NASA OSMA NDE Program
Additive Manufacturing Foundational Effort

Jess Waller (NASA WSTF), James Walker (NASA MSFC), Eric Burke, (NASA LaRC), Douglas Wells (NASA MSFC)

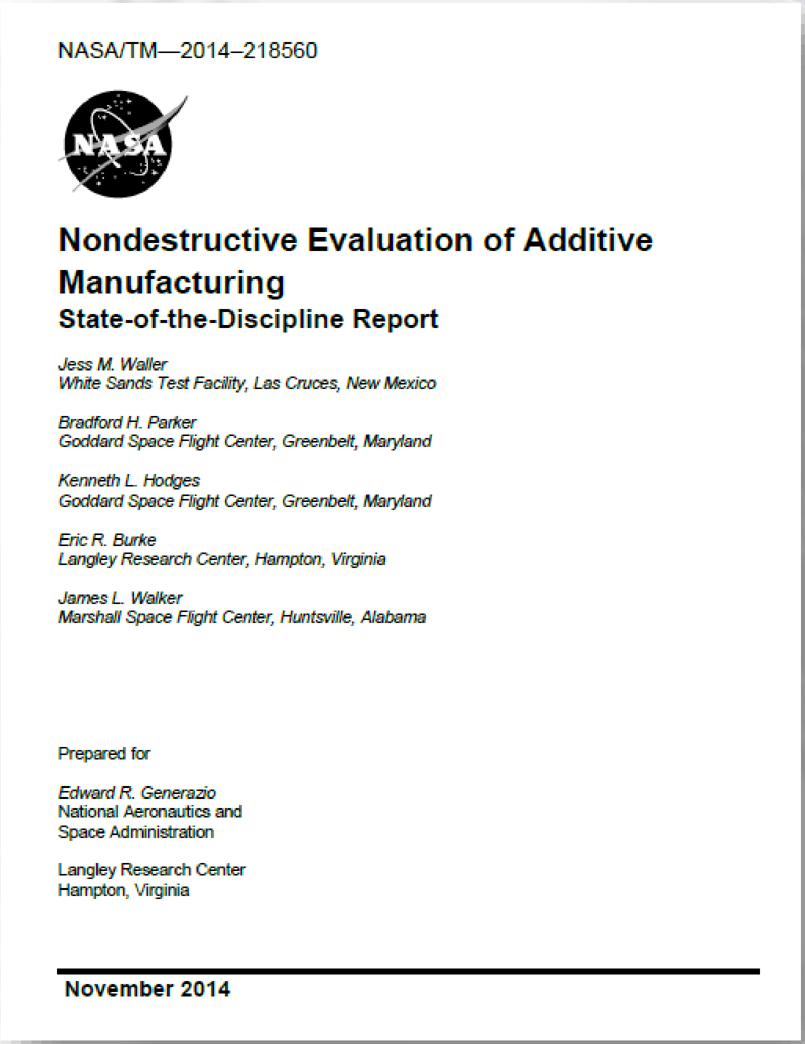
9th ESA-JAXA-NASA S&MA Trilateral Meeting, ISAS, Sagamihara, Japan
Wednesday 14 September 2016 – F2F Meeting, Day 2
Qualification of products fabricated via additive manufacturing
9:40 to 10:20 am JST

Background

- NASA is providing key leadership in an international effort linking NASA and non-NASA resources to speed adoption of additive manufacturing (AM) to meet NASA's mission goals. Participants include industry, NASA's space partners, other government agencies, standards organizations and academia:

- Nondestructive Evaluation (NDE) is identified as a universal need for all aspects of additive manufacturing

Background


NASA/TM—2014–218560

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

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November 2014

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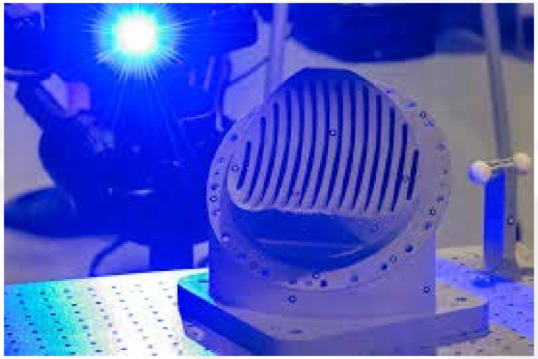
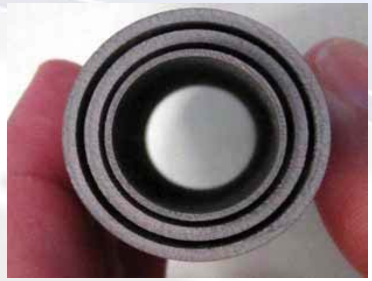
- NASA Agency additive manufacturing efforts were catalogued
- Industry, government and academia were asked to share their NDE experience in additive manufacturing
- NIST and USAF additive manufacturing roadmap were surveyed and a technology gap analysis performed
- NDE state-of-the-discipline was documented

NASA Agency & Prime Contractor Activity



Inconel Pogo-Z baffle for RS-25 engine for SLS



Reentrant Ti6-4 tube for a cryogenic thermal switch for the ASTRO-H Adiabatic Demagnetization Refrigerator

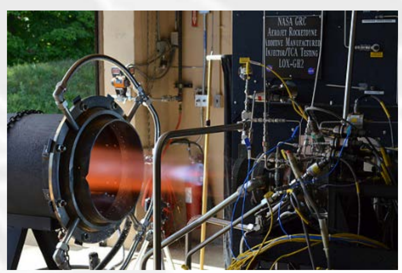
EBF[3] wire-fed system during parabolic fight testing

28-element Inconel 625 fuel injector

Prototype titanium to niobium gradient rocket nozzle

Made in Space AMF on ISS

ISRU regolith structures



Aerojet Rocketdyne RL-10 engine thrust chamber assembly and injector

Dynetics/Aerojet Rocketdyne F-1B gas generator injector

SpaceX SuperDraco combustion chamber for Dragon V2

NDE of AM Technology Gaps

- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- Develop post-process NDE of finished parts
- Develop voluntary consensus standards for NDE of AM parts
- Develop better physics-based process models using and corroborated by NDE
- Use NDE to understand scatter in design allowables database generation activities (process-structure-property correlation)
- Fabricate AM physical reference samples to demonstrate NDE capability for specific defect types
- Apply NDE to understand effect-of-defect, and establish acceptance limits for specific defect types and defect sizes
- Develop NDE-based qualification and certification protocols for flight hardware (screen out critical defects)

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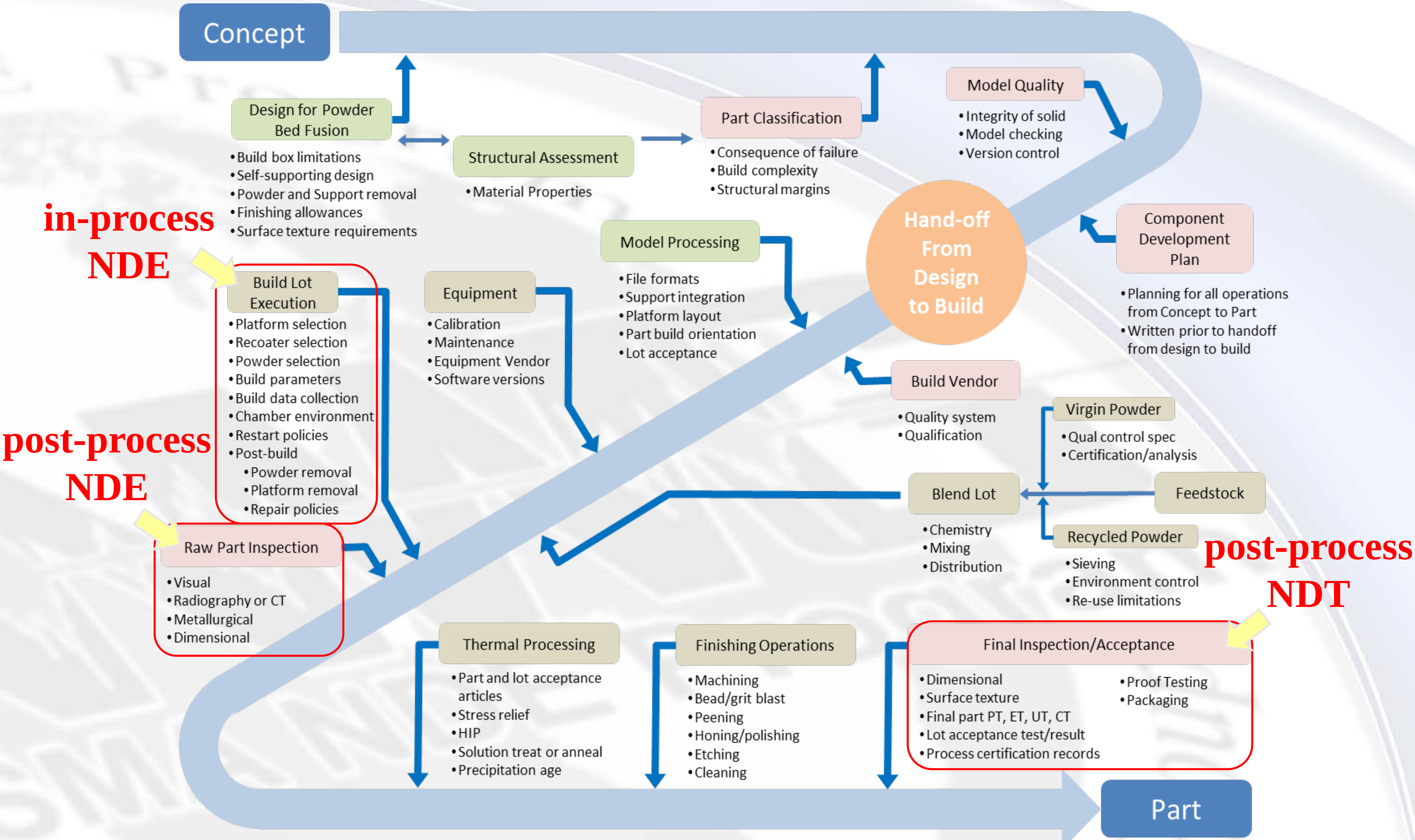
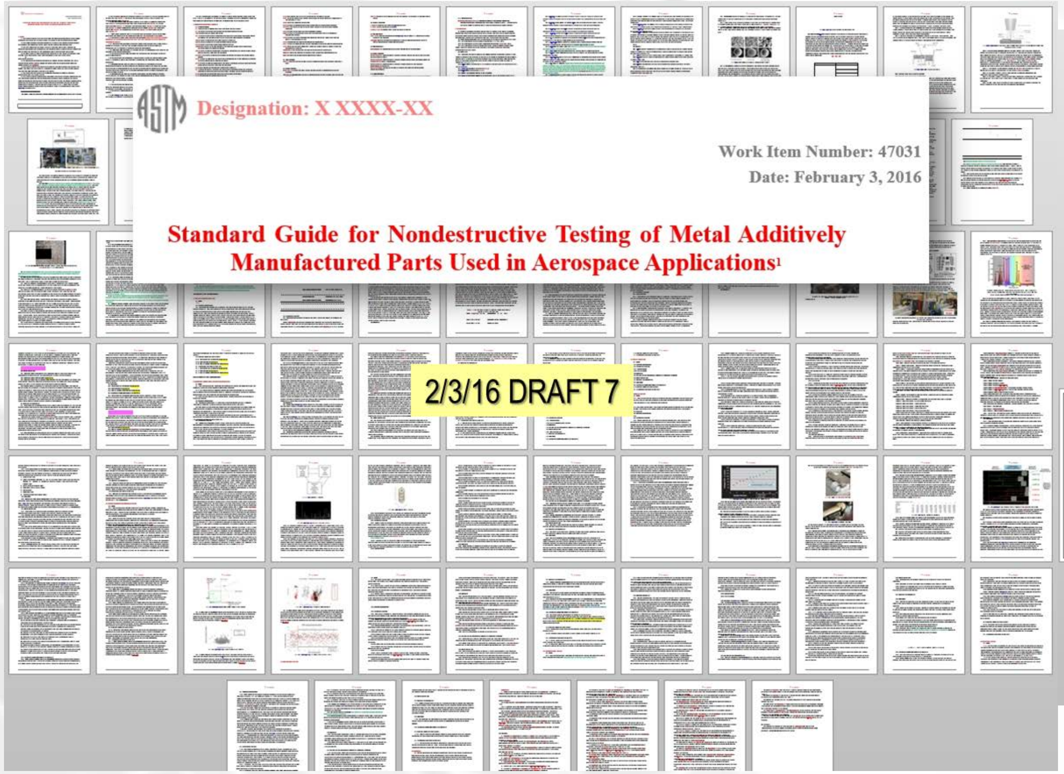
NDE-based AM Part Qualification & Certification



ASTM WK47031, NDE of metal parts used in aerospace applications (NASA leadership)

ASTM E07.10 WK47031 NDE of AM Guide



ISO TC 261 JG59 Best NDE Practice

- First defect catalogues to show defect ↔ NDE linkage
- Process method determines defects
- Defect type & part complexity determine NDE selection

Background

While certain AM flaws (e.g., voids and porosity) can be characterized using existing standards for welded or cast parts, other AM flaws (layer, cross layer, unconsolidated and trapped powder) are unique to AM and new NDE methods are needed.

	Flaw type	Non- NDT	Common in DED & PBF	Covered by current standards	Unique to AM
DED	Poor surface finish	■	■		
	Porosity		■	■	
	Incomplete fusion			■	
	Lack of geometrical accuracy/steps in part	■	■		
	Undercuts			■	
	Non-uniform weld bead and fusion characteristic			■	
	Hole or void		■	■	
	Non-metallic inclusions		■	■	
	Cracking		■	■	
PBF	**Unconsolidated powder**				■
	Lack of geometrical accuracy/steps in part	■	■		
	Reduced mechanical properties	■			
	Inclusions		■	■	
	Void		■	■	
	Layer				■
	Cross layer				■
	Porosity		■	■	
	Poor surface finish	■	■		
	Trapped powder				■

Develop new NDE methods

[§] ISO TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.

Note: DED = Directed Energy Deposition., PBF = Powder Bed Fusion

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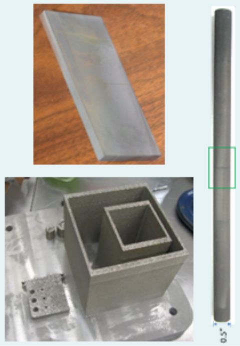
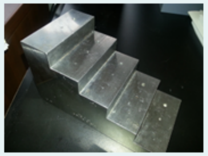
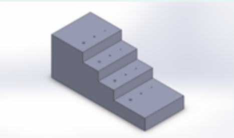
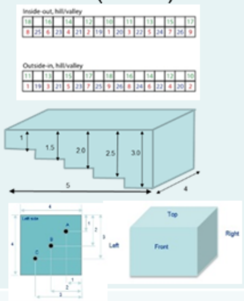
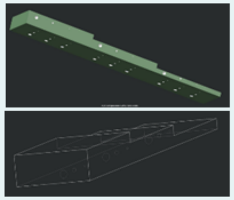
Demonstrate NDE capability

	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): 	2nd 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, lack of fusion	grain structure, natural flaws, residual stress, 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

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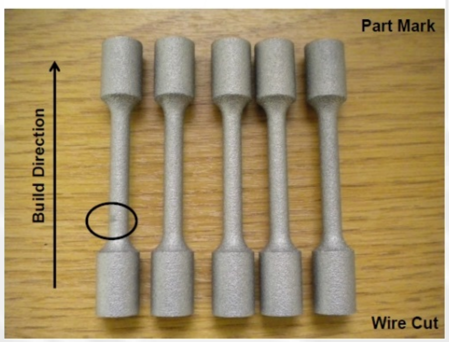
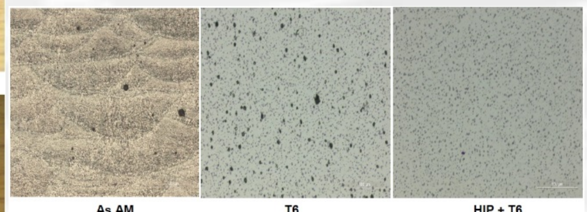
Determine effect-of-defect on sacrificial specimens with seeded flaws

Airbus Laser Powder Bed Fusion (PBF) samples

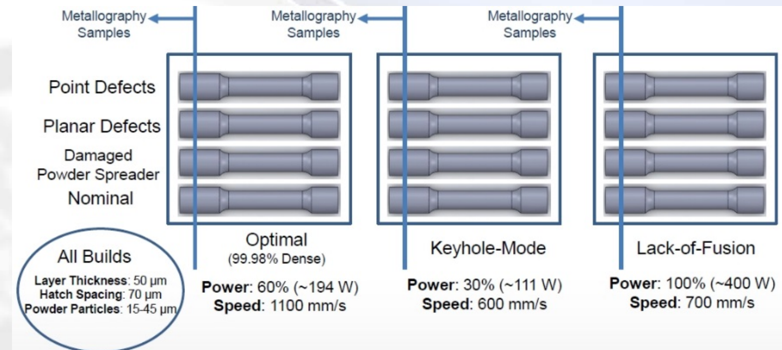


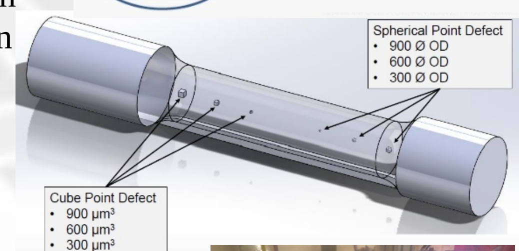
AlSi10Mg ASTM E8 compliant dogbones
13mmØ, 85mm long (6mmØ, 30mm Gauge Length)

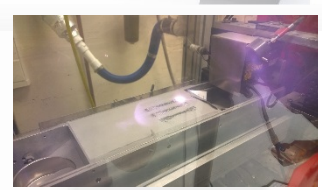


Investigate effect post-processing on microstructure and surface finish on fatigue properties

Advratech Laser PBF samples (in progress§)







Ti-6Al-4V ASTM E8 compliant dogbones for *in situ* OM/IR and post-process profilometry, CT and PCRT

§ FY17 STTR T12.04-9979 Real-Time Geometric Analysis of Additive Manufacturing status (NASA MSFC) Develops a novel process control and part documentation solution for selective laser melting (SLM) additive manufacturing.

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Background

National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
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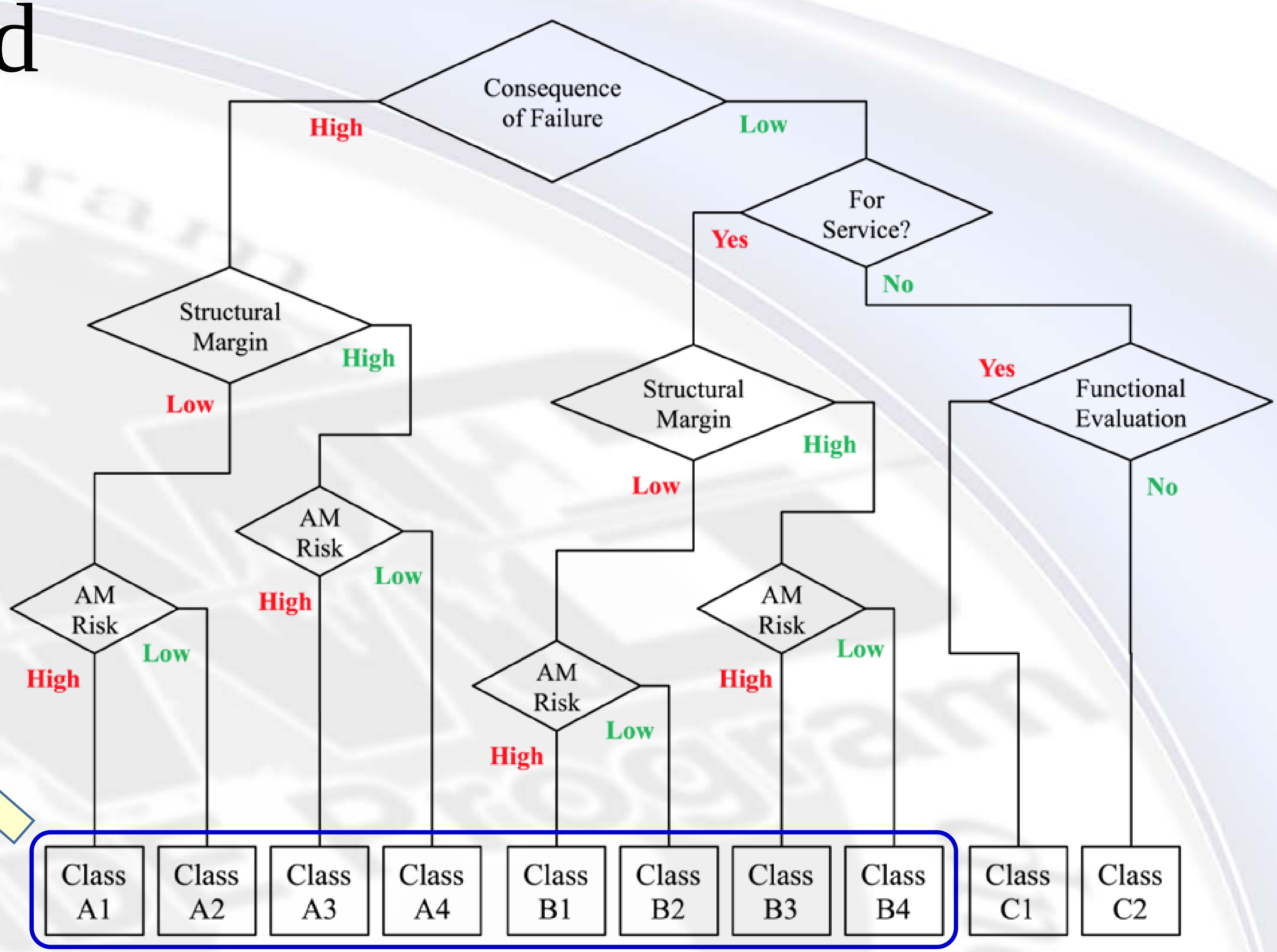
Contact: *Doug Wells (MSFC)*

- Comprehensive draft technical standard is in review
- All Class A and B parts are expected to receive comprehensive NDE for surface and volumetric defects within the limitations of technique and part geometry
- Not clear that defect sizes from NASA-STD-5009[§] are applicable to AM hardware
- NDE procedural details are still emerging

ASTM INTERNATIONAL
Standards Worldwide

[§]NASA-STD-5009, *Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components*

Background



Comprehensive NDE required for surface and volumetric defects

§ NASA classifications should not to be confused with those used in the ASTM International standards for AM parts, such as F3055 *Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion.* The ASTM classes are used to represent part processing only and are unrelated.

FY16 Continuing Projects

- An Assessment of NDE Capability and Materials Characterization for Complex Additive Manufacturing Aerospace Components (Walker, Martin)
- Foundational Methodology for Additive Manufacturing
  Investigation of NDE Flaw Detectability in AM Parts (Koshti, Stanley, Taminger, Hafley, Brice, Burke)
- X-ray Computed Tomography Image Quality Indicator Development (Jones, Fischetti, Kent)
- KSC Foundational Methodol. for Additive Manuf. – Electron Beam Melting NDE (Skow)
- Evaluation of Additively Manufactured Metals for use in Oxygen Systems (Tylka)
- NDE of Aerospace Parts (including Additive Manufactured) Voluntary Censensus Organization Standards and Related Round-Robin Tests (Waller, Nichols)

FY17 New Starts

- A Quantitative Assessment of NDE Capability on Additive Manufactured (Selective Laser Melting) Inconel 718 (Walker, Martin)

- Effect-of-Defect of Unique Laser Powder Bed Fusion Flaw Types: NASA-Industry Round Robin Study (Waller, Nichols)

- Involves the characterization of defect structures of selective laser melting (SLM) Inconel® 718 material within the nominal process window and its limits, build test articles for NDE studies and correlation with destructive test results
- Relevance to parts made for Commercial Crew Program (CCP), Space Launch System (SLS) and Multipurpose Crew Vehicle (MPCV)

Initial Evaluation	Steven J. Gentz
	April 21, 2016

Additive Manufacturing Structural Integrity Initiative (AMSII) Project Oversight and Support

Steven J. Gentz

April 21, 2016

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Questions?

NNMG