In-Space Inspection Needs: Opportunities for advanced NDE tools such as x-ray CT for additively manufactured parts, in-situ resource utilization, geological applications, and more.

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Key Contributors: Ryan Kent/GSFC, Nathan Smith/GSFC, Brett Muehlhauser/NSI, Andrew Glendening/GSFC

Overview

- Brief Introductions
  - My Background
  - NASA Goddard & NDE Lab
  - Recent NASA Agency NDE Efforts
- Motivation for In-Space NDE Tools: Overview of 5 key Beneficiaries
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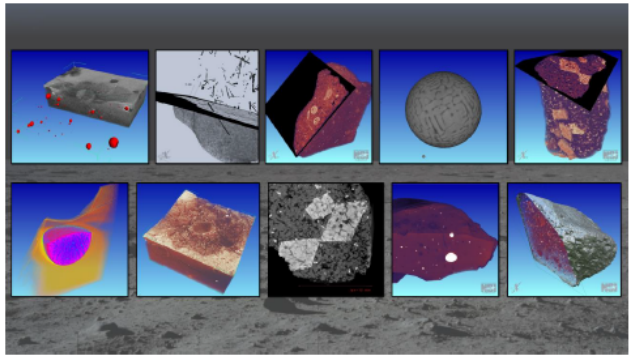
  - Human Space Flight Safety & Mission Assurance
  - Additive Manufacturing (AM) & In-Space Manufacturing (ISM)
  - In-Situ Resource Utilization (ISRU)
  - Scientific Analysis and Return Sample Triage
- Opportunities for Investment and Collaboration
  - NASA Space Exploration Timeline and Goals
  - Recent Efforts to Advance CT in Space
  - NASA Partnership and Funding Programs
  - NASA SBIR Overview



Lunar Exploration in 3D: Volumetric Imaging of Lunar Materials and Manufactured Materials via x-ray Computer Tomography

Authors: James B. Garvin & Justin S. Jones (NASA Goddard, Greenbelt MD 20771)

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Co-signees:

John Grunsfeld (NASA Astronaut), Barbara Cohen (GSFC), Paul Mahaffy (GSFC), Michael Amato (GSFC), George Studor (NASA/NESC), Tracie Prater (MSFC), Lawrence Huebner (MSFC), William Prosser (LaRC/NESC), Juliane Gross (JSC)

Submitted to: National Academy of Sciences *Planetary Sciences and Astrobiology* Decadal Survey as a White Paper

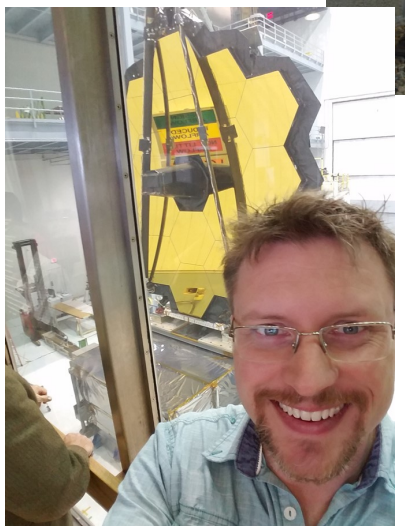
September 15, 2020

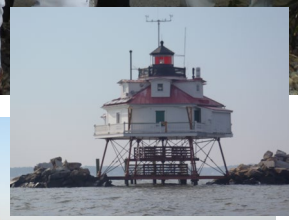
White Paper Submitted to the National Academy of Sciences Planetary Sciences and Astrobiology Decadal Survey

About Me…

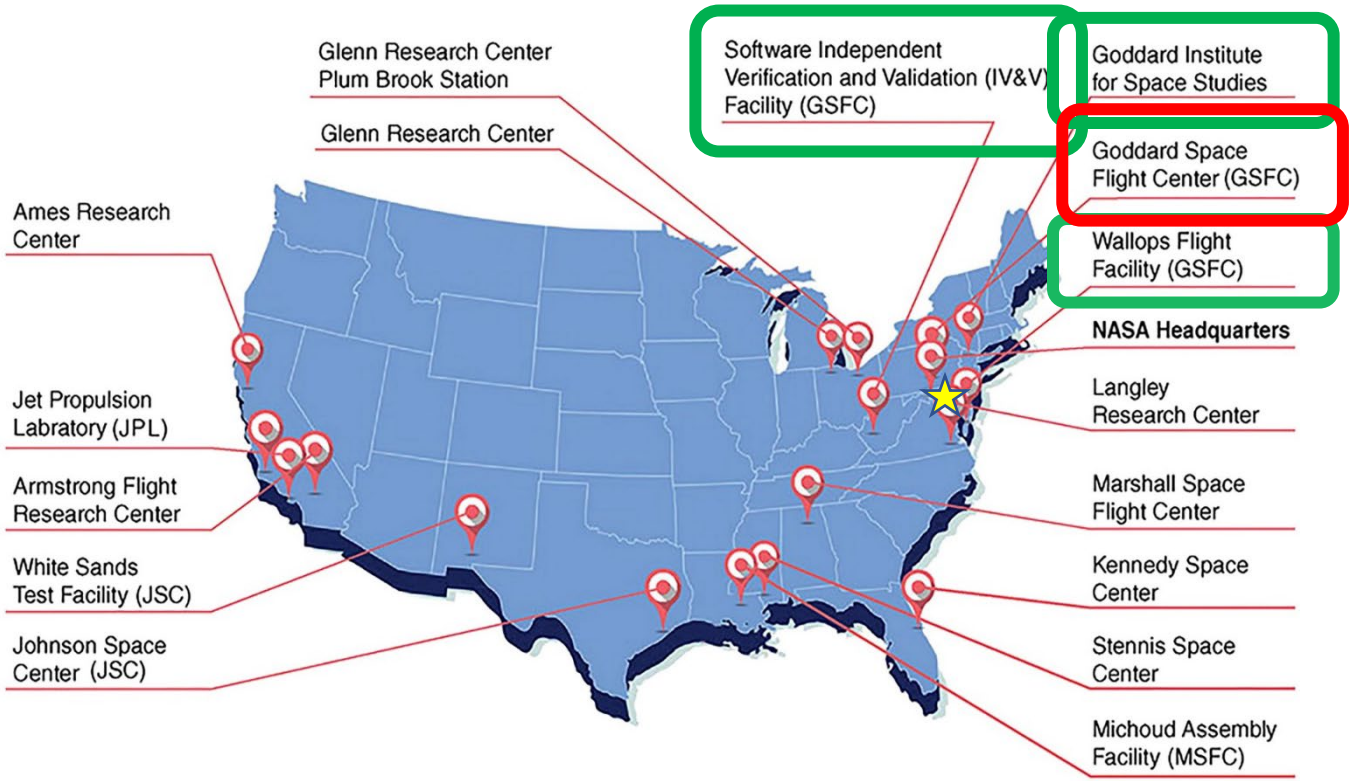
- Father, Husband, Engineer. Live near Annapolis, MD.
- Education
  - B.S. Mechanical Engineering, VCU
  - M.S. Materials, Johns Hopkins University
    - Thesis: "Analytical Modeling of Ultrasonic Wave Interactions in Solids with a Thin Nonlinear Layer"
  - Ph. D., Materials, Johns Hopkins University
    - Dissertation: "Characterization of Interfacial Adhesion Between Carbon-carbon Composite and Plasma-sprayed Aluminum Oxide"
- NDE experience (*influential mentors* highlighted)
  - First NDE experience circa 2000 as an intern at Philip Morris, then full time employment for a few years. Flash IR and x-ray CT of cigarettes under Dr. Mike Watkins.
  - Left for Grad School and met Prof. Bob Green at JHU who helped guide me and introduced me to NDE leaders at NASA.
  - In 2005, Dr. Ed Generazio/Langley/HQ offered me a graduate student internship during Shuttle Return to Flight.
  - In 2010, after graduation and a post-doc at JHU/APL, hired at NASA Goddard to join the Materials Engineering Branch and NDE group.
  - Currently I lead NDE group, helping to address GSFC flight program needs and working with leaders like Dr. James Garvin to help bring In-Space NDE tools to bear for space science and engineering use.
- Hobbies
  - Learning new things (woodworking, painting, metal work, pursuing more hobbies…)
  - Love to sail, golf, metal detect, hike, and spend time with family
  - Taking trips to the MD Eastern Shore and NC Outer Banks

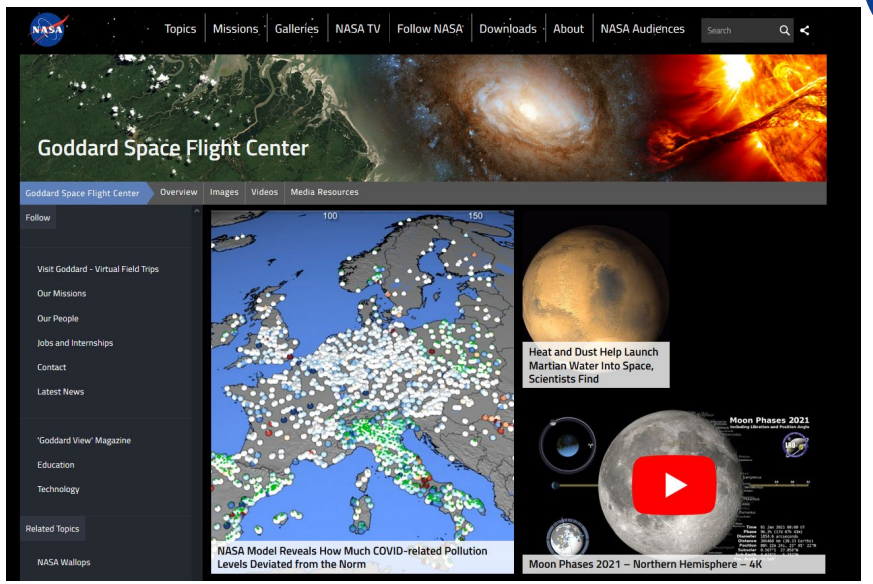
Younger version of me back in 2005 with the NASA NDE "Technical Warrant Holders"! Bob Green, front left

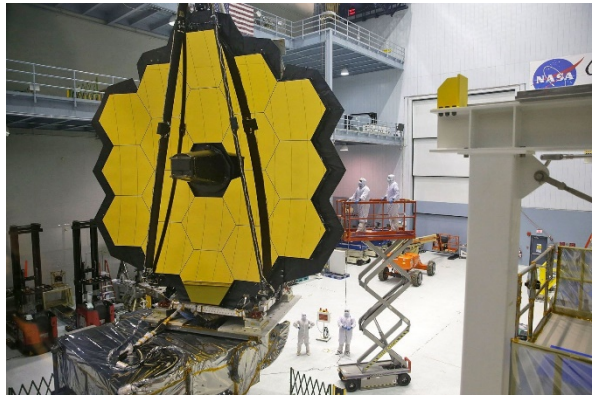




Brief Intro to NASA Goddard







Goddard Lines of Business:

- Astrophysics
- Heliophysics
- Earth Science
- Planetary Science
- Communications/Navigation
- Crosscutting Technologies
- Suborbital Platforms and Range Services

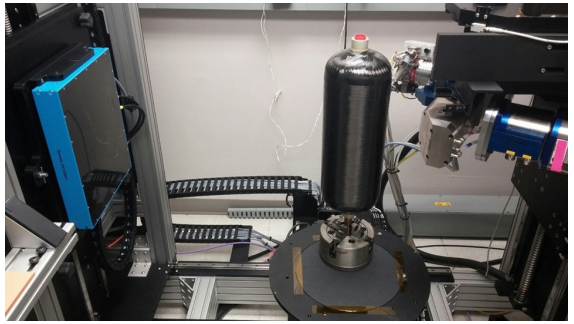
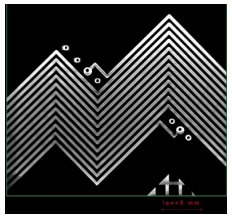
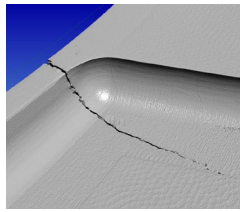
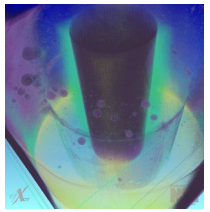
https://www.nasa.gov/centers/goddard/about/index.html

Goddard NDE Lab

Flight Project Support Activities

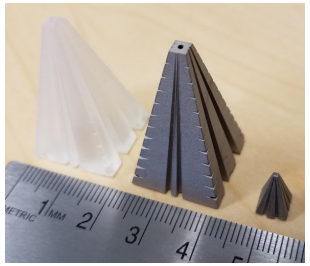
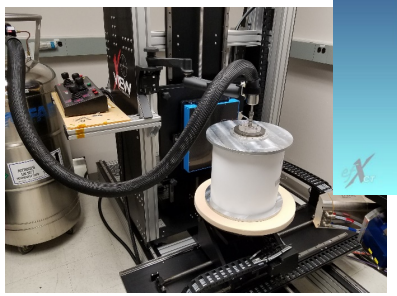
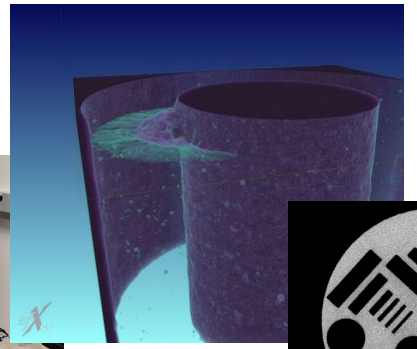
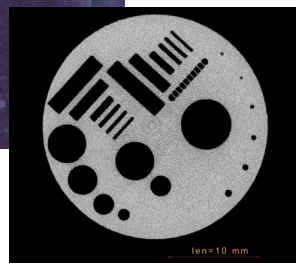
- Full coverage NDE facility, including: x-ray CT and DR, IR thermography, Immersion UT, Dye Penetrant, and Eddy Current
- Flight hardware inspection support to several active flight project/program offices.
- Electronic parts/boards, 3D printed parts, pressure vessels, composites, bonded joints, welds, actuators, valves, etc.



Recent NDE Research Activities at GSFC

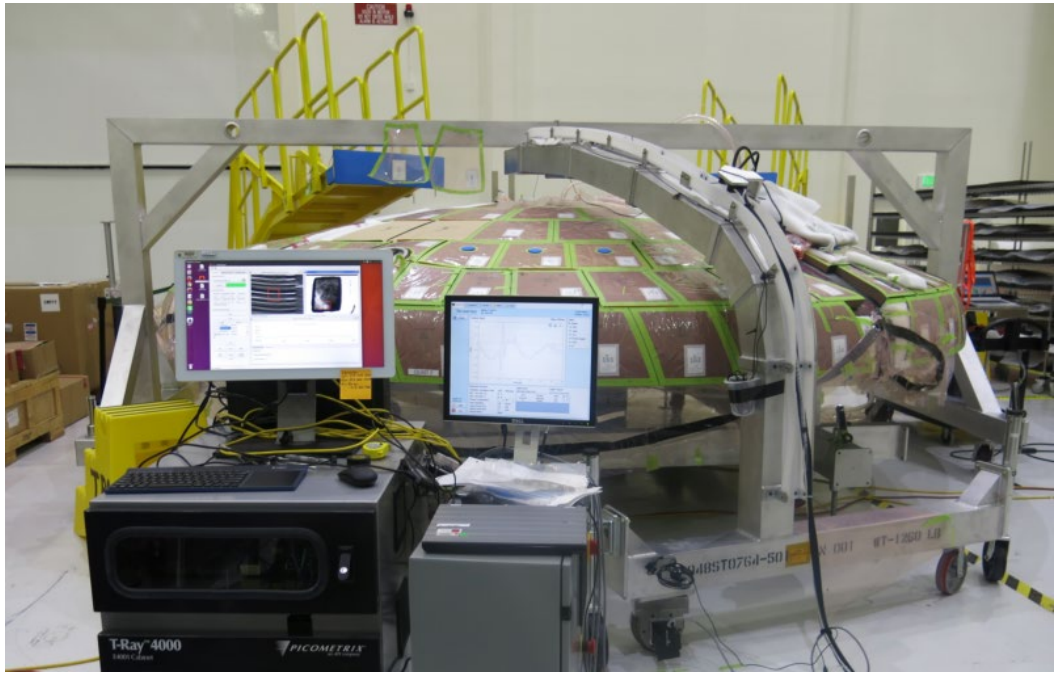
- NDE Dependence on Additive Manufacturing/ Material Parameters (microstructure, surface finish)
- CT In Space concept development
- Portable X-ray Source Miniaturization
- Development of X-Ray Computed Tomography Performance Standards using Additive Manufacturing
- Cryogenic CT Scan System
- COPV Damage Assessment

NASA Agency Level NDE Research

- NASA Agency activities generally supported through Office of Safety and Mission Assurance (OSMA) Agency NDE Program or through NASA Engineering and Safety Center
- Digital Twins, Big Data Management
- Training and Certification
- Model Based Probability of Detection (POD)
- Inspection and Certification of Composites
- In-Situ inspection of Additively Manufactured Parts
- Inspection of Composite over Wrap Pressure Vessels
- Advancements in X-Ray, UT, ET, etc. including the use of quantum materials
- Large Area Inspection
- Advancement in HPC and Algorithm Development

NASA Agency Level NDE Research, Highlights



Langley Research Center's (LaRC) Nondestructive Evaluation Sciences Branch (NESB) working with Lockheed Martin and the NESC to develop a Terahertz inspection system for bond verification of AVCOAT blocks to the Orion EM-1 Carrier Structure

SLS Block 1

- Artemis SLS Block 1 integration: 322' tall, 5.75 million pounds, will produce 8.8 million pounds thrust (15 percent more than Saturn V)
- Artemis 1 will be an uncrewed test flight that will provide a foundation for human deep space exploration, to extend human existence to the Moon and beyond.
- This is currently on-going at Kennedy Space Center in preparation or flight.

Motivation for In-Space NDE Tools

Artist's concept of the Artemis Base Camp.

Overview of 5 key Beneficiaries

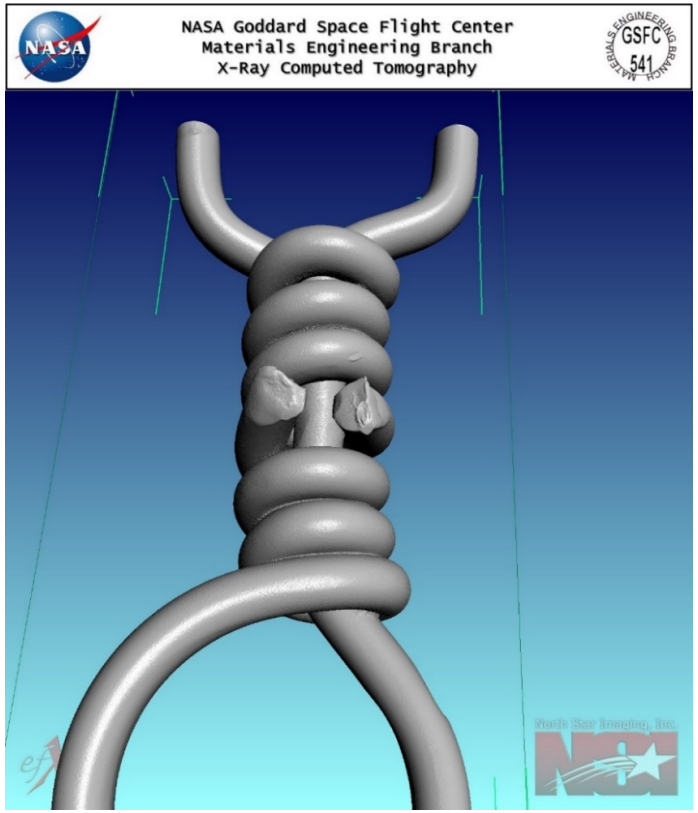
- Engineering Quality Assurance (QA) / Failure Analysis (FA)
- Human Safety/Mission Assurance
- Additive Manufacturing (AM) & In-Space Manufacturing (ISM)
- In-Situ Resource Utilization (ISRU)
- Science Initiatives/Return Sample Triage

Source: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

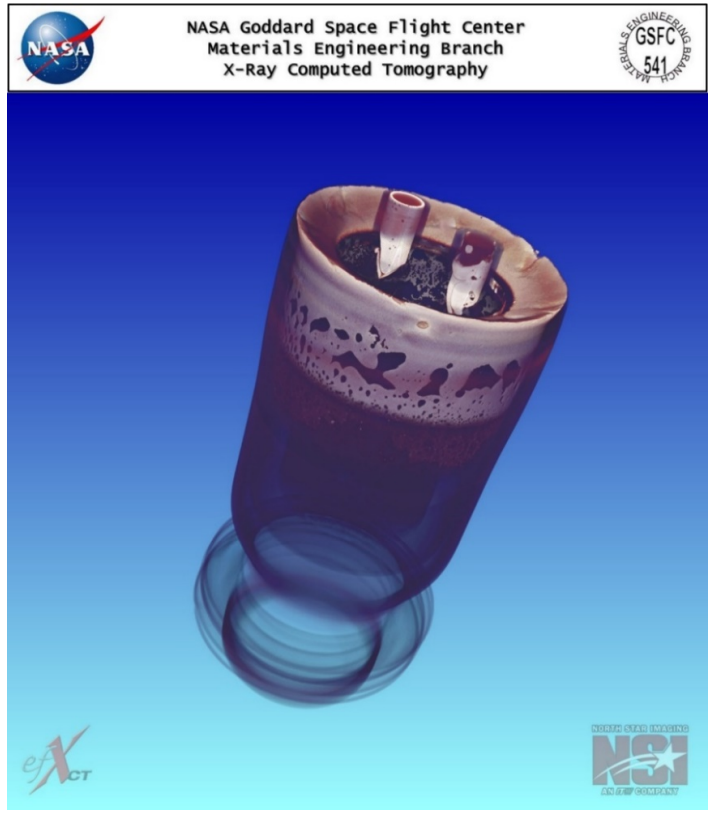
Engineering Quality Assurance (QA)
and
Failure Analysis (FA)

Quality Assurance (QA) & Failure Analysis (FA)

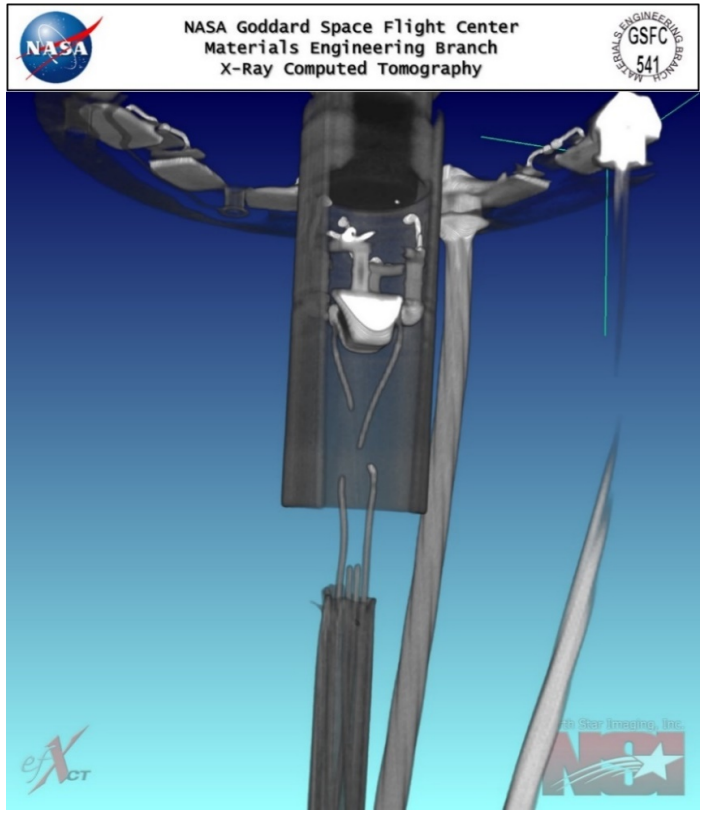
Common engineering applications that demand x-ray CT for flight hardware



Deployment release mechanism wire assembly



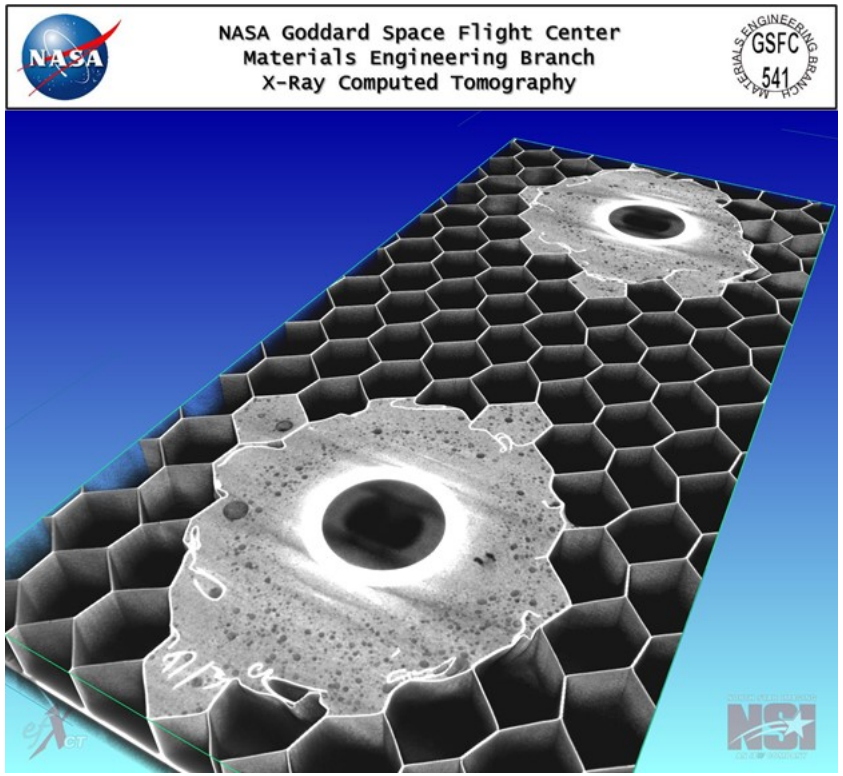
Pyrotechnic actuator braze joint



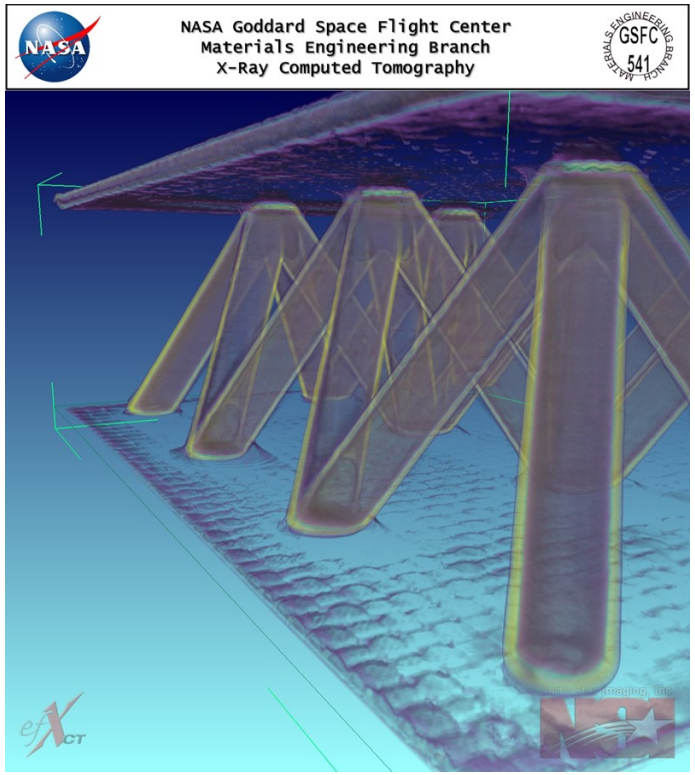
Articulating borescope camera failure

Quality Assurance (QA) & Failure Analysis (FA)

Common engineering applications that demand x-ray CT for flight hardware



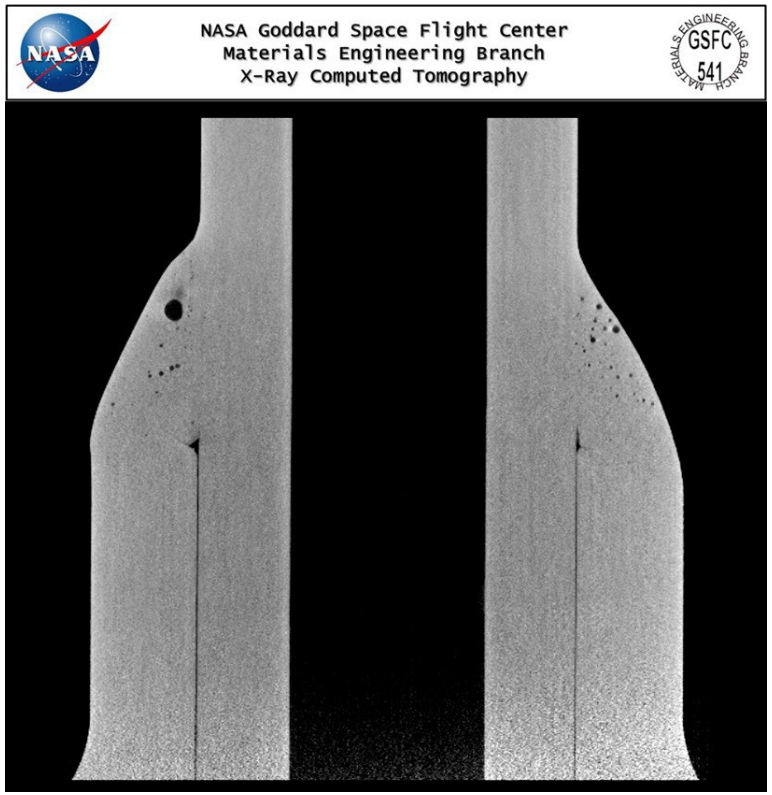
Sandwich panel core with insert fittings



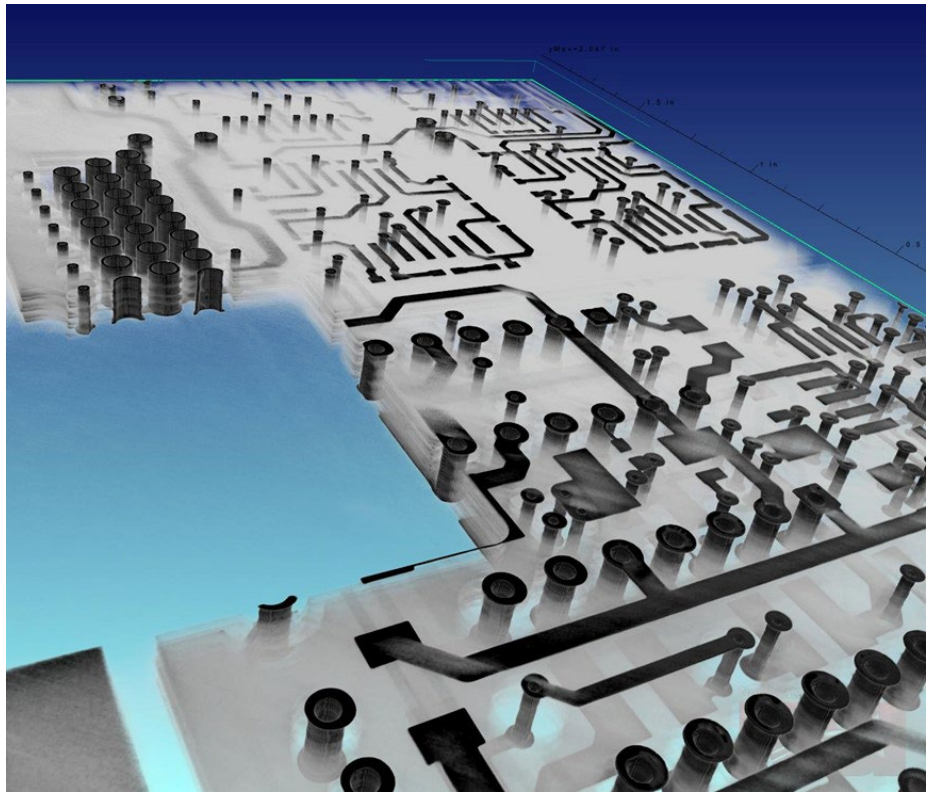
Composite core concept with 3D printed topological structural elements

Quality Assurance (QA) & Failure Analysis (FA)

Common engineering applications that demand x-ray CT for flight hardware



Tube weld inspection showing porosity



Circuit board inspections (often supplemented with IR)

Human Space Flight Safety & Mission Assurance

Human Space Flight Safety & Mission Assurance

- *Composite HUT section inspection for next generation xEMU suit under Artemis Program*
- *Assessing build quality and impact damage assessment using flash IR thermography*

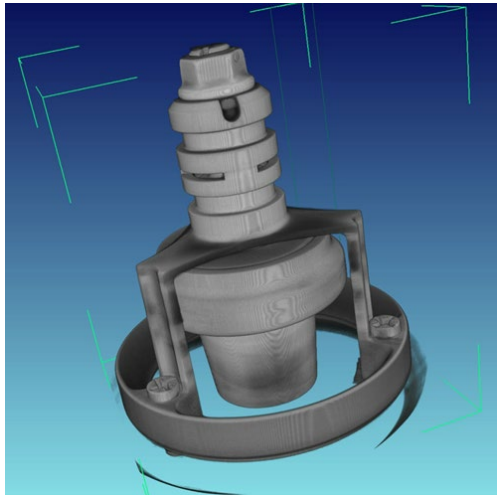
Left: xEMU Upper Torso Assembly, Development Unit (Z2.5). *Center and Right*: Composite version test article under inspection at GSFC.

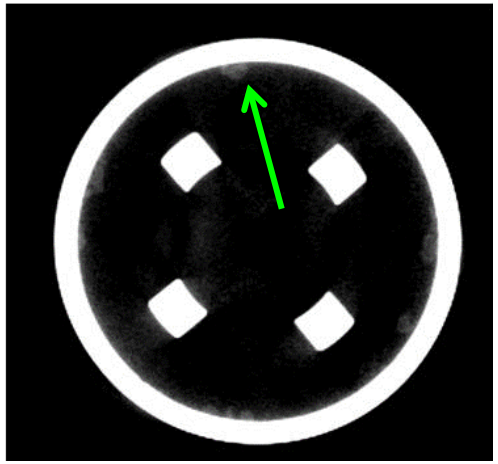
Collaboration with NASA JSC (D. Kim, R. Rhodes) and University of Delaware Center for Composite Materials (S. Yarlagadda). Inspections by Dr. W. Mulhearn/GSFC.

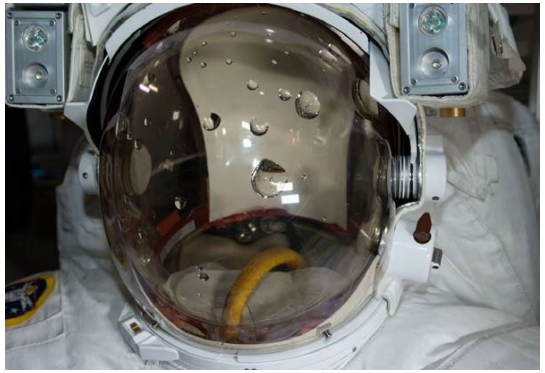
Source: https://www.nasa.gov/image-feature/exploration-emu-xemu-development-unit-7

Human Space Flight Safety & Mission Assurance

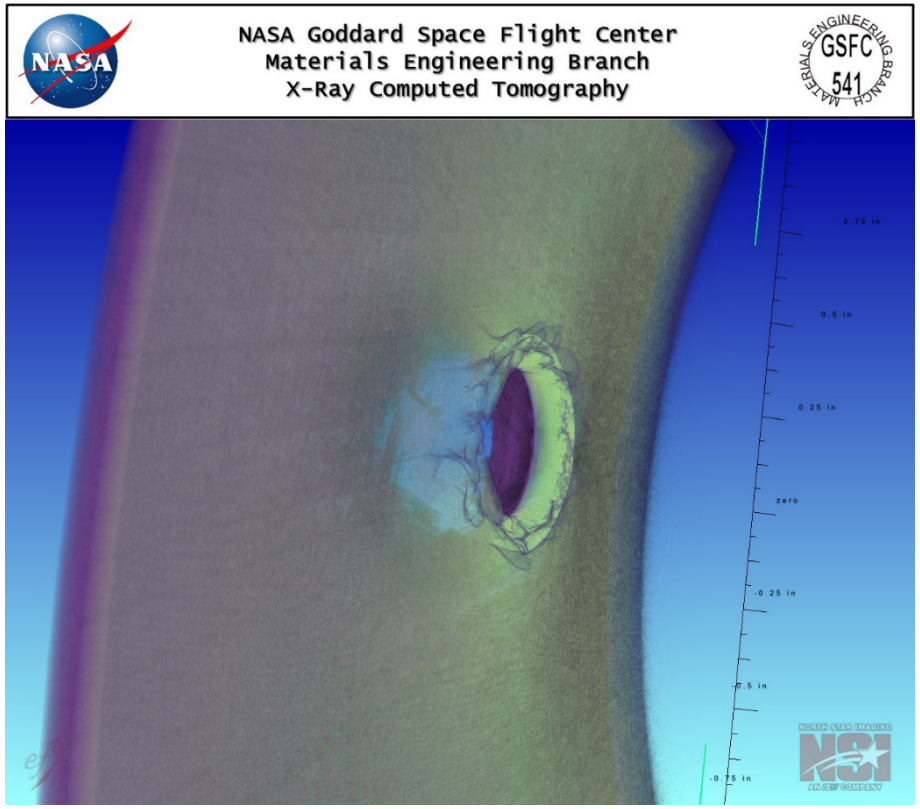
Structural Damage Detection and Human Safety







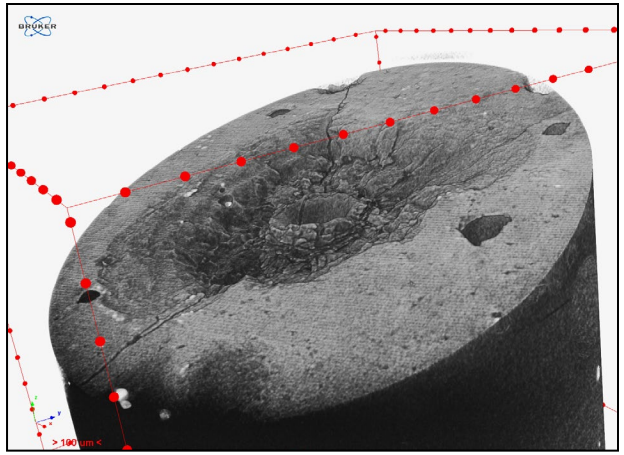
International Space Station (ISS) Extravehicular Activity (EVA) 23 Suit Water Intrusion High Visibility Close Call (HVCC) Mishap Investigation

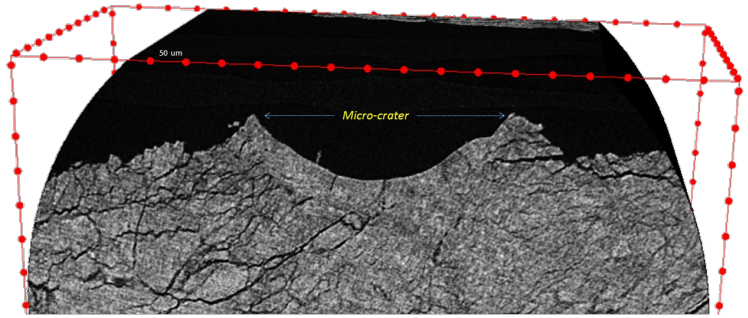


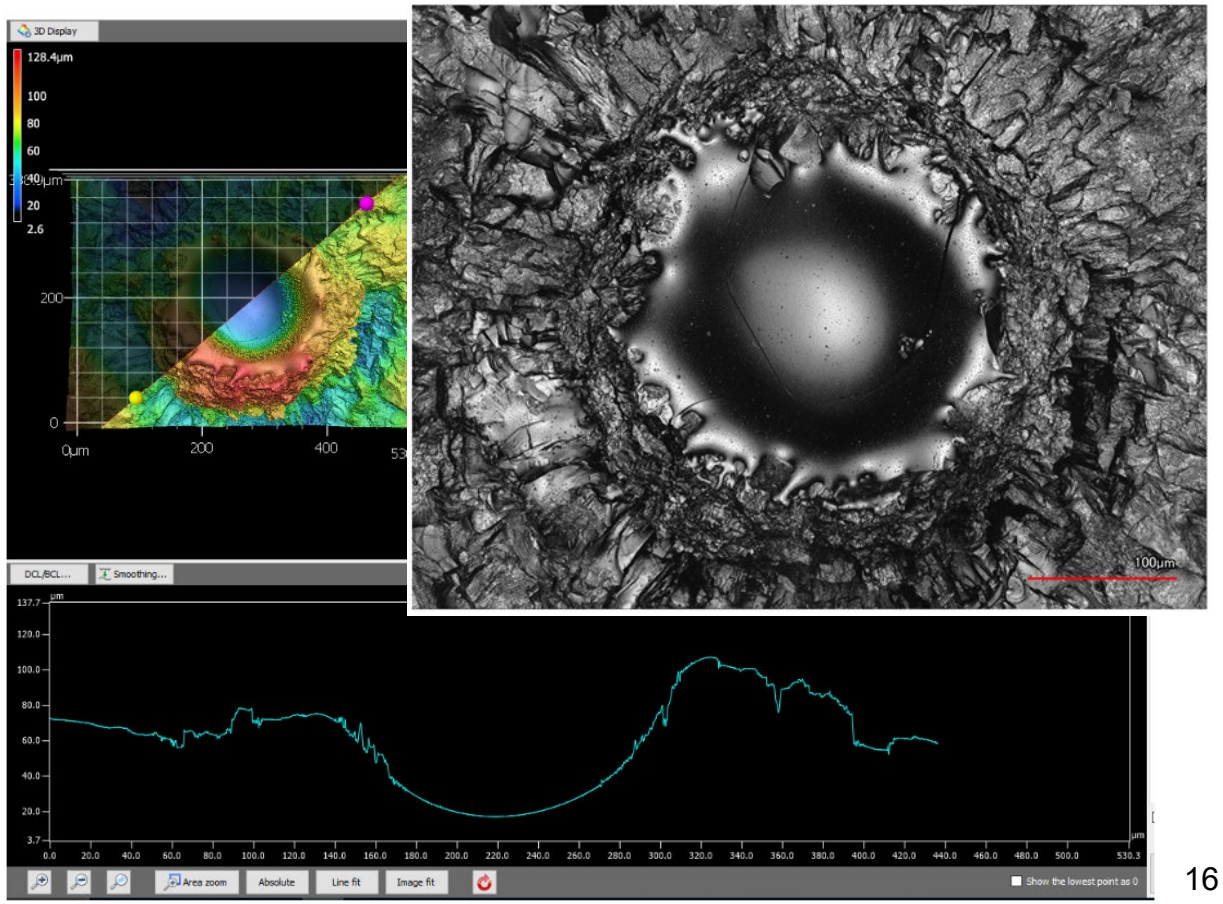
Composite Overwrap Pressure Vessel (COPV) impact damage assessment (simulated micrometeorite)

Human Space Flight Safety & Mission Assurance

Micrometeorite Impact Damage: Lunar Impact Glass "Zap Pit": xCT, followed by LCM





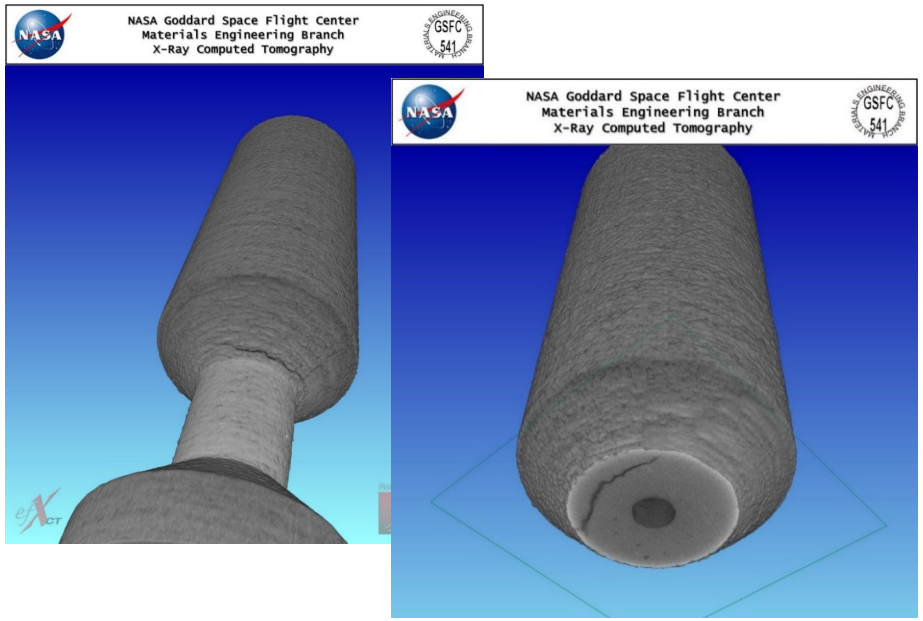


Apollo 16 sample 60095.36 with "zap pit": Left images show nano-focus CT (ARL/Xradia Versa/J. Sietins) and Right images show laser confocal microscopy of impact crater (J. Jones)

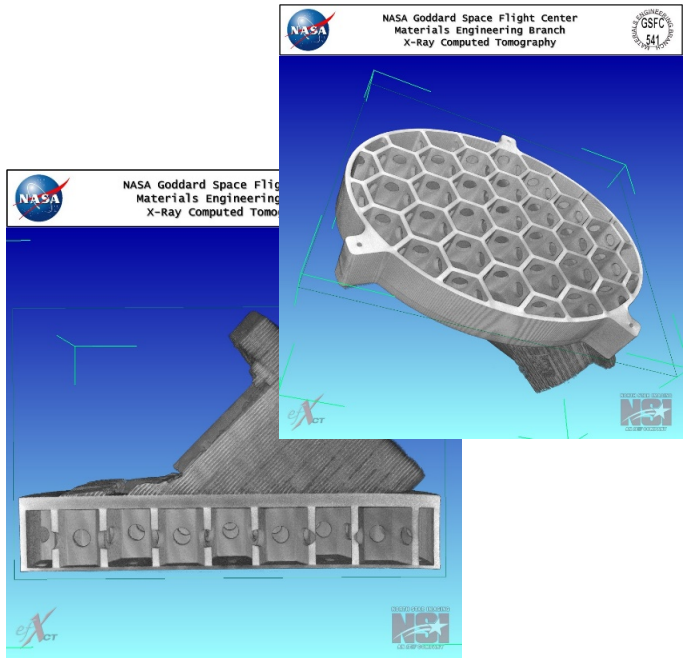
Additive Manufacturing (AM) and In-Space Manufacturing (ISM)

Additive Manufacturing, Qualification/Certification

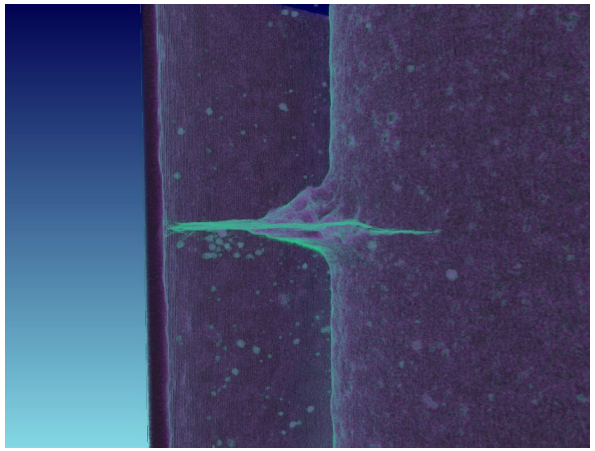
- *Ground-based inspection AM Parts is of immediate concern for NASA*
- *Several centers are working on this and developing standards and approaches*
- *Computed tomography is the most versatile technique used for ground-based NDE of AM parts, though all methods are in play*

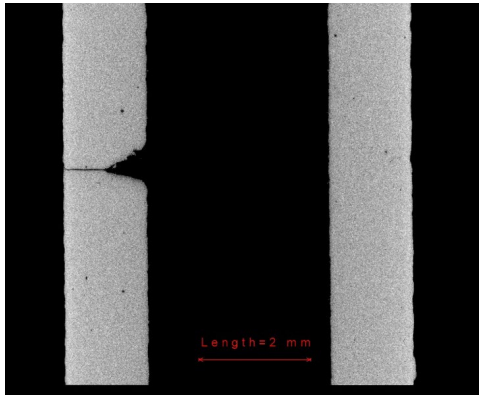


Ti6Al4V AM venturi (non-flight tech demo) with stress relief crack



3D printed prototype mirror back-shell (non-flight tech demo)

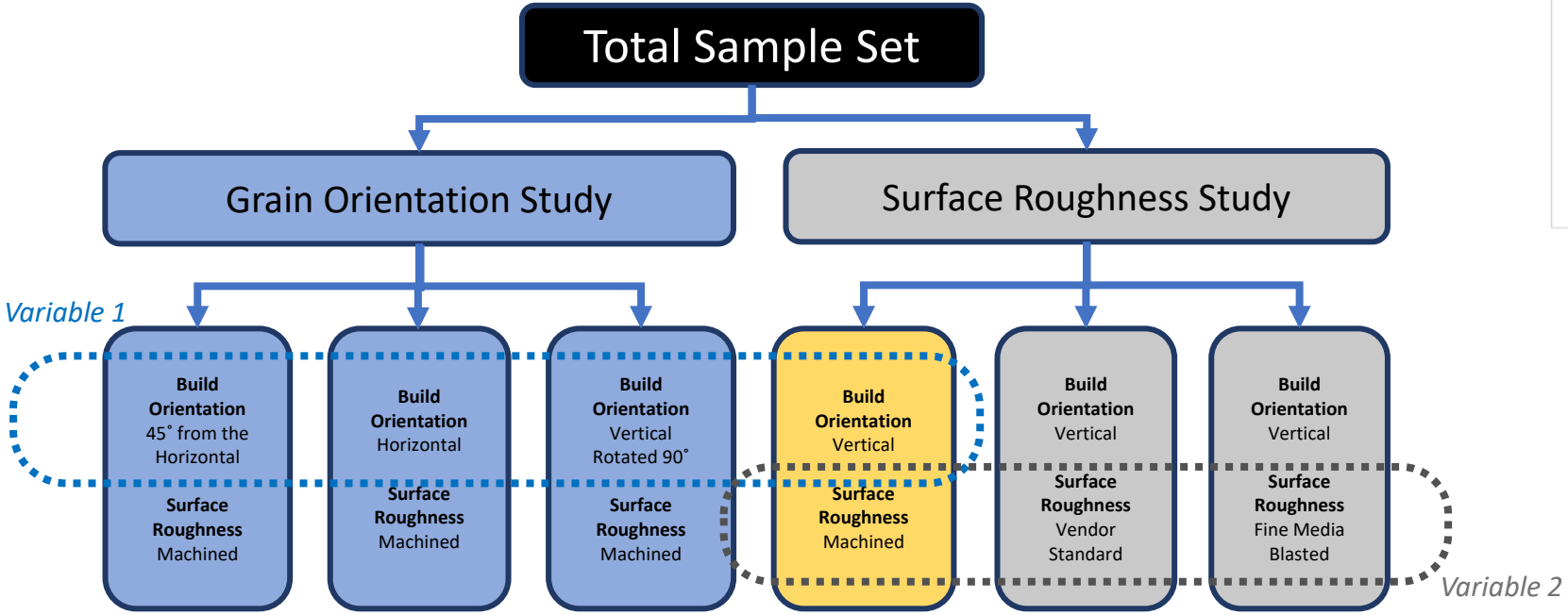


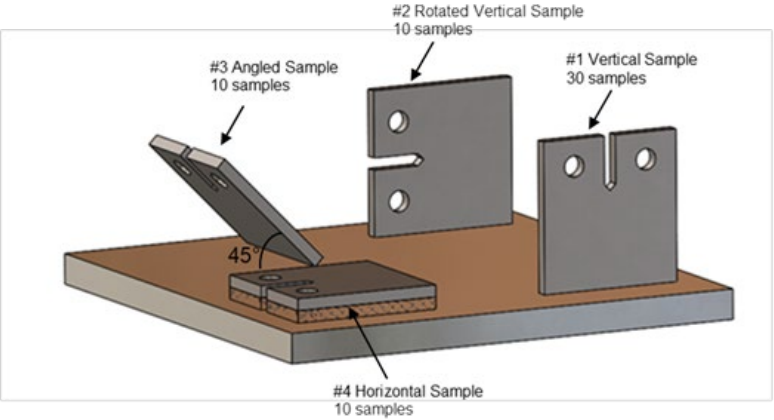


Ti6Al4V AM with radial cracks

Additive Manufacturing, Qualification/Certification

- *Recent OSMA NDE funded study at GSFC aimed to understand if NDE indications of cracks respond differently in AM parts vs traditional*
- *Two parameters of interest:*
  - *Determine if NDE signal response is affected by AM surface roughness.*
  - *Determine if NDE signal response is affected by AM internal grain structure.*

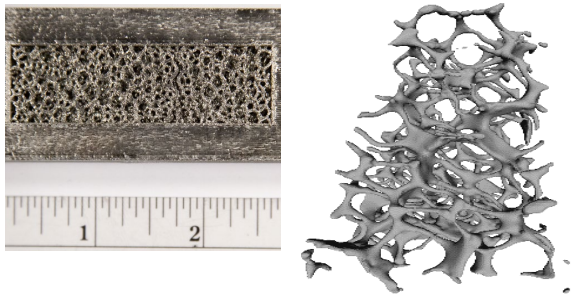




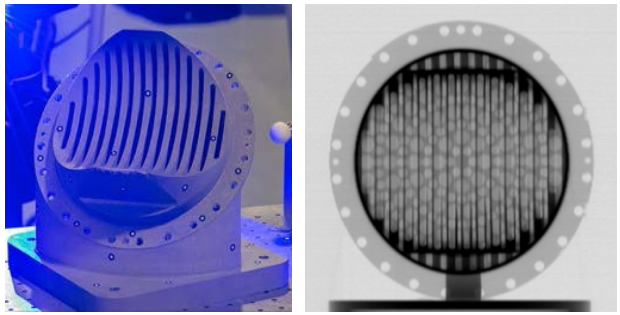
Additive Manufacturing, Qualification/Certification

Towards NDE Certification for Additive Manufacturing…

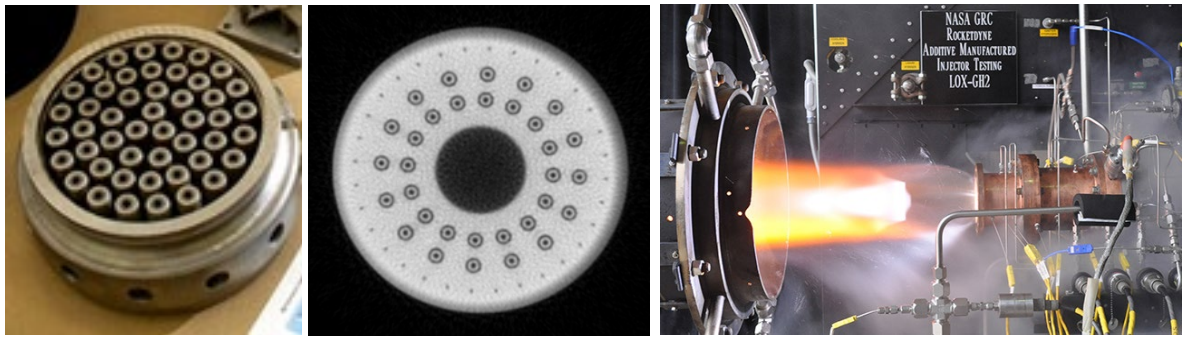
Current Standard Viable Methods	Issues for Standard Viable Techniques	Improvement and Integration
Computed Tomography & Radiography (current "gold standard" method)	Time Prohibitive	Improved process algorithms, ADR and ML techniques
	Ionizing Radiation	Adaptive shielding, advanced materials
	Qualification of CT Systems	IQI based Certification CR and DR systems
Ultrasonic	Internal Structure Beam Steering	Use of beam correction algorithms
	Complex Beam Paths due to geometry	High fidelity modeling for sound placement
Eddy Current	Surface texture	Spec finished parts for inspection
	Depth of Penetration	Articulated scanning techniques for better access
Penetrant	Surface Only	Hybrid approaches for inaccessible regions (e.g. CT w/ tracer particles)
	Contamination	Improved approaches and protective measures
Note: Front End processing and in-situ monitoring is also in the works		



CT Ti-6-4 Metal Foam Reverse Engineering



CT Pogo-Z baffles, RS-25/J2-X



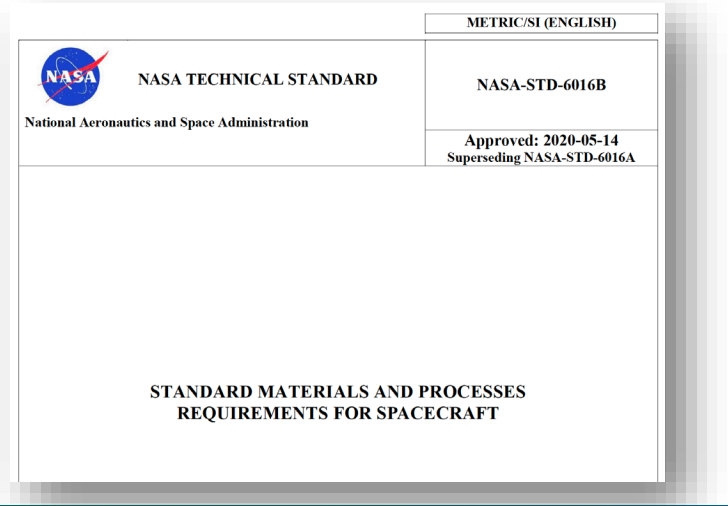
NASA\Rocketdyne GRC Additive Manufactured Rocket Injector

Additive Manufacturing, Qualification/Certification

- *The current logic of additive manufactured part certification is outlined in NASA-STD-6016B, NASA-STD-6030, and NASA-STD-6033.*
- *These new standards provide a policy framework for the <u>development</u> and <u>production</u> of hardware produced using AM processes.*

NASA-STD-6016B

General M&P requirements


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

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

New NASA Technical Standard

Additive Manufacturing Requirements for Spaceflight Systems

NASA-STD-6033

New NASA Technical Standard

Additive Manufacturing Requirements for Equipment and Facility Control

Handbook coming soon with more specifics on implementation.

Additive Manufacturing, Qualification/Certification

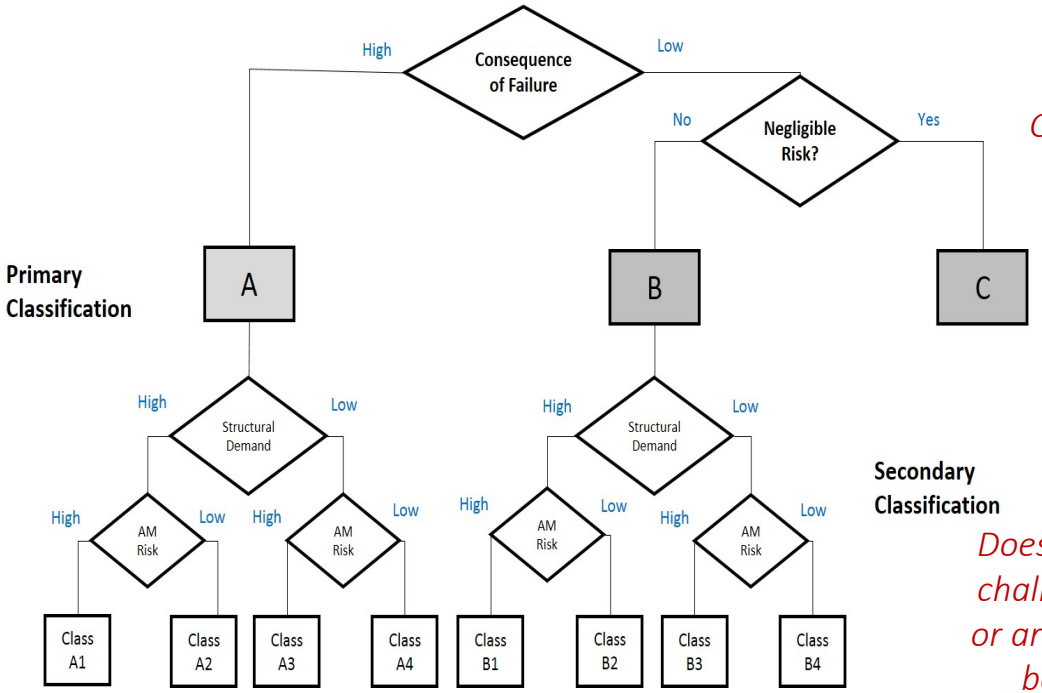
Key messages from STD-6030 concerning NDE:

- **Statement 1**: "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…"
  - Rationale: "NDE provides a necessary degree of quality assurance for AM parts in addition to the process controls of this NASA Technical Standard."

- **Statement 2**: "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…"
  - 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."

- **Statement 3**: "The NDE approach for **Class B** parts ***shall*** meet the **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…"

Risk-based part classifications for AM parts consider the risk of AM manufacturability and inspectability.



Catastrophic Failure?

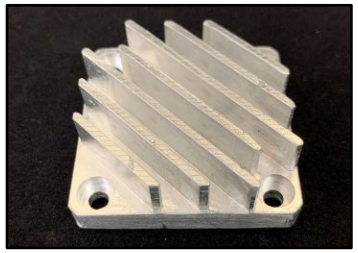
Heavily Loaded?

Does the build have challenging aspects or areas that cannot be inspected?

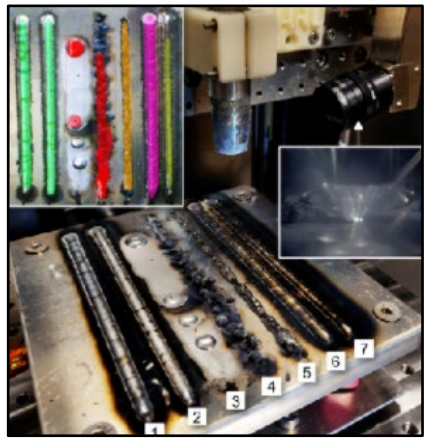
In-Space Manufacturing (ISM)

- *Current metal AM tech. developments for ISM include in-situ monitoring*
- *In-space NDE will be needed for finished parts*

Redwire (Made in Space) Vulcan



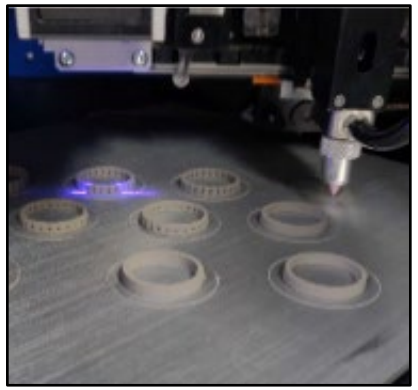
Wire-Arc Additive Manufacturing + Weld Quality Grading Machine Vision

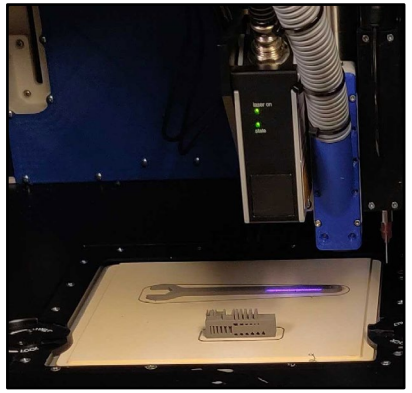


TechShot, Inc. FabLab

Bound Metal Deposition + Laser Profilometry

Ground-based prototype system

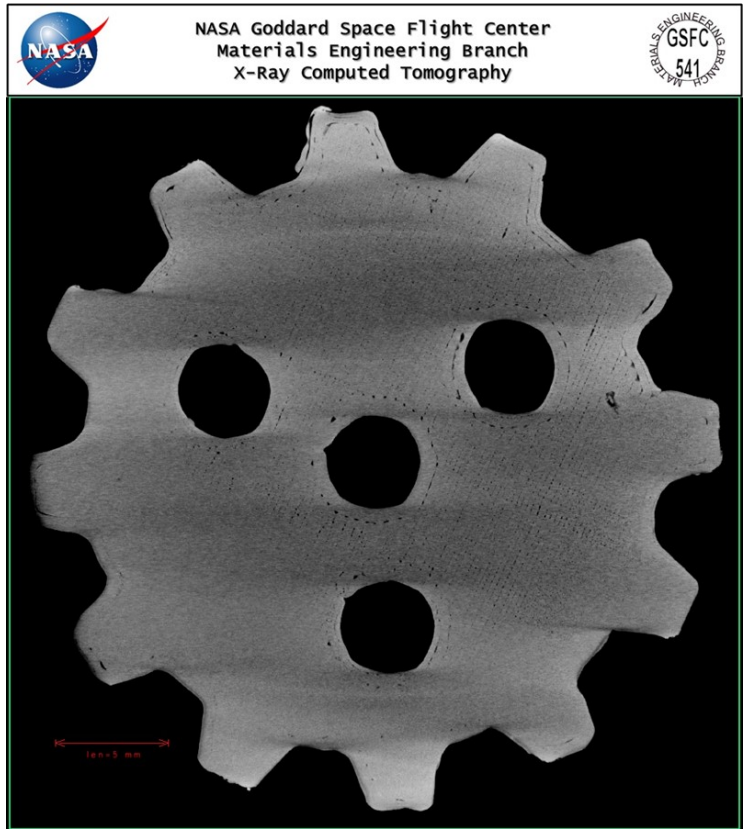


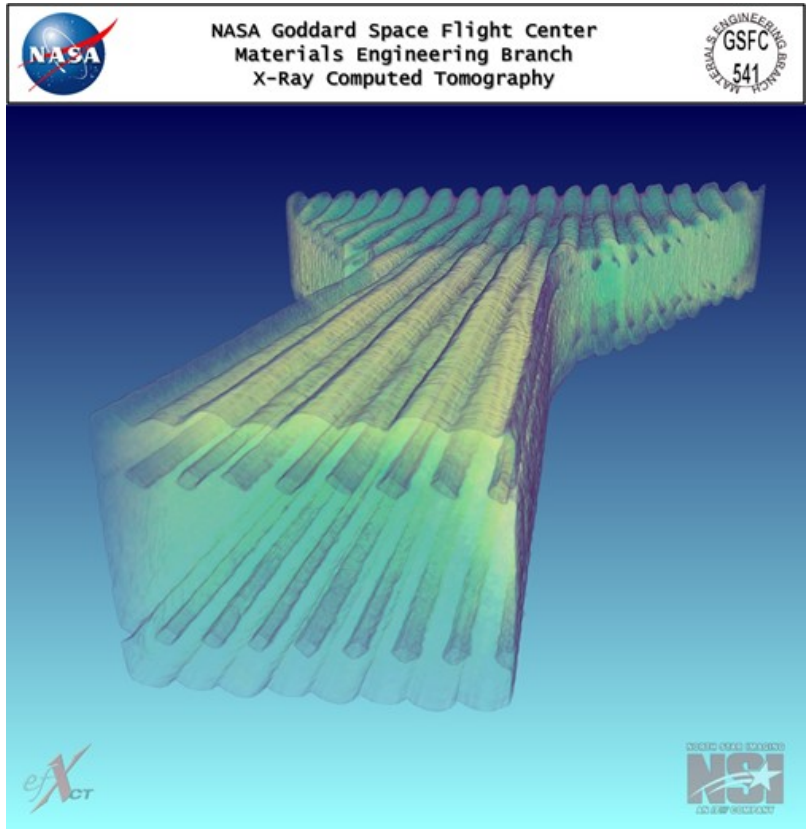


In-Space Manufacturing (ISM)

- *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*

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.

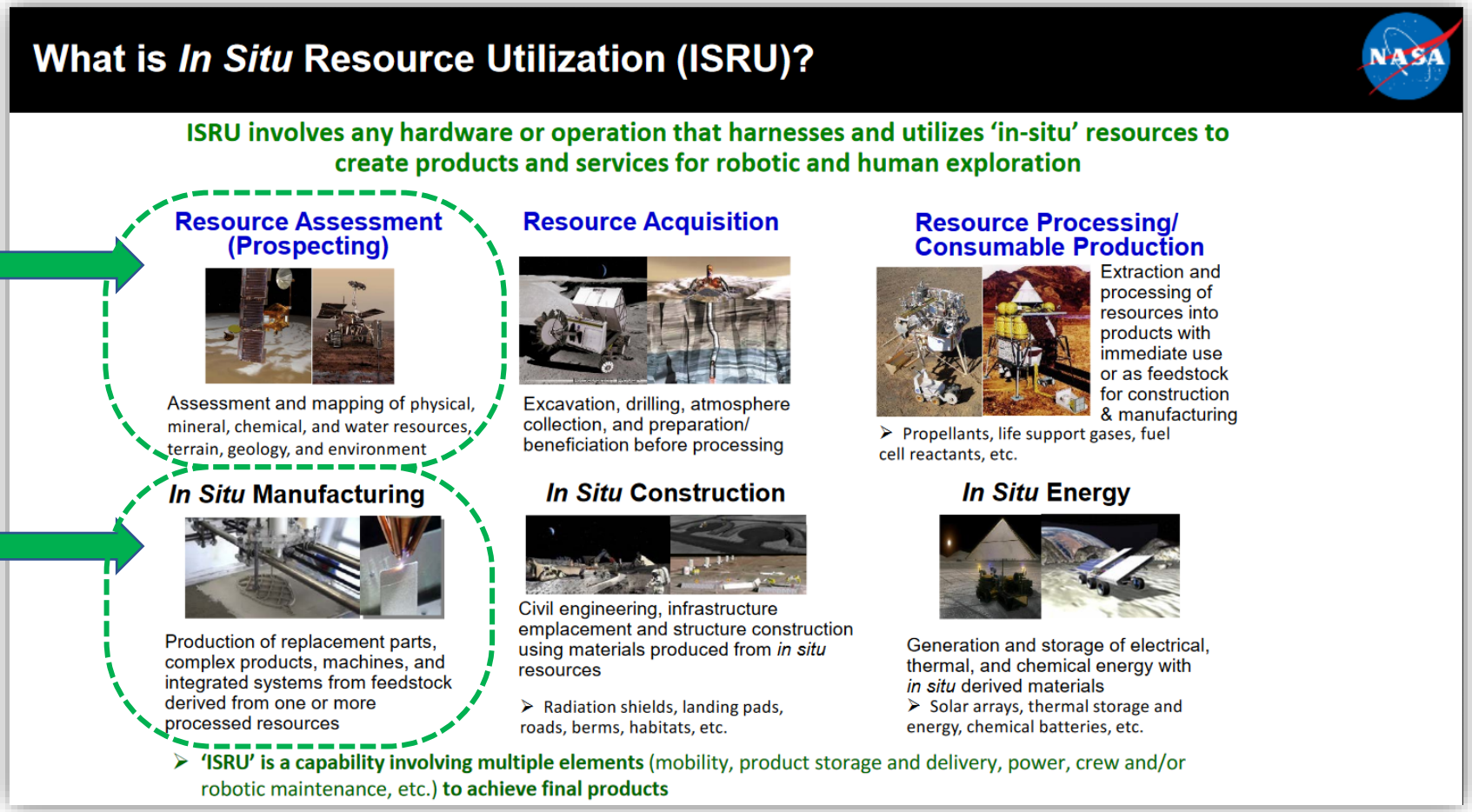




In-Situ Resource Utilization (ISRU)

In-Situ Resource Utilization (ISRU)

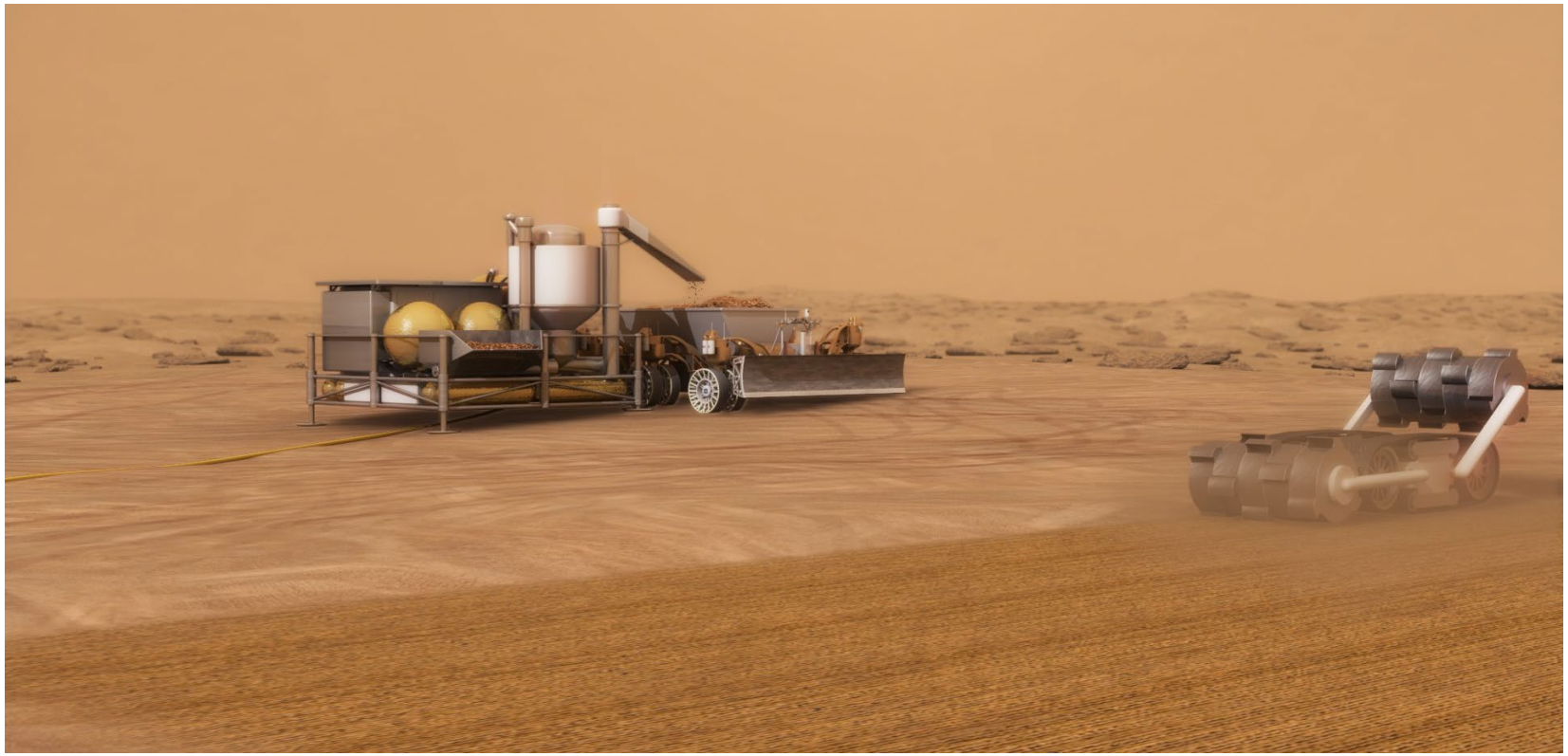
- NDE will directly impact future ISRU initiatives, particularly Resource Assessment and ISM
- New Tools, such as X-ray CT, along with *complementary tools* will be critical to Go/NoGo triage decision
- Complementary tools to provide compositional analysis, structure, shape, etc. (e.g. DIC, SfM, XRF, LIBS)



Source: https://www.nasa.gov/sites/default/files/atoms/files/nextstep-2-isru-baa-industry-forum_11dec2017_0.pdf

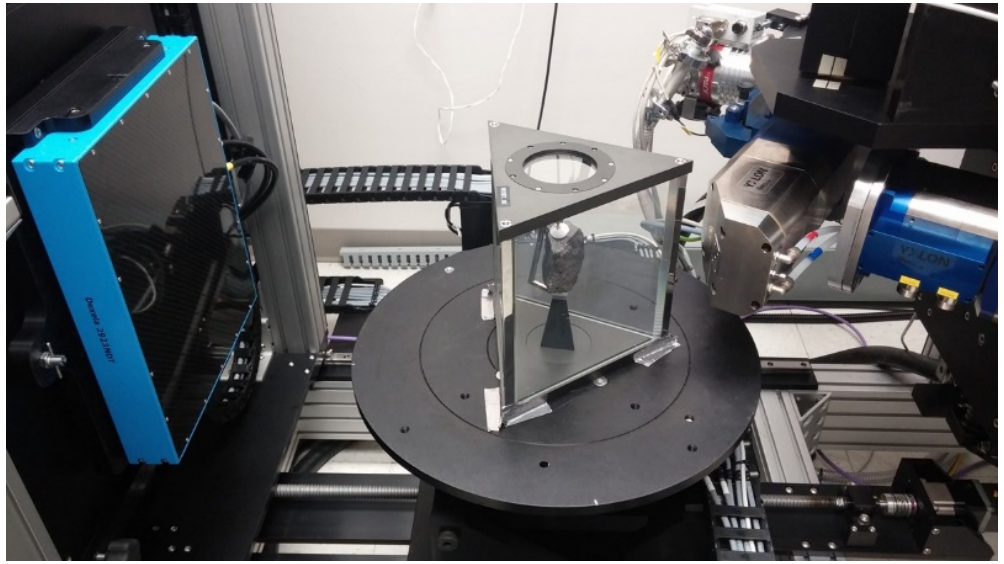
In-Situ Resource Utilization (ISRU)

- X-ray CT concepts for drill core and loose sample inspection are being explored by NASA
- Similar “field based” CT concepts are being considered by the military/ARL (Sietins et al)
- Rapid inspection of a test sample can help identify compositional features of interest, by % volume, which can be pivotal in decision making

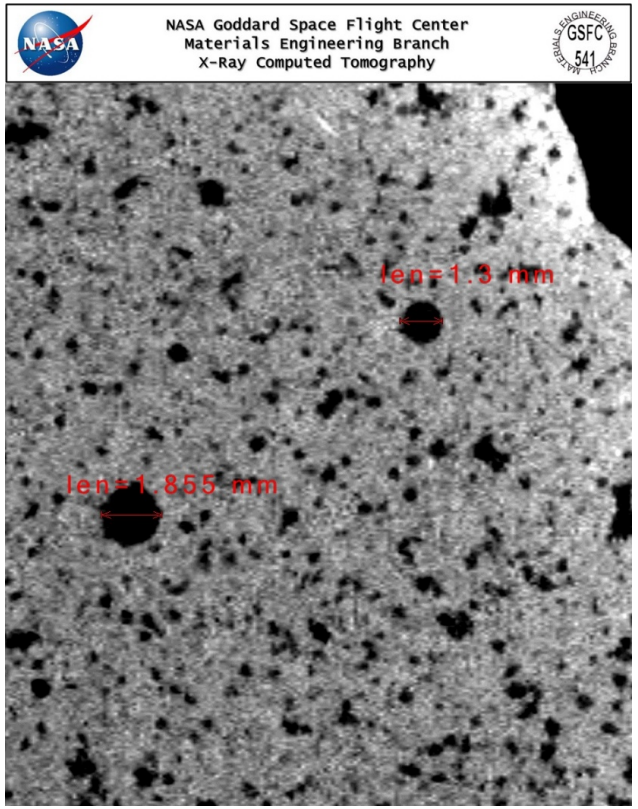


SRU system concept for autonomous robotic excavation and processing of Mars soil to extract water for use in exploration missions.
Source: https://www.nasa.gov/isru/overview and https://www.nasa.gov/nextstep/isru

In-Situ Resource Utilization (ISRU)

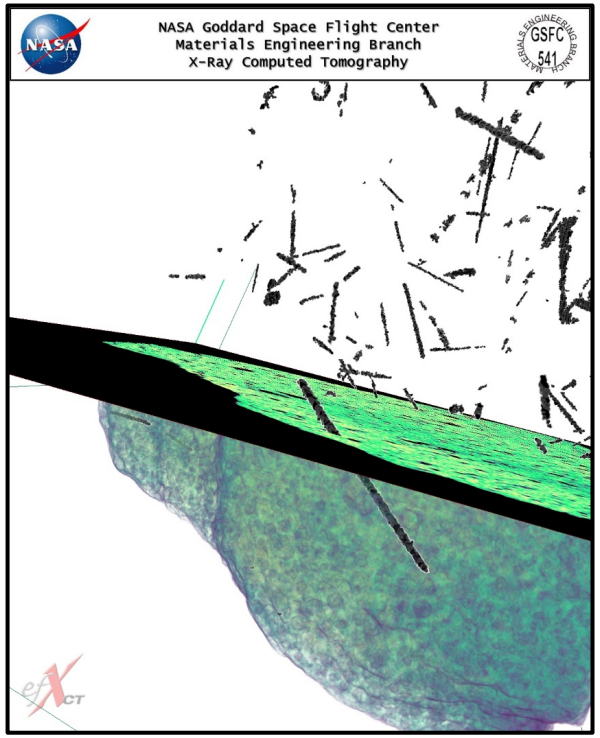


GSFC x-ray Computed Tomography (CT) system (NSI X-5000) showing inspection of lunar basalt sample 10057.3. CT could be used to assess % volume of relative compositions, porosity/tortuosity, and much more.

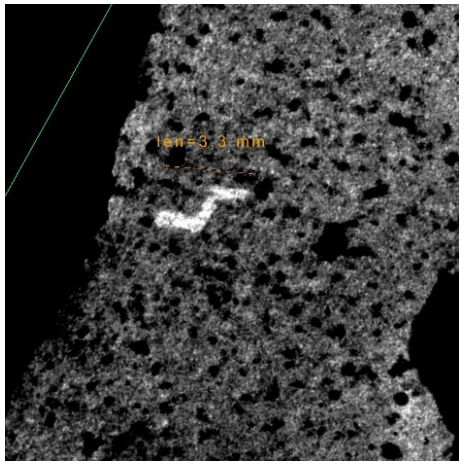


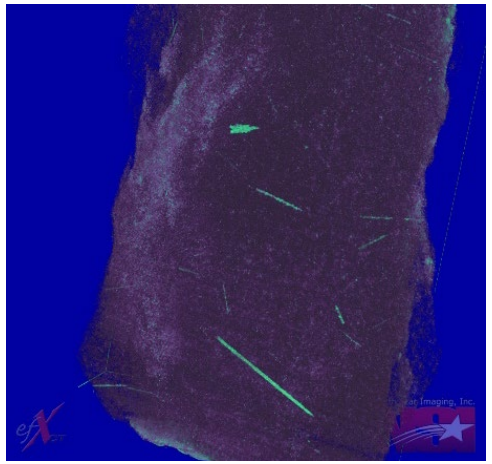
In-Situ Resource Utilization (ISRU)

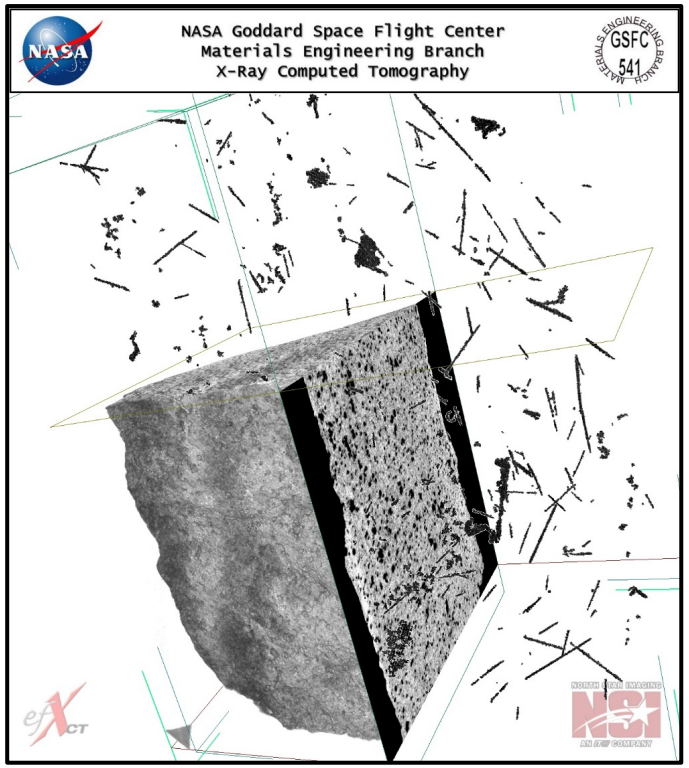
Lunar sample 10057.3, very high titanium (VHT) basalt with unexpectedly large grained interspersed crystals (putatively ilmenite, $FeTiO_3$)



Titanium-rich ilmenite could be a valuable resource on the lunar surface!

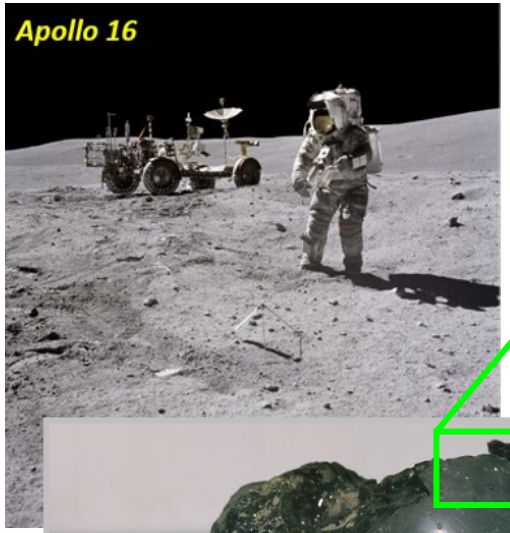


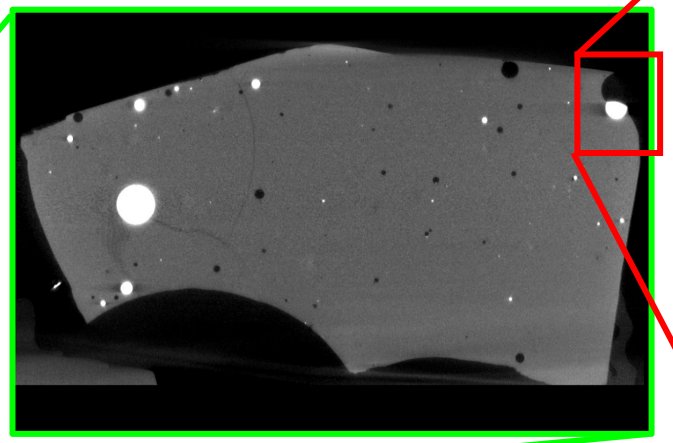


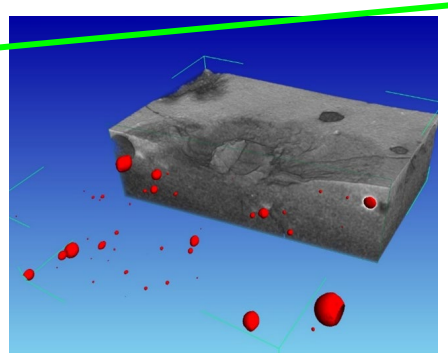


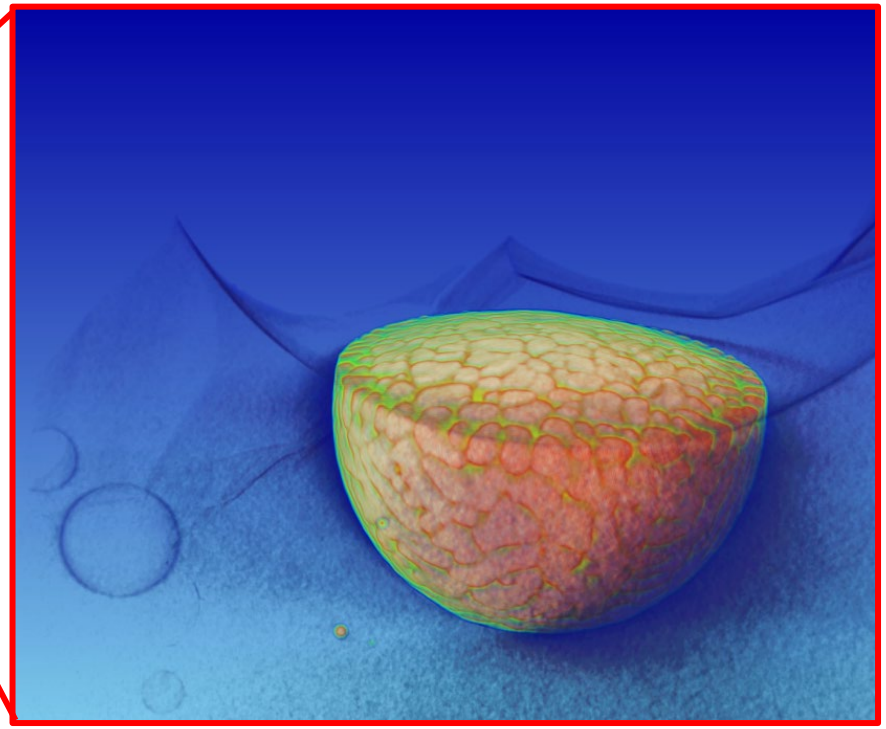
In-Situ Resource Utilization (ISRU)

Apollo 16 lunar impact melt glass fragment (8mm long) sample 60095.36, with tiny interior metal “vugs” (metal-filled vesicles).





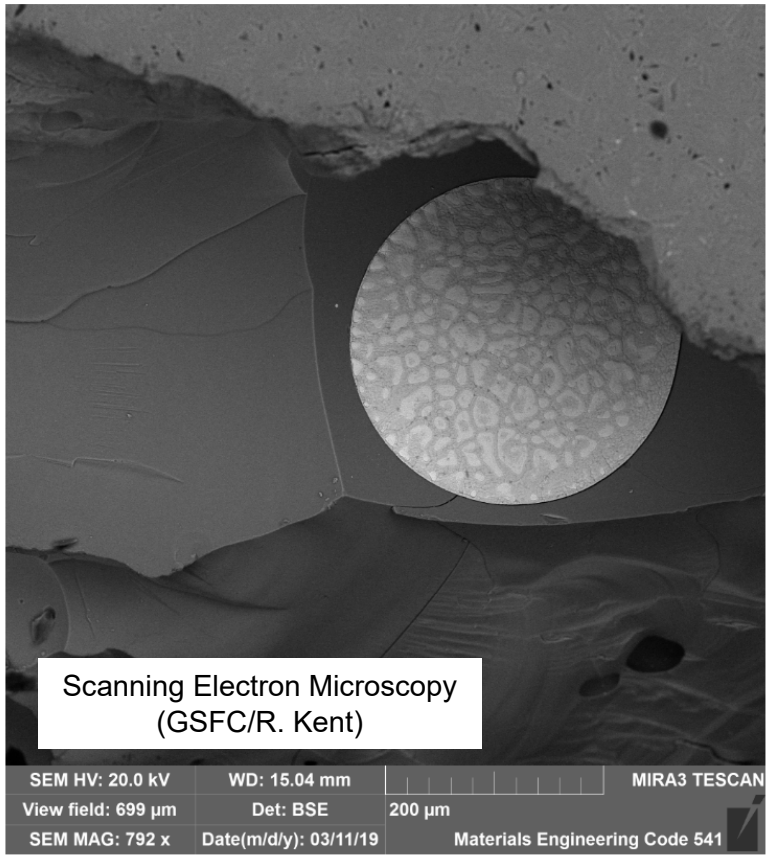




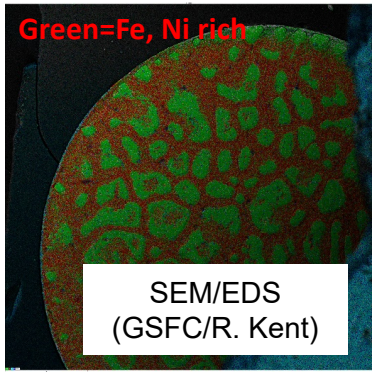
Lower far left image shows lunar glass spheroid, 60095. *Upper Center* image shows GSFC micro-focus CT system cross-section of fragment 60095.36. *Right* image of single 300 micron vug is from nano-focus Zeiss Xradia system at Army Research Lab (J. Sietins), visualized post-scan using NSI software (J. Jones). *Lower Center* image shows multi-volume rendering of 60095.36 to highlight vugs.

In-Situ Resource Utilization (ISRU)

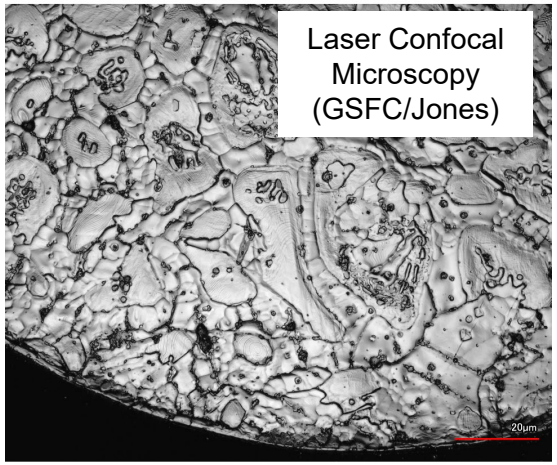
…Upon closer inspection of 60095.36, with complimentary tools (xCT, LCM and SEM)



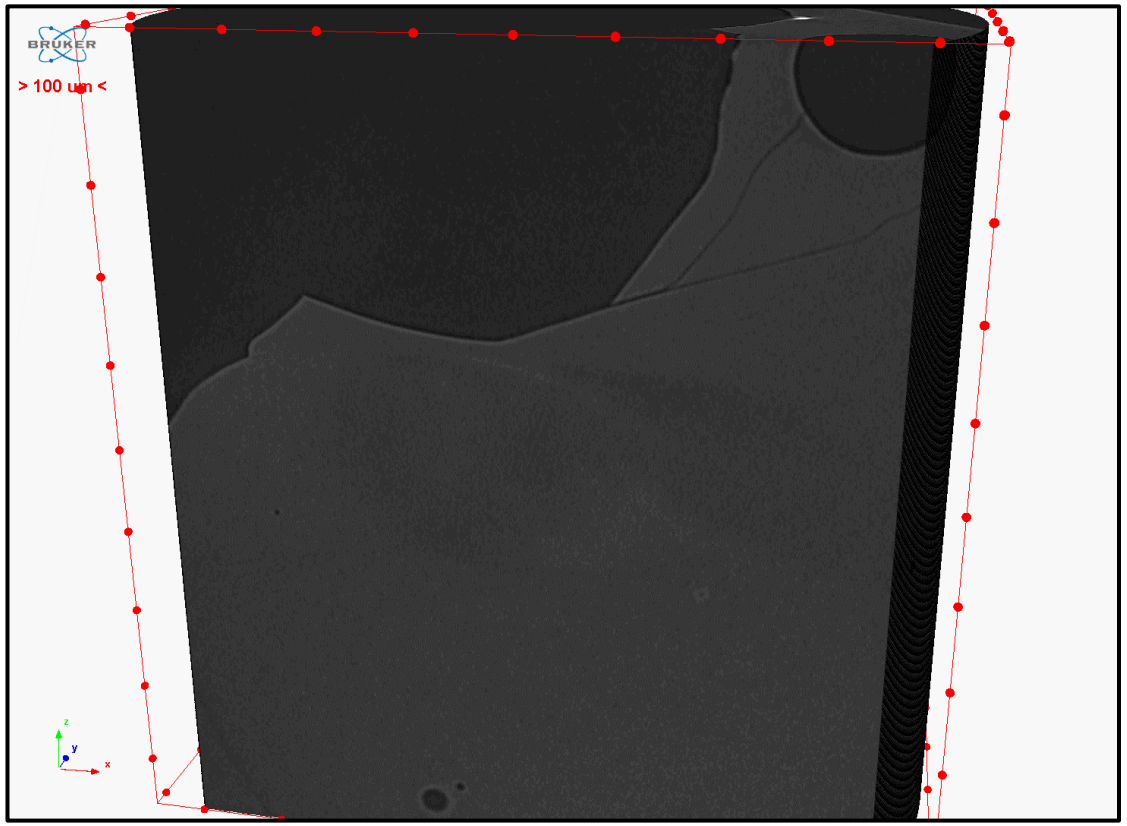
Scanning Electron Microscopy (GSFC/R. Kent)



SEM/EDS (GSFC/R. Kent)



Laser Confocal Microscopy (GSFC/Jones)

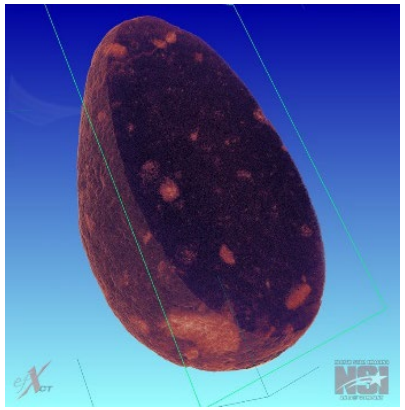


VIDEO: Nano-focus xCT of single, 300 micron "vug" from Apollo 16 sample 60095.36 (Zeiss Xradia Versa (ARL/Sietins) and visualization via Bruker CTVox (GSFC/Jones)

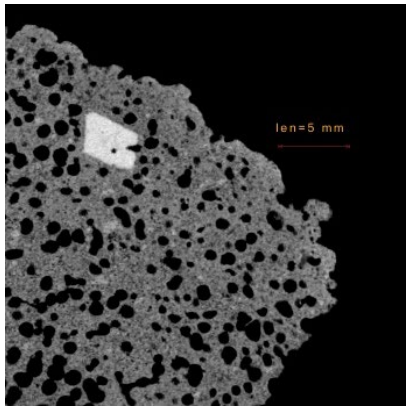
Scientific Analysis and Return Sample Triage

Scientific Analysis and Return Sample Triage

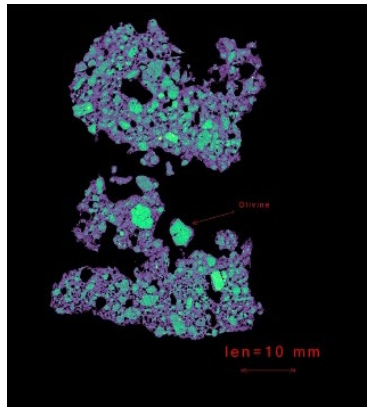
CT put to use for Terrestrial Geology Applications



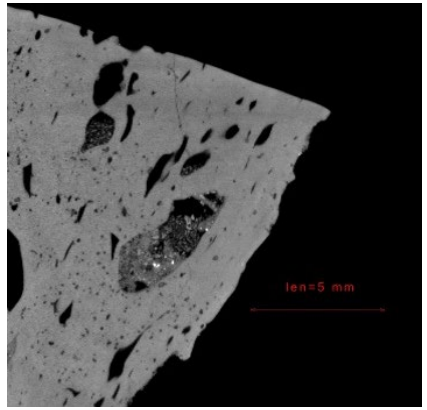
Ultra Mafic Icelandic Basalt



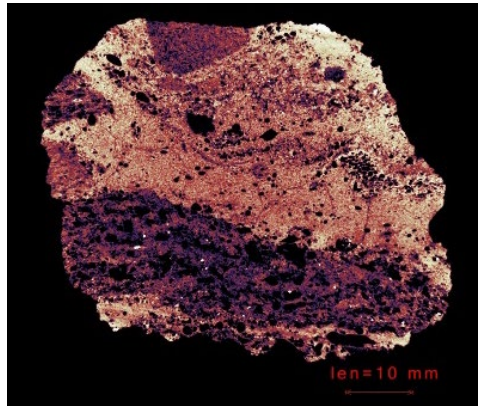
Surtsey Volcanic Basalt



Olivine Basalt

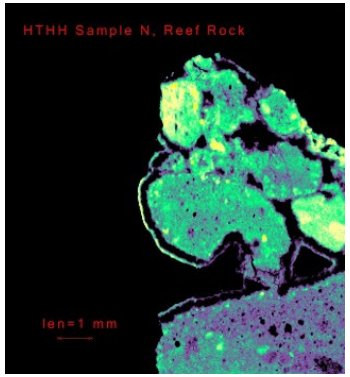


Zhamanshinite Tektite

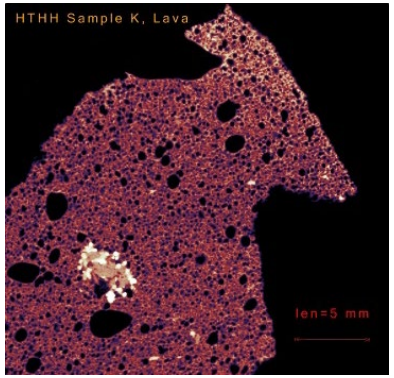


Elgygytgyn Breccia

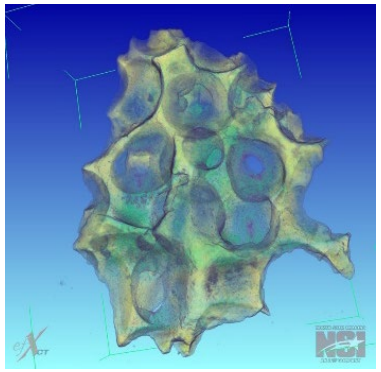
Hunga Tonga Hunga Ha'apai; Newest Landmass on Earth (P.I. J. Garvin)



HTHH_Sample N, Reefrock



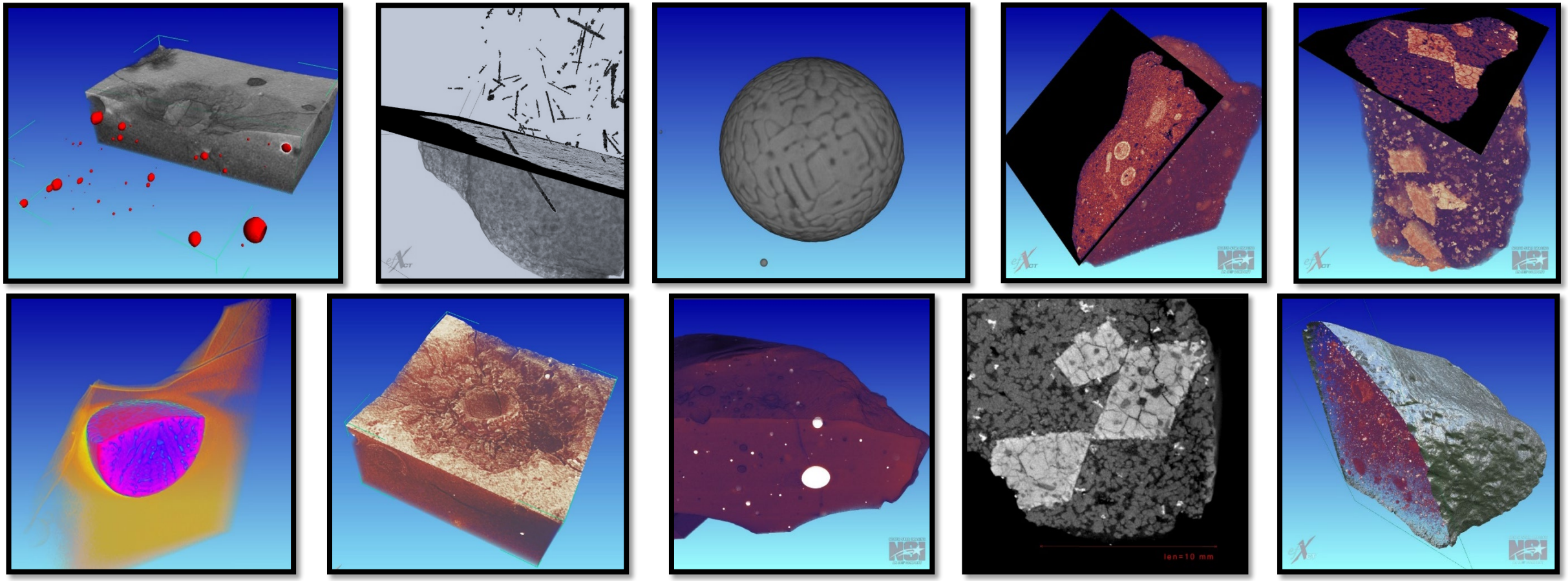
HTHH_Sample K, Lava



HTHH_Sample H, 1Pumice

Scientific Analysis and Return Sample Triage

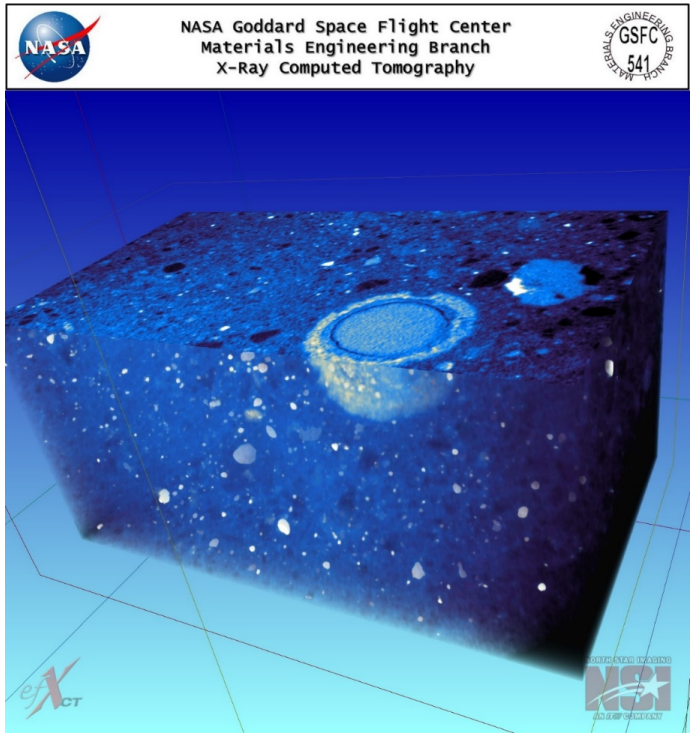
CT for Lunar and Martian Sample Analysis

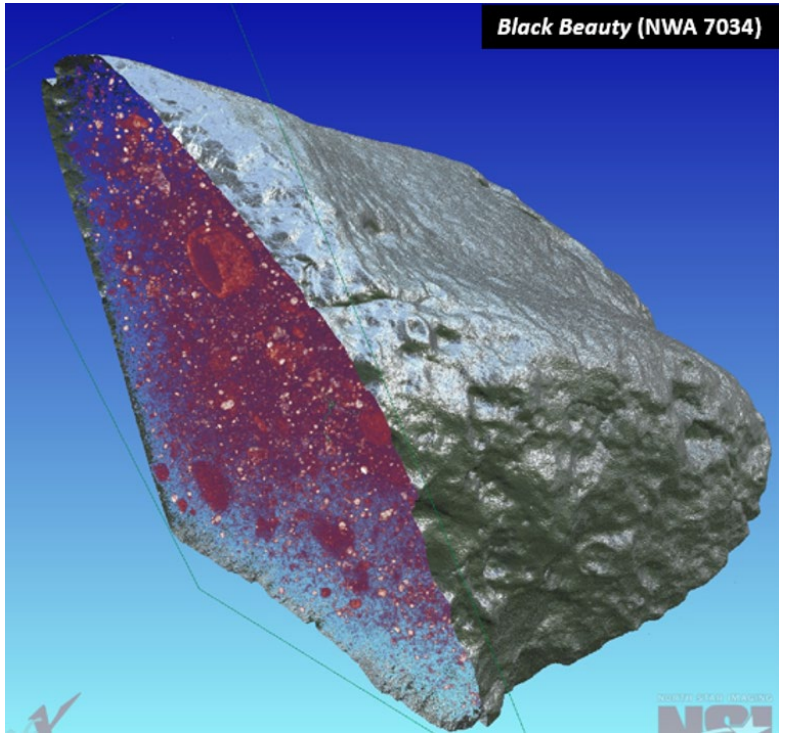


Scientific Analysis and Return Sample Triage

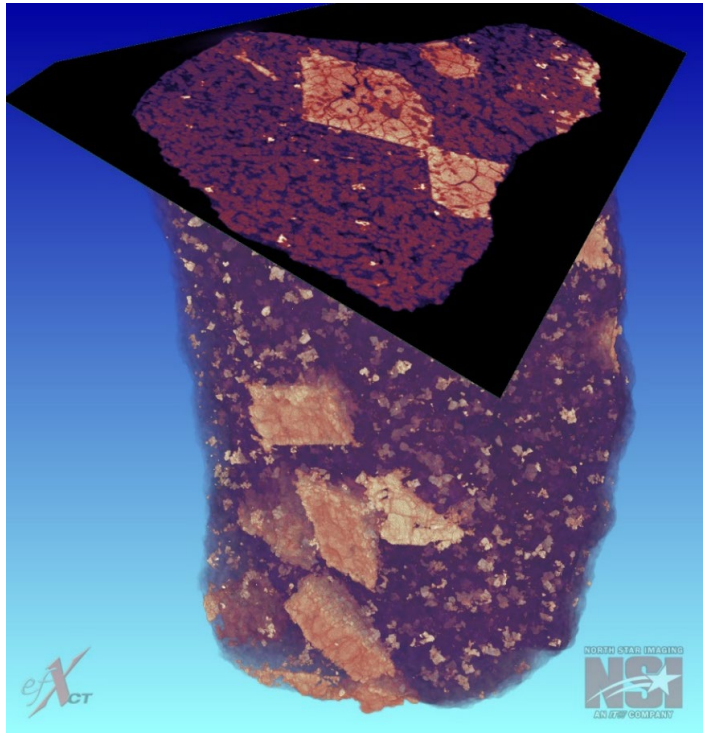
Martian sample analysis showing science-relevant feature identification

Martian meteorites courtesy of the Dr. Jay Piatek Collection





Ultra rare “Black Beauty” Martian meteorite (NWA 7034) showing interior “blueberries” that contain high percent OH-bearing minerals

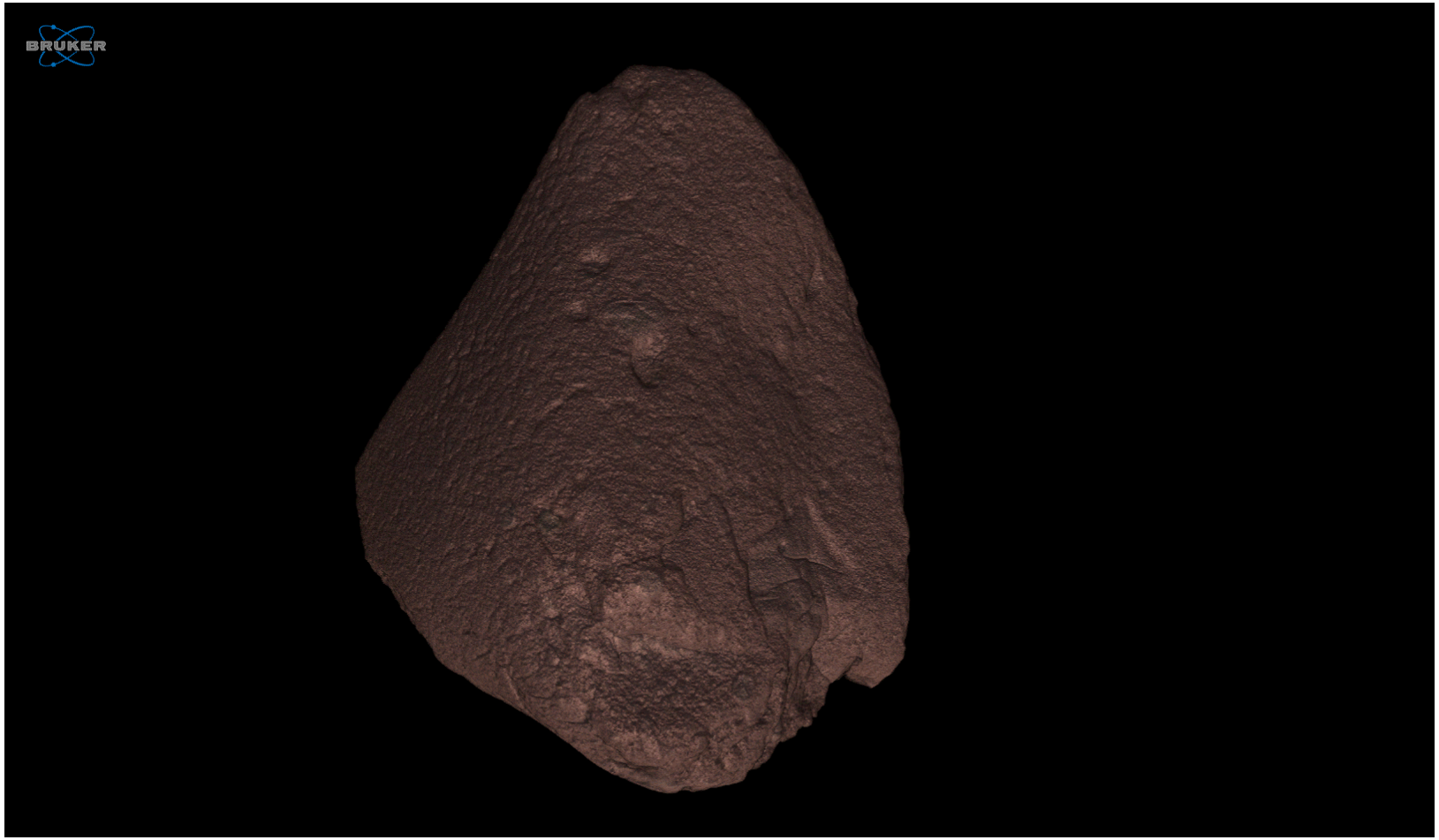


Martian Nakhlite NWA 10153 w/ large interior crystals (not visible outside)

Scientific Analysis and Return Sample Triage

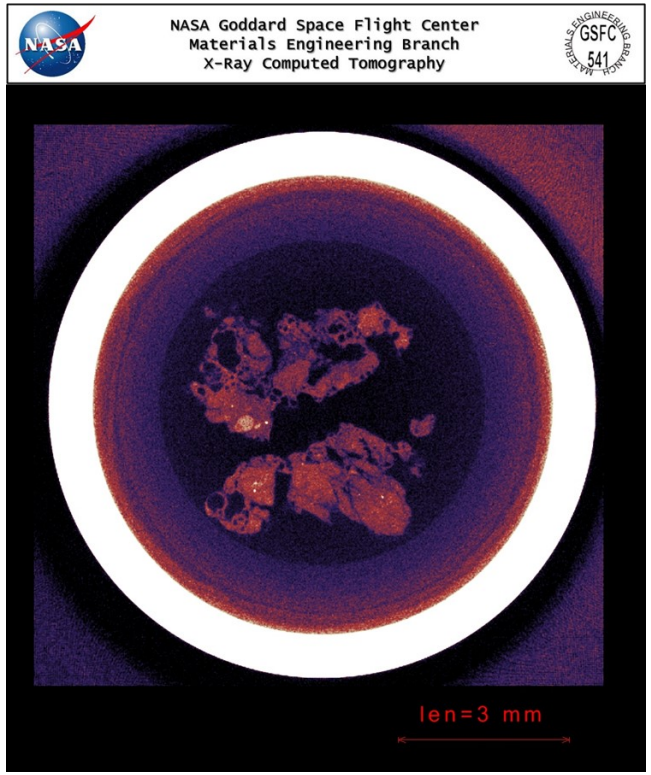
Martian meteorite, the ultra rare “Black Beauty” (NWA 7034) showing interior “blueberries” that contain high percent OH-bearing minerals

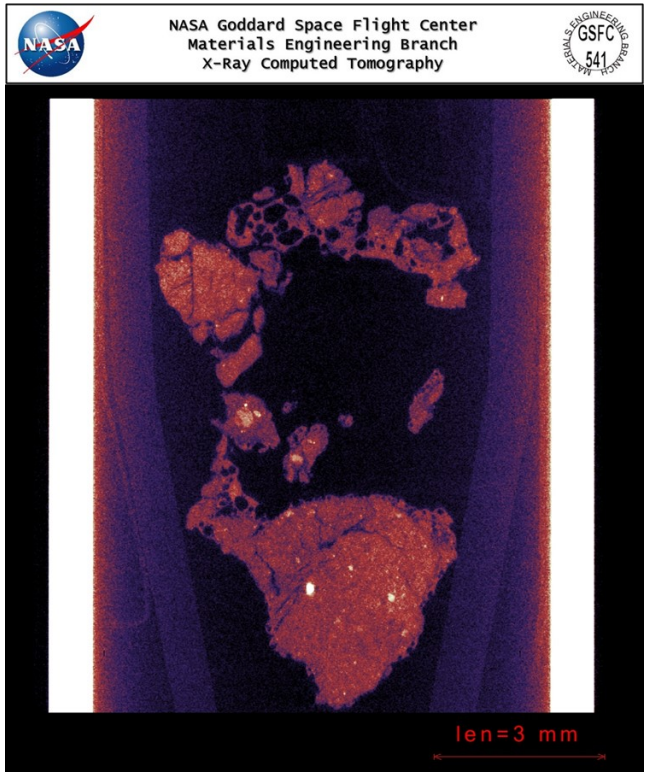
Martian meteorites courtesy of the Dr. Jay Piatek Collection



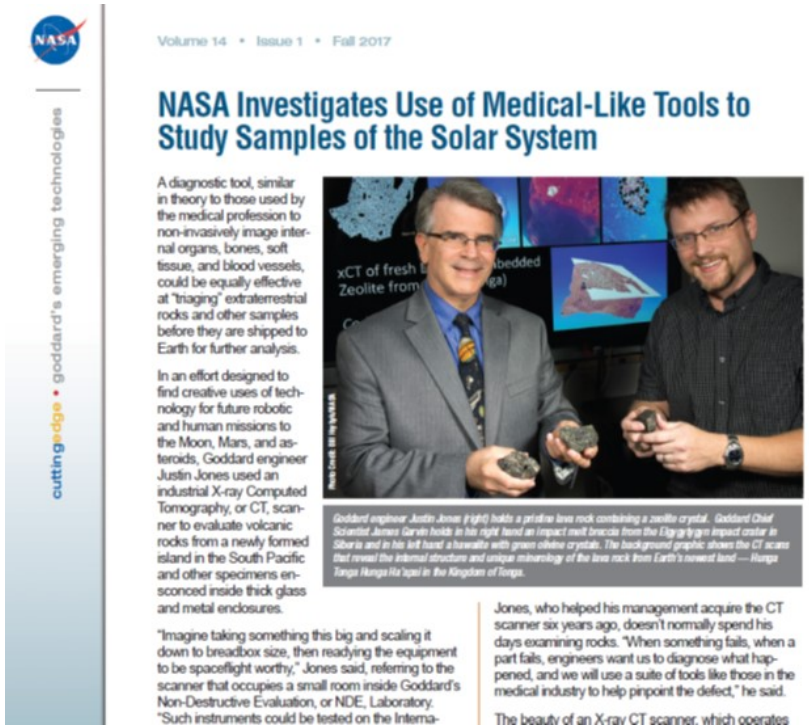
Scientific Analysis and Return Sample Triage

Vital tool for future Sample Return from Moon and Mars





Rare Apollo 16 lunar agglutinates (agglomerated fragments), scanned within a Ti tube to demonstrate non-contact, non-invasive core sample analysis



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cutting-edge • goddard's emerging technologies

NASA Investigates Use of Medical-Like Tools to Study Samples of the Solar System

A diagnostic tool, similar in theory to those used by the medical profession to non-invasively image internal organs, bones, soft tissue, and blood vessels, could be equally effective at "triaging" extraterrestrial rocks and other samples before they are shipped to Earth for further analysis.

In an effort designed to find creative uses of technology for future robotic and human missions to the Moon, Mars, and asteroids, Goddard engineer Justin Jones used an industrial X-ray Computed Tomography, or CT, scanner to evaluate volcanic rocks from a newly formed island in the South Pacific and other specimens ensconced inside thick glass and metal enclosures.

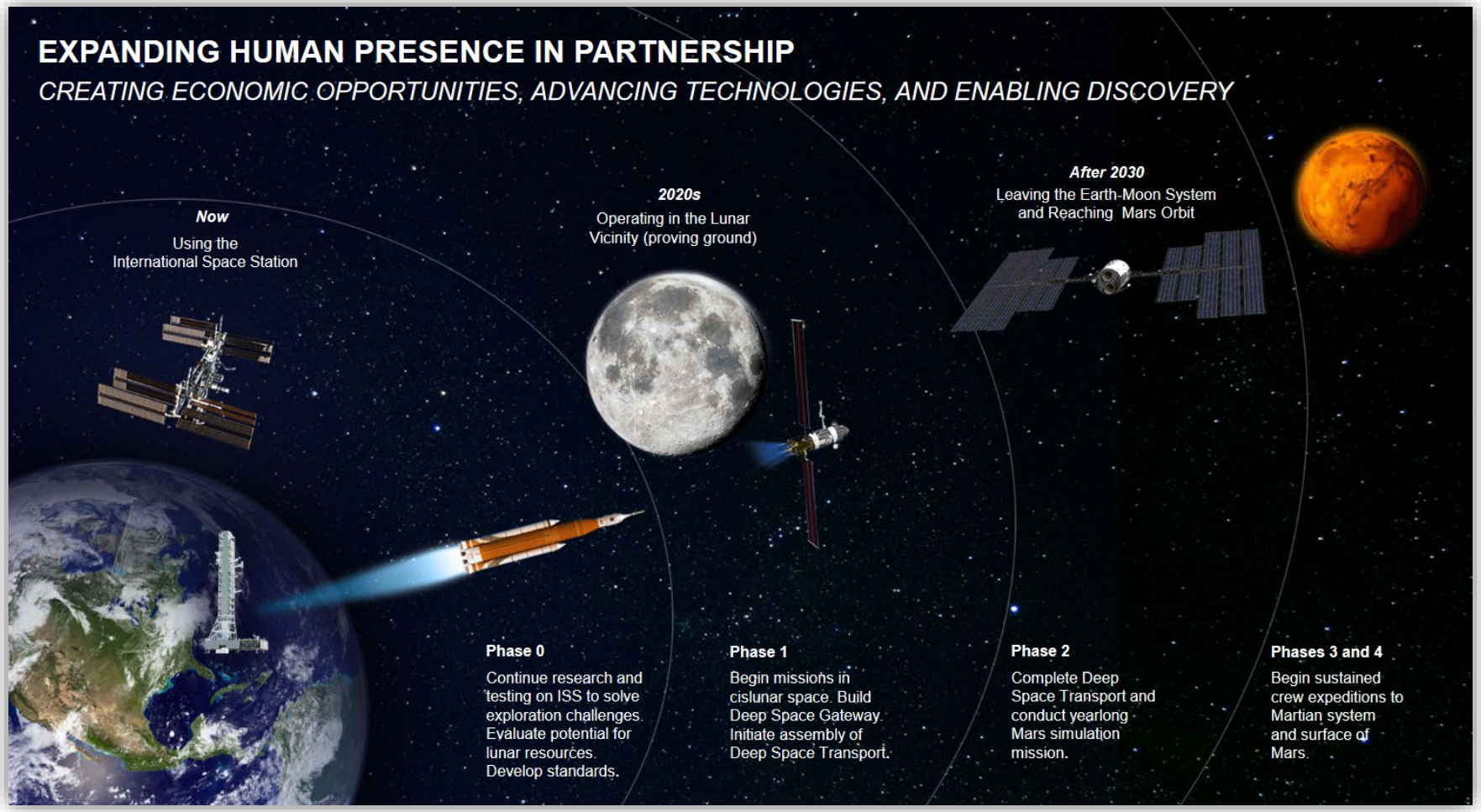
"Imagine taking something this big and scaling it down to breadbox size, then readying the equipment to be spaceflight worthy," Jones said, referring to the scanner that occupies a small room inside Goddard's Non-Destructive Evaluation, or NDE, Laboratory. "Such instruments could be tested on the Interna-

Jones, who helped his management acquire the CT scanner six years ago, doesn't normally spend his days examining rocks. "When something fails, when a part fails, engineers want us to diagnose what happened, and we will use a suite of tools like those in the medical industry to help pinpoint the defect," he said.

The beauty of an X-ray CT scanner, which operates

Opportunities for Investment and Collaboration

Opportunities for Investment and Collaboration

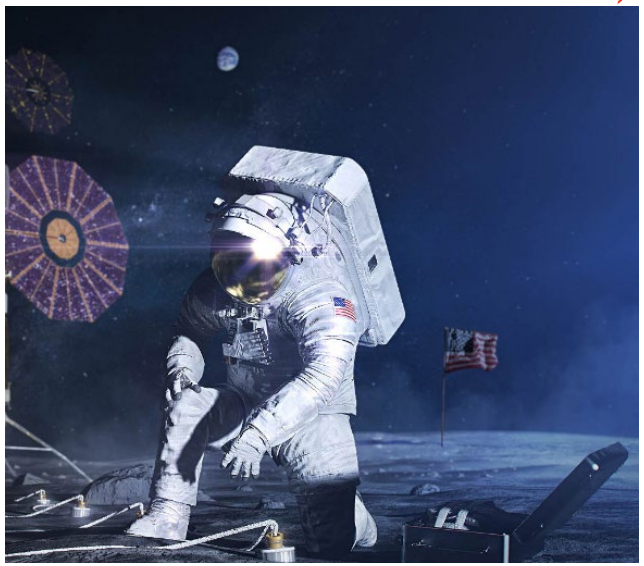


Source: https://www.nasa.gov/sites/default/files/atoms/files/nextstep-2-isru-baa-industry-forum_11dec2017_0.pdf

Opportunities for Investment and Collaboration

***5 Key Beneficiaries** of In-space 3D inspection Capability*

- Engineering Quality Assurance (QA) / Failure Analysis (FA) *(flaws in parts)*
- Human Safety/Mission Assurance *(impact damage, protective gear)*
- Additive Manufacturing and In-Space Manufacturing *(e.g. Made In Space (Redwire), Techshot, FabLab)*
- In-Situ Resource Utilization (ISRU) (resource assessment, drill core analysis)
- Science Initiatives/Return Sample Triage



Extended Pathways for CT in Space Use:

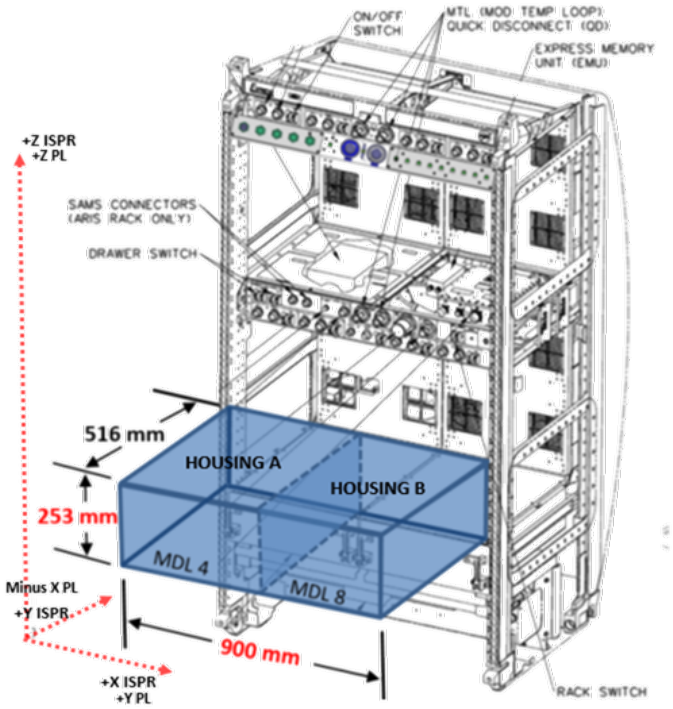
First demonstration (ISS) of xCT in space for NDE of AM samples, planetary samples, and inspection	To the Moon via Gateway or Artemis crewed missions as a critical in situ NDE tool	To Mars for in situ assessment on 2030's mobile labs, in context for drill core sample return	Beyond Moon and Mars is Europa and other ocean worlds	Ultimately, autonomous "commodity style" xCT system with scalable range of applications

Image Source: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

Opportunities for Investment and Collaboration

Recent efforts to assess x-ray CT for operation in a space environment

- 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
- Non-funded partnership agreement with North Star Imaging
- 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



One potential venue for CT in Space could be on an ISS Express Rack (or similar setup on NASA Gateway). Shown above are generic Mid-Deck Locker (MDL) dimensions, representative of the size of such a system (e.g. could be single or double, as shown).

Opportunities for Investment and Collaboration

Relevant links for partnership and funding opportunities

Partnering with NASA

- Partnership Office main page: https://www.nasa.gov/partnerships.html
- Field centers, lines of business and POCs: https://www.nasa.gov/partnerships/contact.html
- Links to key Tech. Development programs: https://www.nasa.gov/partnerships/opportunities.html

Technology Initiatives

- NASA Technology main page and overview: https://technology.nasa.gov/
- NEXT STEP program overview https://www.nasa.gov/content/nextstep-overview
- Technology road-mapping: https://www.nasa.gov/offices/oct/taxonomy/index.html
- Artemis Program Overview: https://www.nasa.gov/specials/artemis/

Funding Opportunities

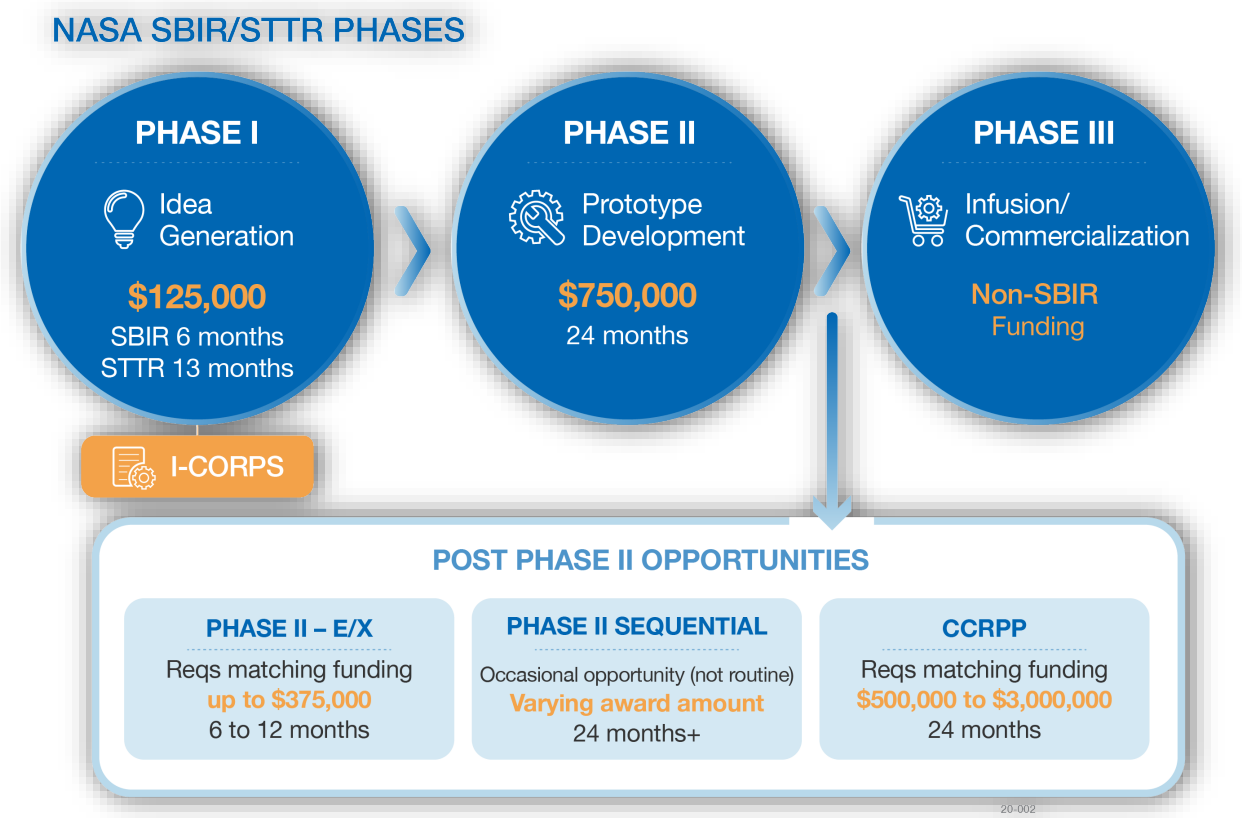
- NASA SBIR and STTR Program (small businesses): https://sbir.gsfc.nasa.gov/
- Open NASA Solicitations and Contracts: https://sam.gov/content/opportunities
  - Formerly FedBizOps, or FBO
- Scientific and Technology Research Funding https://nspires.nasaprs.com/external/
- Space Technology Research Directorate (STMD) Programs: https://www.nasa.gov/directorates/spacetech/solicitations
- STMD Tipping Points program overview: https://www.nasa.gov/directorates/spacetech/solicitations/tipping_points

Neat site for 3D printing and models!

- https://nasa3d.arc.nasa.gov/

Opportunities for Investment and Collaboration

Quick overview of the NASA SBIR/STTR Program



https://sbir.nasa.gov/content/nasa-sbirsttr-basics

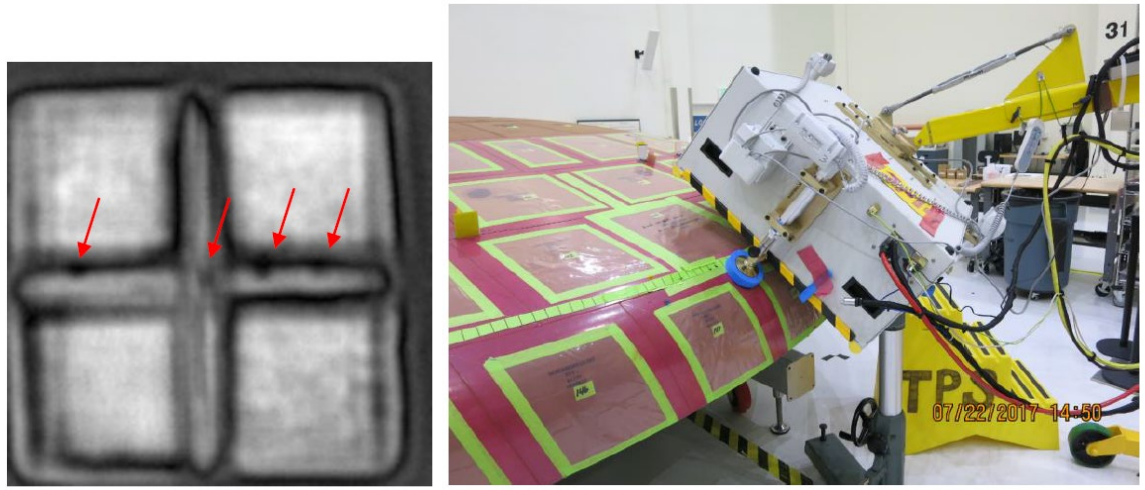
- Phase I: *"NASA receives approximately 1,500 high-quality proposals that go through a rigorous process to ultimately select approximately 400 Phase I proposals for awards across the agency."* https://partnerships.gsfc.nasa.gov/external-partners/pursue-rd-opportunities/

- Phase II: (2021 Year): *"The NASA Small Business Innovation Research (SBIR) Program has selected 140 proposals for follow-on Phase II funding. The awards will provide approximately $105 million to 127 small businesses located across 34 states and Washington, D.C"* https://sbir.nasa.gov/

Opportunities for Investment and Collaboration

SBIR Program: NDE Subtopic (Z4.05, number may not be same next year)

- 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 I and II awards and participated in an additional 37 awards from other subtopics, for a total of 105 awards.
  - NASA technical experts are the reviewers for all the proposals and generally take 2-3 months to complete the review process.
  - Several awards have funded prototypes that are currently deployed to help Artemis and other programs achieve their goals.
- **SBIR/STTR call for proposals is a great place to learn what "NDE Tools" are needed by NASA, as well as what sort of materials challenges are currently relevant**



Physical Optics Corp (POC), 3D backscatter unit (single-sided CT) deployed to KSC to preform thermal protection system gap inspection. This SBIR 3D system is still deployed at KSC.

Questions/Discussion

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- Army Research Lab NDE Group (J. Sietins, W. Green, T. Walter, J. Sun)
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- Goddard Fellows Innovative Challenge (GFIC)
- NASA Engineering and Safety Center (NESC)
- Key Individuals: W. Prosser/NASA NESC, E. Burke/OSMA NDE, G. Studor/NASA NESC-ret.
- NASA CAPTEM, Lunar Return Samples
- Drs. Jay Piatek, C. Agee and the J. Piatek Meteorite Collection
- GSFC Materials Engineering Branch
- GSFC Instrument Development Lab (IDL)
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- GSFC Interns and Early Careers: S. Santoro, O. Denonno, A. Watson-Jones, J. Harwerth, T. Leibengood