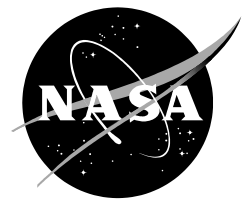


NASA/TM—2014—218560



# **Nondestructive Evaluation of Additive Manufacturing State-of-the-Discipline Report**

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**November 2014**

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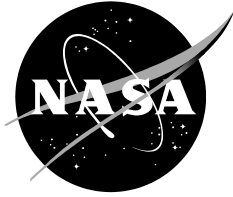
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**November 2014**

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## Acronyms

3D	Three dimensional	JPL	Jet Propulsion Laboratory
ABS	Acrylonitrile-butadiene-styrene	JSC	Johnson Space Center
ADO	Advanced Development Office	KSC	Kennedy Space Center
AFRC	Armstrong Flight Research Center	LAMP	Laser aided manufacturing process
AFRL	U.S. Air Force Research Laboratory	LaRC	Langley Research Center
AM	Additive manufacturing	LCUS	Low Cost Upper Stage
AMAZE	Additive Manufacturing Aiming Towards Zero Waste and Efficient Production	LENS	Laser engineered net-shaping
ARC	Ames Research Center	LS	Laser sintering
ASTM	American Society of Testing and Materials	MSFC	Marshall Space Flight Center
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer	MT	Magnetic particle testing
AWS	American Welding Society	NAMII	National Additive Manufacturing Innovation Institute (America Makes)
COSMIAC	Configurable Space Microsystems Innovations and Applications Center	NDE	Nondestructive evaluation
CT	Computed tomography	NIAC	NASA Institute for Advanced Concepts
CTE	Coefficient of thermal expansion	NIR	Near infrared
DMLS	Direct metal laser sintering	NIST	National Institute of Science and Technology
DoD	Department of Defense	NNWG	NASA NDE Working Group
EB	Electron beam	NRC	National Research Council
EBF <sup>3</sup>	Electron-beam freeform fabrication	OCT	NASA Office of the Chief Technologist
EBM	Electron beam melting	OEM	Original equipment manufacturer
ESA	European Space Agency	ORNL	Oak Ridge National Laboratory
ET	Eddy current testing	OSMA	Office of Safety and Mission Assurance
EUS	Exploration Upper Stage	PAUT	Phased array ultrasonic testing
FTIR	Fourier transform infrared spectroscopy	PEKK	poly(ether ketone ketone)
GH2/LOX	Gaseous hydrogen/liquid oxygen	PMC	Polymer matrix composite
GRC	Glenn Research Center	PT	Penetrant testing
GRCop-84	Glenn Research Copper 84	RT	Radiologic testing
GSFC	Goddard Space Flight Center	SAE	Society of Aerospace Engineers
HIP	Hot isostatic pressing	SBIR	Small Business Independent Research
HQ	Headquarters	SERS	Surface enhanced Raman spectrometry
IRAD	Internal Research and Development	SLM	Selective laser melting
ISO	International Standardization Organization	SLS	Space Launch System
ISRU	In-Source Resource Utilization	SSTP	Small Spacecraft Technology Program
ISS	International Space Station	STMD	Space Technology Mission Directorate
		TM	Technical Memorandum
		TRL	Technology readiness level

TTCP	The Technical Cooperation Program	WSTF	White Sands Test Facility
UT	Ultrasonic testing		
VCO	Voluntary consensus organization		

## Executive Summary

Given NASA's unique needs for highly customized spacecraft and instrument components, additive manufacturing (AM), or 'three-dimensional (3D) printing,' offers a compelling alternative to more traditional manufacturing approaches. NASA's work in AM should enable it to save time, expense, and mass. NASA also has an opportunity to push the envelope on how this technology is used both terrestrially and in zero gravity, and how manufacturing in space will ultimately occur. This Technical Memorandum (TM) presents current work being done both in and outside of NASA on AM, with a focus on nondestructive testing (NDE) of additively manufactured parts. Other AM disciplines not related to NDE are also highlighted in this Technical Memorandum (TM) for reference; however, this TM does not necessarily reflect or make recommendations for the current state-of-the-art for non-NDE disciplines .

While NASA is not leading the national AM effort, it is leveraging associated technology developed internally and externally for its unique needs. Plenary meetings and workshops attended by industry, academia, and government interests, including NASA, have identified NDE as a pervasive need for all aspects of AM. The impact of NDE on AM is crosscutting and spans materials, processing, quality assurance, testing, and modeling disciplines. Simply put, NDE techniques are needed before, during, and after the AM production process.

This Memorandum highlights NASA's AM accomplishments-to-date, first outlining the relevance of the AM effort to the NASA Office of the Chief Technologist, the NASA Space Technology Mission Directorate, the Space Launch System and Orion programs, and to NASA's commercial space partners. The role the NASA NDE Working Group (NNWG) will play in integrating NDE into NASA's AM effort is also discussed. Next, technology gaps impeding widespread adoption of AM by NASA are identified. Gaps are differentiated along lines of materials, process and equipment, consensus standards, and modeling and simulation, to focus effort according to specific technical discipline areas. Special attention is given to technology gaps in AM bridged by NDE. Both traditional and novel NDE approaches are discussed, and the inherent limitations and advantages of each. Based on this gap analysis, a series of recommendations are presented at the end of the document. Included are general recommendations to help unify the NASA's AM effort across participating centers, and more specific NDE recommendations to focus NDE efforts. The latter recommendations are intended to guide Agency investments in NDE for AM and to insure the NNWG is properly positioned to support the use of additively manufactured parts in its ground and flight applications.

The major gaps and recommendations identified in this Memorandum are as follows:

- Lack of NDE and design allowables data specific to AM
  - Fabricate physical reference standards to verify and validate NDE data
  - Augment current NDE dataset to increase agency experience and knowledge
  - Apply NDE to understand feedstock-process scatter in design allowables data generation activities
- Low maturity finished part NDE
  - Apply NDE to understand effect-of-defect and establish acceptance limits
  - Correlate process and destructive test data with NDE and develop process-property recommendations
- Lack of *in situ* process monitoring
  - Implement NDE in closed-loop process control to maximize part quality and consistency, and obtain ready-for-use certified parts directly after processing
  - Develop better physics-based process models corroborated by NDE
  - Use NDE to validate and confirm the effectiveness of post-processing
- Lack of Standards for NDE as applied to AM
  - Develop NDE-based qualification and certification protocols for flight hardware
  - Standardize NDE build records to serve as a permanent quality record
  - NDE qualification of feedstock before build

# 1.0 Introduction

## 1.1 Background and Scope

This NASA Technical Memorandum (TM) briefly discusses the technical challenges and gaps associated with the fabrication of uniform and consistent additively manufactured parts and the certification and qualification of the parts. More specifically, this NASA TM addresses the nondestructive evaluation (NDE) methods that will play a crucial role in the verification of additively manufactured hardware having predictable and controlled properties.

Additive manufacturing (AM) has been around since 1987, with the introduction of stereolithography from [3D Systems, Inc.](#) (Wohlers 2011). Additive manufacturing is the process of making three-dimensional (3D) objects (virtually any shape) from a digital model, and is achieved using an additive process where successive layers of material are laid down to form different shapes. It is different from conventional machining methods, which rely on the removal of material by methods such as cutting or drilling, which are subtractive processes. Additive manufacturing has traditionally been viewed as a tool for rapid prototyping, but in recent years it has taken a substantial shift to the possibility of manufacturing high-quality complex metallic parts for infusion into primary structural hardware. The use of AM has great potential for producing high-value, complex, and individually customized parts, and could revolutionize manufacturing of aerospace parts by enabling novel 'design to constraint' products that could not be fabricated using conventional processes, by reducing waste (green manufacturing), by eliminating reliance on original equipment manufacturers (OEMs) for critical spares, and by extending the life of in-service parts through innovative repair methodologies (Harris 2011; NIST 2013a).

NASA is currently using AM methods to fabricate complex components that are either cost-prohibitive or, in some cases, impossible to fabricate using more traditional fabrication methods. The spaceflight certification and validation of these components by NDE is a high priority; however, no Agency-coordinated multidisciplinary effort currently exists to validate, certify, or qualify these parts made by AM processes.

The path to the qualification and verification of parts made by AM is a universal concern echoed throughout government, industry and academia. Industry adoption of parts made by AM is slow because of ambiguity in current validation and verification approaches, which are intimately tied to NDE capability. A key barrier for AM processes and equipment is that existing NDE methods and techniques are not optimized for AM processes, materials, or parts. Techniques are either non-existent or lacking for *in situ* process NDE, and post-process NDE of finished parts made by AM using conventional NDE techniques is challenging or still emerging (NIST 2013a).

Nondestructive evaluation challenges are crosscutting and span materials, fabrication, quality assurance, testing, and modeling disciplines. Accordingly, NDE represents a pervasive need for AM and impacts all aspects from design and materials, through part build, and on to inspection and certification. The time and cost to develop NDE methods is an ongoing concern, particularly when keeping up with rapidly shifting or emerging AM technologies. However, NDE is versatile and uniquely poised to accelerate broader and more effective use of AM by NASA. NASA applications impacted by integration of NDE into NASA's AM enterprises range from alleviating spares issues due to OEM obsolescence, to certification of flight hardware, to developing safer and more robust systems for space colonization and long duration space flights.

While this TM covers AM parts made from metals, polymers, ceramics and synbio<sup>1</sup> materials using a variety of processes, most of discussion will focus on titanium and nickel alloys formed by electron beam (EB) and laser sintering (LS) AM techniques.

## **1.2 NASA Additive Manufacturing Effort**

### ***Highlights of NASA's Additive Manufacturing Work-to-Date***

Nearly all NASA Centers are engaged in AM, whether in terms of past or future effort. Summaries of AM efforts-to-date at each Center are given below. In some cases, activities in different NASA programs overlap, illustrating the crosscutting nature of some priorities and gaps.

The Advanced Manufacturing Strategic Technology Development Project, which involves multiple centers and discipline areas, represents NASA on the National Advanced Manufacturing Initiative Committee (NRC 2014). The NASA Space Technology Mission Directorate (STMD) involvement and interests cross all Technology Readiness Levels (TRLs), from low-TRL activities, including the Materials Genome Initiative, the NASA Institute for Advanced Concepts (NIAC), research fellows, and Small Business Independent Research (SBIR) projects, to higher-TRL technology development and demonstration projects. Examples include the NIAC Printed Electronics Project at NASA Jet Propulsion Laboratory (JPL), the Small Spacecraft Technology Program (SSTP) Printable Spacecraft Project by the Configurable Space Microsystems Innovations and Applications Center (COSMIAC) at the University of New Mexico in collaboration with the University of Texas at El Paso, and the Made In Space Technology Demonstration project at Marshall Space Flight Center (MSFC) and Ames Research Center (ARC). For the AM of metals, technology development and demonstration efforts are being conducted primarily at MSFC, Langley Research Center (LaRC), and Glenn Research Center (GRC). The NASA Additive Manufacturing Working Group consists of participants from the engineering and technology services and products from all Centers. Despite the existence of this working group, the committee learned that AM researchers at different Centers were not fully aware of work going on at other Centers and determined that better Agency coordination and communication is needed.

### ***Relevance to the NASA Office of the Chief Technologist***

The space technology roadmaps developed by the NASA Office of the Chief Technologist (OCT) highlight 14 critical technology areas (TA01 through TA14) (NASA 2013). The roadmaps target timelines where technology development is needed to enable space exploration, and one of those (TA12, Materials, Structures, Mechanical Systems and Manufacturing) specifically discusses advanced manufacturing, including AM. NASA's strategy for AM can be summarized as migration of capabilities from terrestrial AM capabilities to using the International Space Station (ISS) for development and demonstration of space-based AM, and finally migration of AM capabilities to planetary surface platforms (NRC 2014). Development of NDE as applied to AM will follow a similar strategy.

### ***NASA Nondestructive Working Group Role***

The NASA Office of Safety and Mission Assurance (OSMA)-sponsored NASA NDE Working Group (NNWG) has recommended strengthening inter-Agency communication and collaboration within the NASA AM community by reaching out to center-specific organizations that are either directly or peripherally involved in the procurement, design, fabrication, materials

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<sup>1</sup> Synbio, or synthetic biology, is the design and wholesale construction of new biological parts and systems; and the re-design of existing, natural biological systems for tailored purposes by integrating engineering and computer-assisted design approaches with biological research.

characterization, testing, and inspection of AM hardware. A balanced and diverse set of NDE activities in research and applications to AM are being pursued. The role of the NNWG in this report is to identify AM technology gaps and where best to apply resources to close the gaps. As part of OSMA, the NNWG's role specific to NDE of AM may be stated as follows:

- Establish and assure compliance of AM with NASA OSMA strategies, policies, and standards
- Improve NDE methodologies as applied to AM for risk identification and assessment, and provide recommendations for risk mitigation and acceptance
- Provide NDE analysis and recommendations specific to AM for critical Agency safety decisions
- Sponsor the innovation and rapid transfer of NDE methods applied to AM technologies, processes, and techniques to improve safety and reliability and reduce the cost of mission success

### ***NASA Space Technology and Mission Directorate Role***

The STMD is striving to invest in AM as one of several tools to manufacture components for complex ground equipment and the next generation additive tools that may one day be used to manufacture in space. The investment strategy is focused on exploring pathfinders in-house as well as working with industry to optimize and scale up processes and products that NASA will need for its missions.

Recent STMD investments in AM include a funded collaboration between GRC and [Aerojet Rocketdyne](#) to explore the fabrication and hot fire testing of AM engine components, specifically RL-10 injectors and thrust chamber assembly using Inconel 625 (injector) and copper (thrust chamber assembly); a collaboration between MSFC, GRC, and LaRC to use Glenn Research Copper 84 (GRCop-84<sup>1</sup>) in a selective laser melting (SLM) and electron-beam freeform fabrication (EBF<sup>3</sup>) process to fabricate higher thrust engine systems (Low Cost Upper Stage (LCUS) effort); Materials Genome Initiative effort to develop an intercenter effort including computational, experimental, and processing expertise; and support for the shared ISS 3D Printing in Zero-G effort. Each effort shares in innovative firsts — from design innovation, to use of two AM processes on one part, to the first demonstration of AM in a micro-gravity environment. Also, STMD has invested in the use of AM to fabricate cubesats, and in lower TRL activities such as using AM to manufacture structures using regolith for scenarios such as heat shields and landing pads.

With AM and the ability to fabricate parts with complex geometries comes the need to properly inspect these parts. Within the STMD's funded Materials Genome Initiative effort, test samples are being evaluated at the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source to help understand material properties with greater sensitivity and higher resolution. In addition, within the LCUS effort conventional tools such as visual inspection, computed tomography (CT), and structured light scanning will be used to inspect the parts. For traditional manufacturing processes, parts could be inspected during the build; however, AM does not allow for inspection during build since a single piece is being fabricated. To overcome this obstacle, engineers at MSFC are working with the LCUS team to develop a method that would enable inspection during the build, to allow for real-time inspection to identify material flaws (impurities, voids, etc.). Although the development of these techniques is years away, there is an immediate need to accelerate their development.

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<sup>1</sup> GRCop-84 is a high-temperature copper alloy for high-heat-flux applications. It possesses excellent high-temperature strength, creep resistance and low-cycle fatigue up to 700 °C (1292 °F) along with low thermal expansion and good conductivity.

## **Relevance to the NASA Space Launch System**

To meet future 70- and 130-metric ton heavy-lift Space Launch System (SLS) needs, the MSFC Advanced Development Office (ADO) is pursuing advanced manufacturing strategies, including AM (Higginbotham 2014). Specific AM-related SLS ADO tasks include:

- Characterization of SLM materials for SLS engine components
- SLM integral valve/injector - valve proposal
- SLM integral valve/injector - injector proposal
- SLM integral valve/injector integrated hot-fire testing
- Hot-fire test of liquid oxygen and hydrogen additively manufactured SLM integral valve/injector applicable to the Exploration Upper Stage (EUS)
- Testing of additively manufactured turbomachinery hardware sized for the EUS
- Inconel 625 and Ti-6Al-4V material properties development
- CT sensitivity verification for SLM SLS engine components
- Real time infrared inspection of AM processes

The last effort, notably, applies NDE (infrared inspection) during the NDE process, and is synergistic with America Makes and NASA LaRC activities covered in this Memorandum. In cases where NDE is not called out, NDE still has relevance. For example, one of the key technology development areas for AM is to develop design allowables databases incorporating knowledge of 1) input materials; 2) process (EB, LS, etc.); and 3) test data (destructive and NDE) (Martukanitz 2014; NIST 2013a). Such design allowables databases are predicated on developing concise process-property recommendations, which in turn rely on optimized processes that have been validated using destructive and NDE test data. Therefore, it is conceivable NDE could play a vital role in NASA projects such as the MSFC ADO Inconel 625 and Ti-6Al-4V material properties development task. Inconel 625 and Ti-6Al-4V parts made by the SLM process at MSFC (Figure 1) have been made under a range of process conditions by varying laser wattage, laser speed, and laser hatch spacing; and the properties have thus far been evaluated destructively (hardness, tensile). Use of NDE could further facilitate process optimization and generation of design allowables databases for NASA parts made by AM.



(Photographs courtesy of MSFC)

Figure 1

Selective laser melting equipment (left) and test specimens (right) used in the Marshall Space Flight Center Inconel 625 and Ti-6Al-4V material properties development task.

### ***Relevance to the NASA Orion Program***

The Orion Project has inquired about AM, but it has not been adopted due to the low TRL of AM materials and processes and corresponding NDE. The Orion vehicle has a large titanium structure where near-net-shape AM pre-forms could possibly save significant material and machining costs. Additionally, it is envisioned that AM could be useful for complex life support and structural components.

### ***Relevance to Commercial Space Partners***

NASA's commercial space partners are pursuing opportunities to incorporate AM flight hardware into their spacecraft systems. The benefits of creating AM components for load path optimization, reduced weight, and improved performance are key metrics that make AM an attractive alternative to conventionally manufactured flight hardware. At this time, limited details are available for internal NASA dissemination; however, it is assumed that our commercial partners are encountering materials and NDE-related qualification and certification issues similar to NASA.

Recently, [SpaceX](#) unveiled the Dragon V2, its first manned spacecraft (Figure 2; SpaceX 2014). The Dragon V2 engines, referred to as SuperDraco engines, are more than 160 times more powerful than the Draco engines found in the current version of Dragon, allowing them to produce 16,400 lb<sub>f</sub> thrust. In a departure from the norm, their combustion chambers are 3D-printed using direct metal laser sintering (DMLS).

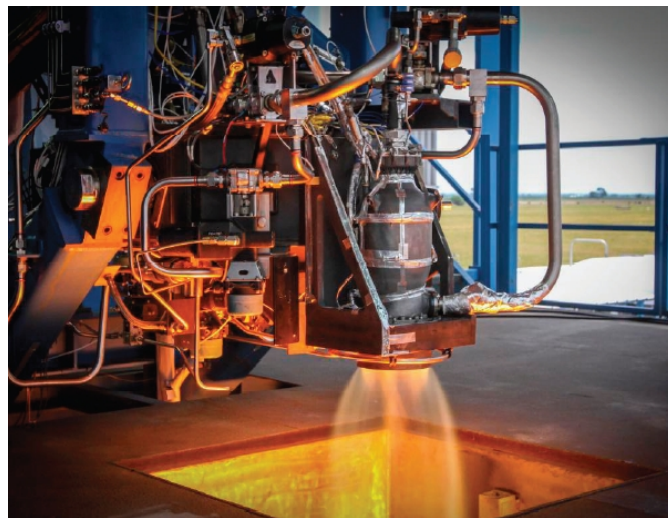


Figure 2

Test of a SuperDraco rocket engine at full power using an additively manufactured Inconel thrust chamber (NRC 2014).

### ***Armstrong Flight Research Center***

The Armstrong Flight Research Center (AFRC) has three AM systems that produce nonstructural plastic acrylonitrile-butadiene-styrene (ABS) parts. Uses-to-date have been commonsensical and non-critical. Examples include fit checks, rapid prototyping/proof-of-concept, and fabrication of unmanned system parts (autopilot mount, data cube enclosure, dead-man mount, and an air cleaner boss). Also, water tunnel parts have been made for ground support equipment.



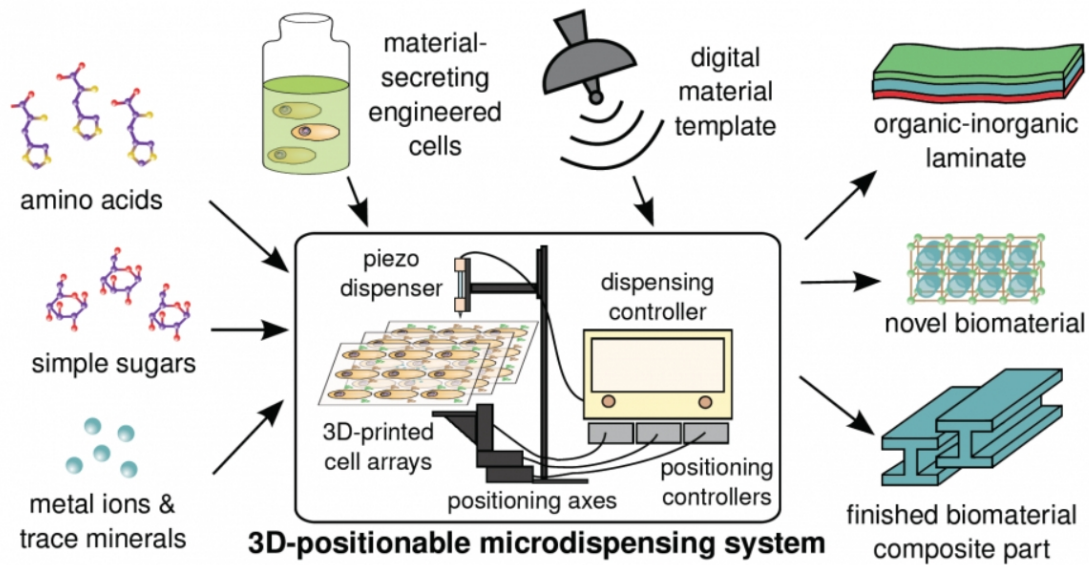
## **Ames Research Center**

The ARC recently created the 'Space Shop,' which is an advanced AM facility modeled after the 'Fab Lab' concept (NRC 2014, Chapter 2), created at the Massachusetts Institute of Technology Center for Bits and Atoms and co-located with the traditional machine and manufacturing shop. The Space Shop facility is made available as a mentored resource to all who have properly trained on the use and operation of the equipment. Other Centers have initiated or have plans for similar in-house, fab lab-type facilities.

The ARC is using AM to develop multifunctional devices and structures for life support and radiation shielding. The research areas include carbon dioxide removal and/or oxygen regenerating systems, supercapacitor devices and radiation resistant structures using both liquid and solid novel materials developed at ARC. In addition, ARC is examining the use of portable non-contact optical Surface Enhanced Raman Spectrometry (SERS) to monitor materials properties during the AM processes. ARC has similar capabilities for high throughput chemical mapping or imaging (Raman, Fourier transform infrared spectroscopy (FTIR)) that have demonstrated value for the semiconductor industry for processing and disk head quality control.

These materials and processes are being studied in the context of synbio systems, but might not be considered synbio products themselves. Regarding advanced manufacturing NDE in general, ARC employs AM as part of its general engineering development resources, as well as a couple of projects that are focused on AM demonstrations in particular. For the former, the majority of the work is aimed at checking/confirming physical make-up, geometry and fit-checks. Thus far, NDE beyond basic inspection has not been a part of the process. Also, ARC is a partner with MSFC in the planned Fall 2014 ISS [Made In Space, Inc.](#) 3D Printing in Zero-G project (Knapp 2014). Another set of advanced manufacturing research projects that ARC is focused on is building block-based materials systems for aerospace structural applications.

In addition, ARC has a unique program in the AM of advanced biocomposites through the printing of synthetic biology altered cells which, subsequent to printing, secrete biomaterials that could not be made any other way. For example, the potential exists to print cells that have been engineered to produce products such as spider silk and rubber resulting in 3D composites. The cells could be fed primarily by the output of photosynthetic cells, thus allowing the production of materials off planet with virtually no inputs other than *in situ*-sourced water, radiation, carbon dioxide and nitrogen (Figure 3). This work is unique both in the Agency and the community at large, and thus is currently being supported by a NIAC Phase I award (Rothschild 2013; Gentry et al. 2014).



(Image courtesy of ARC)

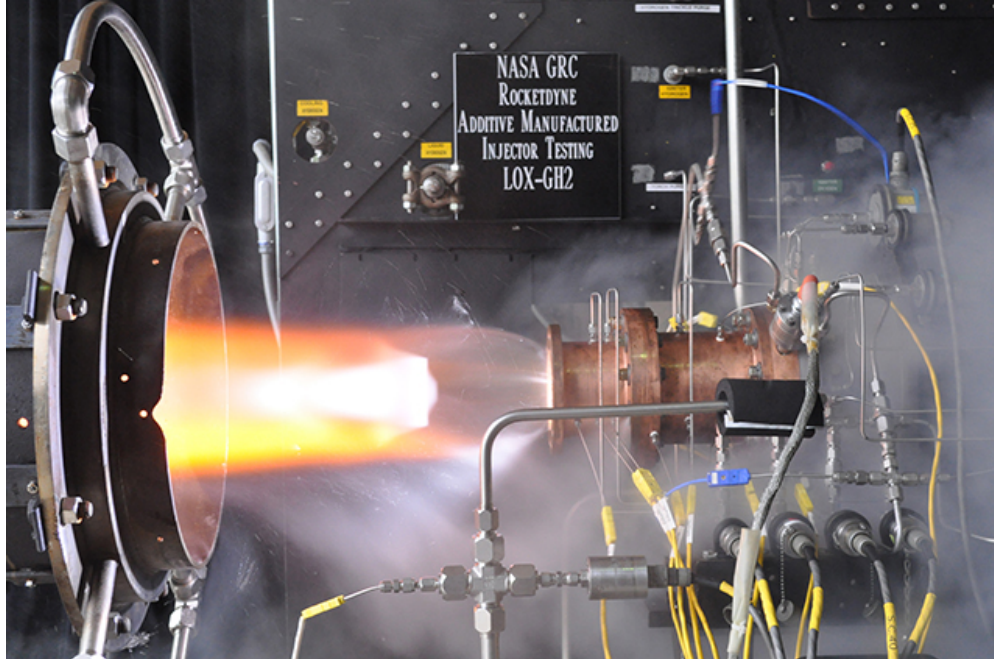
Figure 3

Ames Research Center's combining of synthetic biology and additive manufacturing to create 3D-structured arrays of cells that are bioengineered to secrete different materials in a specified three-dimensional pattern.

### Glenn Research Center

Additive manufacturing efforts at GRC consist of an Air Force-funded project with Aerojet Rocketdyne on liquid rocket gaseous hydrogen/liquid oxygen (GH<sub>2</sub>/LOX) injectors and other structural components for an RL-10 rocket (Figure 4) to demonstrate certification of SLM and electron beam melting (EBM) processes for highly critical rocket engine components, reduction of manufacturing lead time, and cost savings compared to traditional manufacturing processes. GRC is also testing Inconel<sup>®</sup>,<sup>1</sup> 625 injectors in this project. Nondestructive evaluation is being used in the testing of material characterization samples and the development of test plans for full-scale components. Specifically, CT is being performed on all samples and ultrasonic testing (UT) and penetrant testing (PT) are being used on machined surfaces. GRC is also working with [rp+m](#) to develop polymer and ceramic technologies for a 'Fully Non-Metallic Gas Turbine Engine.' A GRC Center Innovation Fund project is using an EB powder bed method to fabricate/join single crystal to polycrystal nickel-base disk and blade alloys, with the goal being to produce a hybrid turbine disk with a single crystal rim and polycrystalline bore. The build is being done at MSFC. Also in collaboration with MSFC, work is being done on the Materials Genome Effort involving microstructural/phase modeling of Inconel 718. GRC has a NASA STMD Game Changing project with MSFC, involving the building of a GRCop-84 combustion chamber liner. GRC is procuring the powder and doing the microstructural and mechanical characterization. GRC is supporting a Headquarters (HQ)/STMD Grand Challenge in AM in collaboration with [America Makes](#) (the National Additive Manufacturing Innovation Institute (NAMII)). Last, GRC is developing methods to additively manufacture ceramics and ceramic composite materials using pre-ceramic polymers.

<sup>1</sup> Inconel<sup>®</sup> is a family of austenitic nickel-chromium-based superalloys and a registered trademark of Precision Castparts Corp., Portland, OR 97239.



(Photograph courtesy of GRC)

Figure 4

Hot-fire test at Glenn Research Center's Rocket Combustion Laboratory of an Aerojet Rocketdyne liquid-oxygen/gaseous hydrogen RL-10 rocket injector assembly built using additive manufacturing.

### ***Goddard Space Flight Center***

Goddard Space Flight Center (GSFC) has recognized the benefits of AM and has taken an approach of not attempting to drive or develop AM manufacturing technologies, but to use the technology that is being developed by industry and academia and to partner with these institutions to meet unique future mission requirements. These partnering activities have primarily been funded by the GSFC Internal Research and Development (IRAD) program. Examples of AM activities include the production of a reentrant tube for a cryogenic thermal switch in the ASTRO-H Adiabatic Demagnetization Refrigerator (Figure 5). This Ti-6Al-4V (Ti 6-4) part is considered a flight spare. The cost of the AM part was an order of magnitude less than the conventionally machined and welded part and was produced in two weeks versus three months. The GSFC IRAD program funded a development of a DMLS Technology Guide. The guide provides best practices for fabricating parts and evaluating basic mechanical properties for a wide range of AM materials produced by multiple outside vendors. The IRAD program is also funding AM production of light-weight low coefficient of thermal expansion optical benches for satellites and other instrument structures that demand dimensional stability using novel iron-nickel alloys produced by DMLS. Other IRAD activities include spot shielding of sensitive electronic parts to space radiation using DMLS-printed Inconel 625. Additive manufactured production of proof-of-concept, fully integrated 3D printed telescopes to save mass, increase dimensional stability, and slash part counts has also been accomplished. GSFC has used DMLS to produce a modulated x-ray source for an instrument being considered for a possible flight on the ISS. The first GSFC flight of an AM part was a poly(ether ketone ketone) (PEKK) battery case that flew on a sounding rocket. For all of these activities, the parts made by AM are being produced by outside vendors. These activities have allowed GSFC to better understand build challenges and where best to infuse the technology.



(Photograph courtesy of GSFC)

Figure 5

Goddard Space Flight Center's reentrant tube made by additive manufacturing for a cryogenic thermal switch for the ASTRO-H Adiabatic Demagnetization Refrigerator.

### ***Jet Propulsion Laboratory***

The JPL effort on AM involves work on amorphous metals created through medial sputtering onto a surface – a form of AM. Specific amorphous metal projects include fabrication of a mirror assembly including the isogrid backing, and the production of a revolutionary new material for a gearbox application. Other AM projects at JPL include the use of AM to fabricate prototype gradient Ti-6Al-4V/niobium rocket nozzles, prototype gradient stainless steel/Inconel engine valves, prototype low coefficient of thermal expansion (CTE) inserts for composites, and a titanium mirror flexure made of deposited titanium on a titanium plate (Figure 6). Also, JPL developed the robotic platform concept known as the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) for In-Source Resource Utilization (ISRU)-based robotic construction technologies (Khoshnevis et al. 2005).

### ***Johnson Space Center***

Johnson Space Center (JSC) has pursued fabrication and qualification of EBF<sup>3</sup> and laser engineered net-shaping (LENS) components for manned space flight applications, including in-space manufacturing. Titanium, aluminum and steel EBF<sup>3</sup> process development and material properties test samples as well as flight-like extravehicular activity tool components, all deposited at LaRC, have been inspected in both the as-deposited and final machined conditions. Nondestructive evaluation methods applied to the EBF<sup>3</sup> samples and parts include x-ray digital radiologic testing (RT) and CT, conventional UT and phased array ultrasonic testing (PAUT), and eddy current testing (ET). Complex conceptual engine components have been manufactured at JSC from Inconel, titanium, and steel using the LENS process. Selected Inconel LENS components have been inspected using x-ray CT.



**Figure 6**

Jet Propulsion Laboratory's metals parts made by additive manufacturing.

### **Kennedy Space Center**

Work in the Kennedy Space Center (KSC) Surface Systems Office and at the University of Southern California under two NIAC awards (Khoshnevis 2011; Khoshnevis 2012) have shown promising results with regolith materials for *in situ* heat shields, bricks, landing/launch pads, berms, roads, and other structures that could be fabricated using regolith that is sintered or mixed with a polymer binder (Figure 7). The technical goals and objectives are to prove the feasibility of AM construction using planetary regolith. Future KSC effort will explore the use of NDE to show that regolith structures have structural integrity and practical applications in space exploration.

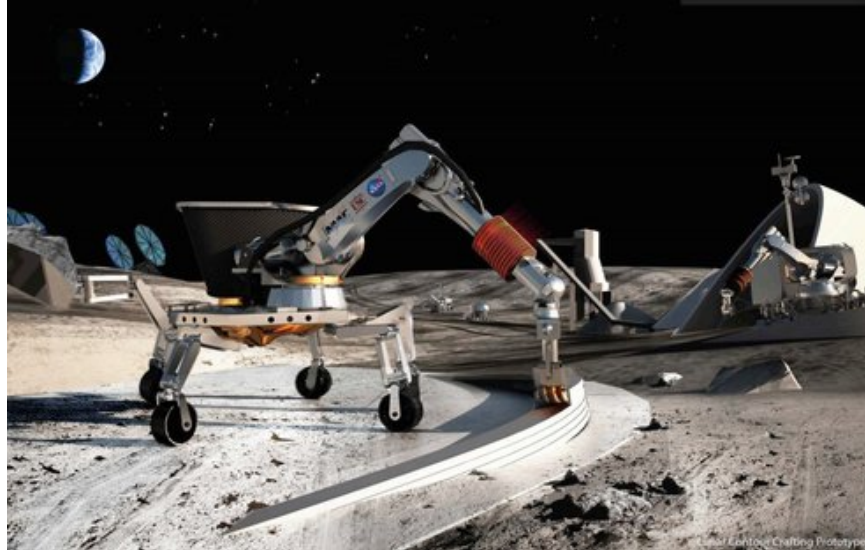
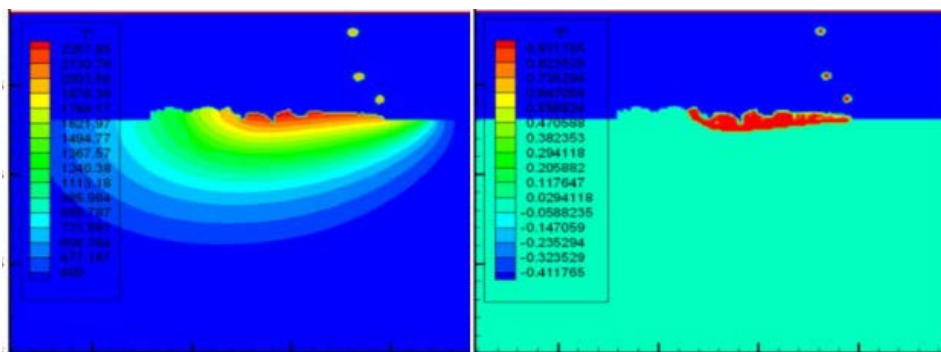


Figure 7  
 Conceptual regolith structures being fabricated on the Moon.  
 (Khoshnevis 2005, 2011 and 2012).

### **Langley Research Center**

Langley Research Center has developed the EBF<sup>3</sup> and LENS processes for fabrication of metallic parts for aerospace and space applications. More specifically, EBF<sup>3</sup> has been used to fabricate functionally graded unitized structures with different alloys and integrated damage tolerance to replace heavier conventional structures. Examples of unitized structures include contoured stiffeners, acoustically tailored fuselage structures, aeroelastically tailored wing structures, layered aircraft structures, and functionally graded stiffeners (e.g., EBF<sup>3</sup> deposited stiffeners onto single-piece cryogenic tank barrel sections of launch vehicle structures). Also, LaRC is developing near infrared (NIR) camera inspection technologies for *in situ* process monitoring of melt pool temperatures, and has successfully imaged the melt pool and solidification areas during EBF<sup>3</sup> processing. In addition, LaRC is applying multi-physics modeling of laser-direct powder feed systems (LENS, Laser Aided Manufacturing Process (LAMP)) and electron beam-wire feed systems (EBF<sup>3</sup>) (Figure 8). Last, LaRC has successfully conducted a KC-135 parabolic flight demonstration to show the feasibility of advanced near-net shape processing in microgravity.



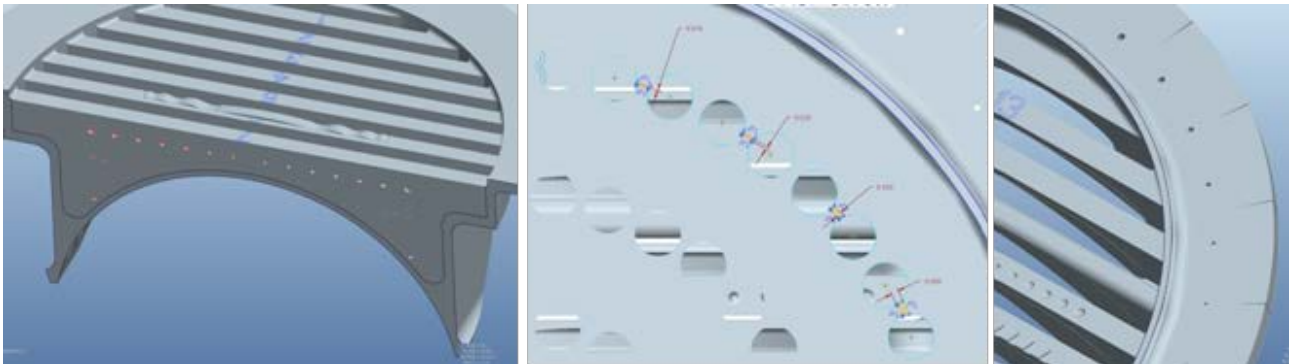
(Image courtesy of LaRC)

Figure 8  
 Langley Research Center's modeling of temperature (left) and phase profile (right) during electron beam freeform fabrication processing.

## **Marshall Space Flight Center**

Past work at MSFC includes an ADO-funded task, titled Characterization of Direct Metal Laser Sintering Materials for SLS (Space Launch System) Engine Components, to investigate applications of NDE to materials used in AM, methods for defect standard formation, and effects-of-defects on material properties. Inspection of dozens of AM components has been conducted, primarily with CT, but also with ET, PT, RT, and UT, to help verify their integrity and to evaluate the usefulness of these methods on structural components. Some of the major components covered are potential items for the RS-25, J2-X, and Morpheus lander including Pogo-Z baffles, nozzles, injectors, and valve bodies. These ranged in size from a few inches to over 12 inches across and covered several Inconel, aluminum, stainless steel and copper alloys. Computed tomography gauge blocks were designed and fabricated to help assess the dimensional accuracy of CT and compare both AM and conventionally machined parts. Finally, an NDE reference standard was designed for the Pogo-Z baffle to help determine inspection characteristics of various NDE methods, in particular CT (Figure 9).

Present work includes performing CT analysis of the aforementioned gauge blocks and fabrication and testing of the Pogo-Z reference standard. The NDE team is actively researching micro-focus CT methods and working with several vendors to test these out on typical engine parts. The team is looking to possibly procure a micro-focus CT system. There is an effort to write a standard/specification to certify powder bed fusion manufactured parts for flight. Lastly, MSFC is working in collaboration with ARC in the Fall 2014 ISS Made In Space, Inc. 3D Printing in Zero-G project.



(Images courtesy of MSFC)

Figure 9

Marshall Space Flight Center's Pogo-Z physical reference standard used to verify and validate NDE measurements made on additively manufactured parts.

## **White Sands Test Facility**

White Sands Test Facility (WSTF) has one system for making nonstructural ABS parts. Uses-to-date have focused on fabrication of mock-up components, piece parts for system fit checks, brackets and fixtures for test setups, and complex components for visual representation when machining flight-like prototypes. WSTF also held a kick-off meeting in January 2014 with American Society of Testing and Materials (ASTM) International Committees E07<sup>1</sup> on Nondestructive Testing and F42<sup>2</sup> on Additive Manufacturing Technologies, and gained support to develop voluntary consensus organization (VCO) standards for NDE of AM (Figure 10). This approach will allow NDE and AM experts drawn from industry, academia, and other government agencies to be leveraged to develop standards having direct value to NASA. Also, WSTF sits on ASTM E07 and F42 and is part of an F42 collaboration team for an ASTM draft Guide for measuring the mechanical properties of parts made by AM (ASTM 2014a). Additionally, WSTF is leading an ASTM E07 effort to develop an ASTM draft Guide for NDE of parts made by AM (ASTM 2014b). Previously, WSTF has analyzed [Optomec](#) test specimens consisting of LENS-deposited nickel on aluminum and titanium alloy substrates for use as lightweight combustion-resistant components for service in enriched oxygen environments.

### **1.3 America Makes**

America Makes, also known as NAMII, is a publicly run consortium composed of companies, universities, non-profit organizations, and government agencies. America Makes funds two tiers of projects: Project Call 1 and Project Call 2. Project Call 1 efforts focus on maturing technologies between TRL 4 (component and/or breadboard validated in a laboratory) and TRL 5 (component and/or breadboard validated in a relevant environment). Project Call 2 efforts focus on maturing technologies between TRL 8 (actual system completed and qualified through test and demonstration) and TRL 9 (actual application of technology is in its final form—technology proven through successful operations). Also, Project Call 2 efforts allocate funding devoted to 1) design; 2) materials; 3) processes and equipment; 4) qualification and certification; and 5) knowledgebase development.

Three NDE-related efforts are currently being funded by America Makes (Macy 2014). More specifically, one Project Call 1 (launched April 2013) and two Project Call 2 efforts (announced January 2014) were identified (Table 1). Possible overlap with NASA NDE efforts is noted where applicable.

Of interest also are two Project Call 1 efforts NASA has co-funded that pertain to AM but do not involve NDE at this point (Table 2).

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<sup>1</sup> American Society of Testing and Materials, Committee E07 on Nondestructive Testing, [astm.org/COMMITTEE/E07.htm](http://astm.org/COMMITTEE/E07.htm).

<sup>2</sup> American Society of Testing and Materials, Committee F42 on Additive Manufacturing Technologies, [astm.org/COMMITTEE/F42.htm](http://astm.org/COMMITTEE/F42.htm)



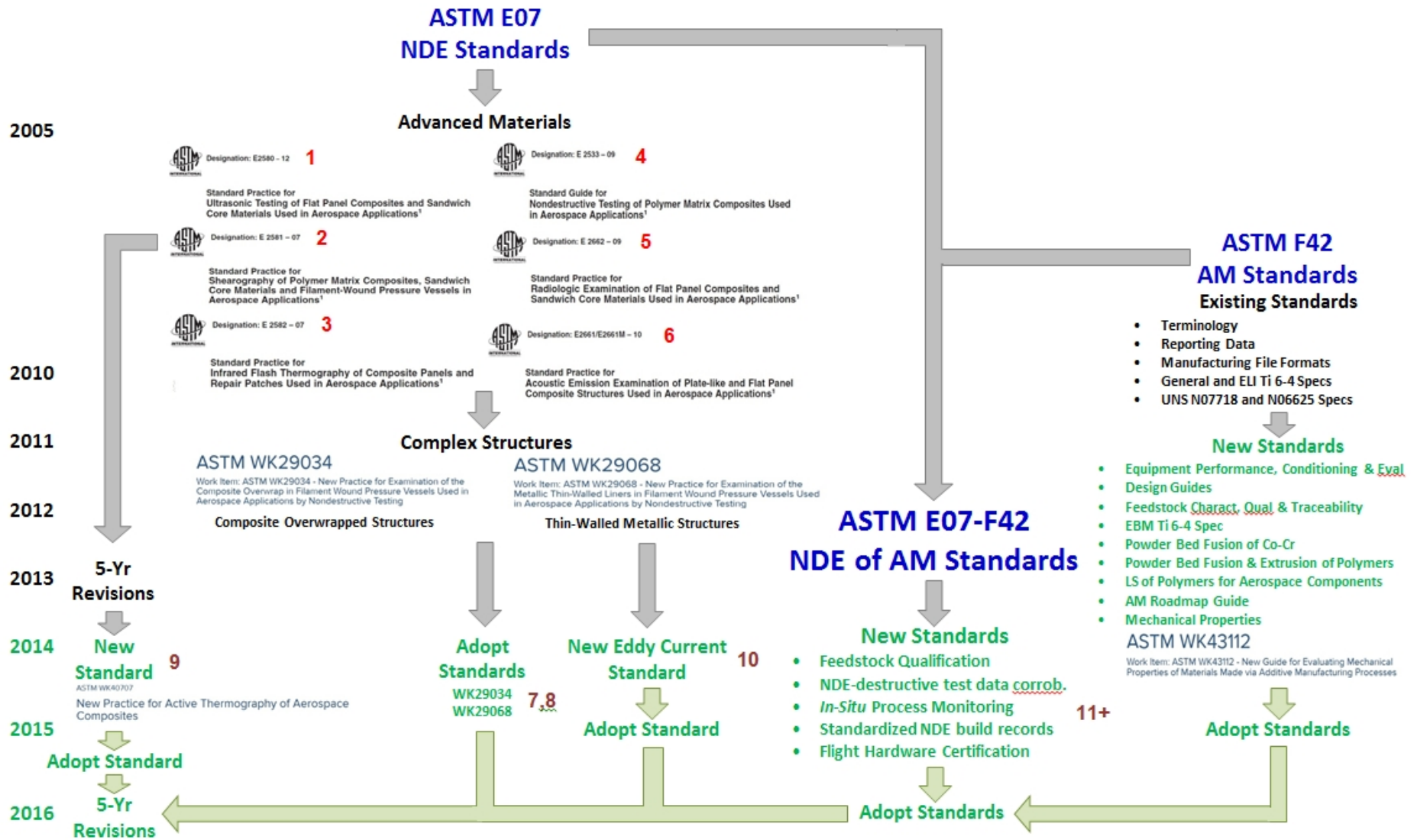


Figure 10  
Timeline showing past (1-6) and current (7-10) White Sands Test Facility-led ASTM E07 standardization efforts related to nondestructive evaluation (NDE), and planned (11) NDE of additively manufactured parts ASTM E07-F42 standardization effort.

**Table 1**  
America Makes-Funded NDE-related Projects

Project Call 1: TRL 4-5 (possible overlap with NASA Langley Research Center's Nondestructive Evaluation (NDE) effort) Targeted Technology Area: <i>In situ</i> process monitoring NDE		
Title	Lead Organization <sup>a</sup> and Team	Key Outcomes
Thermal Imaging for Process Monitoring and Control of Additive Manufacturing	<b>Penn State University</b> , <a href="#">Stratonics</a> , <a href="#">Sciaky Inc.</a> , <a href="#">Optomec</a> , CMU, WSU, Aero Energy Ind.	Thermal imaging for process monitoring and control of electron beam direct manufacturing and laser engineered net shaping (LENS) additive manufacturing (AM)
Project Call 2: TRL 8-9 (possible overlap with NASA Johnson Space Center's NDE effort): Targeted Technology Area: Qualification and Certification using NDE		
Lead Organization and Team	Short Description	
<a href="#">EWI</a> , <a href="#">Lockheed Martin</a> , Sciaky Inc.	Improve ability to ultrasonically inspect titanium alloy components through advancement in process parameters and inspection techniques	
Project Call 2: TRL 8-9 (general relevance): Targeted Technology Area: NDE Methods Knowledgebase Development		
Lead Organization and Team	Short Description	
<a href="#">Northrop Grumman Aerospace Systems</a> , <a href="#">CalRAM Inc.</a> , <a href="#">Concurrent Technologies Corp.</a> , <a href="#">General Electric (ge.com)</a> , <a href="#">Robert C. Byrd Institute</a>	Electron Beam Melted Ti-6Al-4V Component Fabrication, Design Allowables, and NDE methods	

<sup>a</sup> Lead Organization appears in boldface type.

**Table 2**  
America Makes/NASA AM-Related Projects

Project Call 1: TRL 4-5 (General AM, co-funded by NASA): Targeted Technology Area: General AM		
Title	Lead Organization <sup>a</sup> and Team	Key Outcomes
Maturation of High-Temperature Selective Laser Sintering Technologies and Infrastructure	<b>Northrop Grumman</b> , <a href="#">Oxford Performance Materials</a> , <a href="#">Arkema</a> , <a href="#">AST2</a>	Development of lower-cost, high-temperature selective laser sintering process for making air and space vehicle components (Air Force/Navy/ <b>NASA</b> ) and other commercial applications; ability to recycle
Maturation of Fused Depositing Modeling (FDM) Component Manufacturing	<a href="#">rp+m</a> , <a href="#">Stratasys</a> , <a href="#">University of Dayton Research Institute</a> , <a href="#">Boeing</a> , GE Aviation, Lockheed Martin, Northrop Grumman	Design guide; critical materials and processing data; and machine, materials, part and process certification for ULTEM™ 9085 – high temp aerospace parts (Air Force, <b>NASA</b> – strong collaboration)

<sup>a</sup> Lead Organization appears in boldface type.

## 1.4 National Institute of Science and Technology Additive Manufacturing Effort

Following the roadmap exercise completed by the National Institute of Science and Technology (NIST) in May 2013 (NIST 2013a), the NIST Engineering Laboratory in Gaithersburg, MD initiated the Measurement Science for Additive Manufacturing Program. This five-year program, which started October 1, 2013, has four thrust areas that closely match the technology challenges identified in the roadmap exercise. The roadmap technology challenge areas and the linked funded programs are shown in Figure 11.

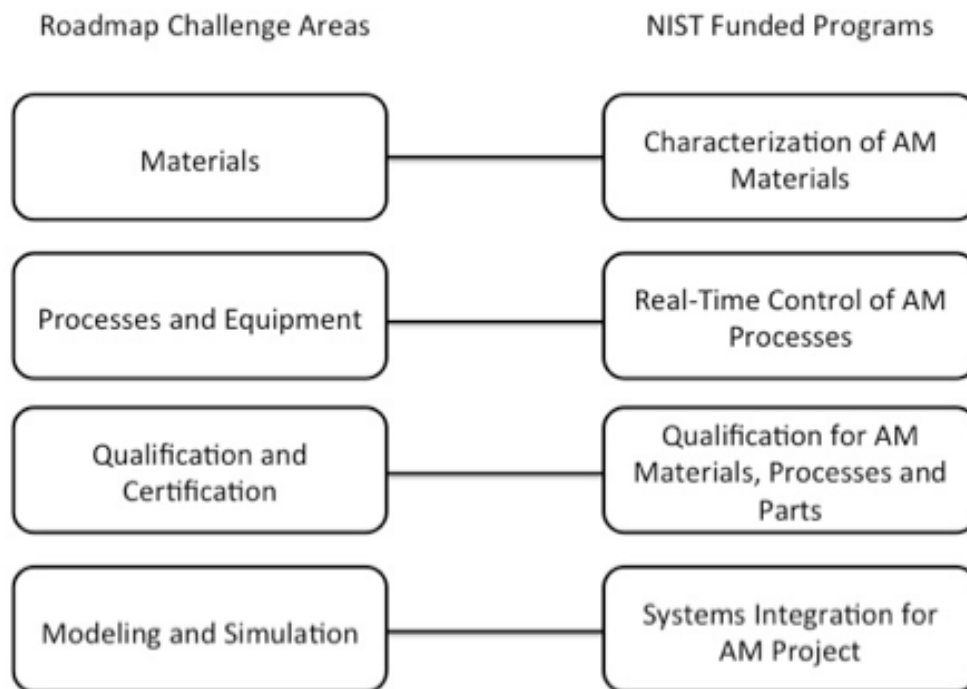


Figure 11

The relationship between the National Institute of Standards and Technology roadmap challenge areas for metal-based additive manufacturing and their funded programs.

The NIST roadmap addressed finished-part NDE as an element in the Process and Equipment challenge area. The action plan for this area called for the evaluation and optimization of existing post-process NDE techniques. However, the corresponding funded program focuses on developing in-process NDE sensing methods that are applied during processing. Based on the description found on the NIST website, the Real-Time Control of AM Processes program (funded) is primarily working to develop sensing techniques to monitor melt pool temperature distribution and geometry, dimension of layers and the detection of defects. The program has the goal of developing high speed imaging techniques for detecting defects such as cracks, delaminations (weak layers) and voids in real time.

The Qualification for AM Materials, Processes and Parts program (funded) suggests the program will focus on testing protocols for qualification and the generation of materials property databases through round robin testing (NIST 2013b). Though NDE may be employed in this activity, it is not emphasized in the program description.

## 1.5 National Research Council Assessment of Space-Based Additive Manufacturing

NASA, the Air Force Space Command, and the Air Force Research Laboratory (AFRL) asked the National Research Council (NRC) to conduct a study of the prospects for the use of AM in space. In response, the NRC established the Committee on Space-Based Additive Manufacturing (NRC 2014) with the following focus areas:

- Assess the current state of AM in the United States and worldwide (especially as relates to small satellites or respective subassemblies)
- Characterize the future applications of AM in space
- Discuss the feasibility of space-based AM of space hardware for missions of relevance to NASA
- Identify the technology gaps for use of AM in space
- Assess the implications that a space-based AM capability would have on launch requirements

The NRC report lists the current technology gaps pertaining to space-based AM that confront NASA and the Air Force. While the gaps identified by the NRC mirror the ones identified by the NIST (NIST 2013), namely, Materials and Processes; Equipment; Certification and Qualification; and Modeling and Simulation (Figure 11), the gaps are more specific to space hardware and the space environment. Regardless, the gaps identified by the NRC effectively bar wider use of AM, even in ground-based environments, and must be resolved first before AM can be used in space-based environments. A comparison of the technological gaps identified by NIST and the NRC is shown in Figure 12. Similar to the findings delineated in the NIST roadmap, NDE has relevance for evaluating part precision, finished part certification, and process control, for example.

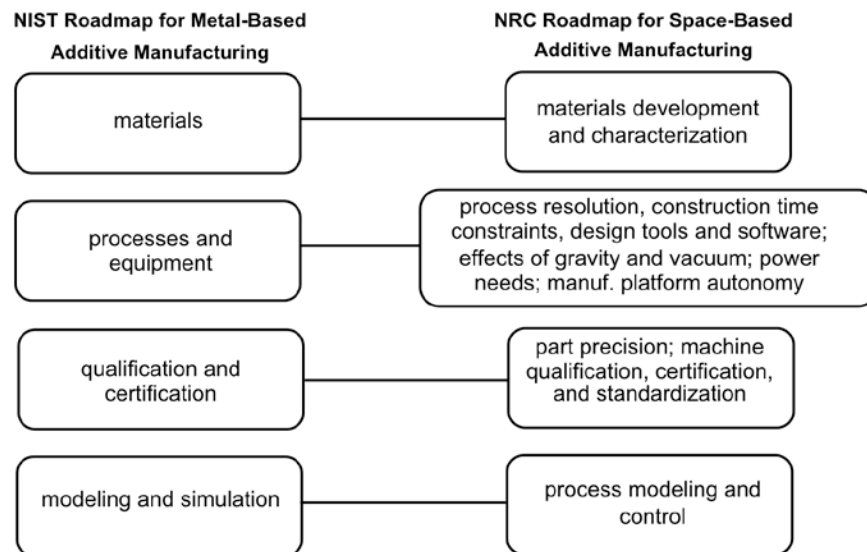


Figure 12

A comparison of the technological gaps identified by the National Institute of Standards and Technology for ground based AM of metals, and the National Research Council for space-based AM (the latter was commissioned by NASA and the United States Air Force).

The NRC report also provides a possible roadmap for NASA space-based AM. Four key factors that will likely have a strong influence on the use of AM in NASA space applications were identified:

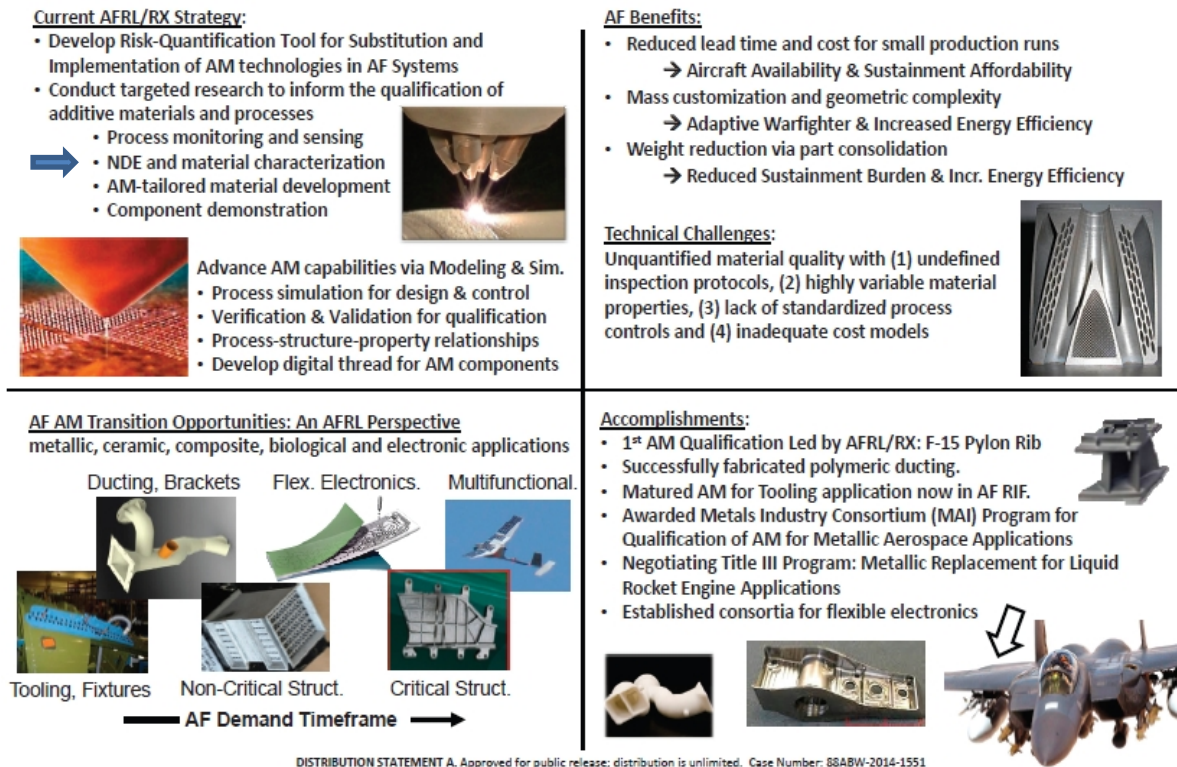
- The degree to which AM will provide technical and programmatic benefits (reduced mass, better volumetric efficiencies, increased design flexibility, better cost and schedule efficiencies)
- The degree to which AM production of space hardware (e.g., cubesats) can be automated and best practices shared
- The availability of resources and infrastructure to insure the effective use of AM systems aboard the ISS (the rate of production of artifacts, the cost effectiveness of the production system, etc.)
- The degree to which space-based (or ground-based) AM technologies and products can be validated as to their utility, efficacy, and applicability.

## **1.6 Department of Defense Additive Manufacturing Effort**

The NNWG has made contacts with key Department of Defense (DoD) personnel involved in AM and NDE through The Technical Cooperation Program (TTCP). A joint meeting of TTCP technical panels TP1 (Metals and Ceramics) and TP5 (Materials State Awareness and Nondestructive Evaluation) was held February 27, 2014 in Arlington, Virginia. TP1 oversees AM efforts within the TTCP member countries (United States, Canada, United Kingdom, Australia, New Zealand). The main purpose of the workshop was to learn about the state-of-the-art of AM, and to identify key challenge areas related to NDE as applied to AM across the TTCP countries and to provide participant panel members with a forum to explore and propose new study and/or operating assignments.

More recently, the NRC has released its findings for both NASA and the U. S. Air Force on the feasibility of space-based AM (NRC 2014). One of the key findings as relates to the U. S. Air Force was that there is at present a lack of knowledge to credibly determine whether or not development of an Air Force-specific, space-based AM production facility would achieve its expected benefit. Given that such a fabrication center would be highly complex and expensive, a detailed system assessment and cost-benefit analysis might be advisable.

The AFRL Materials and Manufacturing Directorate has a significant portfolio of work in AM. While AFRL AM work is extensive, it is, to date, largely aimed at aeronautical/aircraft applications (Figure 13). It is instructive to note that the AFRL and other DoD Branches are actively working on applying NDE to AM. Similar to the hurdles that NASA must surmount, significant additional research will be required by AFRL, for example, to fully close all the gaps to successfully implement AM either in space or on the ground for space applications. The NNWG is actively seeking collaboration that focuses on application of NDE to AM with the AFRL and other DoD Branches.



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(NRC 2014)

Figure 13

The Air Force Research Laboratory’s Additive Manufacturing Strategy emphasizes the development of this technology primarily for ground-based use for aircraft (NRC 2014).

## 1.7 European Space Agency Additive Manufacturing Effort

The European Space Agency (ESA) is using AM to build high-quality, intricate shapes with improved cost savings and reduced waste generation. The ESA’s AM effort is part of its Clean Space initiative, which seeks to apply innovative technologies to reduce the environmental impacts of the space industry (ESA 2014a). Both metallic and polymeric parts have been made and are being considered. For example, ESA’s AMAZE (Additive Manufacturing Aiming Towards Zero Waste and Efficient Production) project currently involves 28 industrial partners across Europe and focuses on metals-based AM (ESA 2014b). The goal of the 5-year AMAZE project is to develop the first complete European Union autonomous supply chain for AM by 2017.

The ESA’s AM efforts include developing AM processes that can be used to build lunar bases in the future (ESA 2014c). The ESA has also overseen the successful manufacturing of high TRL (TRL 9) reduced mass titanium satellite parts (Ghidini 2011a). Propulsion parts (injectors, chambers, nozzles, monolithic thrusters), electrical hardware, and design optimized load-bearing mechanical hardware are also being made (Ghidini 2011b). Despite these successes, ESA has identified three challenges pertaining to AM that still remain open:

- Design challenges (better design tools and rules are needed)
- Manufacturing challenges (better manufacturing protocols are needed to guarantee the accuracy, reproducibility, and reliability of parts made by AM from raw materials to end product)

- Qualification and certification challenges (process verification methodologies, such as those involving NDE, are needed)

Although initial contacts have been made between the NNWG and ESA, the NNWG has not penetrated the NDE-specific ESA effort other than confirming that the ESA NDE effort is currently focusing on CT.

## 2.0 Gap Analysis

The intent of the gap analysis is to identify the challenges (i.e., gaps) that prevent the infusion of AM into NASA and Commercial Space applications and to identify where NDE can play a role in overcoming these challenges. This TM will review specific gaps in the NDE knowledge base and readiness within the Agency, and make recommendations for Agency investments in NDE as it applies to AM, to ensure that the NDE community is properly positioned to support the use of parts made by AM in flight applications.

In 2012, NIST conducted a roadmap exercise for metal AM that focused on measurement science challenges (NIST 2013). Five of the workshop participants were representatives from NASA LaRC, GSFC and MSFC. The NIST workshop report provides a comprehensive breakdown of AM technology challenges that must be addressed to achieve widespread use of additive processes for direct part production, and to realize the potential economic benefits. Gaps identified include measurement methods, performance metrics, and standards to evaluate fundamental AM process characteristics, improve the performance of AM equipment, improve the accuracy of parts made by AM, and increase confidence in the mechanical properties of parts fabricated using these systems. These gaps are grouped into the following challenge areas: Materials; Process and Equipment; Qualification and Certification; Standards; and Modeling. Examination of these challenge areas shows that NDE is a crosscutting technology that will play a key role in closing the gaps in each area.

Widespread use of AM in NASA will require developing NDE methods that span the gap between TRL 3 (analytical and experimental critical function and/or characteristic proof-of-concept) and TRL 6 (system/subsystem model or prototype demonstration in a relevant environment) (Figure 14).

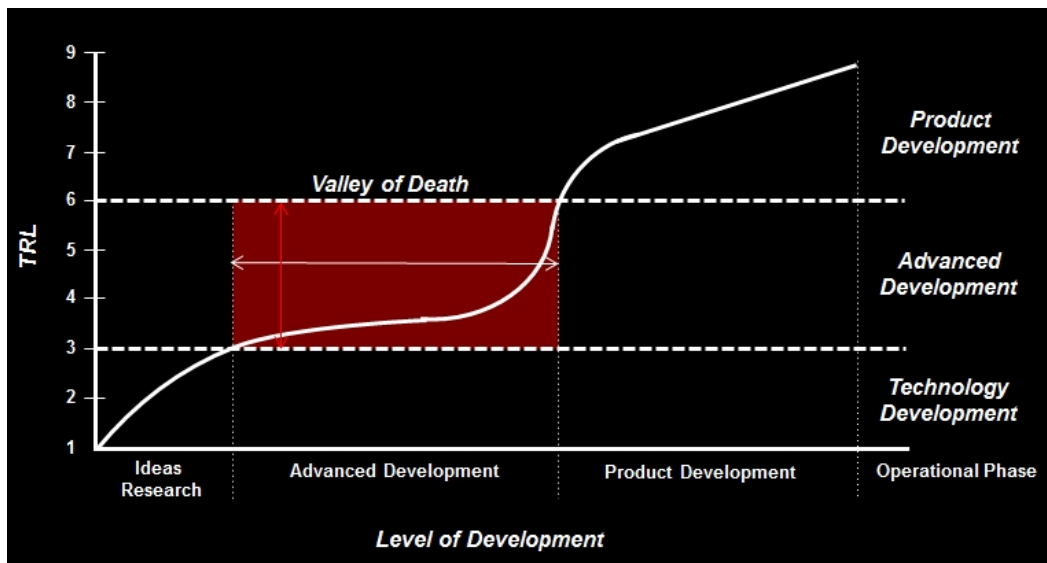


Figure 14

Technology transition showing area of needed nondestructive evaluation development between Technology Readiness Levels 3 and 6 (Higginbotham 2014).

## 2.1 Organizational Gaps

In addition to these technology-related challenge areas, the NASA NDE community faces an organizational challenge since the AM efforts are spread across the Agency. Much of the NASA effort-to-date has been delegated to individual Centers along the lines of core competencies. These efforts have reached a stage of development where sufficient overlap exists to warrant greater cooperation and coordination between the NASA Centers.

From an NDE perspective, this TM is unique since the mechanism for coordination between NASA Centers was non-existent before January 2014, which was when the NASA NDE community began to discuss coordinating efforts and initiated the writing of this TM. The TM is one of the primary mechanisms for coordination. The intention is that this NASA TM be used as a guide or catalyst for greater future coordination between the NASA Centers to improve technical and scientific synergy, reduce redundancy, and maximize efficient utilization of NASA resources and investments.

The need for greater coordination reiterates one of the key findings in the NRC report (NRC 2014) that often occurs in emerging technologies such as AM: a lack of coordinated effort outside of the driving organization's primary needs (STMD is highlighted). The lack of coordination could be due to several factors such as 1) disconnects between technology possibilities and actual end-user applications; 2) linkage between manufacturing and end-user applications; and 3) no overarching mechanism "to facilitate communication, discussion, and collaboration" on space- and ground-based AM technologies agency wide. From the NDE perspective, NASA would benefit from coordination of its many and diverse NDE efforts related to AM. Similarly, NASA's full use and application of NDE as related to AM could be made more efficient and effective if there were a stronger associative link between NDE method developers and end users. Benefits may include improved efficiency and complexity, and cost reductions.

## 2.2 General Additive Manufacturing Gaps

### **Materials**

*Design Allowables* – There is a lack of documented and shared fracture toughness, fatigue strength and other key properties for AM metals. The challenge is compounded by the potential for machine-to-machine variations, feed stock variations, and the large processing parameter space inherent in AM. Nondestructive evaluation can be useful in characterizing test specimens and has the potential to provide insight into the effect-of-defects on properties. The need for a centrally located, non-proprietary database which contains design allowables data and other pertinent information has been expressed by industry, academia, and various government agencies (Martukanitz 2014). The three aspects of the design allowables generation activity are knowledge of 1) input materials; 2) manufacturing platform (i.e., EB or LS); and 3) test protocol. This is a challenge or gap area where NDE can help close the gap.

*Feed Stock* – NIST has taken a lead in testing and characterizing powder and wire feed stock materials, which not only need to be consistent but also need to be optimized for AM processes. The techniques used to measure particle size, shape, and chemical composition are mature. Once feed stock characteristics are optimized, standards or specifications need to be developed to insure consistent feed stock.

### **Process and Equipment**

*In Situ Process Control* –It is recognized that *in situ* process monitoring is a requirement for producing consistent parts made by AM; however, current AM machines are not equipped for closed-loop feedback systems. Once it is understood what *in situ* measurements are needed, sensors designed for the AM build environment must be developed and employed for closed-loop



feedback. Thermal imaging to monitor the weld pool temperature, optical imaging to measure shape and distortion during the build, and techniques for addressing residual stress, homogeneity, and defects are areas for development.

*Residual Stress* – Residual stress is an inherent problem with parts made by AM and can result in part distortion as well as part failure due to cracking. As a consequence, AM production protocols need to be optimized to reduce residual stress. Oak Ridge National Laboratory is leading the way with neutron tomography imaging for mapping residual stress. More affordable solutions and an increased knowledge base are needed in order to reduce residual stress.

*Post Processing* – Protocols are needed for post processes such as hot isostatic pressing (HIP), heat treating, and shot peening. Nondestructive evaluation can play a role in helping understand the effect of these processes on final part properties and consistency.

*NDE* – The NIST report identified the need for optimizing and adapting NDE for parts made by AM (NIST 2013b). It is recognized that CT is a key technique for parts with complex geometries, and the challenge of implementation of this technique is the availability of affordable high power and high resolution systems. Thermography was also identified as a key capability for *in situ* process monitoring. NASA has world-class CT and thermography capabilities dispersed across the Agency. What lacks is a knowledge base of AM part inspections, which is needed to understand defect types and their detectability.

*In-Space Processing* – This is a challenge area, unique to NASA, which will require the development of potentially unique equipment and processing protocols. Advances leading to closure of the many equipment and processing challenges for industrial AM manufacturing will help drive the TRL of in-space processing.

### **Qualification and Certification**

*Guidelines* – There is a recognized lack of guidelines for how to qualify and certify AM processes as well as parts made by AM. The gap in process certification and qualification guidelines is complicated by the wide variety of machine types and the vast processing parameter space.

### **Technical Standards**

*Input Material and Finished Part Standards* – No technical or voluntary consensus organization standards exist for measuring the size, shape, chemistry, or microstructural homogeneity/heterogeneity of input material powders, spools, etc., and very few standards exist for measuring the mechanical or physical properties of finished parts (ASTM 2014a). Standards for the 1) preparation of measurement test pieces and 2) creating, reporting, and storing AM test data also do not exist. To address this gap, such standards will be developed under the jurisdiction of ASTM Committee F42.

*Equipment Standards* – Standards are particularly critical to ensure machine-to-machine consistency and routine or periodic calibration to ensure optimal operation and performance, and thus, part quality. To address this gap, AM equipment standards will be developed under the jurisdiction of ASTM Committee F42.

*Standard Guidelines and Methods for Qualification and Certification* – Standard guidelines for qualification and certification are lacking. Challenges include the ability to define the type and quantity of guidelines and wide variations in machines and end users. ASTM qualification and certification guidelines for AM machine components are currently lacking or inadequate. To

address this gap, uniform standards are being developed along with a taxonomy that encompasses all AM methods and is flexible to accommodate new technologies as they emerge.

*Standards for Round-Robin Build and Material Testing* – No documented standards and protocols exist for round-robin build and materials testing for AM. To address this gap, a set of protocols are being created for round-robin testing, beginning with a single source powder and going through part production, process, build, and inspection using, for example, composition (scanning electron microscope/energy dispersive spectrometer and x-ray diffraction), size measurement, morphology, and flow-ability/sifting mesh.

*Miscellaneous Voluntary Consensus Organizations* – In addition to AM-related standards developed by ASTM Committee F42, standards developed by other voluntary consensus standards organizations such as SAE (Society of Aerospace Engineers), AWS (American Welding Society) and ISO (International Standardization Organization) are also being surveyed and monitored. For example, SAE has a handful of standards on an alternative ion fusion AM method, construction of cubesats using AM, and fast, high-volume AM processes. ISO has recently adopted standards on terminology, data processing, uniform file format, process categories, feedstock, etc., that parallel ASTM Committee F42's efforts.

*Relevant NASA Standards* – AM parts used in NASA ground applications and non-human rated and human rated spacecraft must meet several NASA standards. The first standard (NASA-STD-6016) sets detailed Materials and Process requirements for spacecraft (NASA 2008a). This standard is currently being revised to include guidance on qualification of AM processes and parts made by AM. The second standard (NASA-STD-5009) sets NDE inspection requirements for fracture-critical metallic components (NASA 2008b). A third standard (NASA-STD-5001) provides uniform engineering and technical requirements for processes, procedures, practices for design, and factors of safety for spaceflight hardware (NASA 2014). Any general standards for parts made by AM will adhere to and defer to these overarching NASA requirements documents.

### ***Modeling and Simulation***

*Physics Based Predictive Models* – Again due to the rapid pace of change in AM, there is a lack of physics-based predictive models for the various AM processes. The models need to be able to predict residual stress, grain size distribution, spatial homogeneity, material properties, and defects. Nondestructive evaluation will play a key role in validating these models, which will be fundamental in process optimization.

*In situ Sensors* – The lack of *in situ* sensor capabilities is also hindering model validation. There is a clear need to know the dynamics of weld pool temperature being achieved in a build process in order to predict the end product quality.

## **2.3 Gaps in the NDE of Additively Manufactured Parts**

Challenges for NDE of AM include: complex part geometry, a lack of defined critical defect types and sizes, a lack of physical NDE reference standards, a lack of written inspection procedures tailored for AM processes, and a lack of probability-of-detection data. In addition, there is a recognized need to develop in-process monitoring techniques to inspect parts during the build process.

## ***Critical Defects***

While there may be new or unknown defect types in metal parts made by AM, current NASA fracture mechanics and control requirements will still rely on NASGRO<sup>®1</sup> analysis to provide critical flaw size and orientation for any part with the appropriate geometry, stress, and material property inputs. Typically, fracture analysts use standard NDE flaw sizes defined by NASA-STD-5009 for assessments, unless a smaller critical crack size is required, in which case special NDE methods are used. Fracture mechanics analysts need NDE input to ensure that flaws larger than the critical initial flaw size are screened at some defined probability of detection and confidence level. Therefore, instead of defining a critical crack for a part made by AM, it is probably better to validate NDE techniques that are known to not miss standard-sized flaws at a specified probability and confidence level. A possible complicating factor is that the assumption of a single rogue flaw detected by NDE methods developed using well-characterized physical reference standards may not apply for parts made by AM. In AM, well-characterized physical reference standards are still being developed. Also, finished AM parts typically have greater ranges of porosity and lack of fusion, with defects distributed throughout the part, rendering sizing of relevant flaws or assumption of a single rogue flaw difficult.

The above factors make identification and quantification difficult for the relevant flaw types and sizes of defects that must be detected by NDE for parts made by AM. Furthermore, there is often industry ambiguity in defining what constitutes a critical defect in a complex-geometry AM part. This information will only become available once AM processes have matured and after exhaustive effect-of-defect studies have been completed, which is still years away from being finished. A further complication is presented by the numerous AM processes and the complex processing parameter space for AM. The situation is analogous to the inspection evolution that occurred during the early years of polymer matrix composite (PMC) development and implementation, during which NDE inspection criteria were often driven by what could be reasonably detected and not by what needed to be detected. These challenges can set the stage for a dangerous scenario where true critical defect types and sizes are missed in an AM part inspection because of inexperience and unfamiliarity with the true failure modes of the materials.

## ***Complex Geometry***

The AM process is most suited for parts with complex geometries, and these geometries present a challenge for conventional NDE methods like UT, ET and even RT. Likewise, many parts made by AM have internal structure that may not be accessible for the less geometry-sensitive methods such as PT and magnetic particle testing (MT). Hence, the most promising technique for complex geometry parts appears to be x-ray CT. However, CT has limitations. For example, CT is not well suited for crack detection, and is time consuming both for data acquisition and data analysis (slice by slice visual interpretation). CT sensitivity will also degrade as parts get physically larger/thicker. The CT systems currently employed by NASA may not have the combination of penetrating power and resolution to detect critical defects in larger parts made by AM.

## ***Physical Reference Standards***

Physical reference standards are a basic requirement for any NDE process. However, they are just starting to be designed and fabricated for the AM processes and are a needed first step in understanding the capabilities of the various NDE methods and techniques that are being used on these materials. Again, this will take time because of the numerous AM processes and the vast processing parameter space. Furthermore, until critical defect types and sizes are

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<sup>1</sup> NASGRO<sup>®</sup> is a registered trademark of Southwest Research Institute, San Antonio, TX.

properly quantified, representative defect reference standards are being designed and fabricated using engineering judgment.

### ***Inspection Procedures***

The lack of standardized procedures (ASTM or otherwise) for the NDE of finished parts made by AM has been discussed. Although many of the existing NDE standard procedures for conventionally wrought, forged, and molded metal and plastic parts are generally applicable to parts made by AM, specific requirements such as geometrical complexity, porosity, surface finish and deeply embedded flaws may exist that must be addressed by newer standardized NDE procedures.

### ***In-Process Monitoring***

It is recognized that in-process monitoring of the part during the build may be a game changer in 1) improving the consistency, repeatability, and uniformity across machines and 2) qualification and certification of parts made by AM (NIST 2013a; NRC 2014). Part qualification during manufacturing is essential because of the difficulty in applying NDE methods to inspect complex parts made by AM after their fabrication. Research on in-process infrared monitoring of weld pool temperature and profile is underway, and high-speed visual monitoring techniques are available. However, automatic defect recognition algorithms need to be developed, and current AM fabrication equipment will likely require modification prior to the successful implementation of these novel inspection techniques. Again, this will likely take years because of the many processes and complex processing parameter space previously discussed.

### ***Qualification and Certification***

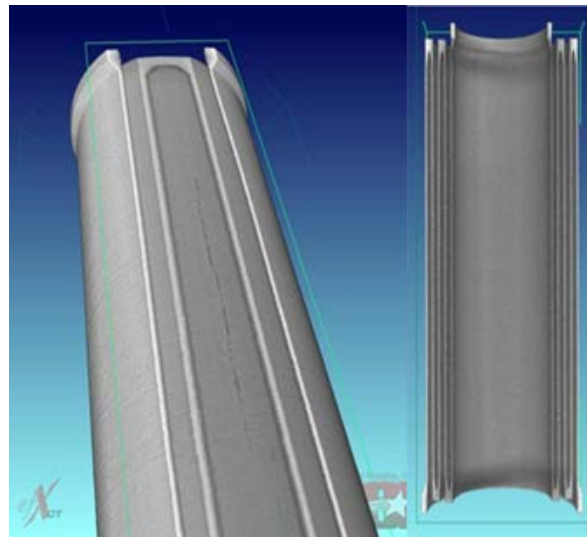
Once the effects of critical defects are understood, physical reference standards have been fabricated, and suitable NDE inspection procedures have been developed, qualification and certification of parts made by AM becomes achievable and practical. The need to qualify and certify parts used in flight applications is especially relevant since NASA (Kjelgaard 2013; Higginbotham 2014) and its commercial space partners (SpaceX 2014) are already aggressively pursuing AM to make flight hardware. However, there are no NDE protocols currently in place to evaluate the quality, workmanship and acceptability of these parts. Central to NDE-based qualification and certification of parts used in NASA ground applications and non-human rated and human rated spacecraft are several NASA standards. Central to NDE-based qualification and certification of parts used in NASA ground applications and non-human rated and human rated spacecraft are several NASA standards: NASA-STD-5001, NASA-STD-5009, NASA-STD-6016 (NASA 2014; NASA 2008b; NASA 2008a). Nondestructive evaluation protocols developed to qualify and certify parts made by AM will adhere to and defer to these overarching NASA requirements documents.

## **2.4 NASA NDE Data: Illustrative Examples**

### ***Computed Tomography***

Computed tomography scans of a Ti-6Al-4V ASTRO-H adiabatic refrigerator component (Figure 15) and Pogo-Z baffles, RS-25/J2-X nozzles, injectors and valve bodies (Figures 16 and 17), demonstrate the ability of CT to detect simulated internal flaws and inaccessible internal features. CT has also demonstrated utility to confirm closure of porosity by HIP post-processing and to detect high-density inclusions in EBM as-manufactured Ti-6Al-4V specimens subjected to HIP (Figure 18). This demonstrates the value of CT to 1) detect deep or embedded defects; 2) interrogate inaccessible features; 3) confirm the effectiveness of post-process treatments

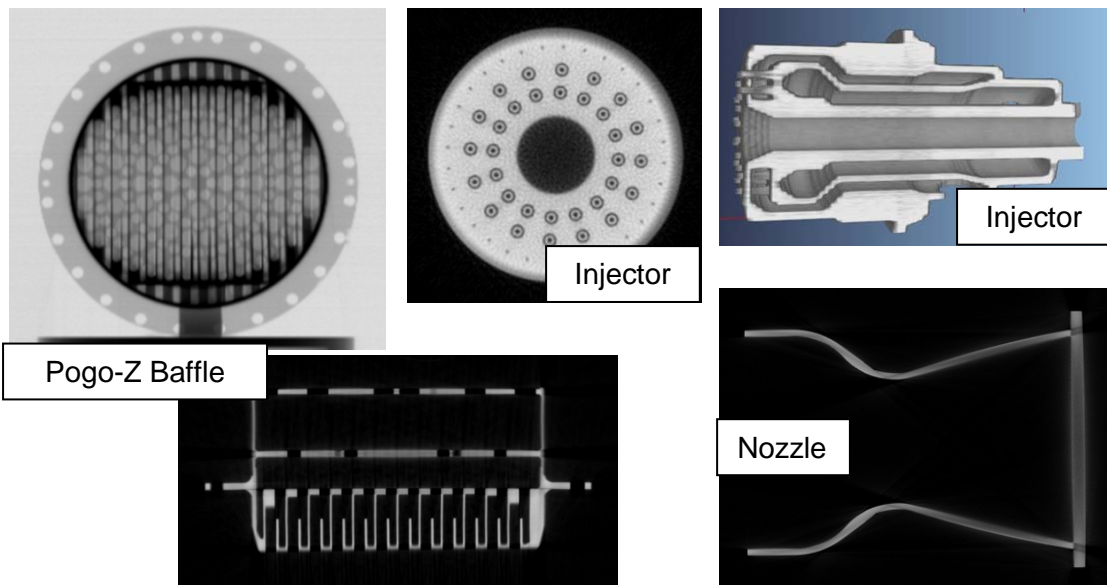
often required to make usable parts made by AM; and 4) to characterize and qualify as-manufactured parts made by AM. One limitation of CT is the inability to reliably detect cracks, since cracks oriented perpendicular to the x-ray beam may not be detected.



(Images courtesy of GSFC)

Figure 15

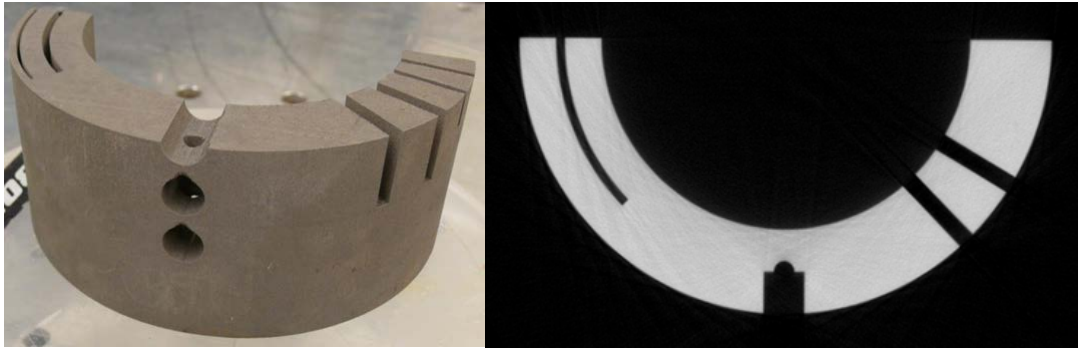
Computed tomography images of an indexing seam on the interior wall (left), and internal structure of a Ti-6Al-4V ASTRO-H adiabetic refrigerator component (right).



(Images courtesy of MSFC)

Figure 16

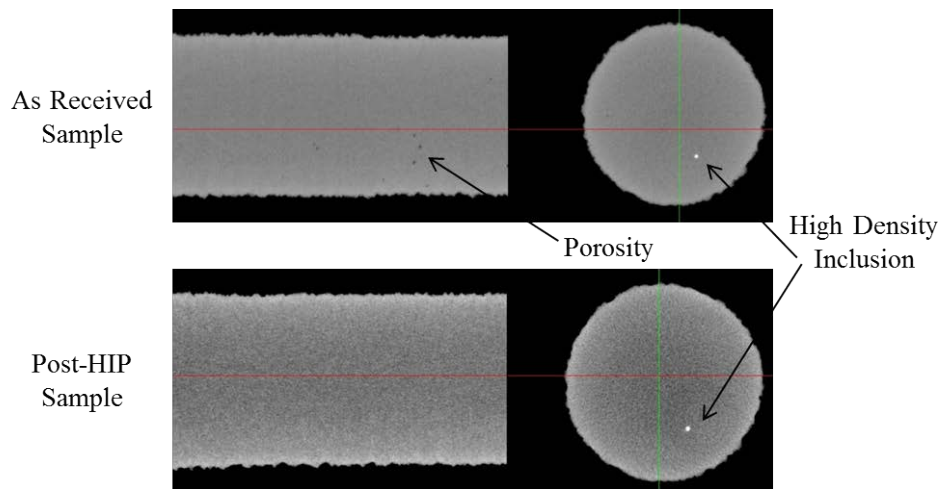
Computed tomography images of Pogo-Z baffles, RS-25/J2-X nozzles, injectors and valve bodies made by a direct metal laser sintering process



(Images courtesy of MSFC)

Figure 17

Photography (left) and computed tomography image (right) of a direct metal laser sintered aluminum gauge block



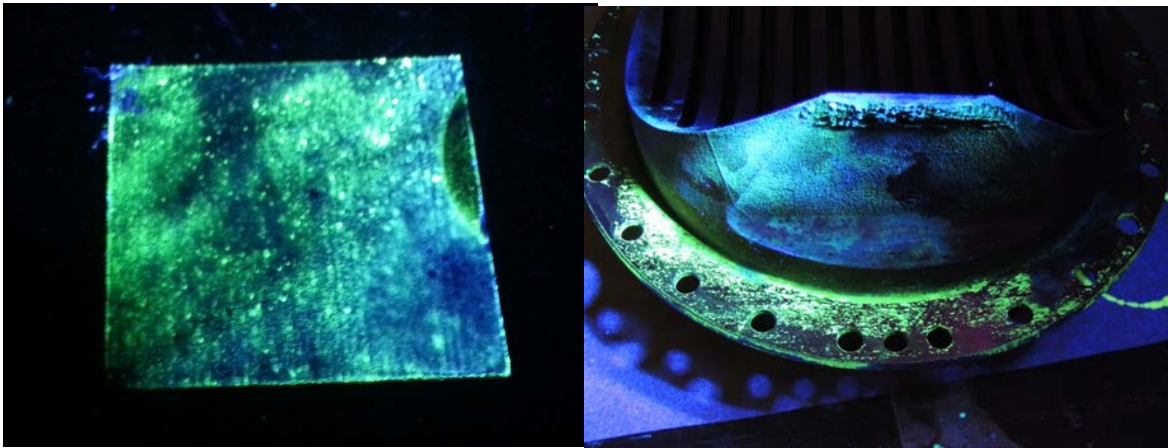
(Images courtesy of GRC)

Figure 18

GRC computed tomography of an as-received Ti-6Al-4V tensile sample and following hot isostatic pressing, confirming closure of porosity.

### ***Penetrant Testing***

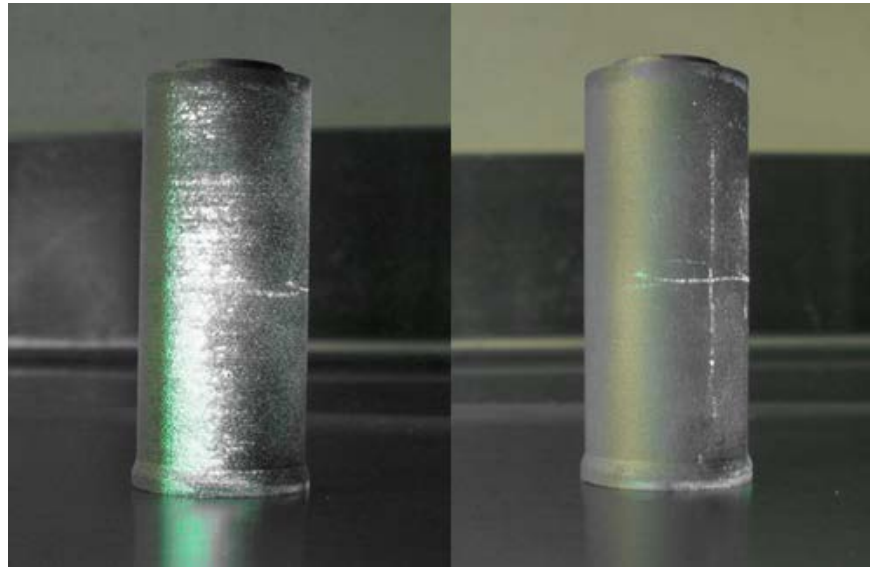
A survey of representative NDE data acquired-to-date is informative and reveals some of the advantages and limitations of NDE as well as specific technological challenges that need to be addressed and advanced. For example, one of the prominent features of parts made by AM is higher levels of porosity compared to conventional wrought, cast or molded parts. The irregular or rough surfaces present in these parts make traditional NDE methods for the detection of surface defects difficult to impossible to accomplish. For example, PT of an as-manufactured Ti-6Al-4V specimen and a machined surface of a Pogo-Z baffle highlight the fact that PT may not be a realistic method for inspection of porous or rough parts made by AM without special post-process machining and polishing (Figures 19 and 20).



(Images courtesy of GRC and MSFC, respectively)

Figure 19

Penetrant testing of a Ti-6Al-4V block under development for a liquid rocket gaseous hydrogen/liquid oxygen (GH<sub>2</sub>/LOX) injector (left) and a Pogo-Z baffle (right) showing high background noise due to as-manufactured surface roughness.



(Images courtesy of GFRC)

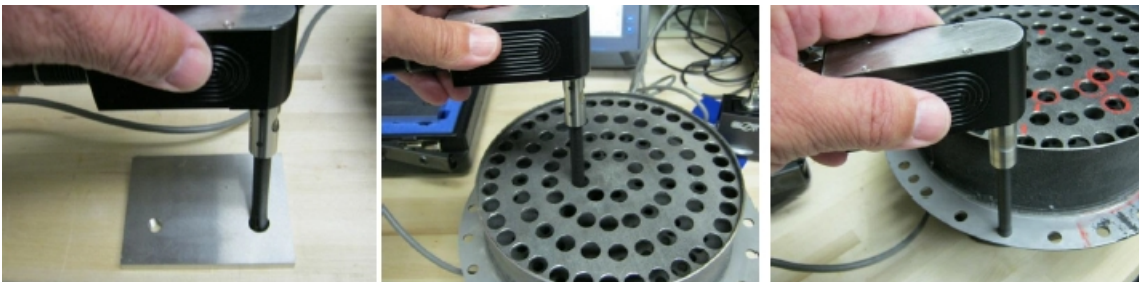
Figure 20

Optical photograph of variable background penetrant indications (left) and of penetrant indications from indexing seams on a Ti-6Al-4V ASTRO-H adiabatic refrigerator component (right).

Similarly, understanding how to measure complex internal/lattice structures containing deep or inaccessible defects will represent a daunting task. Clearly, newer, more sensitive, and non-contact NDE methods are needed to overcome issues that limit the effectiveness of techniques complementary to CT, such as PT, ET, and UT.

### **Eddy Current Testing**

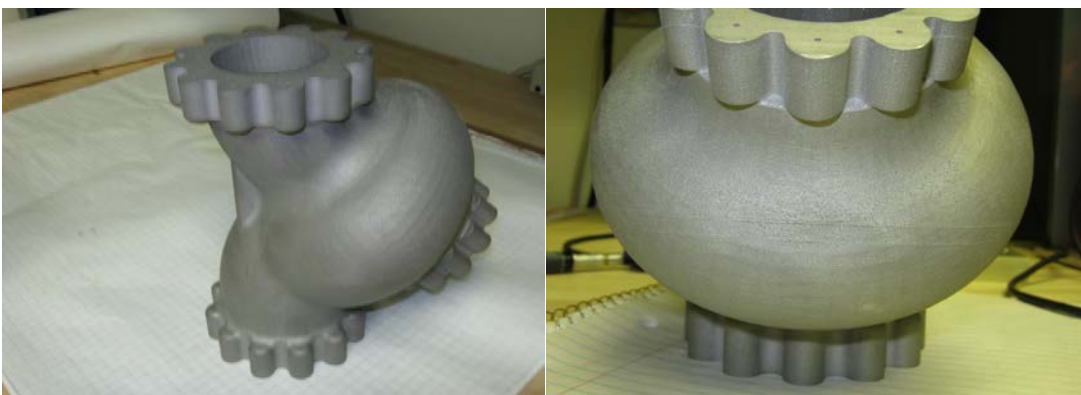
Eddy current testing of accessible regions of additively manufactured components should prove to be very similar to that of conventionally formed (machined, cast) metals. As for any metal component subjected to ET, surface finish and grain structure play a huge role in the success of the method in finding critical defects. For example, ET of an Inconel Pogo-Z baffle (Figure 21) showed that holes not properly prepared had a high degree of background noise. The as-build surface finish was too noisy for ET and had to be completely removed to get a good baseline signal. Regions that were machined smooth behaved well. Similarly, ET of cracked areas of a SLM valve body (Figure 22) revealed no discernable signals from the scratches due to overall surface roughness of the part (signal from smooth area was only slightly less noisy than signal from scratched area). Some research into the understanding of the basic grain structure of the material still needs to be performed, and this grain structure will probably drive additional probability of detection studies to prove out the method for each unique AM material and fabrication process.



(Photographs courtesy of MSFC)

Figure 21

Eddy current testing of a Pogo-Z baffle showing the ET probe in the standard set-up hole (left), probe in Pogo-Z bottom hole (center), and probe in Pogo-Z flange hole.



(Photographs courtesy of MSFC)

Figure 22

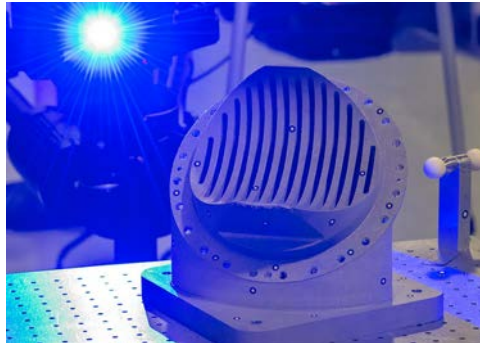
Selective laser melting valve body showing smooth area on side (left) and the scratched area that were inspected by eddy current testing.

### **Structured Light**

Given the possible geometrical and property variation that can occur during deposition of successive layers during the AM build process, control of both part uniformity and dimensions are extremely important. One NDE technique that has emerged is structured light, which can be used to verify part accuracy to ensure close engineering tolerances are met prior to service or



are maintained during service. Marshall Space Flight Center has been actively applying structured light NDE to characterize the dimensional accuracy and surface feature of the Pogo-Z baffle (Figure 23).



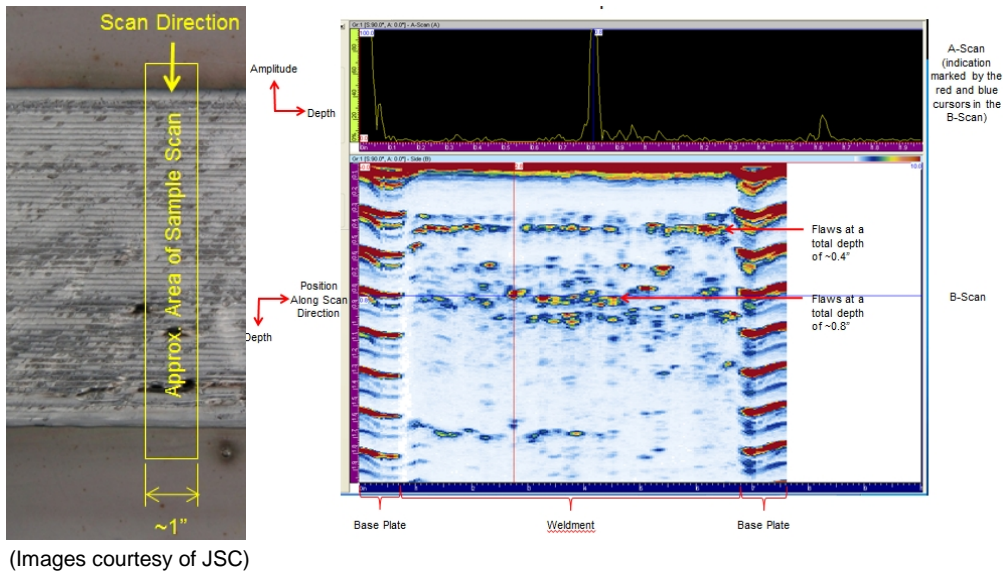
(Image courtesy of MSFC)

Figure 23

Structured light characterization of a Pogo-Z baffle.

### Ultrasonic Testing

Ultrasonic testing and PAUT are being used by JSC for interrogating embedded voids or weak deposition layers in 2219 aluminum EBF<sup>3</sup> parts (Figure 24).



(Images courtesy of JSC)

Figure 24

Ultrasonic testing (UT) inspection of a 2219 aluminum electron-beam freeform fabrication part showing the area scanned (left) and the UT A- and B-scans (right).

### Near Infrared Camera Measurement for In Situ Process Monitoring

Several advancements in the area of feedback and control using near-infrared imaging and machine vision techniques are being used to improve the quality of EBF<sup>3</sup> processing (Figure 8). Advancements include temperature calibration of commercial NIR cameras for measurement and characterization of weld pool characteristics. Additional advancements include multiple cameras, real-time tracking, and feedback algorithms to improve weld shape consistency. Implementations of these systems have improved the consistency of stainless steel straight wall samples. Use of calibrated NIR cameras has been shown to enable detection of defects in parts during fabrication. Several advancements in the area of feedback and control using NIR imaging

and machine vision techniques are being used to improve the quality of EBF<sup>3</sup> processing. Advancements include techniques for temperature calibration of commercial NIR cameras for measurement and characterization of weld pool characteristics. Temperature calibrations are specific to each individual camera and temperature range of the material being inspected. This is achieved using black body calibrations in the temperature ranges of the solidification ranges of the material under investigation. Multiple cameras allow for simultaneous top and side view weld characterizations in real-time. Real-time shape and tracking algorithms allow implementations of power feedback to control the temperature of the weld pool faster than what is humanly possible. Various parameters of temperature, shape, and cooling rate can be used to create metrics for feedback and control in real-time.

## **3.0 Recommendations**

### **3.1 General Considerations for Additive Manufacturing**

General considerations for AM that do not involve NDE are offered here with the caveat that the considerations made do not necessarily reflect the current state-of-the-art or current thinking within the general AM disciplines. As such, the considerations given below are provided to help guide the NDE-related recommendations in Section 3.2. The need for general effort in the following technology push areas specific to AM but not including NDE has been demonstrated. These gaps are (not listed in order of priority):

- Develop an expert system for AM design
- Generate and use design allowables
- Develop a shared, standardized third-party data repository for input materials data, process data, and final part property data
- Validate physics- and properties-based predictive models for AM
- Develop standard data structures, definitions, and metrics for AM models
- Develop in-space processing methods for metals and polymers
- Refine post-processing requirements
- Implement closed-loop process control
- Develop standard guidelines and methods for qualification and certification of parts made by AM
- Adopt standards for AM equipment
- Adopt standards for input materials and finished parts
- Adopt standards for round-robin build and materials testing

Progress in many of these areas must be made before progress is made resolving the NDE-related gaps, discussed next.

### **3.2 NDE-Specific Recommendations for Additive Manufacturing**

This TM demonstrates clearly the vital role NDE will play in closing many of the gaps or challenges associated with the advancement of AM. The push to use AM parts in NASA applications is relatively new and, as a consequence, the knowledge base of NDE as applied to those parts is immature. Nondestructive evaluation will be necessary for the qualification and certification of AM parts; therefore, resources must be invested to make sure NDE is capable of performing this function. There is need for effort in the following technology push areas specific to AM and including NDE. These gaps are (not listed in order of priority):

- Develop mature techniques for NDE of finished parts

- Apply NDE to understand effect-of-defect, including establishment of acceptance limits for certain defect types and defect sizes
- Apply NDE to understand scatter in design allowables database generation activities
- Fabricate physical reference standards to verify and validate NDE data
- Develop *in situ* process monitoring NDE to improve feedback control, to maximize part quality and consistency, and to obtain certified parts that are ready-for-use directly after processing
- Develop better physics-based process models using and corroborated by NDE
- Develop NDE-based qualification and certification protocols for flight hardware that rely on testing and modeling
- Develop ASTM E07-F42 standards for NDE of AM parts

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14. ABSTRACT This report summarizes the National Aeronautics and Space Administration's (NASA) state of the art of nondestructive evaluation (NDE) for additive manufacturing (AM), or "3-D printed," hardware. NASA's unique need for highly customized spacecraft and instrumentation is suited for AM, which offers a compelling alternative to traditional subtractive manufacturing approaches. The Agency has an opportunity to push the envelope on how this technology is used in zero gravity, and enable in-space manufacturing of flight spares and replacement hardware crucial for long-duration, manned missions to Mars. The Agency is leveraging AM technology developed internally and by industry, academia, and other government agencies for its unique needs. Recent technical interchange meetings and workshops attended by NASA have identified NDE as a universal need for all aspects of additive manufacturing. The impact of NDE on AM is cross cutting and spans materials, processing, quality assurance, testing and modeling disciplines. Appropriate NDE methods are needed before, during, and after the AM production process.					
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