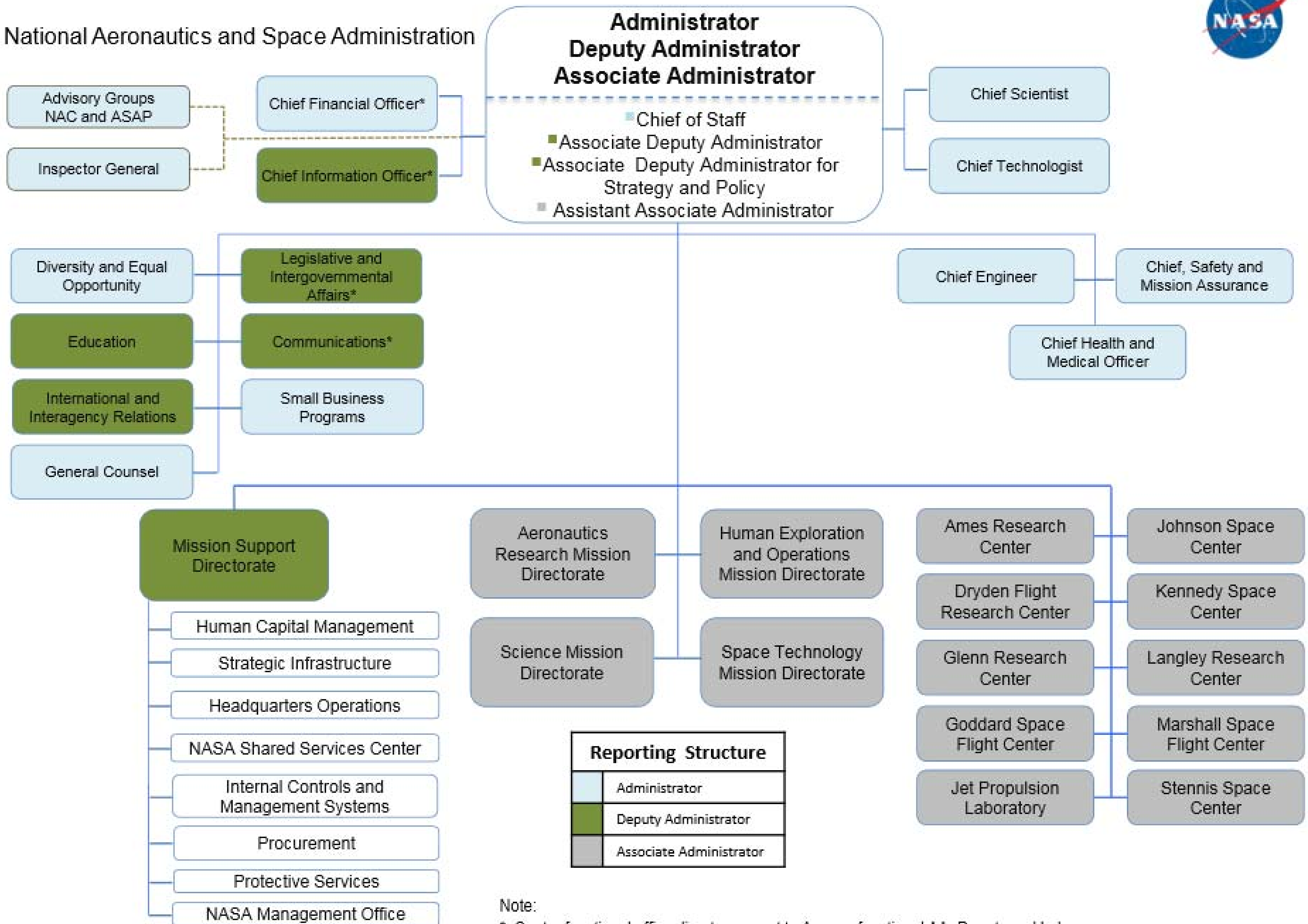
NASA NDE Program

Ed Generazio
Office of Safety and Mission Assurance
NDE Program Manager

Eric Burke
Office of Safety and Mission Assurance
Deputy NDE Program Manager

National Science and Technology Council NDE Communication Group Meeting
April 7-8, 2015
Institute for Defense Analyses, Alexandria, VA

National Aeronautics and Space Administration



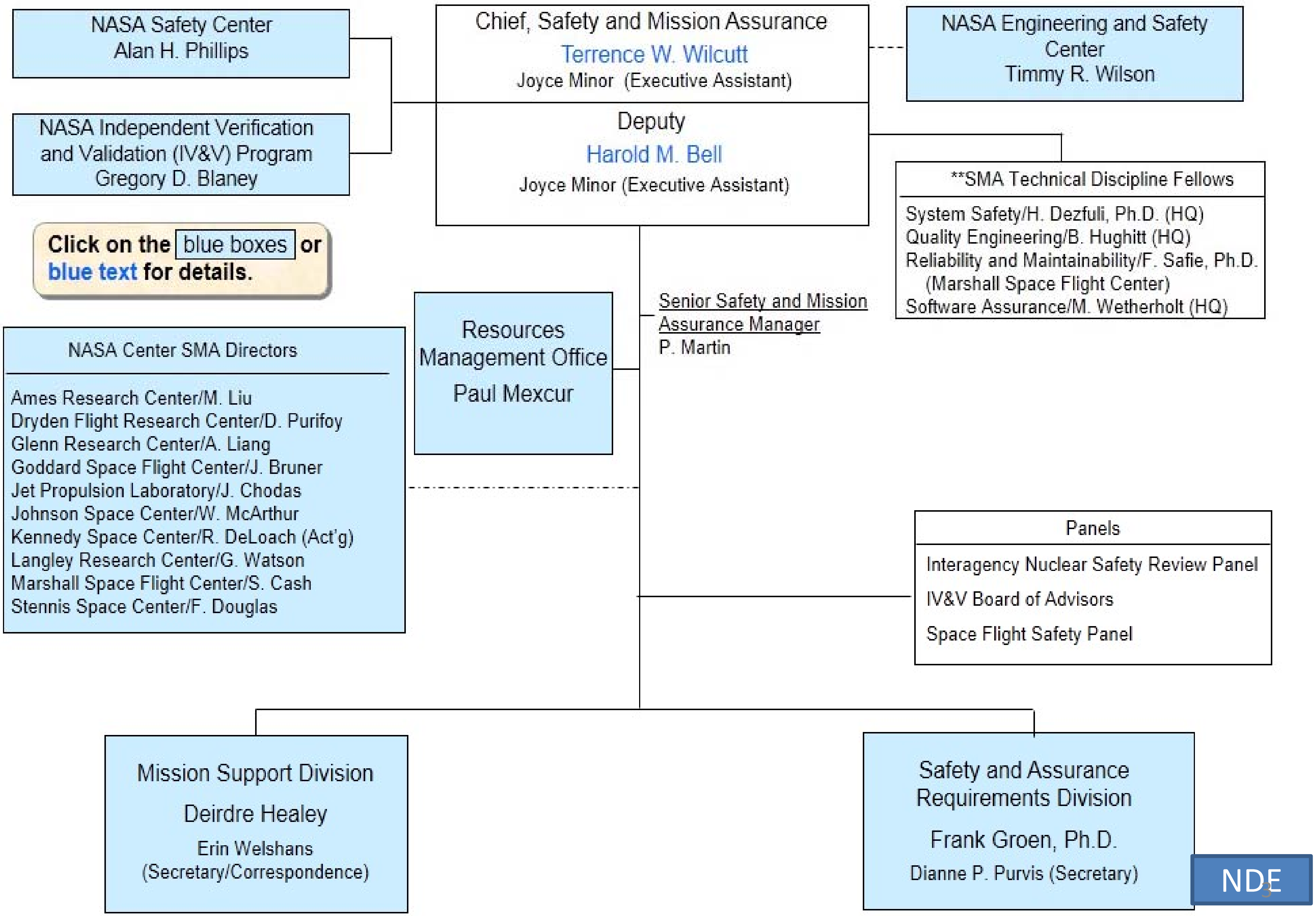
Note:

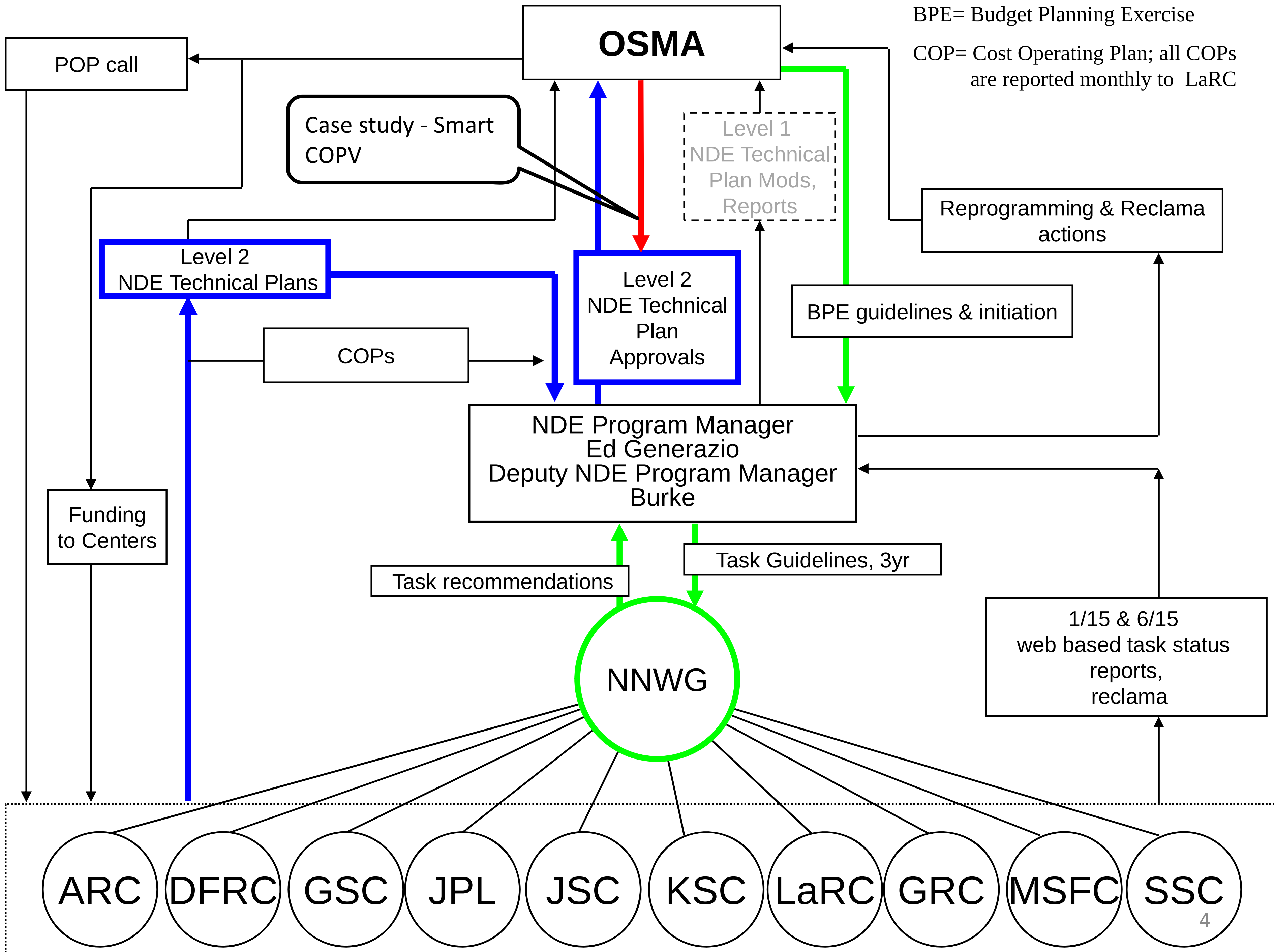
* Center functional office directors report to Agency functional AA. Deputy and below report to Center leadership.

www.nasa.gov

February 2013

Office of Safety and Mission Assurance





BPE= Budget Planning Exercise

COP= Cost Operating Plan; all COPs are reported monthly to LaRC

Program/Discipline Overview

- **Mission:** Develop and maintain NDE infrastructure and technologies to meet NASA Program quality assurance requirements. Develop and maintain NDE Standards and Specifications for quality assurance in aerospace applications. Broaden the use of industry standards within NASA, and support mission critical NDE activities that are unresolved by programs and require concerted efforts to assure mission success.

- **Strategic Goals:** Update and validate POD physical Standards, document Standards, and POD methodologies. Composites remain to be an inspection challenge, therefore credible inspection technologies and methodologies for composite systems are to be developed. Technologies for evaluation real-time on-orbit integrity of thermal protections system (TPS) are to be developed. Develop and adapt NDE technologies supporting commercial space flight, identification of suspect counterfeit EEE parts, and establishing quality of additive manufactured components.

Activities

	Title	Activity Lead/Center	FY 2015 Approved
1	NDE Commercial Space Partner Liaison	K. Elliott Cramer /LaRC	
2	Fracture Critical POD Validation	Charles Nichols/WSTF Ed Generazio/LaRC	
3	NDE of Ablative TPS	Carlo Abesamis/JPL	
4	Monitoring of Thermal Prot Sys	Larry Hudson/AFRC	
5	Physical Standards for Welded Tubing	Ajay Koshti/KSC	
6	Penetrant Inspection Corner Crack Detectability	Bradford Parker/GSFC	
7	NDE Assess. of Underground Pipes	Son Le/SSC	
8	NDE for Suspect Counterfeit EEE Parts	Carlo Abesamis/JPL	
9	Quality Assurance of Composite Panels and Systems	Rick Russell/KSC	
10	NDE Standards and Validation	Regor Saulsberry/WSTF	
11	NNWG Newsletter Website	Charles Nichols/WSTF	

Activities

	Title	Activity Lead/Center	FY 2015 Approved
A	NDE Methods for Additive Manufacturing a) Evaluate NDE Method b) Manufacture Sample c) Modeling	Eric Burke/LaRC	
B	Development of X-ray CT Performance Standards	Justin Jones/GSFC	
C	Pressure Vessel NDE Scanner – Probably of Detection (POD) Study (Commercial Partners): a) Complete an in progress coupon level AL, Ti, and Inconel study b) Utilizing NESC supplied liner and vessels conduct a full POD Study (minimum 29 defects) c) Recommend modifications based on POD experience.	Regor Saulsberry/WSTF Buzz Wincheski/LaRC	

Activities

	Title	Activity Lead/Center	FY 2015 Approved
D	Smart COPV Integrated Demonstrator (SCID)	Regor Saulsberry/WSTF	

Activity 1 - Content

- Activity Title: **NDE Commercial Space Partner Liaison**
- **Purpose:** Establish a Liaison Point-of-Contact (POC) between the OSMA NDE Program and the Commercial Space Companies
- **Justification:** An NDE liaison will help identify, build, monitor, and strengthen NASA-Commercial Partner bridges by working the commercial partners and the NDE Program's Agency-wide NDE POCs to make space commercial partners aware of appropriate NASA expertise and capability that could be used to address NDE issues.
- **Summary:** To establish contacts in the NDE community at the Commercial Space Partners and work to understand their NDE needs and challenges. Inform the commercial partners of the agency NDE capabilities and **establish grass-roots collaborations between NASA NDE researchers and their commercial counterparts.** And to establish an informal **Commercial Space NDE Working Group** to facilitate technical interchange and collaboration.

Activity 2 - Content

- Activity Title: **Fracture Critical Probability of Detection POD Process Validation**
- **Purpose:** Validate POD methodologies used for applications to failure critical inspections required for quality assurance.
- **Justification**: We are seeing a variety of POD methods, having various degrees of integrity, being used for establishing the capability of inspection personnel and systems and this variability introduces unknown risk. Inconsistent inspection capabilities are being reported.
- **Summary:** Validation of Standards on inspection capabilities, and a comprehensive**, decision-support document that provides guidelines on practical risk-informed decisions involving POD and confidence level utilizations.**

Fracture Critical POD Process Validation

Annual Goals/Initiatives

- Review the most common 90/95 probability of detection (POD) methods and draft an appendix to the current standard, titled *Best Practices for Performing POD Analyses and Storing NDT Test Standards*.
- Create a centralized repository for POD specimens/capabilities essentially providing a living NDE capabilities table for NASA-STD-5009.

Accomplishments

- The Design of Experiments POD (DOEPOD) V 1.0 software was ported from Windows XP to Windows 7 V1.2 and now includes network support.
- Directed Design of Experiments for Validating Probability of Detection Capability of NDE Systems (DOEPOD) Manual v.1.2 was approved for NTRS publication – Sep '14
- Familiarization training for LaRC/GSFC file structure and DOEPOD performed. – Oct '14
- Electronic and hard copy data have been consolidated at WSTF. – Nov '14
- Software requirements agreed to for Phase I of the NNWG POD Standards Library (NPSL): catalog and search capabilities. – Jan '15

Risks/Challenges/Concerns

- Waiting on estimate from JSC IT to determine if *Phase I* NPSL tasks can be completed in FY15 with present funds.

Schedule Status/Coming Events

- Inventory all data; identify and fill gaps, should they exist.
- Alpha test/approve NPSL entry and query capabilities in June.
- Create a platform-independent POD analysis tool – FY16
  - Extract, interpret, and integrate macros from DOEPOD into NPSL.
  - Code in MLE as presented in NASA/TM–2014-218183, April 2014.
  - Add internal and external validation test for MLE estimates (these have been draft coded into DOEPOD, but not released).
- Analyze and log the following NNWG POD standards – FY17
  NDE Methods: UT, RT, ET, & PT
  - ~101 flat plates with fatigue cracks (Al, INCO, & Ti)
  - 61 plate weld specimens with lack of fusion (Al & Ti)
  - 20 plates welded with an EDM notch specimens (Al, INCO, SS & Ti)
  - ~33 1" or 2" tubes welded with an EDM notch (INCO, SS)
  - ~61 1" or 2" tubes welded with lack of fusion (INCO & SS) and
  - 61 fastener hole crack specimens (Al & Ti)

Fracture Critical POD Process Validation

Notional “Inspection Standard” Interface – Unofficial, For Discussion Only

NNWG POD Standards Library

Group Code: A3 **Flaw ID:** AII-1-1

Standard S/N: A3 AII-1-1

Description: Inconel 718 Flat Plate Fatigue Panel

Dimensions: 4 8 0.25 WxLxD in

Condition: Good

Storage Loc.: WSTF-B201 Rm 159

Availability: In Use **Comment:** POD Study

Contact: Charles Nichols

Flaw Class: Crack

Location: Bottom, X5.88, Y1.13 (inches) B/L3

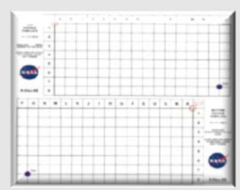
Flaw Length: 60.8 **Width:** 5.6 **Depth:** 20.1

Flaw Units: mils **Angle [°]:** 90 **Ref:** X-axis

Your Permission Level for this standard: Administrator

Top Side Click to Enlarge

Bottom Side Click to Enlarge



Click to View/Edit Registration Grid

Reference Documents

Add to List

Edit this Standard

Return to Main Menu

Fracture Critical POD Process Validation

Notional "POD Overview" Interface

NNWG POD Standards Library

Group Code: A3 **POD%:** 90 **Confidence%:** 95

Description: Inconel 718 Flat Plate Fatigue Panels

Flaw Class: Crack

Flaw Dimension: Length

Flaw Range: 11.9 **to** 697.8 mils

Inspection Method: UT Inspection System FS6R546N

Minimum Acceptably Detectable Flaw Size: 43 mils

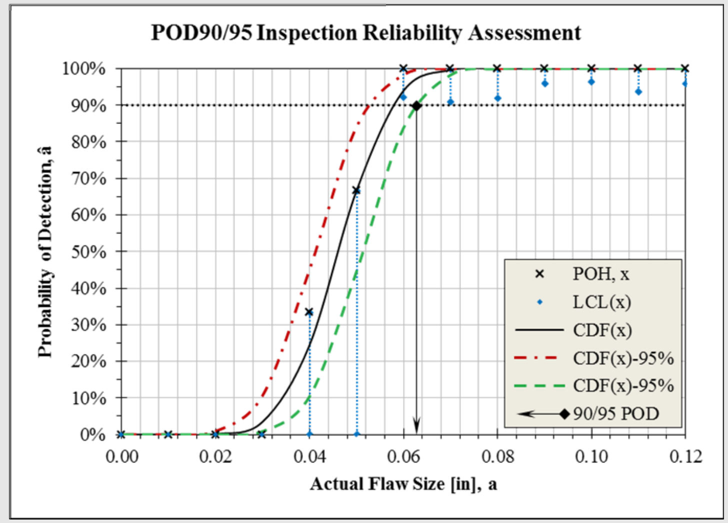
Total Flaws: 12 **Number of Inspectors:** 3

Hits: 24 **Misses:** 12 **Success Rate [%]:** 67

Accepts: 0 **False Calls:** 0 **False Call [%]:** 0

View/Edit Inspections | Export Inspection Data

Your Permission Level for this Study: Administrator



Click to Enlarge

Chart Options

- CDF
- CDF+
- CDF-
- Hit/Miss
- LCL
- POH
- POD

Inspection Standards

Reference Documents

Estimate POD at Flaw Size

Edit this POD Study

Return to Main Menu

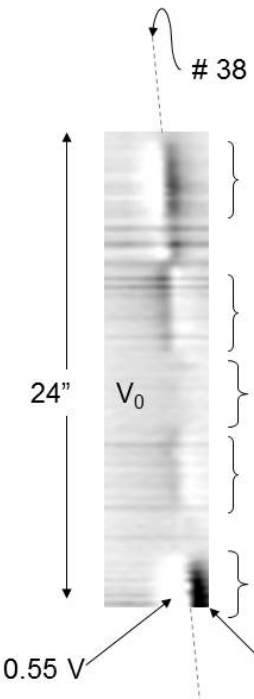
Activity 4 - Cont.

- Activity Title: **Electric Field Imaging** (Manager's Special)
- **Purpose:** Ability to **image static and electrostatic potentials and fields**
- **Justification:** There are currently no methods for remotely evaluating **electrostatic** and quasi-static fields emanating from, around, and passing through objects. **Remote health monitoring of astronauts.**
- **Summary:** The project work elements include optimized sensor designs for quantified images of static and electrostatic potentials and fields, 2D array. Suite of sensors designs for EFI of solid, liquids, gases, and plasmas

EFI: New Electrostatic Eyes

EFI Electrostatic Potential Image of latent charge distribution generated by triboelectrically drawing the letters “NASA” on PTFE. The EFI image is ovelaid onto the area scanned.

Tethers

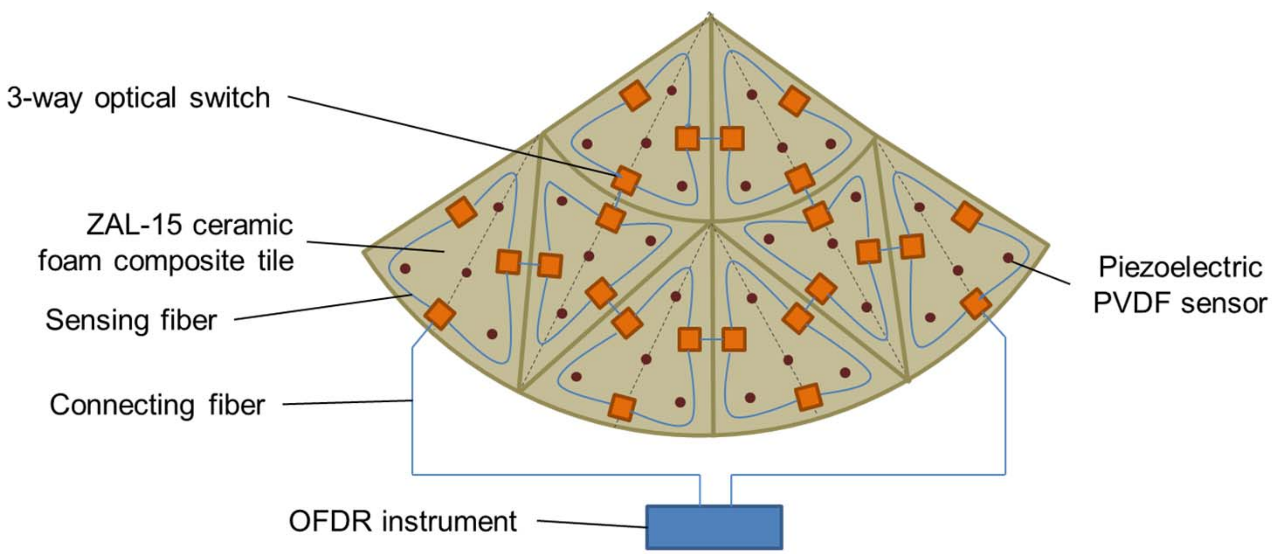


Activity 4 - Content

- Activity Title: **Monitoring of Thermal Protection Systems Using Robust Self-Organizing Optical Fiber Sensing Networks** (a fundamental technology providing full field strain & temperature mapping for TPS, space partner COPVs)
- **Purpose: Detect & evaluate MMOD (Micrometeroid Orbital Debris) impact damage** to thermal protection systems using embedded acoustic and fiber optic thermal sensor networks
- **Justification:** There are currently no in-flight inspection methods that can accurately and thoroughly assess the health of TPS and thereby ensure safe operation prior to reentry. The project is directly aligned with NASA Office of Chief Technologists Space Technology Roadmap TA09.1.5 – Entry Descent & Landing Systems, Instrumentation and Health Monitoring.
- **Summary:** The project work elements include the development of a robust, electronically-reconfigurable sensor network and a demonstrator prototype that consists of a segmented, circular ablative thermal protection system. The final outcome of the project will be incorporation of the monitoring system into a larger-scale TPS experimental structure at NASA in FY15.

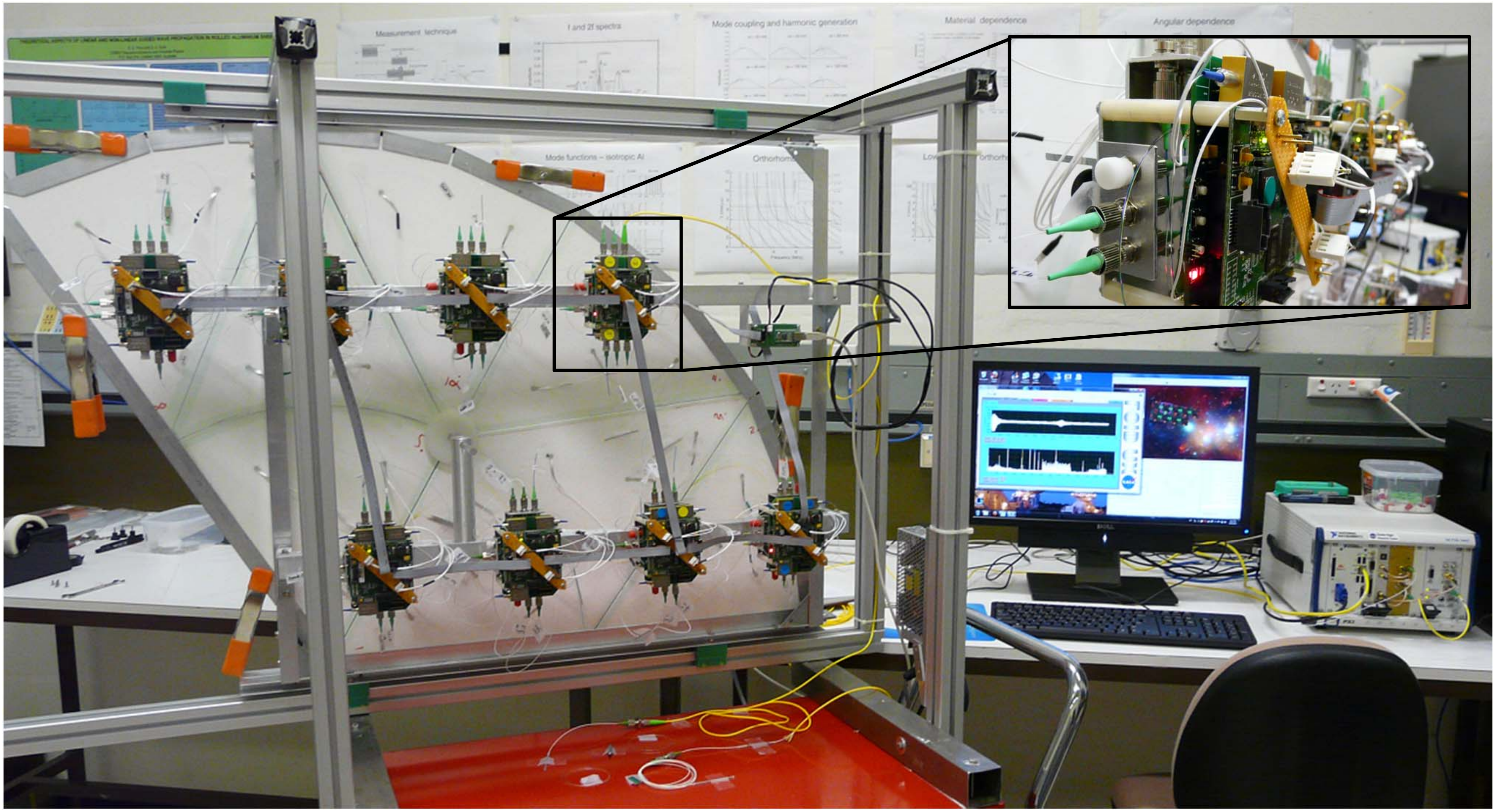
Final System Design

- The final design of the systems consists of 8 triangular tiles
- The 8 tiles will cover a 120 degree segment of a 5 foot diameter circle
- Each tile has an optical and electrical connection to their adjacent neighbor
- Fiber-optic measurement system has 2 channels to connect to the sensing network



Schematic of Demonstrator

Complete TPS Monitoring System Demonstrator

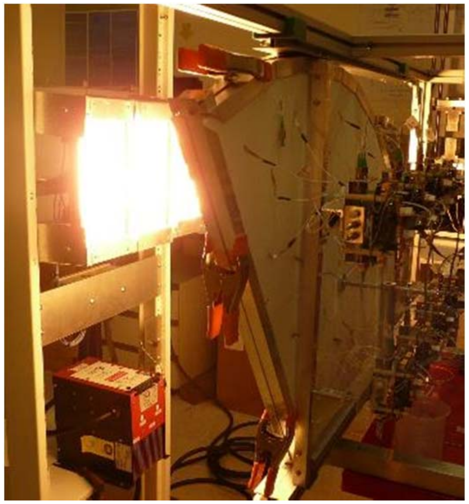


Rear View

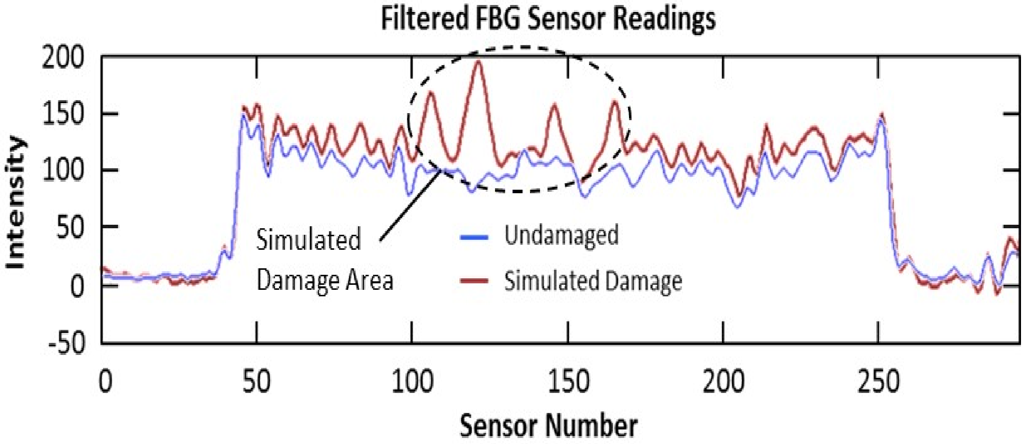
Progress – Simulation Testing

- Identifying damaged regions on tiles requires finding the sensors that heat at a higher rate than normal, and take into account small variations in the sensitivity of each FBGs
- Severity of TPS damage is evaluated through secondary sensing using FBG temperature sensors
- Results of large area heating test verified with local heating
- Damage detected in FBG sensors directly behind the simulated damage area and in sensors up to 20mm away

"Damaged" TPS



Thermal Health Check

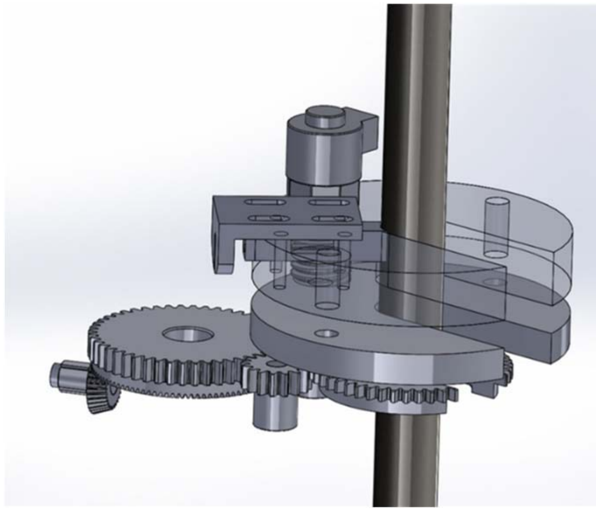


Activity 5 - Content

- Activity Title: **Development of In-situ NDE Techniques and Physical Standards for Inspection of Welded Tubing used in Spacecraft**
- **Purpose:** Develop a prototype eddy current scanner and physical validation standards for in-situ inspection of orbital tube welds in pressurized tubing assemblies.
- **Justification:** Closeout welds in spacecraft environmental control and propulsion system tubing often cannot be X-rayed due to access restrictions. An alternative to X-ray inspection is required to ensure the structural integrity of the welds.
- **Summary:** Custom eddy current probes and a **prototype scanner have been designed, fabricated, and tested on tubing samples containing inner and outer diameter machined notches.** Optimized procedures will be developed on additional representative samples containing crack-like flaws at various locations and orientations in tubing welds.

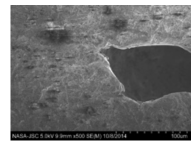
NDE/Development of In-Situ NDE for Welded Tubing used in Spacecraft

Orbital Weld Eddy Current Inspection Tool



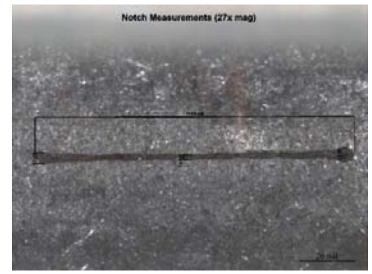
FlawTech 0.115” Long x 0.015” Deep Tube I.D. Flaw

500x SEM Image

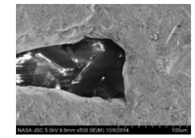


Left end

100x Optical Image of a Cross Section after Etching



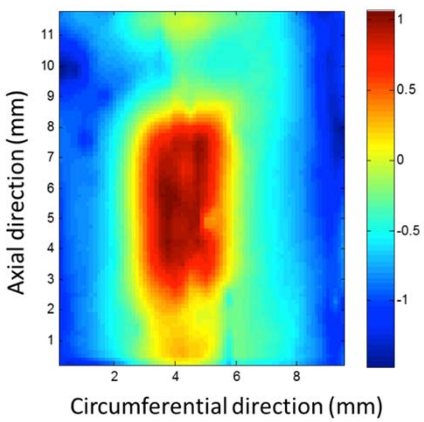
500x SEM Image



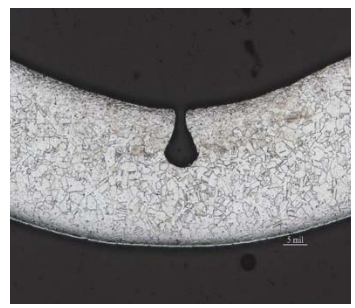
Right end

The surface of the sample adjacent to the flaw exhibited a “hammered” appearance (blue box) suggesting the sample was cold worked in order to reduce the surface opening. Opening is less in middle compared to either ends

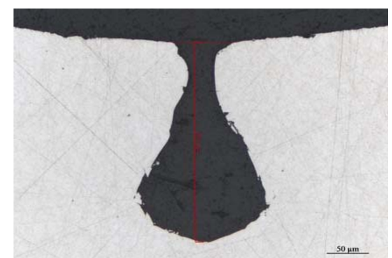
Circumferential Eddy Current Probe Response at 200 kHz Drive Frequency for the FlawTech Sample



Cross Section Through Center of the Flaw



The material microstructure at the tube wall O.D. and I.D. both show evidence of cold working, i.e. compressed grains



The depth of the flaw measured 10.2 mils verses the target depth of 15 mils

Note the narrowed surface opening possibly due to cold working of the tube I.D.

Activity 6- Content

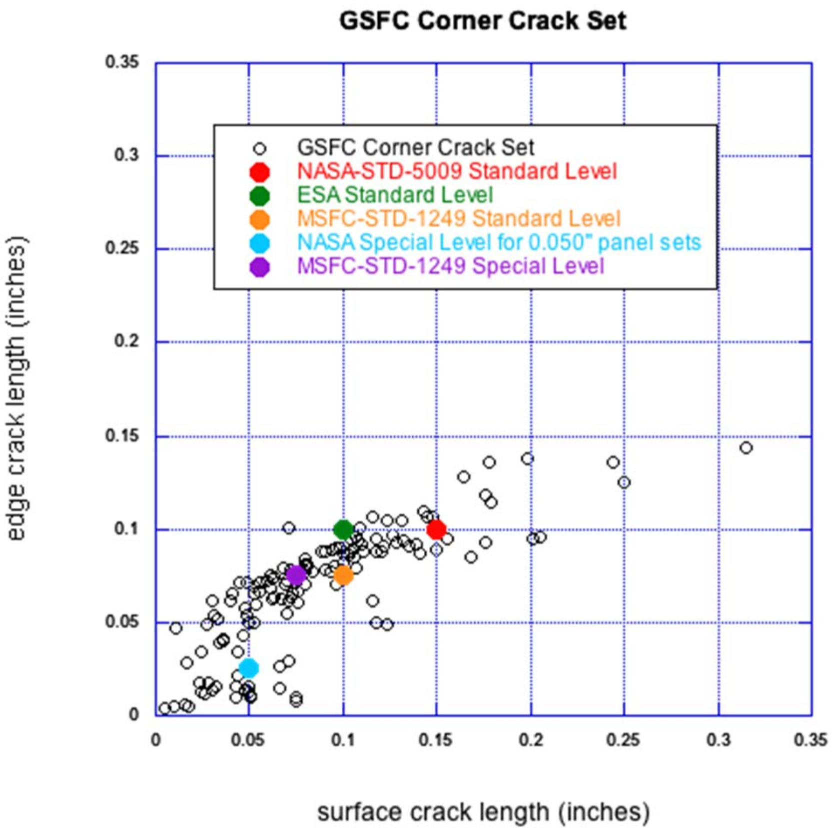
- Activity Title: **Investigation of Penetrant Inspection Corner Crack Detectability**
- **Purpose:** Validate the penetrant inspection (PT) corner crack assumed detectable (a 90/95) size in NASA-STD-5009.
- **Justification:** The assumed **detectable corner crack size for PT in NASA-STD-5009 is not based on inspection demonstration data.** The size was increased during the migration from MSFC-STD-1249 to NASA-STD-5009. The **PT corner crack size has become the most common flaw type driving designs.**
- **Summary:** Four sets of corner crack specimens have been borrowed from JSC and are being evaluated for suitability for use in PT demonstration tests. These sets are all corner cracks at holes (CC04 in NASGRO). Production of set of specimens with cracks in rectangular plates (CC01 in NASGRO) is near completion. Suitable specimen sets will be used in capability demonstration testing. The results of the study will result in a validated PT corner crack assumed detectable (a 90/95) size in NASA-STD-5009.

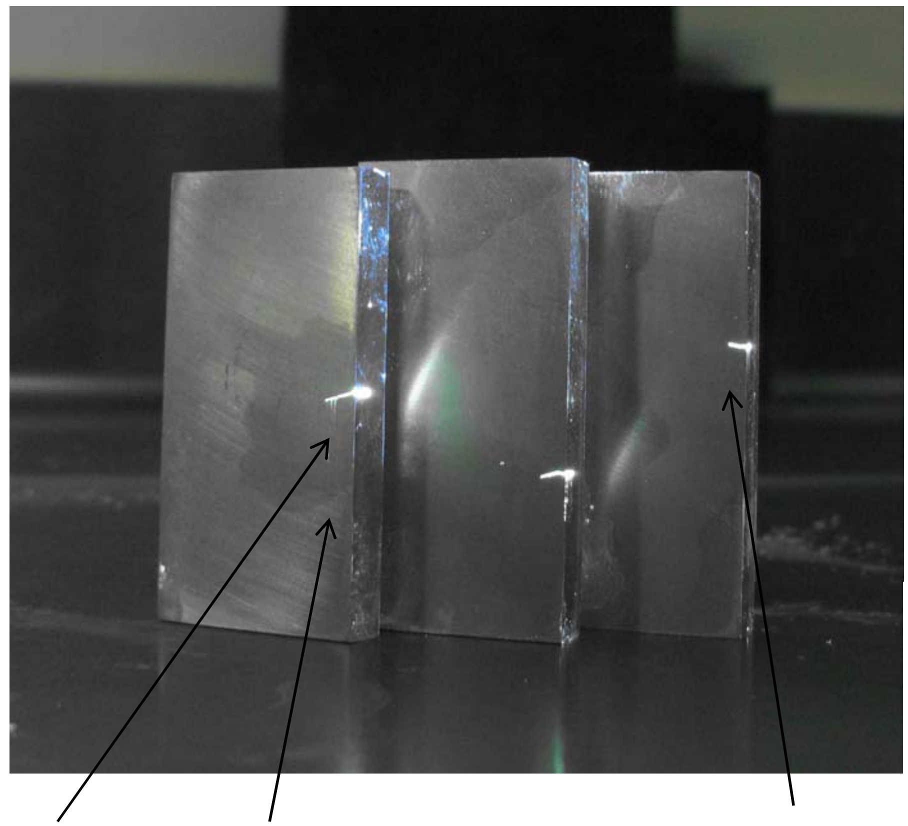
CC01: Corner Crack in Rectangular Plate

Current NASA-STD-5009 PT CC01 c = 0.150" a = 0.100"

Proposed recommendation changing CC "a" from 0.100" to 0.075"

152 specimens, 154 low cycle fatigue cracks.





0.150" by 0.100" 0.100" by 0.100" 0.075" by 0.075"

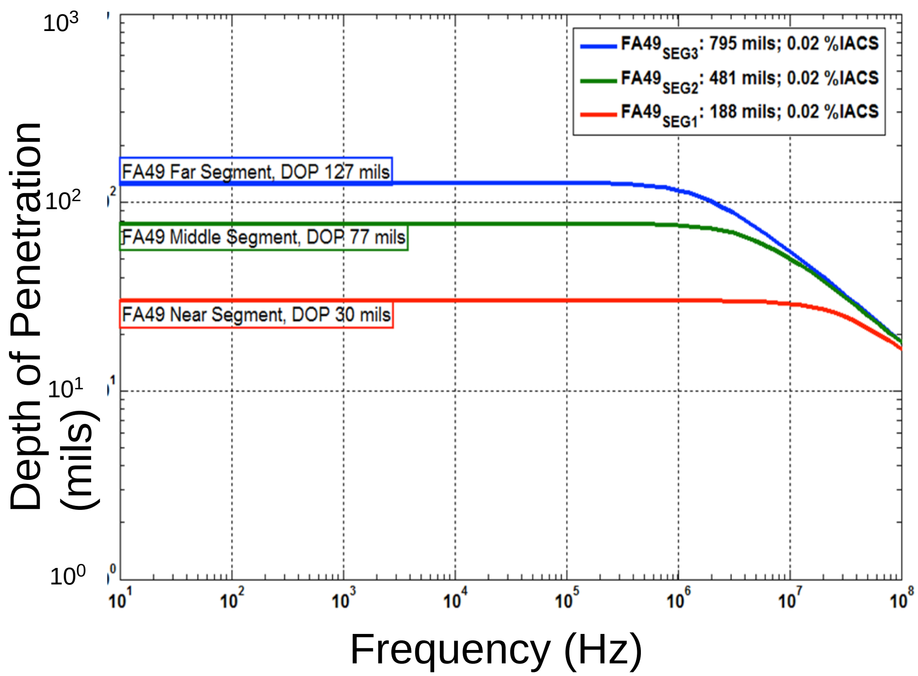
Activity 8 - Content

- Activity Title: **NDE for Suspect Counterfeit EEE Parts**
- Purpose: Select viable NDE tools and techniques for counterfeit electronic parts mitigation.
- **Justification:** New NDE tools and/or techniques using existing technology present opportunities to better meet the ever evolving threat of counterfeit parts .
- **Summary**:
  - Continue scanning components using the DTEK process and complete the assessment.
  - Integrate the Sonoscan Computed Tomography Equipment into the suite of counterfeit inspection tools at JPL.
  - Integrate real time X-Ray process into the suite of counterfeit inspection tools at JPL.
  - ChromoLogic's new QuanTEK system has similarities to and differences from their predecessor **DTEK system, which was determined to be unacceptable.** The hope is that the differences of the QuanTEK system will overcome the shortcomings of DTEK.

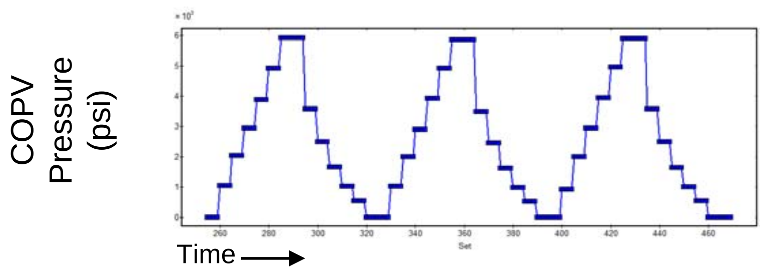
Activity 9 - Content

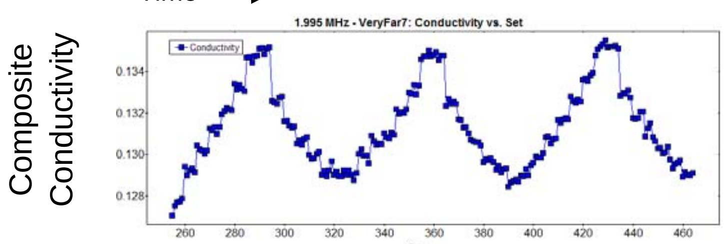
- Activity Title: **Quality Assurance of Composite Panels and Systems**
- Purpose: To design and demonstrate the fundamental ability of NDE sensors for the **measurement of damage and internal stresses affecting the quality and fitness for service of composite panels and systems**
- **Justification:** Currently there is no simple method of determining the internal stresses of a composite panel or system. In particular there are no current screening techniques to monitor the internal stresses of these systems to determine assist in component acceptance for fitness for service or for predicting pending failures.
- **Summary:** Products for FY15 will include hardware delivery and an final report which will include development of a detailed plan for transition through flight qualification and testing.

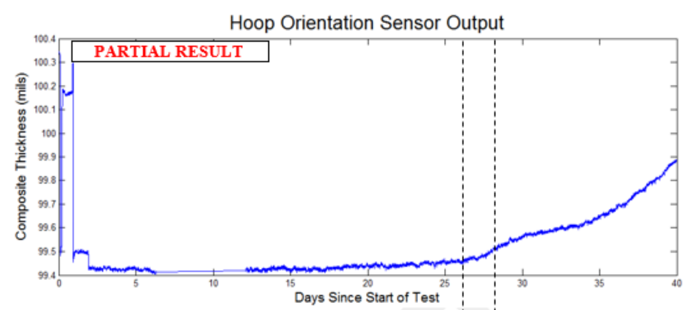
Depth of penetration variation with frequency for MWM-Array FA49

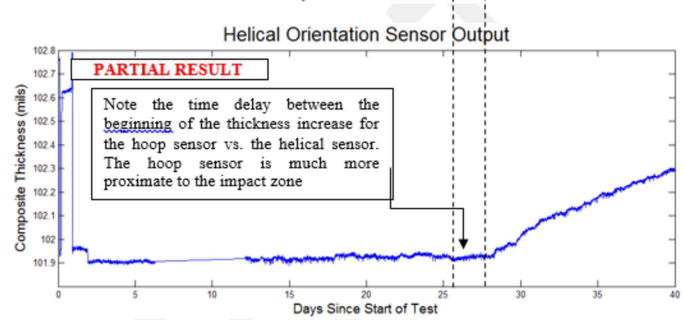


Test set-up at NASA White Sands









Activity 10 - Content

- Activity Title: **NDE Standards and Validation to Assist Commercial Partners and NASA Programs**
- **Purpose:** 1) Develop voluntary consensus standards for fracture critical composites and composite overwrapped pressure vessels used in commercial partners and NASA missions. 2) Mature NDE procedures into quantitative accept-reject criteria for the entire life cycle, focusing on new high sensitivity NNWG eddy current scanner
- **Justification:** Aligns with OSMA goals to support Space Launch System/ORION (Crew Vehicle), Commercial Crew human Mars missions by generating critical NDE standards and an eddy current scanner development to provide safer COPV.
- **Summary:** Provide fundamental **NDE standards and equipment necessary to ensure safe composite and liners** being used in NASA and commercial spacecraft. The internal eddy current scanner is matured and Standard will be document for application to NASA and commercial programs.

NDE Standards and Validation

Key Objectives/Initiatives

- Develop voluntary consensus standards for fracture critical composites and metals, hybrid composite/metal material systems, and additively manufactured parts to assist commercial partners and NASA missions
- Mature Scanning Eddy Current processes, do a coupon Probability of Detection study and move the refined processes to an ASTM standard

Accomplishments

- Flat Panel Composites:
  - 5-yr. approvals: E2581/Shearography; E2582/Thermography; E2661/Acoustic Emission, E2662/Radiology; and E2533/NDE Guide
  - Work initiated on a new flash thermography standard
- Hybrid Composite/Metal Material Systems:
  - ASTM D2982-14 (NDE of thin-walled metal liners) approved
  - ASTM D2981-15 (NDE of composite overwraps) approval pending
- Fracture critical metal structures:
  - Production Eddy Current scanner to be completed Feb. 2015. POD study in planning phase; refined procedures will go in an ASTM standard
- Additively manufactured parts:
  - Team assembled, draft standard begun (WK47031)

Risks/Challenges/Concerns

Technical

- Composite effect-of-defect hard to determine
- Detecting critical initial flaw thin metallic is hard
- NDE not incorporated in additive manufacturing

Safety

- Commercial partners need help with composite vessels and liners

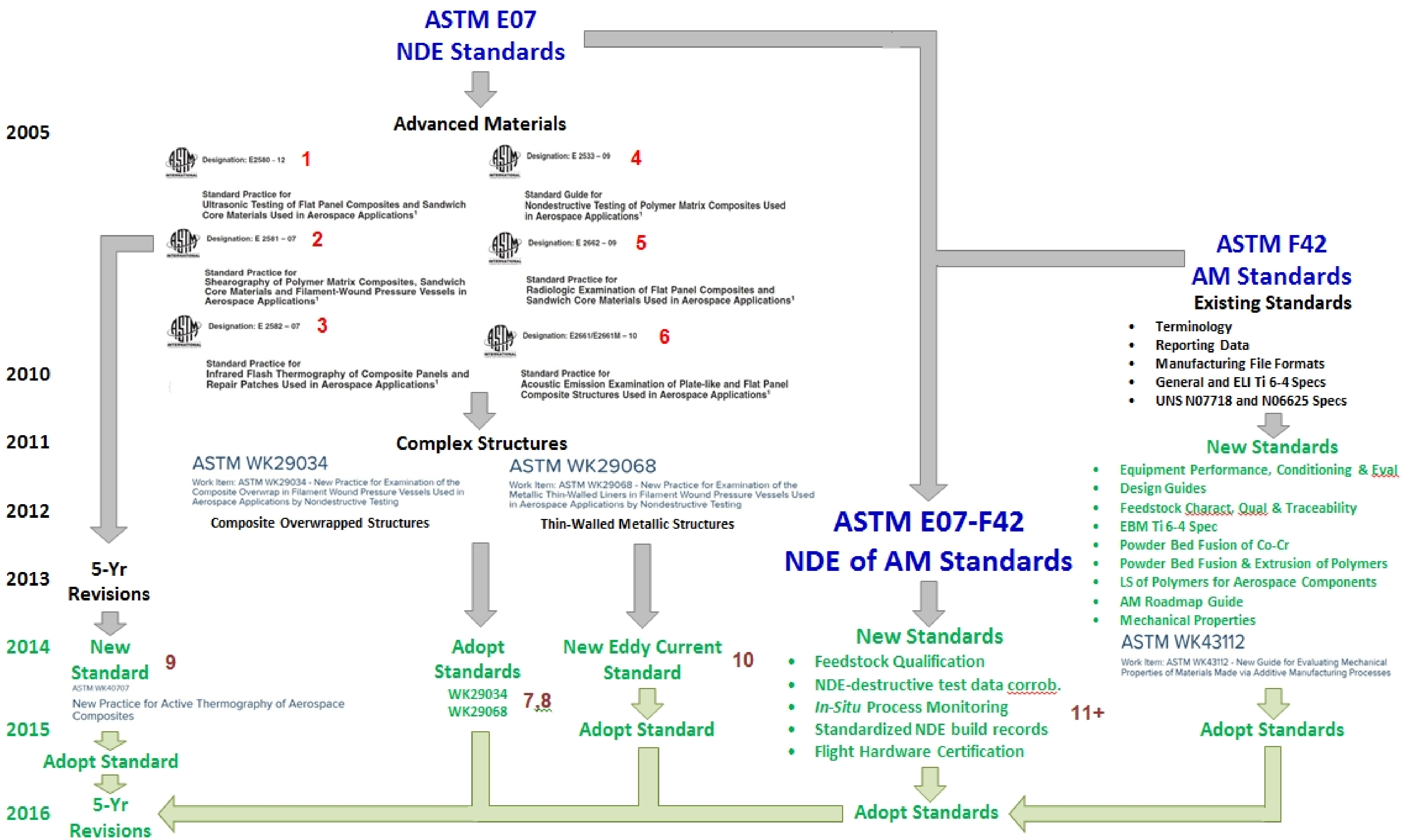
Budget

- Probability of Detection studies needed to validate NDE methods are very expensive

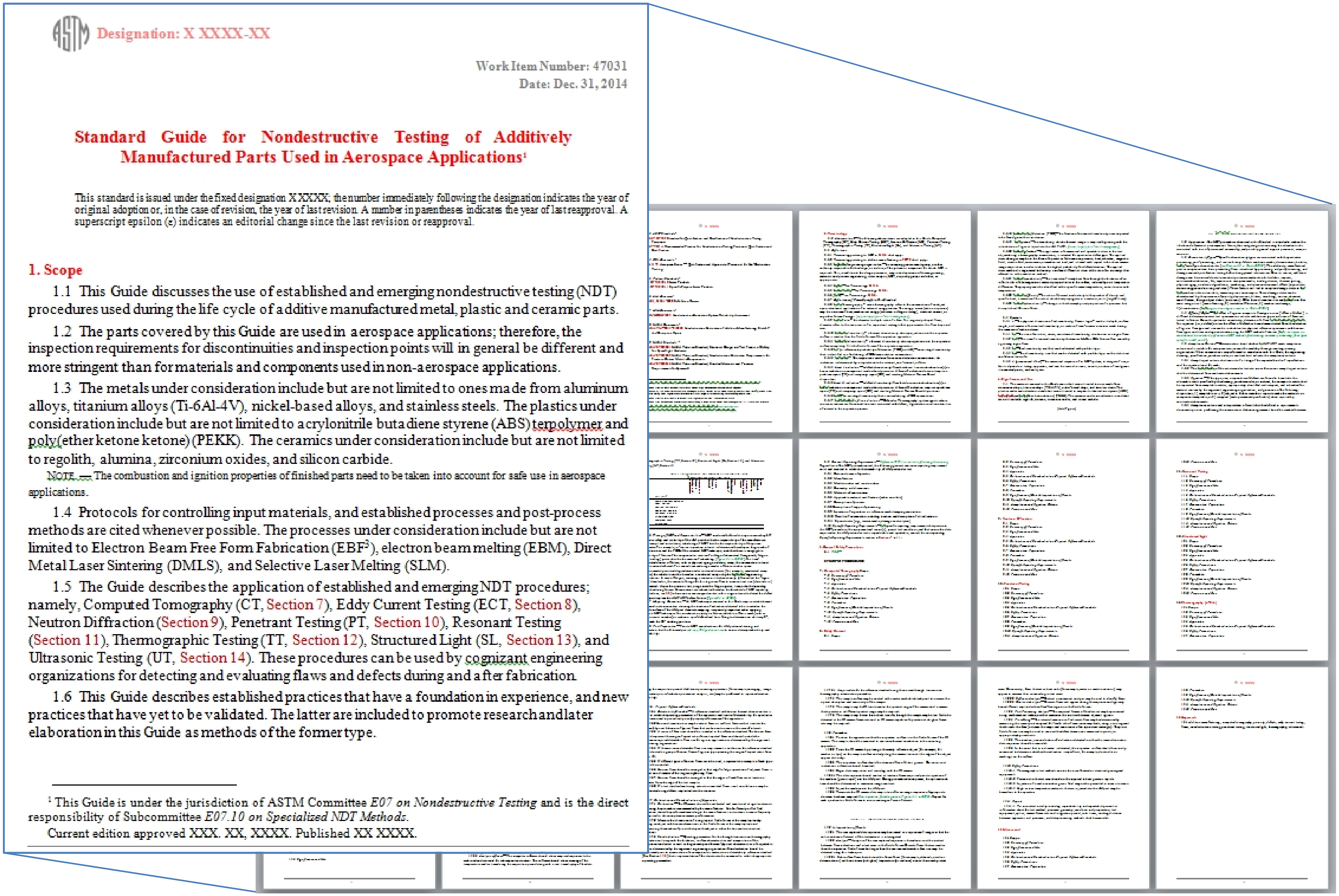
Schedule Status/Coming Events

Milestone	Date
Eddy Current coupon-level POD complete	8/2014
WK29068 (NDE of metal liners) approved as ASTM D2982-14 WK43438/E2581 (shearography of polymer composites) reapproved WK46042/E2582 (thermography of polymer composites) reapproved	9/2014
WK47031 (NDE of additive manuf.) draft completed, team assembled WK47026 (NDE of polymer composites) E2533 5-year revision begun	12/2014
ASTM E07.10 Task Group on NDE of Aerospace Materials meeting • WK44903/E2662 5-year rev status (radiology of polymer composites) • Initiate E2661 5-year rev (acoustic emission of polymer composites)	1/2015
EC production scanner scheduled completion and POD start WK29034 (NDE of overwrap) ASTM D2981-15 approval expected WK40707 (active thermography of composites), begin writing	2/2015
ASTM E07.10 Task Group on NDE of Aerospace Materials meeting	6/2015
Closure/status on E2661, WK40707, WK44903, WK47026 (E2533), and WK47031. FY16 plan due.	9/2015

NDE Standards and Validation



NDE Standards and Validation



Designation: X XXXX-XX

Work Item Number: 47031
Date: Dec. 31, 2014

Standard Guide for Nondestructive Testing of Additively Manufactured Parts Used in Aerospace Applications[1]

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This Guide discusses the use of established and emerging nondestructive testing (NDT) procedures used during the life cycle of additive manufactured metal, plastic and ceramic parts.

1.2 The parts covered by this Guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points will in general be different and more stringent than for materials and components used in non-aerospace applications.

1.3 The metals under consideration include but are not limited to ones made from aluminum alloys, titanium alloys (Ti-6Al-4V), nickel-based alloys, and stainless steels. The plastics under consideration include but are not limited to acrylonitrile butadiene styrene (ABS) terpolymer and poly(ether ketone ketone) (PEKK). The ceramics under consideration include but are not limited to regolith, alumina, zirconium oxides, and silicon carbide.

NOTE — The combustion and ignition properties of finished parts need to be taken into account for safe use in aerospace applications.

1.4 Protocols for controlling input materials, and established processes and post-process methods are cited whenever possible. The processes under consideration include but are not limited to Electron Beam Free Form Fabrication (EBF^3), electron beam melting (EBM), Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM).

1.5 The Guide describes the application of established and emerging NDT procedures; namely, Computed Tomography (CT, Section 7), Eddy Current Testing (ECT, Section 8), Neutron Diffraction (Section 9), Penetrant Testing (PT, Section 10), Resonant Testing (Section 11), Thermographic Testing (TT, Section 12), Structured Light (SL, Section 13), and Ultrasonic Testing (UT, Section 14). These procedures can be used by cognizant engineering organizations for detecting and evaluating flaws and defects during and after fabrication.

1.6 This Guide describes established practices that have a foundation in experience, and new practices that have yet to be validated. The latter are included to promote research and later elaboration in this Guide as methods of the former type.

[1] This Guide is under the jurisdiction of ASTM Committee *E07 on Nondestructive Testing* and is the direct responsibility of Subcommittee *E07.10 on Specialized NDT Methods*.
Current edition approved XXX. XX, XXXX. Published XX XXXX.

Activity C - Content

Activity Title: **Accomplish Multi-purpose Pressure Vessel NDE Scanner Probability of Detection (POD) Study**

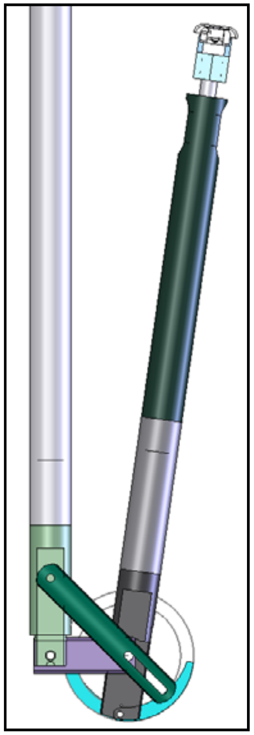
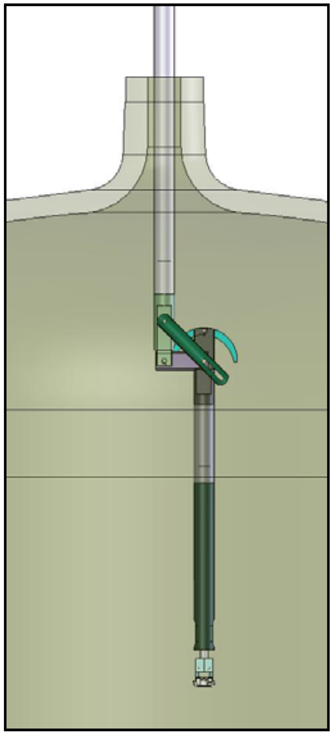
Purpose: Is to allow quantification of the Multi-purpose Pressure Vessel NDE Scanner flaw detection probability of detection capacity.

- Should allow widespread replacement of out dated dye penetrants methods which are currently not capable of detecting small critical flaws in high performance composite pressure vessel liners and thin wall metallic vessels and provide other quality screening functionality

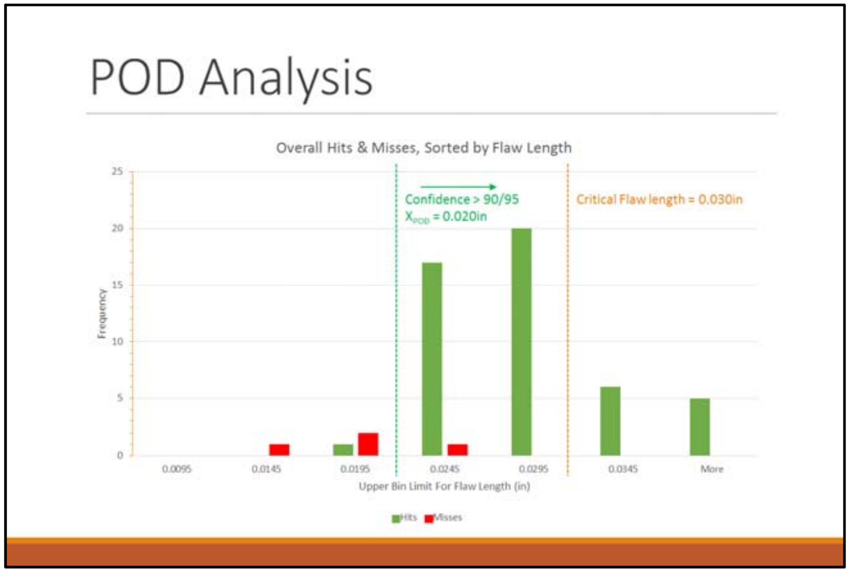
Justification: Commercial Spaceflight recently had a serious liner failure pointing to an urgent need to produce and quantify the performance of this NDE system. The need for sensitive and reliable flaw screening has been a well-recognized and long-term need in the composite pressure community of practice.

Summary: Once validated by a POD study, this system should be "game changing" in terms of manufacturing in-process NDE and should significantly improve our composite overwrapped and conventional pressure vessel safety and reliability.

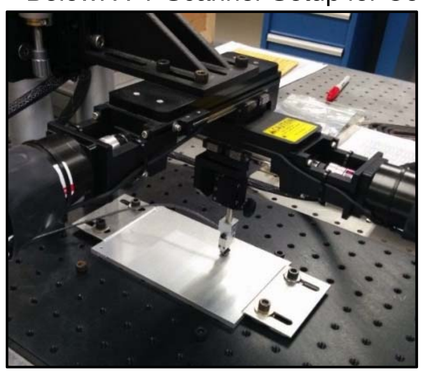
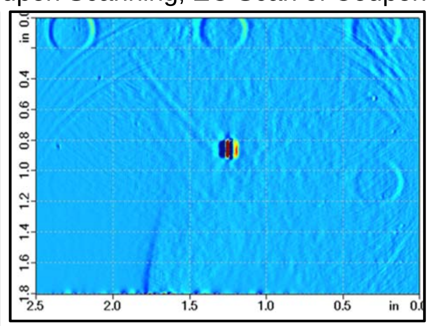
NDE Standards and Validation

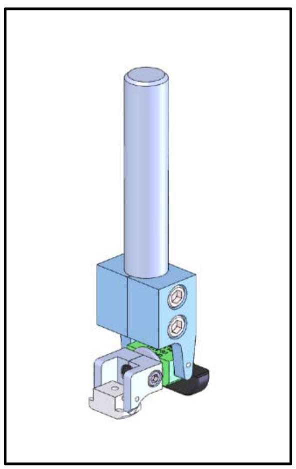
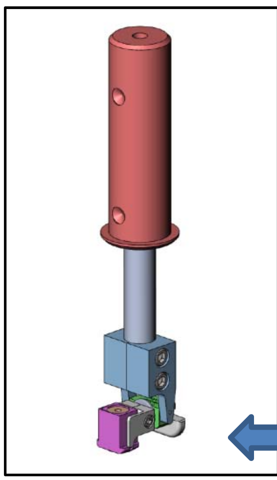



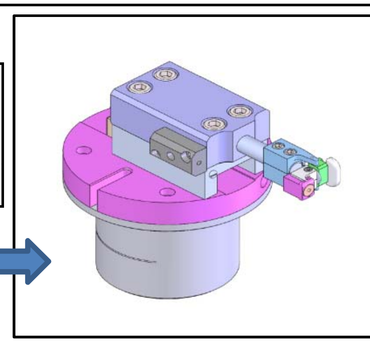
Above: Internal Articulation Arm



Above: Coupon POD Results, 90/95 confidence is achieved.
Below: X-Y Scanner Setup for Coupon Scanning, EC Scan of Coupon



Thickness Mapping and Flaw Detection Eddy Current Probes

Above: WSTF Production Scanner Modified for Eddy Current Scanning

32

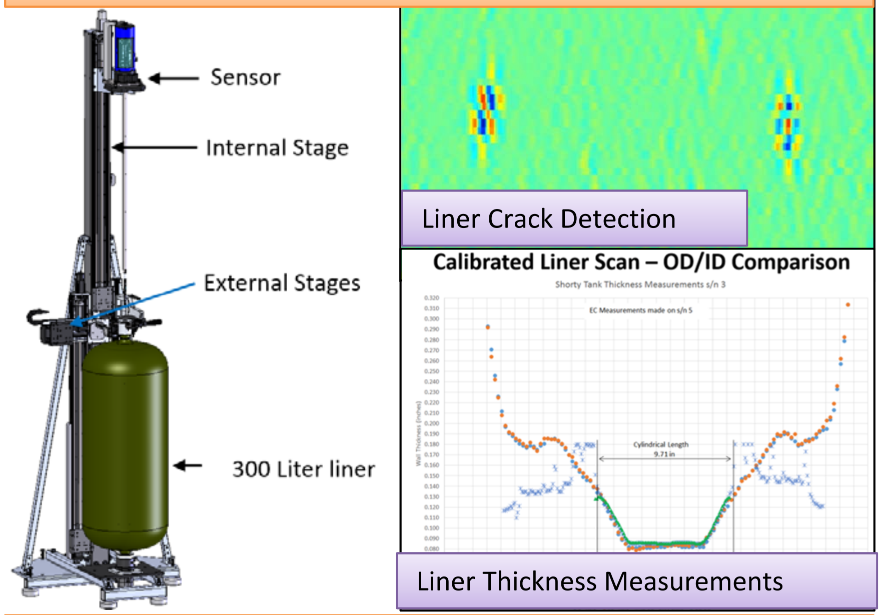
SMART COPV RESTARTED

Activity D - Content

- Activity Title: **Smart COPV Integrated Demonstrator (SCID)**
- **Purpose:** Reduce current high composite vessel risk: 1) Down-select and applying mature NDE methods; 2) push the above NDE methods from Technology Readiness Level (TRL) 3 to a TRL 6 flight demonstration unit, 3) improve the reliability of composite overwrapped pressure vessels in their resistance to MMOD and handling damage, 4) improve vessel reliability by implementing new NDE technologies used during manufacturing to reduce variance.
- **Justification**: Unresolved issues with the long-term use of pressure vessels and other fracture critical hardware in NASA missions still persist, requiring acceptance of risk and overreliance on analytical models versus experimentally validated NDE accept-reject criteria
- **Summary:** 6 NASA Centers have evaluated 7 candidate NDE methods for use during and after manufacturing, and eddy current, multi-axial strain grids, acoustic emission, and piezoelectric smart strips have been down-selected. After flight demonstration tests, a TRL 9 autonomous structural health monitoring unit will be delivered.

Smart CPOV Technologies Being Advanced

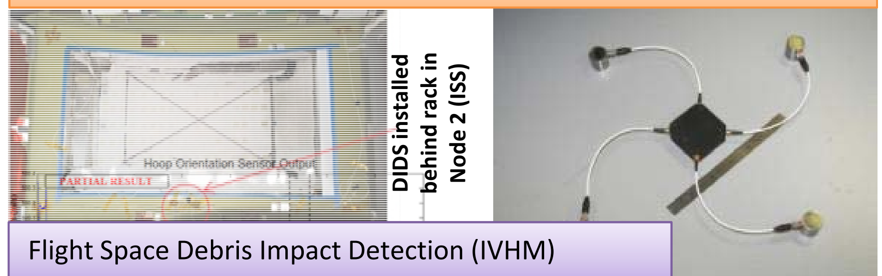
COPV Scanner – WSTF/LaRC (Structure QA)



Liner Crack Detection

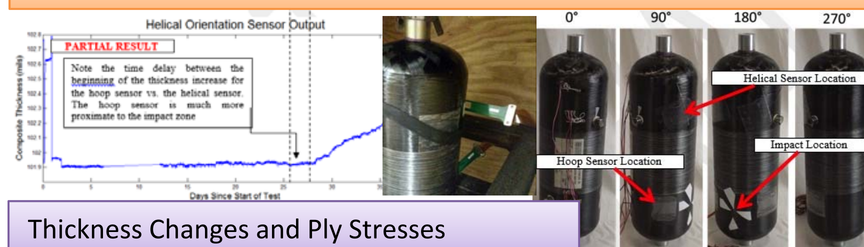
Liner Thickness Measurements

Distributed Impact Detection System - LaRC



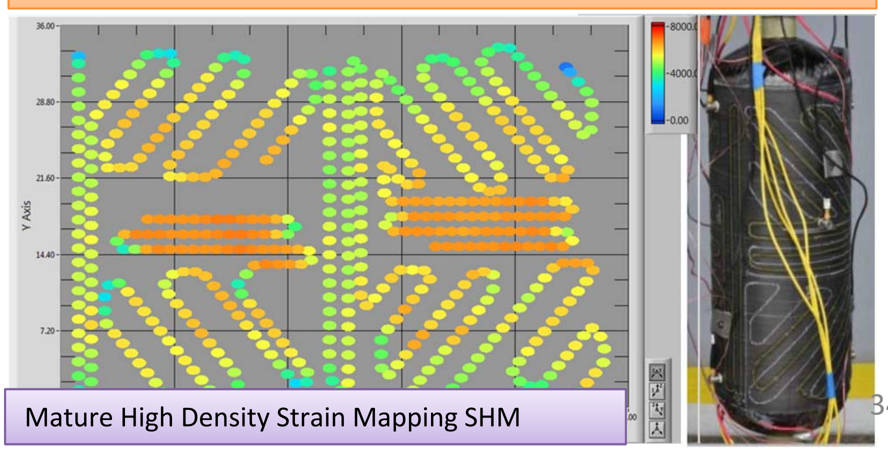
Flight Space Debris Impact Detection (IVHM)

Magnetic Stress Gage System – KSC



Thickness Changes and Ply Stresses

FOSS/FBG Strain Measurement - AFRC



Mature High Density Strain Mapping SHM

Acellent PZT Smart Strips - MSFC

Composite Damage Detection, Location & Quantification

Additive Manufacturing

Activity A - Content3

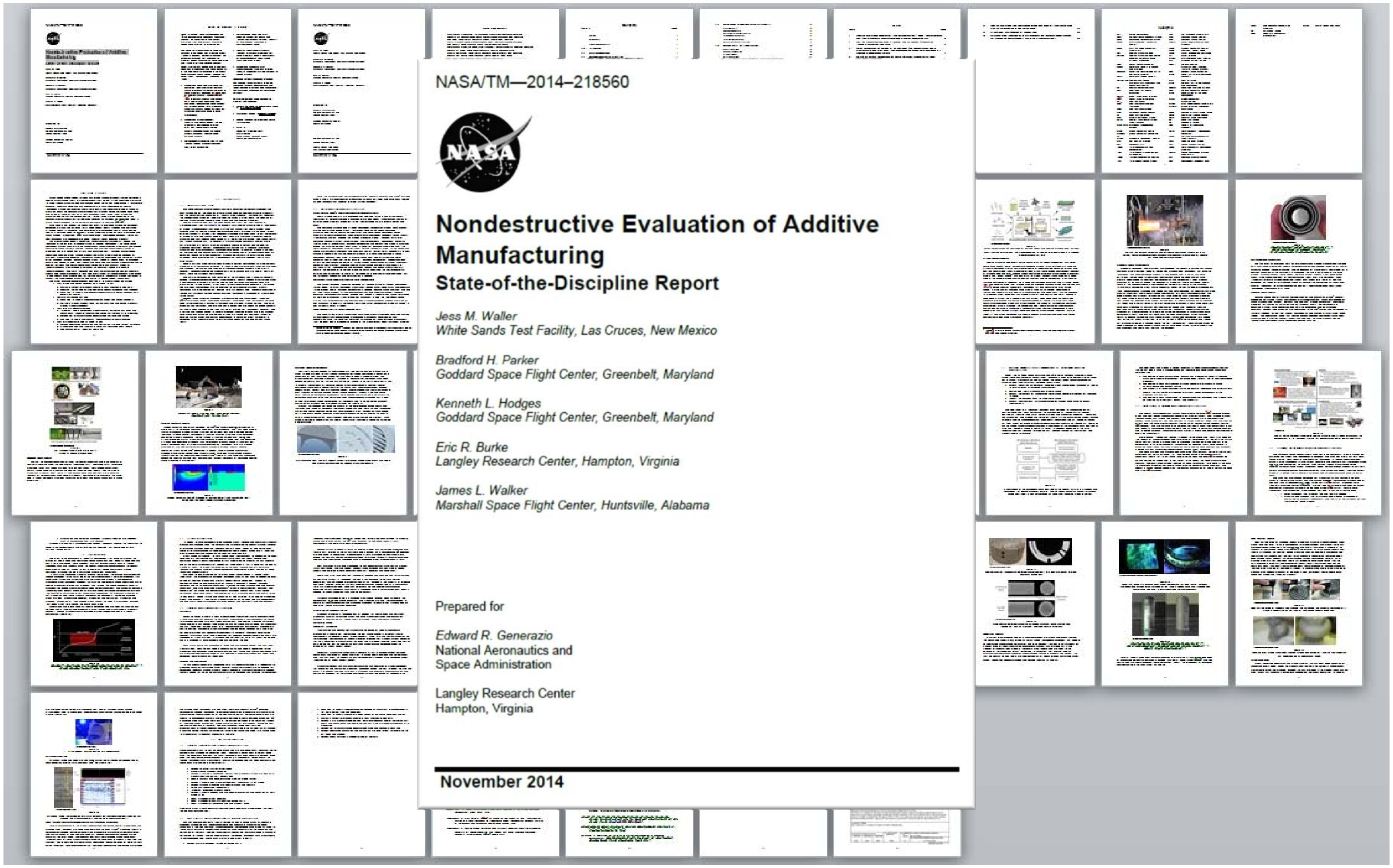
- Activity Title: **Foundational Methodology for Certification of Additive Manufacturing (AM) Parts and Materials**
- **Purpose:** Develop **certification methodologies designed to ensure the production of safe and reliable AM parts for spaceflight applications.** Emphasis will be placed on metals and AM processes used in fabrication of propulsion system components.
- **Justification:** AM is a rapidly emerging technology and there is a recognized lag in AM process and part validation and certification methodologies. NDE has been identified as one key technology to close this gap.
- **Summary:** The OSMA state of the art AM report will be used to define highest priority needs/gaps for NDE of AM parts. Resources will be used to down select and optimize NDE techniques that will then be combined with NDE modeling for a cost-effective methodology for verifying part quality. A workshop will be held mid year to assess progress and further define needs.

Types of Printing[1]

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- 3D Printing (3DP)
- Laminated Object Manufacturing (LOM)
- Syringe Extrusion
- Direct Metal Laser Sintering (DMLS)
- Laser Engineered Net Shaping (LENS)
- Ultrasonic Additive Manufacturing (UAM)
- Electron Beam Freeform Fabrication (EBF^3)
- etc

[1] Dr. Scott Roberts (JPL) Understanding the Additive Manufacturing Process

NDE of Additive Manufacturing State-of-the-Discipline Report



Industry, government and academia have been actively solicited to share their NDE experience relevant to additive manufacturing

NDE of Additive Manufacturing State-of-the-Discipline Report

Program/Discipline Health Status

- Yellow Status for:
  - Develop NDE Certification and Qualification protocols to assure part quality and acceptability
  - Develop S-Basis design allowables using NDE
  - Mature NDE protocols used during and after manufacturing
- Green Status for:
  - Identify NDE technology gaps to guide future NASA investments

Proposed Highlights

- Prioritize and align Agency NDE assets vis-à-vis additive manufacturing
- Develop concise NDE-based Qualification and Certification protocols
- Incorporate NDE best practice into voluntary consensus standard(s)
- Build relationships with commercial space partners, government agencies, industry, academia and the European Space Agency
- Accelerate use of additive manufacturing in NASA missions
- Assure quality and safety of parts

Background Information

- This technology is still emerging and rapidly changing
- Recommendations will be made to guide Agency investments in NDE vis-à-vis additive manufacturing, which will ensure NASA is properly poised to use additively manufactured hardware in future ground and flight applications.
- The major gaps and recommendations identified in the report are:
  1. **Lack of NDE and design allowables data specific to additive manufacturing**
  2. **Low maturity finished part NDE**
  3. **Lack of in-situ NDE process monitoring**
  4. **Lack of Standards for NDE of additive manufacturing**
- Maintain report as a living document
- Nurture relationships especially with industry and the European Space Agency
- Exploit US-European synergies to bootstrap NASA NDE qualification and certification protocols

NDE of Additive Manufacturing State-of-the-Discipline Report

NDE-Specific Recommendations

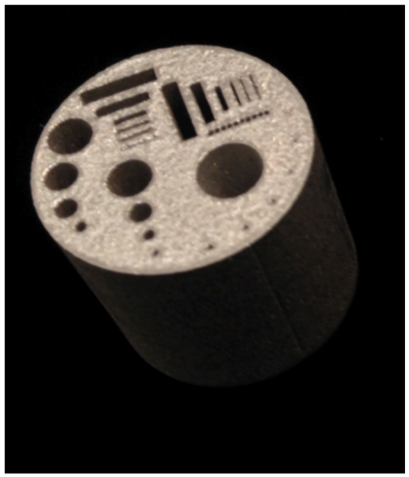
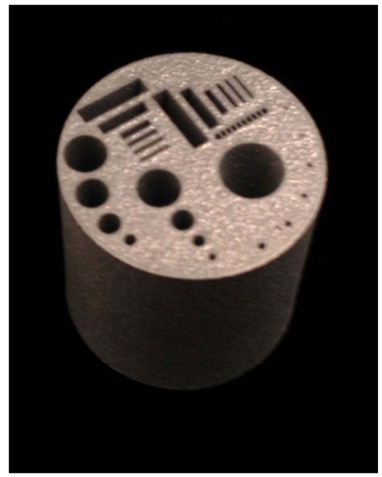
- Develop mature techniques for **NDE of finished parts**
- Apply NDE to understand effect-of-defect, including **establishment of acceptance limits** for certain defect types and defect sizes
- Apply NDE to understand scatter in design allowables database generation activities
- Fabricate physical **reference 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

Activity B - Content

- Activity Title: **Development of X-ray Computed Tomography Performance Standards**
- **Purpose:** Design and produce X-ray Computed Tomography (CT) performance standards for use at all NASA Centers performing CT.
- **Justification:** CT has become a mainstream NDE technique across the Agency with systems at GSFC, GRC, JSC, KSC, LaRC and MSFC. Unlike two-dimensional radiography, there are no enhanced computed tomography image quality indicators IQI targeting AM for industrial CT. This task will design and produce **CT IQIs that will then be used to document the capabilities of all the Agencies' CT systems**.
- **Summary:** ASTM E1695 dictates that CT resolution be based on the modulation transfer function calculated across the exterior edge of a round coupon. While this may be sufficient for an order of magnitude assessment, the image sharpness of the exterior edge is not representative of interior boundaries and only serves as an indirect measure. We propose to develop IQIs more consistent with NASA-related materials and using internal features/defects more representative of actual inspections.

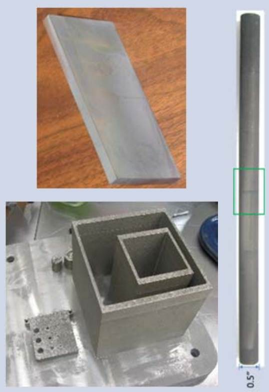
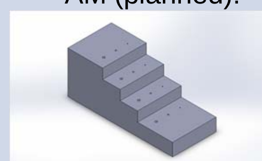
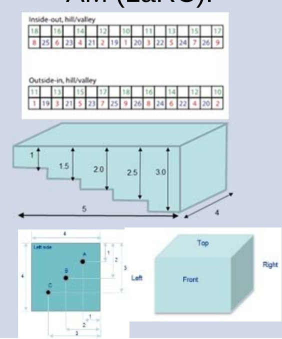
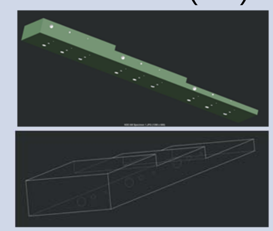
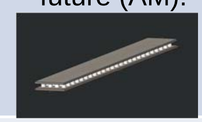
Development of X-Ray Computed Tomography Performance Standards

Fabrication of Preliminary X-ray CT Image Quality Indicators using Additive Manufacturing


Material	PH1 Stainless Steel (15-5 analog)	Titanium 6Al-4V	Vero White Plus RGD835 (proprietary photopolymer)
Manufacturer	GPI Prototype and Manufacturing Services	GPI Prototype and Manufacturing Services	Alio Designs
Build Method	Direct Metal Laser Sintering	Direct Metal Laser Sintering	PolyJet
Layer Thickness (µm)	40	30	30
Minimum Feature (mm)	0.3	0.5	1.6

NASA AM Physical Reference Standards

	MSFC-GRC	GSFC	LaRC	JSC-LaRC	KSC
AM process method	DMLS	DMLS (metal), LS (plastic)	LS	EBF^3	EBM
alloys	titanium, Inconel, and aluminum	titanium, SS PH1, vero-white RGD835	SS	titanium	titanium
reference standard geometries			Conventional:  AM (planned): 	wrought (JSC) and AM (LaRC): 	2^{nd} iteration (AM):  future (AM): 
features interrogated	complex geometries; large/thick/dense and very thin cross sections; (universal NDE standard, slabs, rods, gage blocks)	rectangular prisms, rows of cylinders, cylinders, flat-bottom holes, cone	steps, flat bottom holes	bead arrays, steps, holes	36 printed in-holes beginning at surface; 9 printed in-spheres internal to the part; cold plate (future)
AM defects interrogated	porosity/unfused matl. (restart, skipped layers), cracks, FOD, geometric irregularities	hole roughness and flatness/centricity	porosity, residual stress	grain structure, natural flaws, microstructure variation with EBF^3 build parameters	internal unfused sections
NDE method(s) targeted	post-process 2 MeV and μCT; PT, RT, UT, ET	post-process **? MeV CT**	post-process **? MeV CT**	post-process UT, **PAUT**	in-process NDE, not UT
Comments	collaboration with MSFC AM Manufacturing Group & Liquid Engines Office	flat IQI not suitable due to 3D CT artifacts	x-ray CT LS step wedge	Transmit-Receive Longitudinal (TRL) dual matrix arrays	collaboration with CSIRO

Questions?

Foundational Methodology for Additive Manufacturing: Ultrasonic Phased Array Inspection

2015 Key Objectives/Initiatives

- Make phase 1 Ti 6-4 AM specimen small billet samples using Electron Beam Free Form (EBF3) welding. (LaRC, JSC).
- Procure Ti 6-4 wrought material specimen. (JSC)
- Machine pre-programmed flaw set in base materials for phase 1 specimens. (JSC)
- Procure appropriate ultrasonic phased array (PA) probes for Olympus Omniscan (JSC).
- Procure ultrasonic simulation software ESBeamTool 5/6 and preform preliminary simulation of various beam angles.

Accomplishments

- First of three deliverable blocks for FY15 has been deposited
  - Approximately 20 lbs of deposited Ti-6Al-4V
  - Roughly 4” wide by 4” tall by 7” long
  - Slice taken off the end via wire EDM for future analysis
  - No visible discontinuities in slice
  - Future blocks will be path sequence variations of same geometry
- ESBeamTool5 Software Procured

Risks/Challenges/Concerns

- Ultrasonic instrument to be procured in FY 2016 due to cut in funding in FY 2015.
- Current implementation of ESBeams Tools does not account for possible changes in sound velocity due to EBF3 manufacturing process.

Schedule Status/Coming Events

- Evaluate Olympus PA probes using vendor demonstration before selecting PA and instrument for procurement.
- Procure appropriate demonstrated PA probe.
- Procure Ti 6-4 wrought material specimen

Foundational Methodology for Additive Manufacturing: Thermal Modeling for Inspection & Closed Loop Control

Annual Goals/Initiatives

- Improve the AM process (reduce costs and improve quality) by developing, validating and implementing NDE models.
- Investigate thermal modeling technique to simulate heat flow interaction with various flaw types during the additive manufacturing processes. Validate the thermal NDE model with acquired thermal data using electron beam or laser sintering (LS).

Accomplishments

- Designed and fabricated sensor mounting ring installed on NASA Langley electron beam free form fabrication (EBF3) system. This ring will allow for multiple sensors to be mounted for closed loop control development.

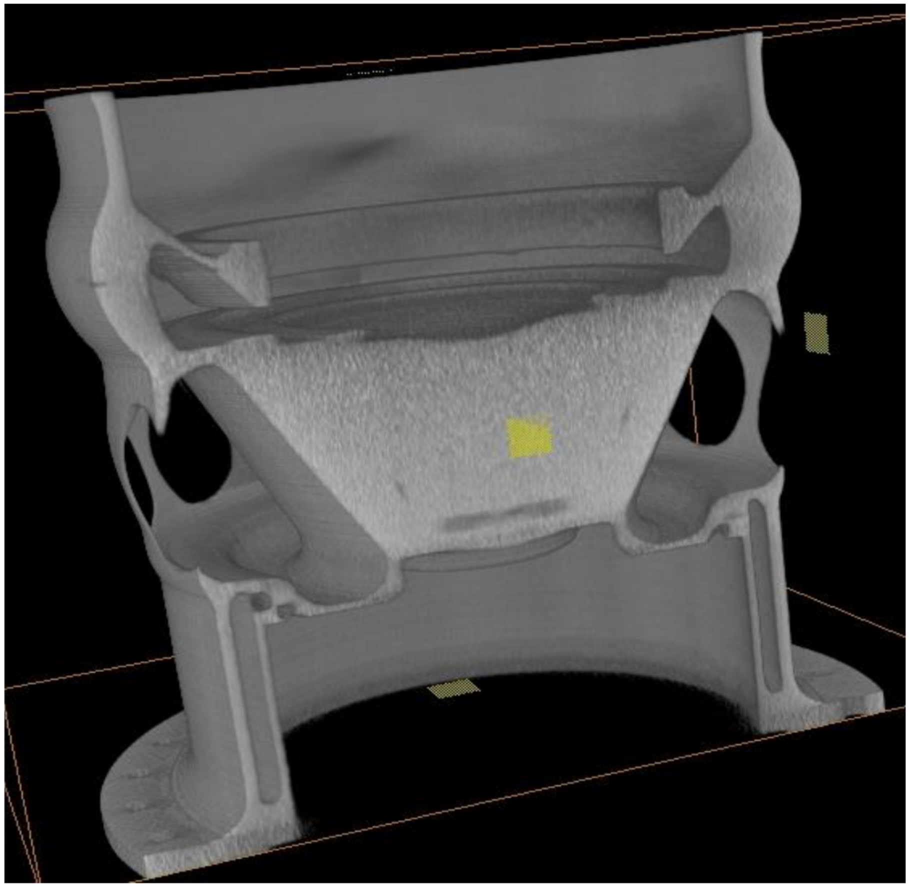
Risks/Challenges/Concerns

- Initial focus will be to leverage existing systems for experimental data, however existing commercial additive manufacturing systems can be difficult to modify to implement additional sensors. NASA Langley electron beam facility is not a commercial system and will allow for modification to add NDE sensors.

Schedule Status/Coming Events

- Identify whether initial focus will be EBF3 and/or LS, depending on accessibility of facilities and specimens
- Identification/development of appropriate sample geometry and material constituents → 02/2015
- Identification/development of appropriate NDE modeling techniques for EBF3 and/or LS processes and for characteristic flaw types →09/2015

An Assessment of NDE Capability and Materials Characterization for Complex Additive Manufacturing Aerospace Components



James L. Walker (MSFC)
Richard E. Martin (GRC)

OBJECTIVES

Task 1

- Perform a fundamental investigation of the correlation between nondestructive evaluation (NDE), mechanical testing, microstructure and processing for typical/naturally-occurring flaws in additive manufacturing (AM) components.
  - ➢ Titanium, Inconel and Aluminum alloy
  - ➢ Direct metal laser sintering (DMLS) and electron beam melting (EBM)
- Coordinate with MSFC AM Materials and Processes Team to evaluate materials study samples and Liquid Engines Office to evaluate engine components (some with real defects)
- Use NDE to select specimens for testing to failure, and then correlate the failure site back to the NDE results and subsequent fractography.
- Study the effect of hot isostatic pressing (HIP) on AM components using NDE and photomicroscopy to track the change in defect states.
- Compare results with those from conventionally formed materials of similar alloy.

Task 2

- Conduct a round-robin study of NDE methods suitable for complex AM components
  - ➢ Universal NDE reference standard as initial test case
  - ➢ Internal NASA NDE sources and outside entities
  - ➢ Produce a list of state-of-the-art NDE methods for complex AM components including their strengths and weaknesses

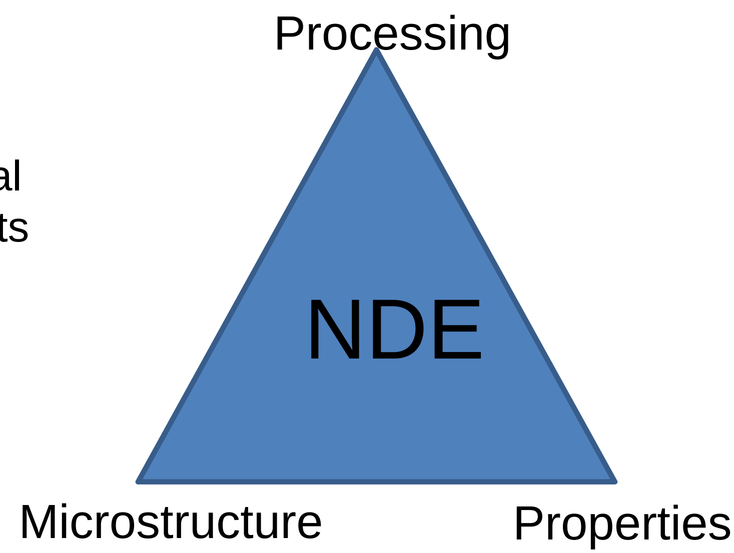
BACKGROUND

- **Additive manufacturing**
  - Has the potential for creating complex parts with a significant cost and time savings
  - Pitfalls due to unknowns and variations in the AM process
  - Uniquely different grain structure and flaw morphologies
  - Highly complex and hidden geometries will limit access for NDE

- **Parties highly interested in AM materials**
  - NASA (Code Q has identified AM NDE as a critical focus area)
  - Department of Defense (DOD)
  - Aerospace engine manufacturers

- **Prior Work**
  - Propose to build on and leverage recent fundamental and applied NDE research efforts for AM components

- **Primary focus of this work**
  - Establish fundamental relationships between processing, mechanical testing, materials characterization, and NDE
  - Understand what NDE methods are best utilized for characterizing actual AM produced components



TECHNICAL METHODOLOGY/APPROACH

- Two year effort with two parallel running tasks

Part 1

- Focus on the effects-of-defects
- Determination of typical flaws and sizes
- Test matrix for mechanical testing, NDE, and materials characterization
  - Inconel, Titanium, Aluminum alloy
  - Direct metal laser sintering and electron beam melting
- Design and fabricate samples with a range of expected defect geometries (verified through microstructure analysis)
- NDE used to characterize the flawed samples
- Mechanical test the flawed samples
- Correlate the flaws back to the NDE results
- Performed fractography to assess these flaws and correlate with NDE results
- Study the effect of HIP processing on flaw characteristics

Part 2

- Request for information (RFI) to evaluate complex AM components

PART 1. EFFECTS-OF-DEFECTS STUDY

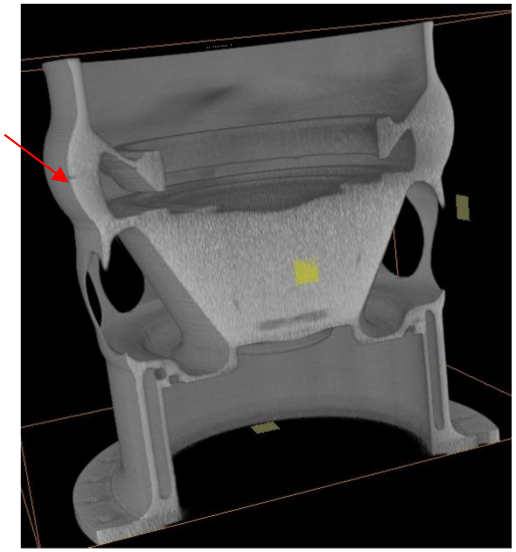
Prior work:

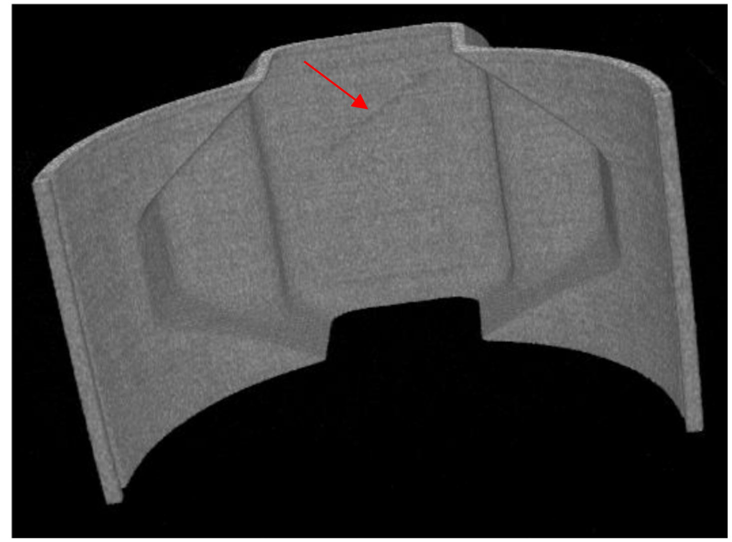
- MSFC: Materials study and NDE
  - CT of many DMLS engine components
  - Characterization of DMLS Materials for SLS Engine Components (Beshears, Brown, Wells) => Funded by the Advanced Developments Office in 2013 to investigate applications of NDE to AM materials, methods for defect standard formation, and effects of defects on material properties.
- GRC: Baseline NDE development for commercial aerospace company engine components
  - Includes use of CT, penetrant, and ultrasonics (UT) prior to mechanical testing of AM Ti alloy specimens to characterize quality of AM manufactured test samples and correlate with failure sites and metallographic characterization
  - Includes development of CT method for complex-shaped components

Schedule:

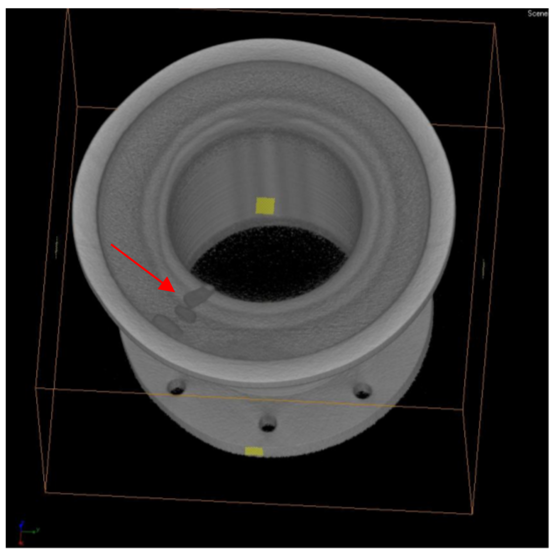
	Q1-Q2	Q3-Q4	Q5-Q6	Q7-Q8
Consult AM manufacturing and Engine Project for critical flaws	XX			
Construct test matrix	XX			
Design/fabricate/verify samples with a range of defects for microstructural characterization	X	X		
Design/fabricate/verify samples with a range of defects for NDE characterization		XX		
Evaluate NDE capability		X	XX	
Perform materials testing on select samples to see effect of defect(s)			X	X
Report				X

RECENT CT SCANS OF AM ENGINE RELATED PARTS





Inconel chamber



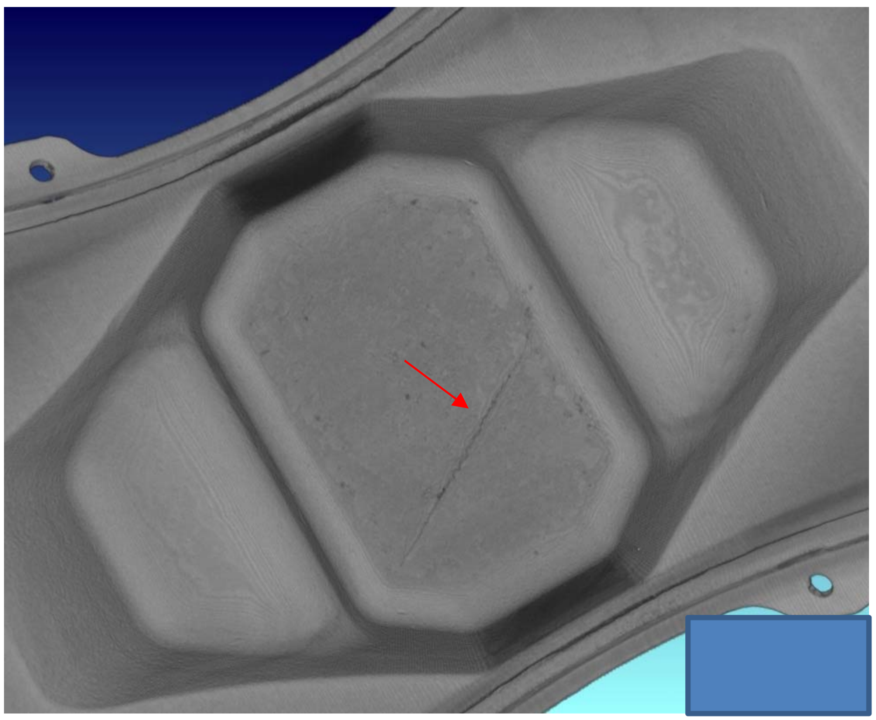
Inconel axial compression joint

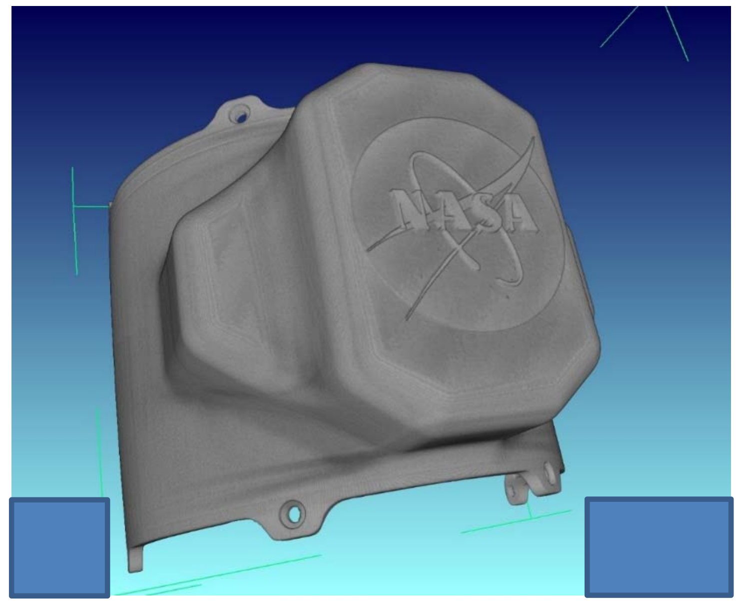
DMLS Aluminum cover

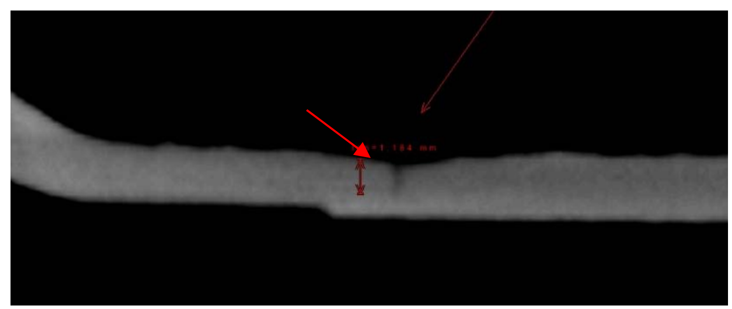
RECENT μCT SCANS OF AM ENGINE RELATED PART

DMLS Aluminum cover

- μCT resolves part features
- Depth of indication on back of part reveale



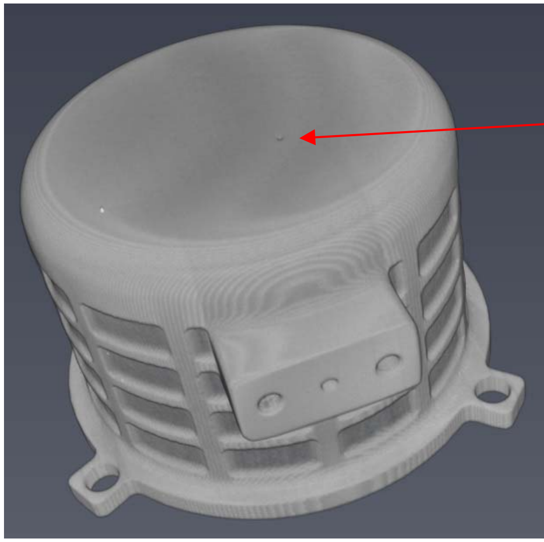




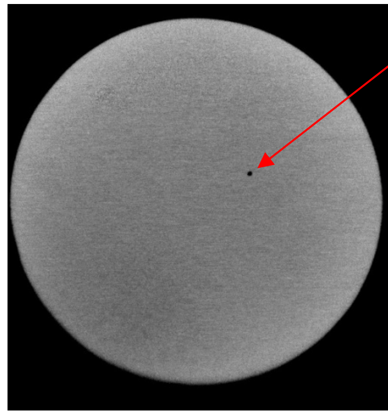
RECENT µCT SCANS OF AM ENGINE RELATED PART

DMLS Aluminum Cap

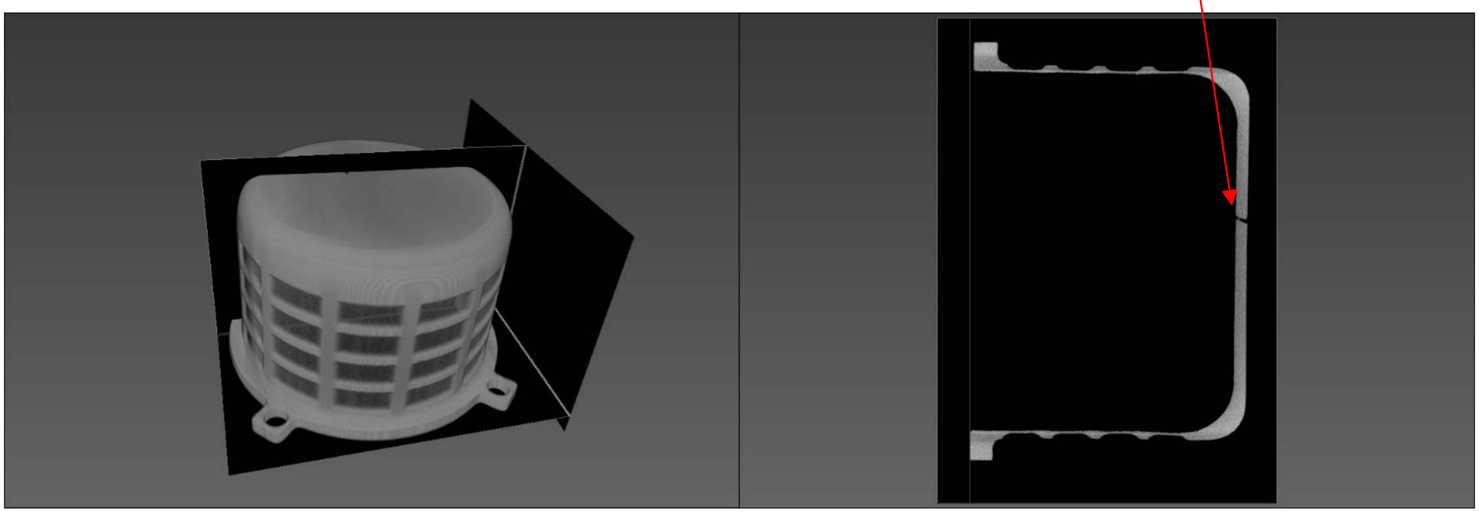
- µCT resolves part features.
- Pinhole indication on top of cap resolved in detail. Identified as a through hole with CT.
- µCT resolution ~28µm.



Volume Rendering of Al Cap

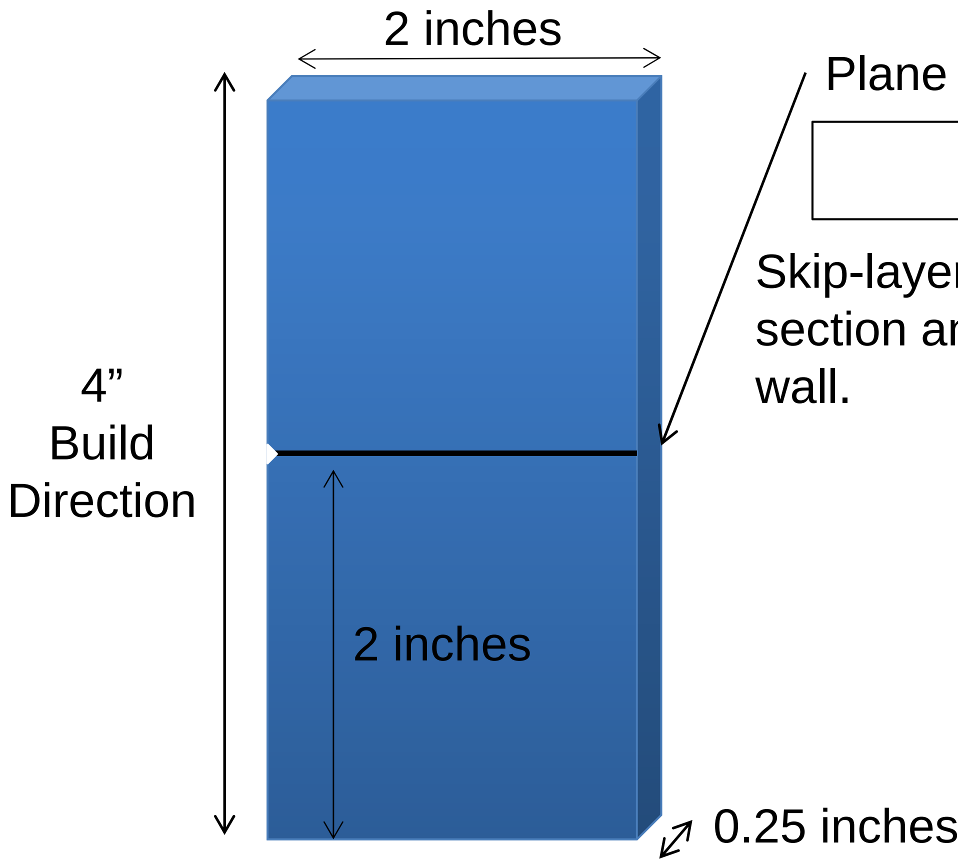


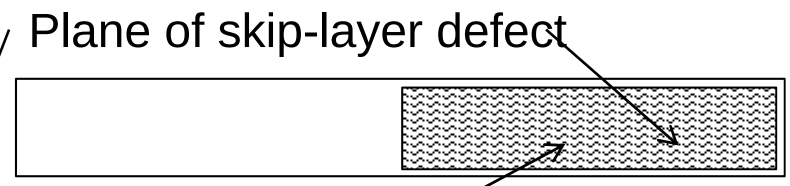
CT slice through top of cap.

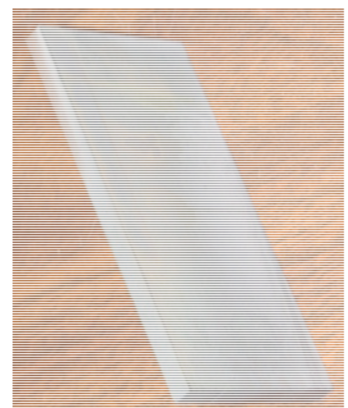


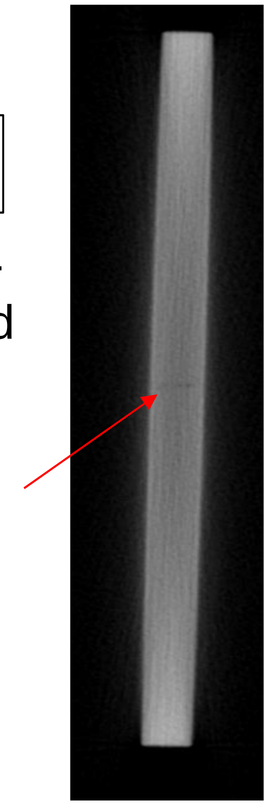
CT slice through pinhole feature.

RECENT DEFECT CREATION EFFORTS – SKIPPED LAYERS







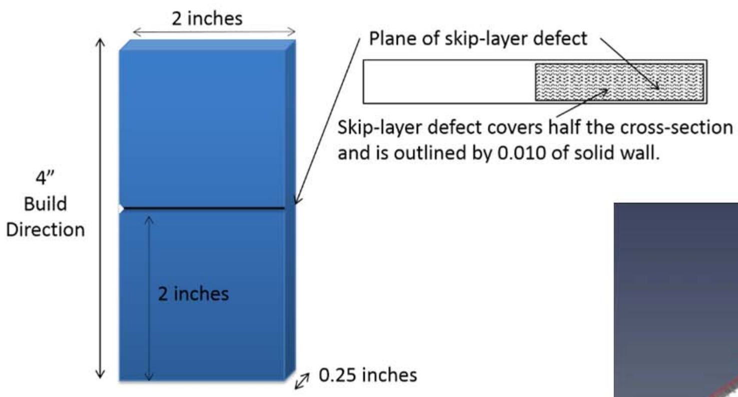


CT

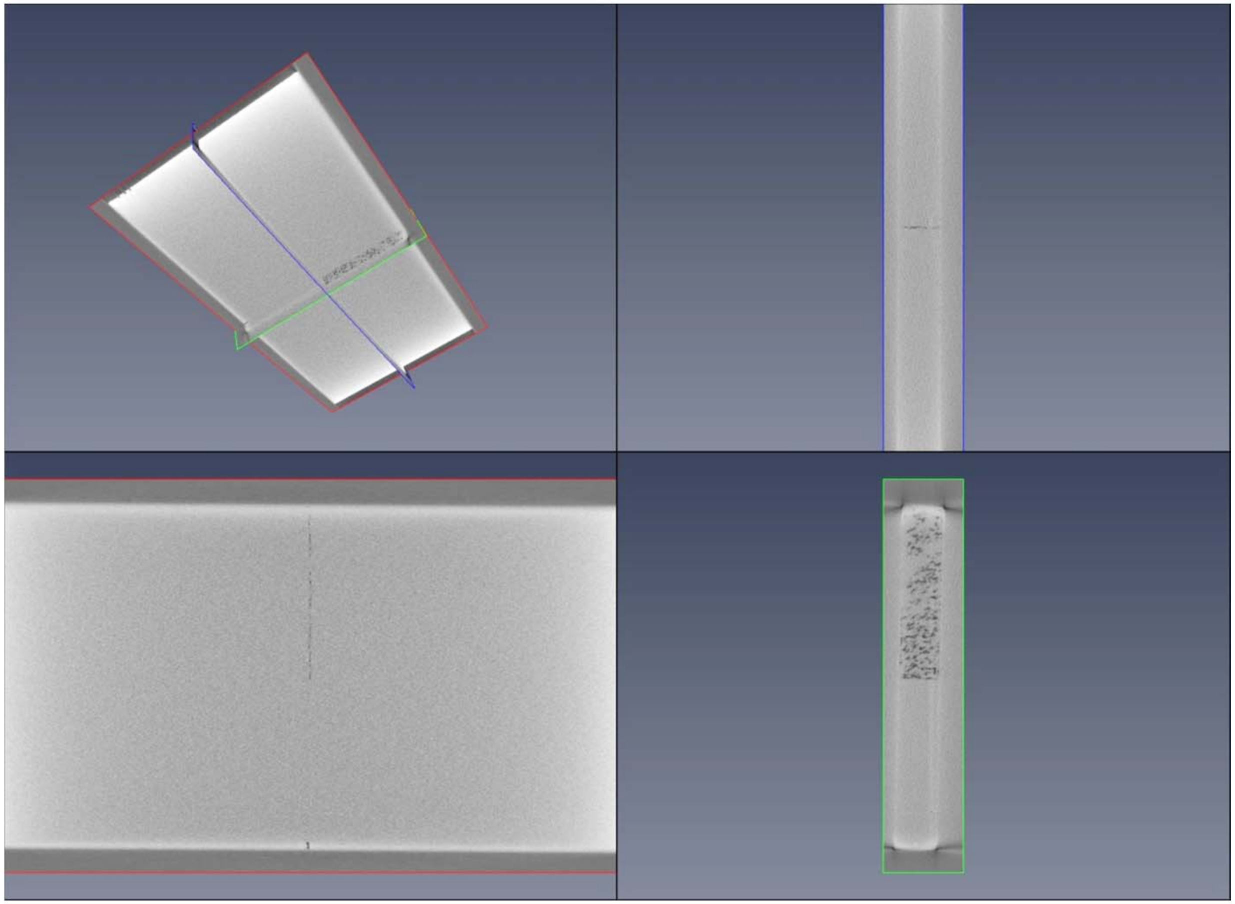
- Evaluating before and after HIP
- Samples have 4, 6 and 8 skipped layers
- Evaluated with the MSFC 2MeV CT system, could only see largest number of skipped layers
- Pulled two samples from materials testing lot and sent to GRC for μCT
- Plan to get samples being cut from these bars for tensile testing and perform μCT

RECENT DEFECT CREATION EFFORTS – SKIPPED LAYERS

μCT Results



- **μCT was able to resolve skipped layers. As scanned resolution ~28μm**
- **Thickness and density of material are limiting factors for μCT**
- **Plan to re-scan samples following sectioning and prior to mechanical testing.**



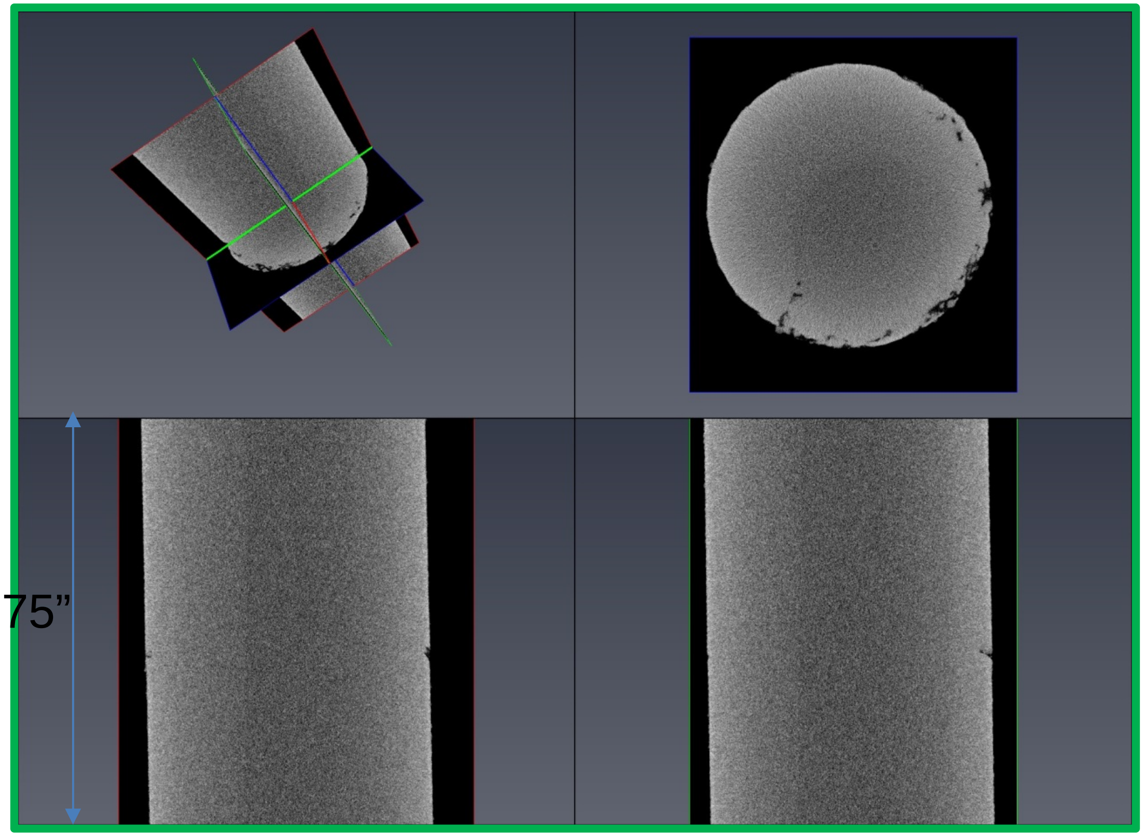
Various CT views of an Inconel bar with skipped layers at the center. Views show extent of defect across width of sample.

RECENT DEFECT CREATION EFFORTS – AM MACHINE RESTART

μCT Results

- **Inconel rod with restart type condition. Various times between restart on each rod.**
- **μCT was able to resolve internal indications at restart location. As scanned resolution ~10μm**
- **μCT will be conducted on remaining locations to correlate NDE indications to length of time between restart.**

0.75”

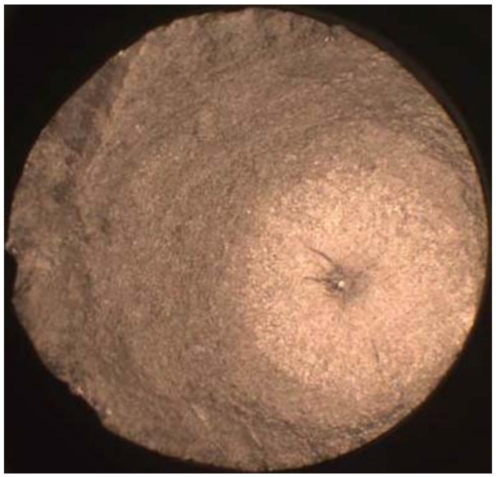


0.5”

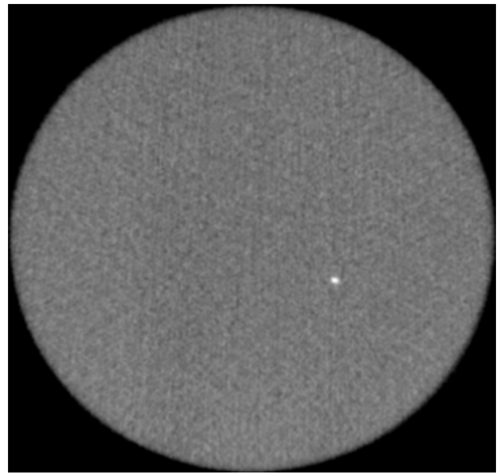
Photo of DMLS Inconel rod with various “restart” event features. Lines in sample show locations of restart events. Box indicates approximate location of CT data.

RECENT EFFORTS ON FRACTOGRAPHY – CT CORRELATION

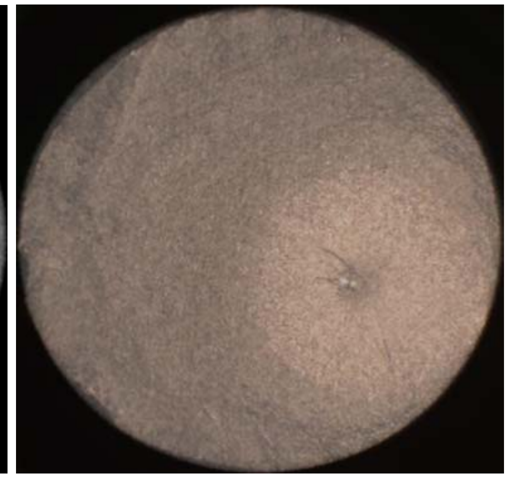
- Performing micro-focus CT scans of Ti 6-4 tensile and fatigue test samples and comparing μCT results to fracture surface analysis.



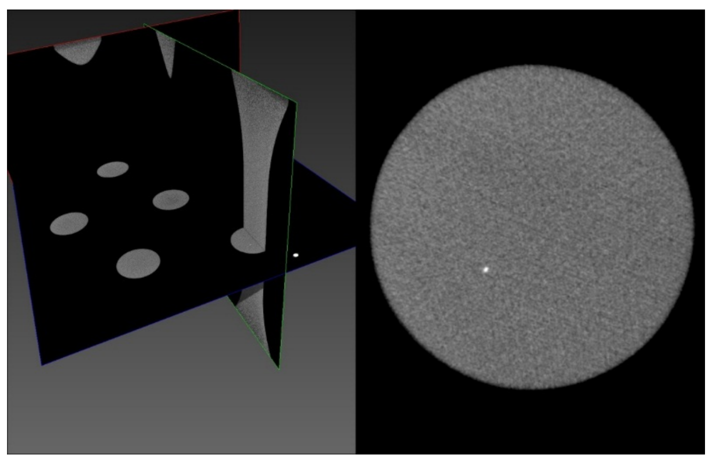
Optical



μCT Slice



μCT overlay on Optical



Ortho Views to show location of μCT Slice

PART 2. DETECTION CAPABILITY DEMONSTRATION FOR COMPLEX GEOMETRY PARTS

Purpose: Perform an industry search for state-of-the-art NDE methods applicable to complex AM components.

Task Description: Will utilize a universal NDE reference standard with dimensional and structural defects to perform a nationwide survey of NDE vendors and researchers.

Current work:

2013 Tech Excellence funding

- Attempted to fabricate an Inconel POGO-Z baffle with programmed defects but it kept failing the build
- Designed and fabricating a series of modular components that will allow assembly of a complex AM part

Schedule:

	Q1-Q2	Q3-Q4	Q5-Q6	Q7-Q8
In-house evaluation of part	XX			
Prepare a request for information solicitation to evaluate a complex AM part and submit	XX			
Collect responses and prepare a down select/priority plan	X	X		
Send part out for testing, collect the results and tabulate findings		X	XX	X
Report				X