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.

Justin S. Jones, Ph.D.
GSFC NDE Lead and Subject Matter Expert
Materials Engineering Branch
NASA Goddard Space Flight Center
justin.s.jones@nasa.gov

Co-Authors: James Garvin, Ph.D./GSFC, Eric Burke/HQ, Jennifer Sietins, Ph.D./ARL, Erin Lanigan/MSFC

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
  • Engineering Quality Assurance (QA) / Failure Analysis (FA)
  • 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

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
Brief Intro to NASA Goddard

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

Goddard Lines of Business:

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

- 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

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)
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)
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**
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.

**Total Sample Set**

<table>
<thead>
<tr>
<th>Variable 1</th>
<th>Variable 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build Orientation 45° from the Horizontal</td>
<td>Surface Roughness Machined</td>
</tr>
<tr>
<td>Build Orientation Horizontal</td>
<td>Surface Roughness Machined</td>
</tr>
<tr>
<td>Build Orientation Vertical Rotated 90°</td>
<td>Surface Roughness Machined</td>
</tr>
<tr>
<td>Build Orientation Vertical</td>
<td>Surface Roughness Machined</td>
</tr>
<tr>
<td>Build Orientation Vertical</td>
<td>Surface Roughness Vendor Standard</td>
</tr>
<tr>
<td>Build Orientation Vertical</td>
<td>Surface Roughness Fine Media Blasted</td>
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</tbody>
</table>
Additive Manufacturing, Qualification/Certification

Towards NDE Certification for Additive Manufacturing...

<table>
<thead>
<tr>
<th>Current Standard Viable Methods</th>
<th>Issues for Standard Viable Techniques</th>
<th>Improvement and Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computed Tomography &amp; Radiography (current &quot;gold standard&quot; method)</td>
<td>Time Prohibitive</td>
<td>Improved process algorithms, ADR and ML techniques</td>
</tr>
<tr>
<td>Qualification of CT Systems</td>
<td>Ionizing Radiation</td>
<td>Adaptive shielding, advanced materials</td>
</tr>
<tr>
<td></td>
<td>Quality of CT Systems</td>
<td>IQI based Certification CR and DR systems</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Internal Structure Beam Steering</td>
<td>Use of beam correction algorithms</td>
</tr>
<tr>
<td></td>
<td>Complex Beam Paths due to geometry</td>
<td>High fidelity modeling for sound placement</td>
</tr>
<tr>
<td>Eddy Current</td>
<td>Surface texture</td>
<td>Spec finished parts for inspection</td>
</tr>
<tr>
<td></td>
<td>Depth of Penetration</td>
<td>Articulated scanning techniques for better access</td>
</tr>
<tr>
<td>Penetrant</td>
<td>Surface Only</td>
<td>Hybrid approaches for inaccessible regions (e.g. CT w/ tracer particles)</td>
</tr>
<tr>
<td></td>
<td>Contamination</td>
<td>Improved approaches and protective measures</td>
</tr>
</tbody>
</table>

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

- These new standards provide a policy framework for the development and production of hardware produced using AM processes.

**NASA-STD-6016B**
General M&P requirements

**NASA-STD-6030**
New NASA Technical Standard
Additive Manufacturing Requirements for Spaceflight Systems

**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-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…”

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

<table>
<thead>
<tr>
<th>Primary Classification</th>
<th>AM Risk</th>
<th>Structural Demand</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Secondary Classification</th>
<th>AM Risk</th>
<th>Structural Demand</th>
<th>Negligible Risk?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A1</td>
<td>High</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Class A2</td>
<td>Low</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>Class A3</td>
<td>Low</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>Class A4</td>
<td>Low</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>Class B1</td>
<td>High</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Class B2</td>
<td>Low</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>Class B3</td>
<td>Low</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>Class B4</td>
<td>Low</td>
<td>High</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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**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)

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](https://www.nasa.gov/isru/overview) and [https://www.nasa.gov/nextstep/isru](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.
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)

[Image: 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, Reef Rock
HTHH_Sample K, Lava
HTHH_Sample H, 1Pumice
Scientific Analysis and Return Sample Triage

*CT for Lunar and Martian Sample Analysis*
Ultra rare “Black Beauty” Martian meteorite (NWA 7034) showing interior “blueberries” that contain high percent OH-bearing minerals

Martian Nakhliite NWA 10153 w/ large interior crystals (not visible outside)
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.
Opportunities for Investment and Collaboration
Opportunities for Investment and Collaboration

EXPANDING HUMAN PRESENCE IN PARTNERSHIP
CREATING ECONOMIC OPPORTUNITIES, ADVANCING TECHNOLOGIES, AND ENABLING DISCOVERY

New
Using the International Space Station

2020s
Operating in the Lunar Vicinity (growing ground)

After 2030
Leaving the Earth-Moon System and Reaching Mars Orbit

Phase 0
Continue research and testing on ISS to solve exploration challenges. Evaluate potential for lunar resources. Develop standards.

Phase 1

Phase 2
Complete Deep Space Transport and conduct yearlong Mars simulation mission.

Phases 3 and 4
Begin sustained crew expeditions to Mars and surface of Mars.

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

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/
Quick overview of the NASA SBIR/STTR Program

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.
- For more information, visit: 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.
- For more information, visit: https://sbir.nasa.gov/

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

Acknowledgments:

• Army Research Lab NDE Group (J. Sietins, W. Green, T. Walter, J. Sun)
• NASA MSFC, In-Space Manufacturing Group
• NASA Center Innovation Fund (CIF)
• NASA Office of Safety and Mission Assurance NDE Program (OSMA NDE)
• 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)
• CT In Space Concept Team: R. Kent, N. Smith, S. Thorn, S. Kenyon
• GSFC Interns and Early Careers: S. Santoro, O. Denonno, A. Watson-Jones, J. Harwerth, T. Leibengood