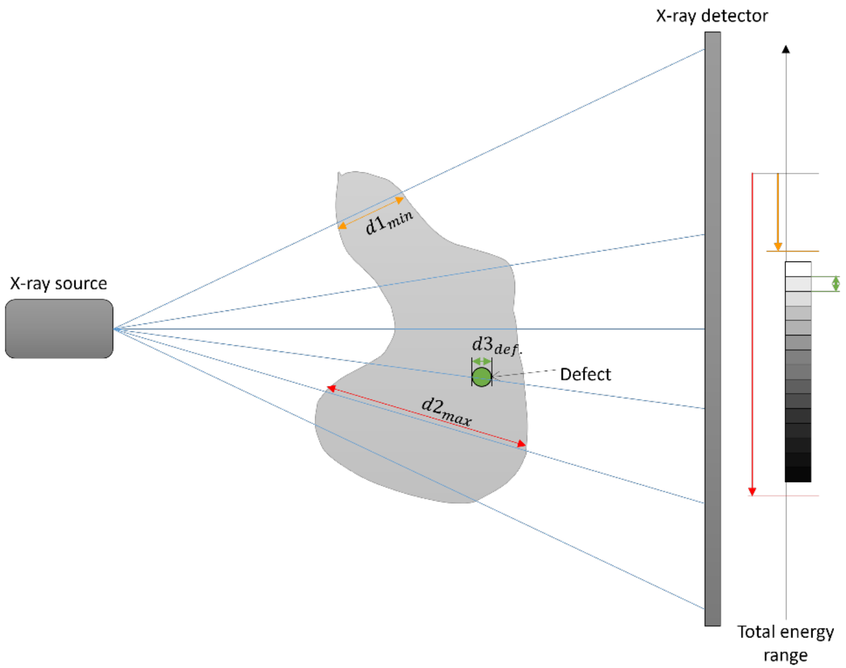


Diagram of the effects of attenuation path length

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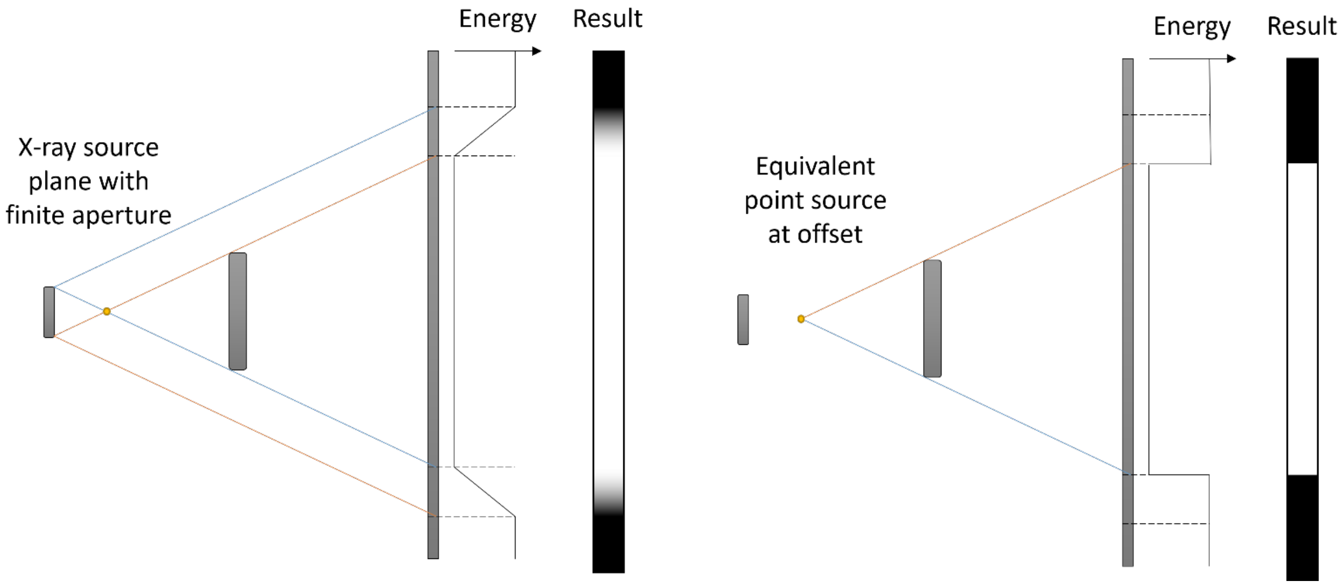
Design for Inspection (LaRC):

- Next phase plans
  - Continue development on algorithm, into high performance computing resources for fast results
  - Integrate additional physics into calculation
  - Utilize more generalized equipment parameters to make results applicable to wider array of use cases
  - Evaluate more designs, feedback results into design cycle
  - Using AM built parts, measure changes in inspectability of real structures pre and post DFI analysis and feedback
  - Begin connecting output and models to a Model-driven Inspection Solution Development (MISD) strategy



Strategy for considering the effects of aperture size and resulting penumbra. Effect can be estimated using a point source with an offset

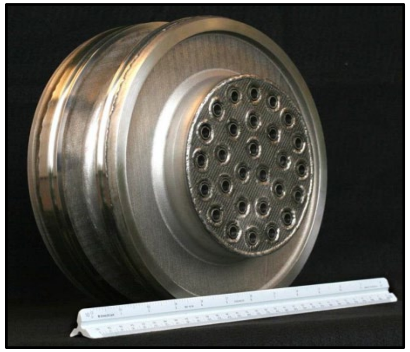
NASA is interested in qualifying in-situ monitoring for complex, critical parts that are difficult to inspect using traditional NDE.

28-Element Inconel® 625 Fuel Injector

Reduced 163 parts to 2

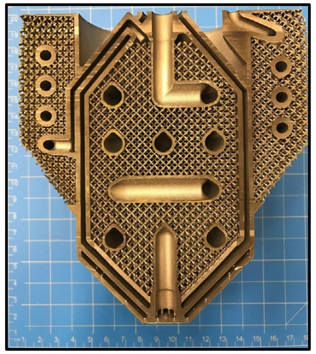
Schedule reduced from 1 year to 4 months

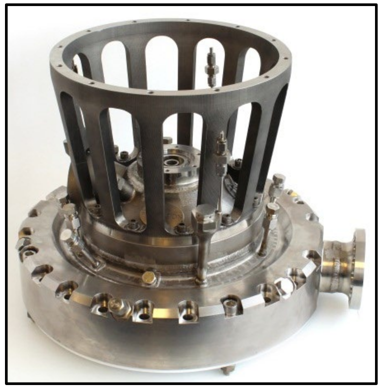
70% cost reduction



July 2022 – NASA sponsored an ASTM workshop at MSFC

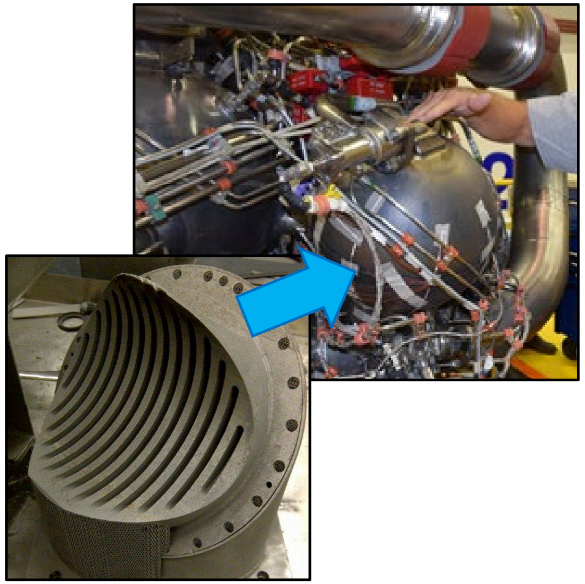
Cryogenic Heat Exchanger-Injector-Condenser Demo





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

Overview: The In-Situ Project

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What: The In-Situ Project

– Correlating In-situ monitoring data and Non-Destructive Evaluation (NDE) methods to characterize defect populations in Laser Powder Bed Fusion (L-PBF) material

How: Analyze defect detection capabilities of in-situ monitoring by comparison to traditional NDE using flaws created with controlled off-nominal build parameters and verified by metallography

– Create samples with known defects on EOS M290

– Record layer to layer AM process quality with EOState Optical Tomography Monitoring system

– Compare results using North Star Imaging X5000 Mini-/Micro-Focus CT and UES RoboMet serial sectioning system

Why:

– Supports developing roadmap for qualifying in-situ monitoring technologies to support NASA-STD-6030 certification approach

  – Proven causal correlation between indications in in-situ monitoring data and final state of the part

– Supports Agency Lunar Infrastructure objectives

ASTM International Conference on Additive Manufacturing – 2022 - NASA technical reports server (NTRS) NASA. Available at: https://ntrs.nasa.gov/citations/20220016357 (Accessed: 13 July 2023).

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Summary Of Results Build 1 Pre Heat Treatment

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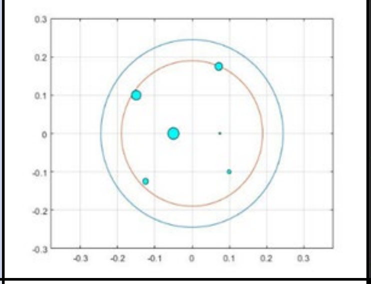
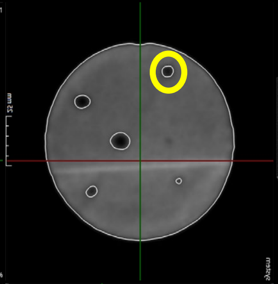
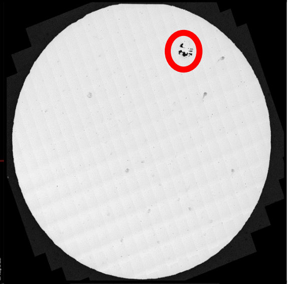
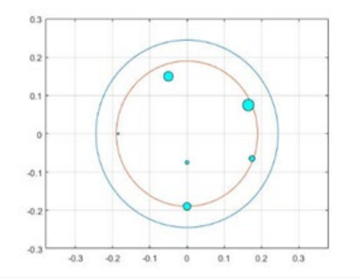
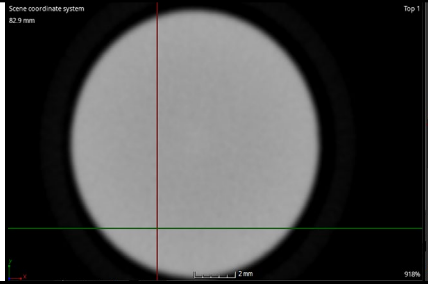
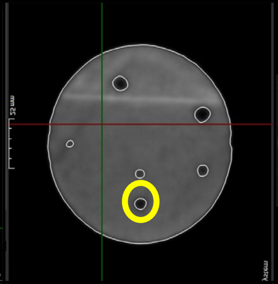
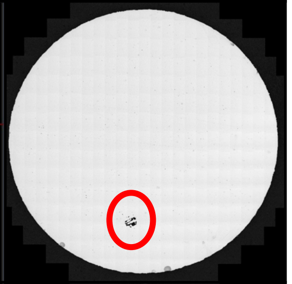
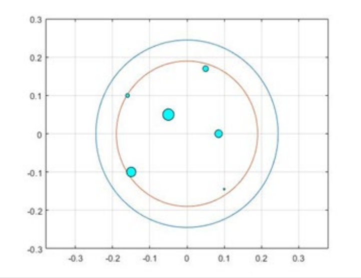
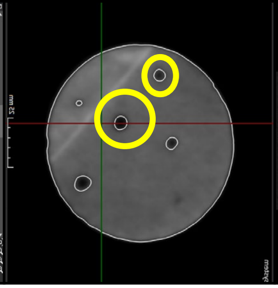
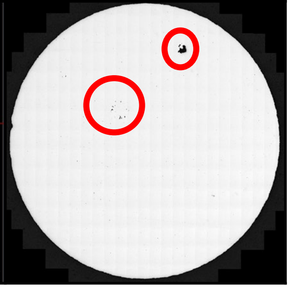
Computed Tomography (CT) showed no seeded defects

In-situ monitoring captured an image for every layer showing insertion of seeded defects as designed

RoboMet slices seeded defect sample at planes 1, 2 & 3

– 1 or 2 defect remnants per plane: only the higher thicknesses remain

Comparison of Detection Methods for S1-AB-1 (Skipped Layer)

	MATLAB	Mini CT	In-situ	RoboMet
Plane 1				
Plane 2				
Plane 3				

1. S1 samples: Skipped Layer (Unfused Powder) Defects = no power
2. S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power
3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

HT: Heat Treated
AB: As Built

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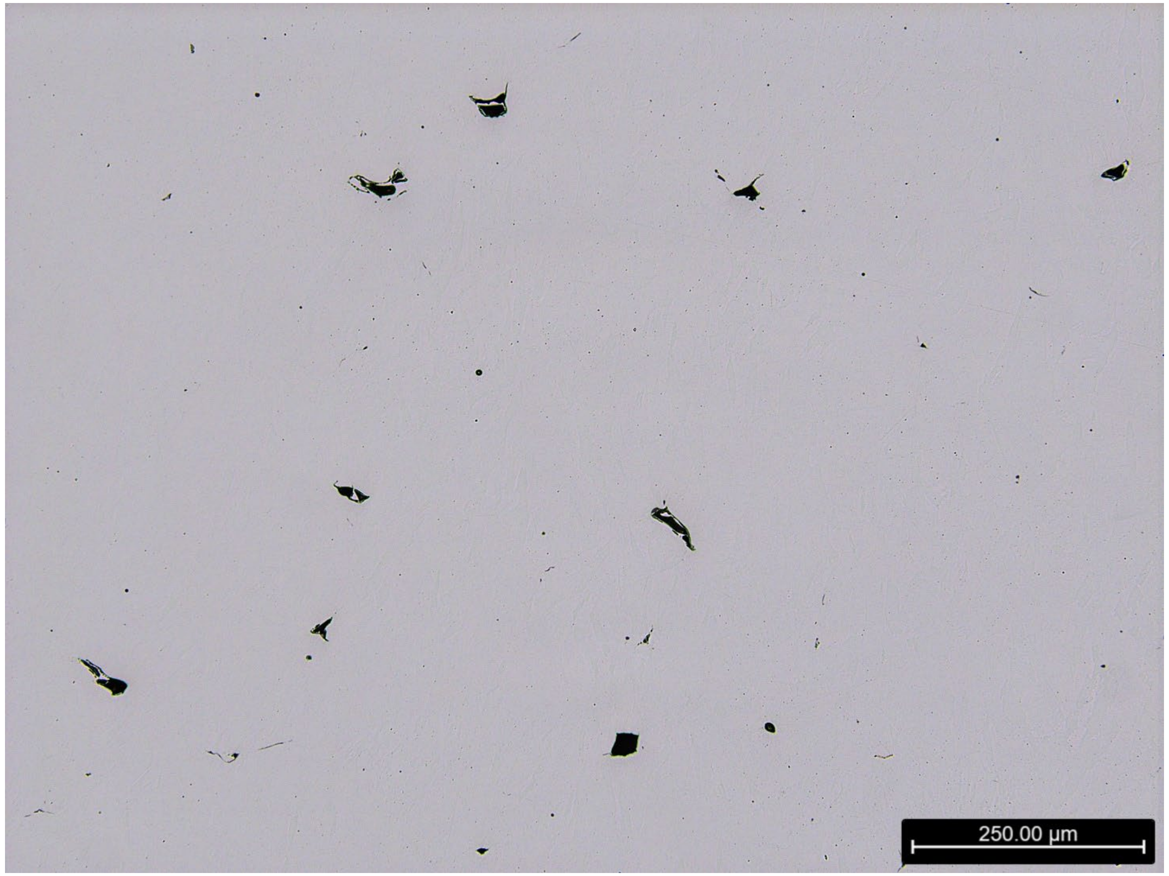
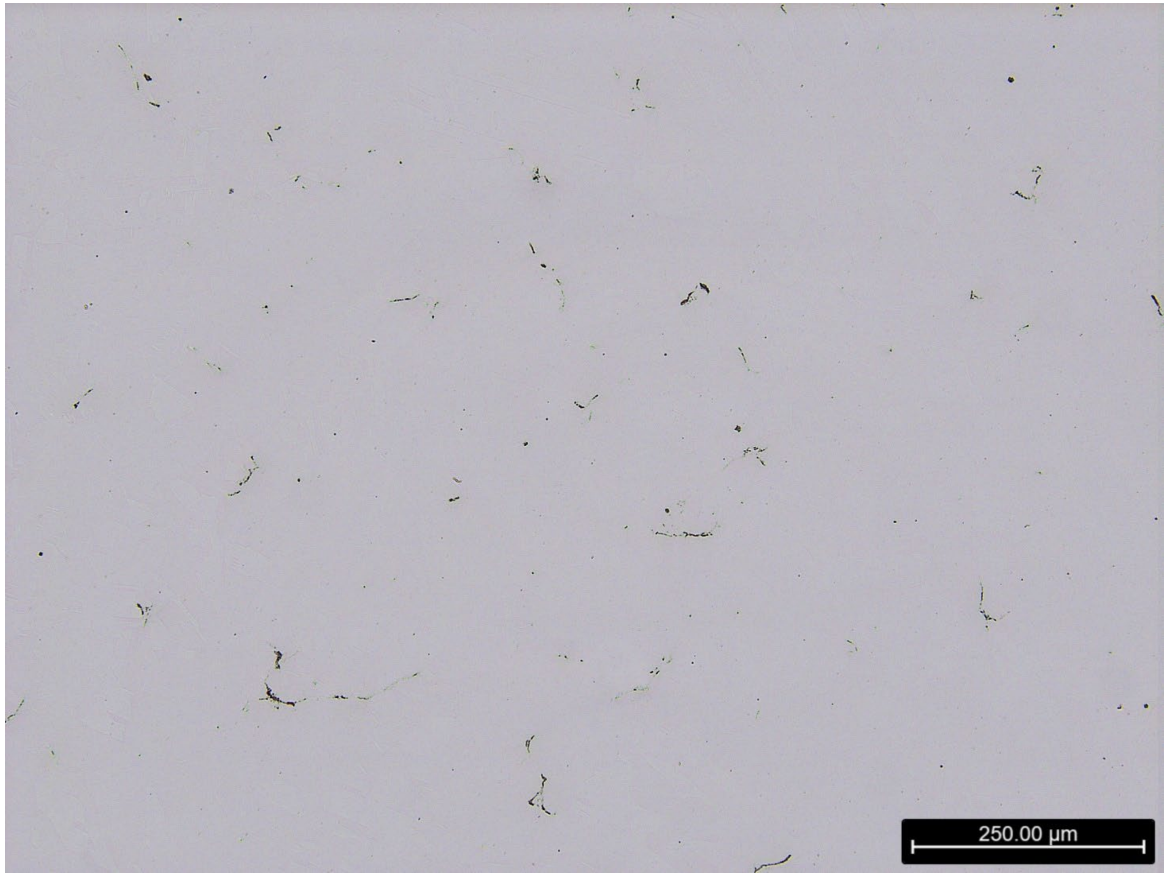
75% Laser Power Sample



75% Pre Heat Treatment

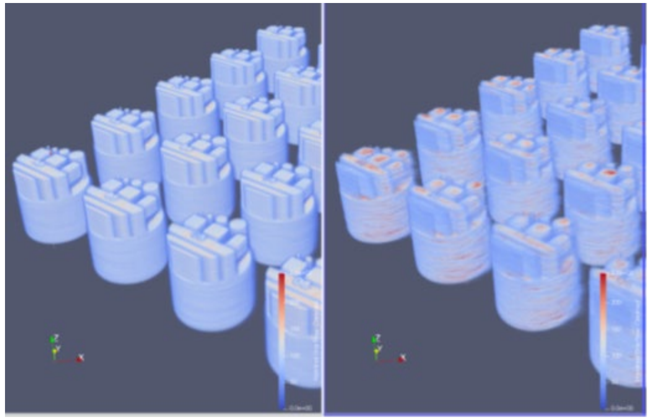


75% Post Heat Treatment

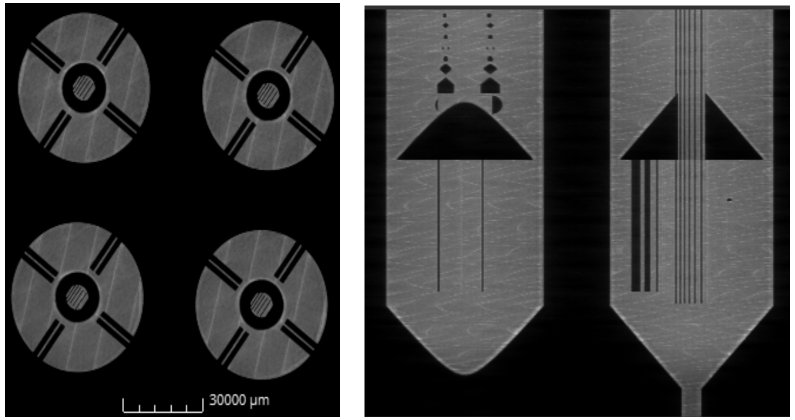
In-Situ Work Continued

Additive Manufacturing In-Situ Monitoring - Progressing from Research into Development (MSFC):

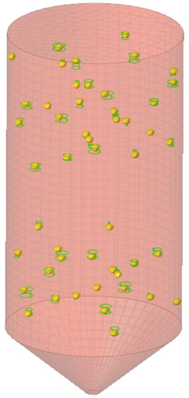
- Continued research into the use of in-situ process monitoring compared to standard and advanced NDE techniques. Develop a better understanding of the risk associated with using in-situ monitoring to certify fracture critical flight hardware.
- Flaw detection through various in-situ sensor modalities:
    - Development of a challenge geometry artifact for natural flaw creation and characterization
    - Flaw creation through interrupting shielding gas flow and creation of steep overhangs.
    - Peregrine software from Oak Ridge National Lab is being used for model training and defect detection.
- Investigation using flaw information from in-situ data in a finite element model (FEM) for stress and fracture analyses.
- A build with seeded flaws has been built to test the probability of detection with in-situ monitoring and computed tomography.
- These efforts will help validate the capabilities of various in-situ monitoring systems, including optical tomography and fringe projection height mapping.
- Will contribute to NASA policies, standards and TM.



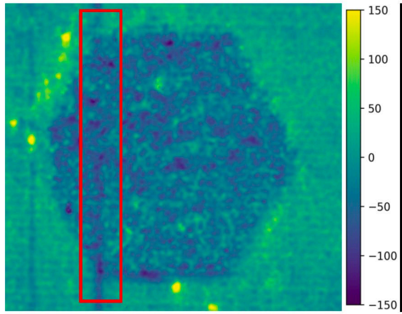
In-Situ Data for Nominal airflow data (left) and degraded airflow data (right)



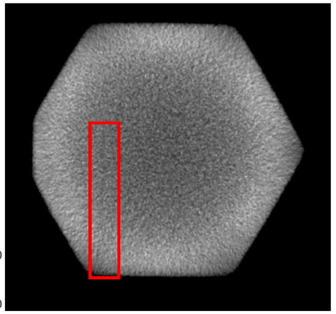
Challenge Geometry Artifact: In-situ Data



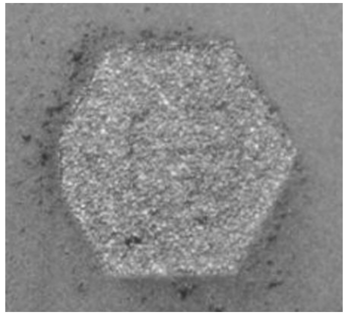
FEM: Yellow Nodes correspond to the flaw location detected with in-situ monitoring



Powder height anomaly detected in Phase3D height map



Resulting structured porosity visible in computed tomography inspection



Visual image of layer showing anomalies are not visible

Nondestructive Evaluation (NDE) SBIR Overview Highlights

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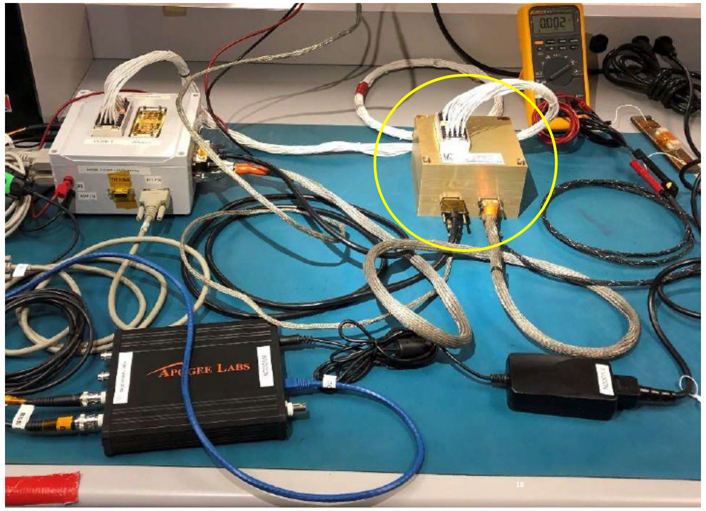
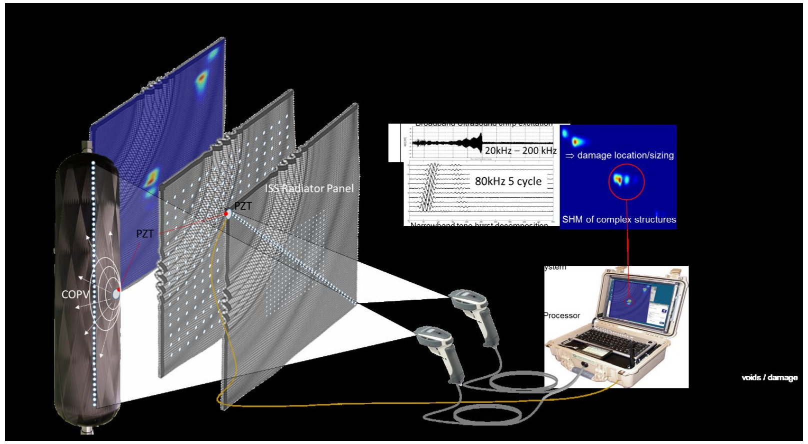
- The NASA NDE community has been very active in the NASA (SBIR) Program for the past decade.
  - Since 2010 NDE has had over 68 phase 1 and phase 2 awards and we have participated in an additional 37 awards from other subtopics, for a total of 105 Phase 1&2's.
  - Several of these prototypes are currently deployed to help the Artemis program achieve its goals.



Wireless Kinetic Impact Position System



- Several of the prototypes that have been produced by the SBIR program are directly applicable to inspection in space.
  - Hypervelocity Kinetic Impact Position System
  - 3 Dimensional Backscatter Xray inspection.
  - Multimode Laser Vibrometry inspection system.

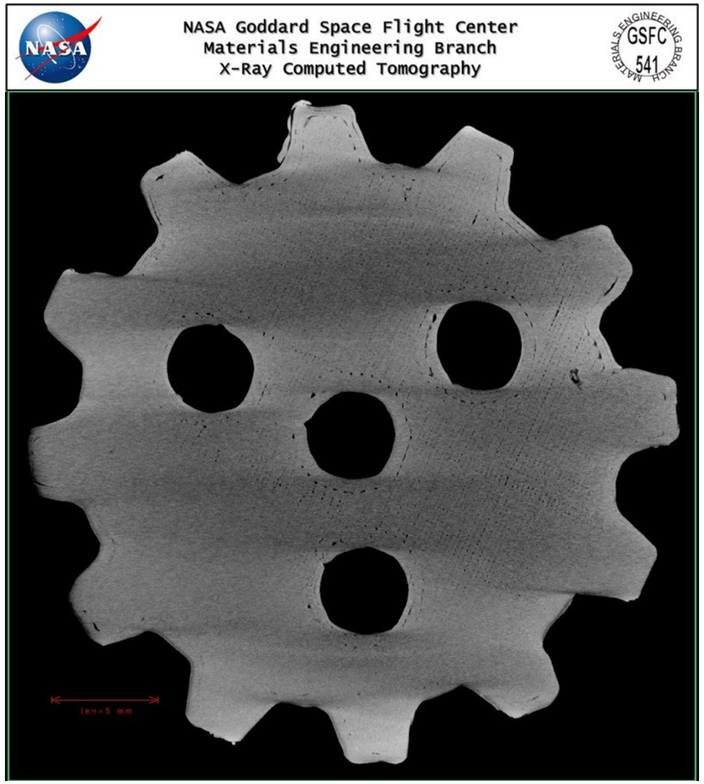
NDE for In-Space Manufacturing (ISM)

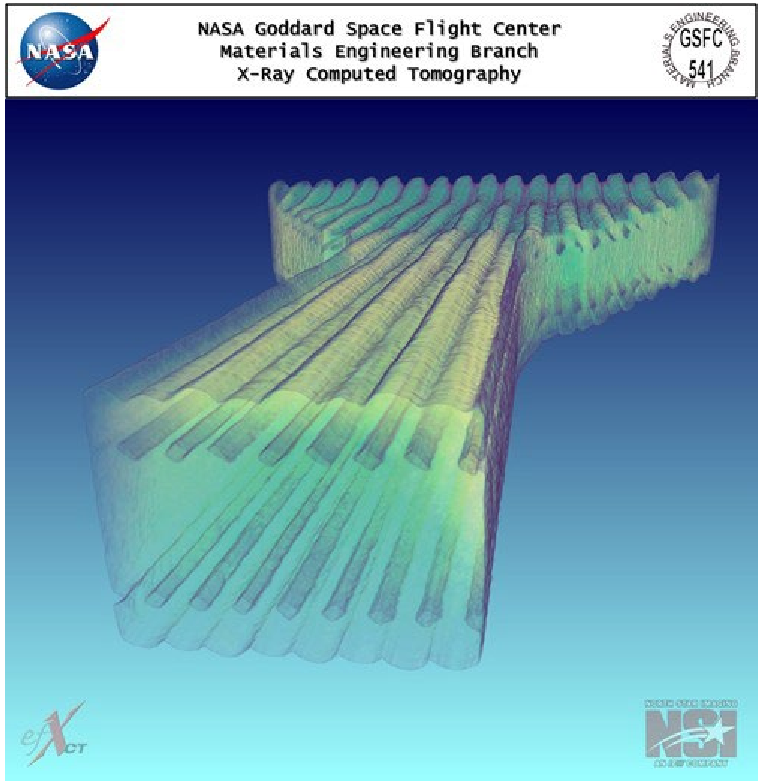
- GSFC NDE has worked with MSFC + Techshot to inspect preliminary AM ISM parts
- CT scan system on ISS would be crucial to certify parts for structural use applications
- These scans have been critical in establishing Key Performance Parameters (KPP) for in-space x-ray sources and imaging systems

GSFC x-ray Computed Tomography (CT) images of early prototype Techshot bound metal deposition parts (non-optimized builds).

Left image shows gear, with minor voiding in and around shells.

Right image is of a tensile coupon showing columnar cavities running along the length of sample.



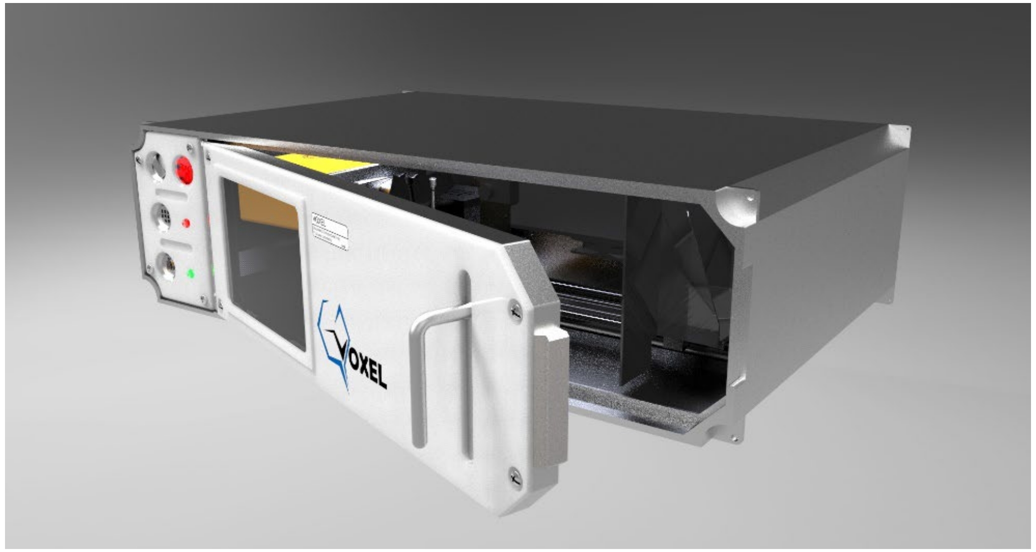


Jones, J. S. (n.d.). Additive manufacturing (AM) activities and non-destructive evaluation (NDE) at GSFC. NASA Technical Reports Server (NTRS). Retrieved July 13, 2023, from https://ntrs.nasa.gov/citations/20170001434

Recent efforts to assess X-Ray CT for operation in a space environment

ICAM 2024

- NASA Goddard Space Flight Center (GSFC) has led efforts to investigate In-Space X-ray Computed Tomography (CT) for multi-use applications, in collaboration with other centers
- Efforts include Concept Development and Trade Studies to assess feasibility for CT in different environments (ISS, lunar, Martian, crewed/non-crewed)
- Instrument Design Lab (IDL) study in late 2019 - early 2020 demonstrated core system feasibility and key requirements met for a pathfinder, prototype design, including deep dives into 12 major subsystems. New study to develop CEMA cost estimates by July ’23.
- Non-funded partnership agreement with North Star Imaging and collaborative efforts kicking off with Aerospace Corp. to explore “open CT” concepts



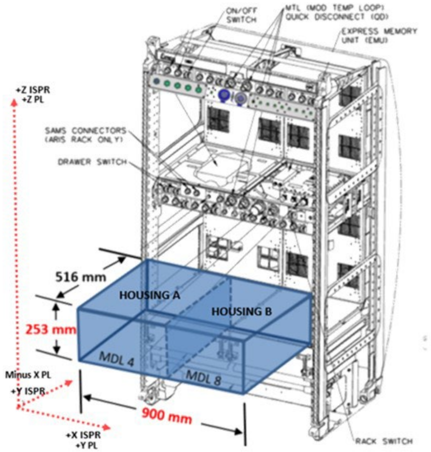


Image Credit: NASA

One potential venue for CT in Space could be on an ISS Express Rack (or similar setup on NASA Gateway). Shown above are an exterior rendering of "VOXEL" IDL design concept and generic Mid-Deck Locker (MDL) dimensions, representative of the size of such a system (e.g., could be single or double, as shown). Such a system would be human-tended, with astronauts loading samples. System could be controlled in space or remotely from Earth. Other concepts underway are non-cabinet-based systems, oriented for remote/telerobotic applications.

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