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NUREG/CP-0310

Proceedings of the Public Meeting on Additive Manufacturing for Reactor Materials and Components

Office of Nuclear Regulatory Research

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Manuscript Completed: July 2018
Date Published: July 2019

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ABSTRACT

The U.S. Nuclear Regulatory Commission's (NRC's) Offices of Nuclear Regulatory Research (RES), Nuclear Reactor Regulation (NRR) and New Reactors (NRO) organized this *Workshop on Additive Manufacturing for Reactor Materials & Components (AM-RMC).* The workshop was held November 28-29, 2017, at NRC Headquarters, 11545 Rockville Pike, Rockville, Maryland.

The NRC had been earlier informed in mid-2017 that reactor components made by additive manufacturing (AM), and especially by powder bed fusion/direct metal laser melting (DMLM)/sintering, were being considered for applications in the operating fleet as early as calendar year 2018. Given the anticipated level of activity, the objectives for this public meeting were to:

(1) Engage with industry and Government counterparts to obtain information needed for anticipated licensing actions related to AM.

(2) Address topics such as:
- The state-of-the-art of AM
- Industry activities in AM
- Irradiation testing & effects on AM
- AM qualification
- Standards for AM
- Nondestructive evaluation (NDE) of components fabricated using AM
- American AM activity in international context
- Cyber-security for AM
- Regulatory perspectives
- Computer modeling
- AM in nuclear fuel

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ACRONYMS AND ABBREVIATIONS

AIA	Aerospace Industry Association
AM	Additive manufacturing
AMAFT	Additive Manufacturing as an Alternative Fabrication Technique
AM-RMC	Additive Manufacturing for Reactor Materials & Components
AMC	Additive Manufacturing Consortium
AMM	Advanced Methods for Manufacturing
AMMD	Additive Manufacturing Materials Database (NIST).
AMSC	Additive Manufacturing Standardization Collaborative
ANSI	American National Standards Institute
AR	Advanced reactors
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BNCS	Board of Nuclear Codes and Standards (ASME)
BOP	Balance of Plant
BPTCS	Board on Pressure Technology Codes and Standards (ASME)
CANM	Center for Advanced Nuclear Manufacturing (CTC)
CMB	Corrosion & Metallurgy Branch (in NRC/RES)
CF	Corrosion fatigue
CFCG	Corrosion fatigue crack growth
CMTR	Certified mill test report
CT	Computed Tomography
CTC	Concurrent Technologies Corporation
CUI	controlled unclassified information (CUI)
DED	Directed energy deposition
DDM	Direct digital manufacturing
DMD	Direct metal deposition
DMLR	Division of Materials & License Renewal (in NRC/NRR)
DMLM	Direct metal laser melting
DMLS	Direct metal laser sintering
DOD	Department of Defense
DOE- NE/ AMM	Department of Energy Office of Nuclear Energy AMM
DRDC	Defence Research and Development Canada
EPRI	Electric Power Research Institute
EWI	Previously known as Edison Welding Institute
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FSH	Full Screen Height
GAIN	Gateway for Accelerated Innovation in Nuclear
GAMA	General Aviation Manufacturers Association
GEH	General Electric Hitachi
HIP	Hot isostatic pressing
HTGR	High temperature gas reactor
IASCC	Irradiation Assisted Stress Corrosion Cracking
ICME	Integrated Computational Materials Engineering
INL	Idaho National Laboratory
IR	Infrared
LAM	Laser additive manufacturing
LOF	Lack of Fusion

LPB-AM	Laser Powder Bed – Additive Manufacturing
LPBF	Laser Powder Bed Fusion
MARPA	Modification and Replacement Parts Association
MDF	Manufacturing Demonstration Facility, ORNL
MMPDS	Metallic Materials Properties Development and Standardization
MRL	Manufacturing Readiness Level
MSR	Molten salt reactor
MVIB	Vessels & Internals Branch (in MRC/NRR)
NARA	National Archives and Records Administration
NASA	National Aeronautics and Space Administration
NASA-JSC WSTF	NASA – Johnson Space Center White Sands Test Facility
NASA-MSFC	NASA - Marshall Space Flight Center
NAVSEA	Naval Sea Systems Command
NDE	Nondestructive evaluation
NDI	Nondestructive inspection
NEET	Nuclear Energy Enabling Technologies (DOE program)
NEI	Nuclear Energy Institute
NF	Nuclear fuels
NIST	National Institute of Standards and Technology
NNES	National Nuclear Energy Strategy
NPM	Nuclear plant module
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation in NRC
NSUF	Nuclear Science User Facilities (DOE)
NSWC	Naval Surface Warfare Center, Carderock Division
OE	Operating experience
OEM	Original equipment manufacturers
ORNL	Oak Ridge National Laboratory
PBF	Powder bed fusion
PM-HIP	Powder metallurgy hot isostatic pressing
PWHT	Post-weld heat treatment
Q&C	Qualification & certification
RES	Office of Nuclear Regulatory Research (in NRC)
RR	Rolls Royce
SA	Surface annealing
SBIR	Small Business Innovative Research
SCC	Stress corrosion cracking
SMR	Small modular reactors
TPD	Thimble plugging device
TRL	Technology Readiness Level
TVA	Tennessee Valley Authority
TWG	Technology working group (under GAIN)
UAM	Ultrasonic additive manufacturing
UTK	University of Tennessee, Knoxville
WEC	Westinghouse Electric Company

1 INTRODUCTION

This NUREG/CP document is designed to summarize the presentations and discussions at an AM-RMC international workshop on November 28-29, 2017 at the NRC Headquarters office in Rockville, MD. Papers associated with the presentations are included, along with brief summary reports for papers within the four sessions of the workshop, which were organized to assess: (1) State-of-the-art of AM, (2) Industry activities in AM, (3) Irradiation testing and effects on AM, (4) AM qualification, (5) Standards for AM, (6) Nondestructive evaluation of components fabricated using AM, (7) American AM activity in international context, (8) cybersecurity of the manufacturing process, (9) Regulatory perspectives on AM, (10) Computer modeling, and (11) AM in nuclear fuel. It is imperative that the NRC utilize these papers and continue the sharing of information across agencies and private industry when developing regulations for the use of AM components in nuclear applications. The next page of this introduction contains a summary table of the presenters, their company or agency, and the topic(s) on which they presented and have significant knowledge. This table should be used as a guide when gathering information and is not considered a complete representation of the capabilities and knowledge of each presenter.

The views and opinions presented in this report are those of the individual participants and publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein. As such, these proceedings are not a substitute for NRC regulations. Rather, the approaches and methods described in these proceedings and the recommendations from the discussions are provided for information only, and compliance is not required. Moreover, use of product or trade names herein is for identification purposes only and does not constitute endorsement by the NRC.

Table 1 Technical Areas of Additive Manufacturing Presentations at November Public Workshop on AM-RMC

Organization/Speaker	State of Art of AM Processes	Industry Activities	Irradiation Testing & Effects	AM qualification	Standards for AM	NDE
NEI (Mark Richter)		■				
EPRI (Dave Gandy)	■					■
FAA (Michael Gorelik)				■	■	
CTC (Scott Zimmerman)						
EWI (Bill Mohr)				▒	▒	
EWI (Frank Medina)	■	▒				
GEH (Myles Connor)		■	▒			
WEC (Zeses Karoutas)		■				
WEC (Bill Cleary)		■				
WEC (Paula Freyer)		▒	■			
Novatech (C. Gramlich)		■	■			
NuScalePower (S. Wolbert)		■				
DRDC (Shannon Farrell)						▒
RollsRoyce (Dave Poole)						
DOE (Alison Hahn)	■					
ORNL (Andrew Worrall)		■				
INL (Isabella van Rooyen)				■		
NSWC (Sam Pratt)	■					
NAVSEA (Justin Rettaliata)				■		
NIST (Paul Witherell)				■		
ORNL/UTK (Suresh Babu)				■		
NASA/MSFC (Doug Wells)	■					▒
NASA/WSTF (Jess Waller)						■
NIST (Kevin Jurrens)				▒	■	▒
ANSI (Jim McCabe)					■	
ASME (Kate Hyam)					■	
ASTM (Mohsen Seifi)					■	
NRC/NRR (Dave Rudland)					■	
NRC/NRR (Allen Hiser)						

Table 1 Technical Areas of Additive Manufacturing Presentations at November Public Workshop on AM-RMC, (cont.)

Organization/Speaker	Degradation in AM components	American/ international context	Cyber-security	Regulatory Perspectives	Computer Modeling	Nuclear Fuel
NEI (Mark Richter)						
EPRI (Dave Gandy)					■	
FAA (Michael Gorelik)				■		
CTC (Scott Zimmerman)			■			
EWI (Bill Mohr)	■					
EWI (Frank Medina)						
GEH (Myles Connor)	■					
WEC (Zeses Karoutas)						
WEC (Bill Cleary)						■
WEC (Paula Freyer)	■					
Novatech (C. Gramlich)						■
NuScalePower (S. Wolbert)						
DRDC (Shannon Farrell)	■	■				
RollsRoyce (Dave Poole)		■				
DOE (Alison Hahn)						
ORNL (Andrew Worrall)						■
INL (Isabella van Rooyen)						■
NSWC (Sam Pratt)	■					
NAVSEA (Justin Rettaliata)						
NIST (Paul Witherell)						
ORNL/UTK (Suresh Babu)						
NASA/MSFC (Doug Wells)						
NASA/WSTF (Jess Waller)						
NIST (Kevin Jurrens)						
ANSI (Jim McCabe)						
ASME (Kate Hyam)						
ASTM (Mohsen Seifi)						
NRC/NRR (Dave Rudland)						
NRC/NRR (Allen Hiser)				■		

2 WORKSHOP AGENDA

Table 2 Agenda for Additive Manufacturing Presentations at November Public Workshop

Tuesday, November 28, 2017		
Industry Activities and Perspectives		
Time	**Presentation (#)/Title**	**Organization– Presenter**
(Session 1 Moderator: Amy Hull, NRC)		
0800	(1.00) Opening Remarks.	NRC – Mike Weber
0815	(1.0) NRC's AM Workshop: Meeting Logistics.	NRC - Rob Tregoning
0830	(1.1) AM for Reactor Materials & Components: Industry Perspective.	NEI – Mark Richter
0900	(1.2) ICME & Process Monitoring for Component Qualification via LPB-AM.	EPRI – Dave Gandy
0930	(1.3) Regulatory Considerations for AM Qualification and status of FAA AM Roadmap.	FAA - Michael Gorelik
1000	Break	
1030	(1.4) Industry Insights - Cybersecurity for Additive Manufacturing.	CTC – Scott Zimmerman
1100	(1.5) Reflections on Fatigue for AM Components.	EWI - Bill Mohr
1130	(1.6) Selecting the Correct Material and Technology for Metal AM Applications.	EWI - Frank Medina
1200	Lunch	
(Session 2 Moderator: Carol Moyer, NRC)		
1300	(2.1) Evaluation of Additively Manufactured Materials for NPP Components.	GEH – Myles Connor
1330	(2.2) The 'Big Picture' Vision for AM in Nuclear Industry.	WEC – Zeses Karoutas
1340	(2.3) Current Westinghouse Efforts.	WEC – Bill Cleary
1410	(2.4) Laboratory Testing & Evaluation of Unirradiated and Neutron Irradiated Additively Manufactured Alloys.	WEC – Paula Freyer
1430	(2.5) Additive Manufacturing for Nuclear Components.	Novatech – George Pabis; Craig Gramlich
1500	Break	
1510	(2.6) Additive Manufacturing for Reactor Materials & Components.	NuScale Power – Steve Wolbert
1540	(2.7) Metal Additive Manufacturing Innovations.	AddiTec – Brian Matthews
1555	(2.8) Analysis of Seeded Defects in Laser Additive Manufactured 300M Steel	DRDC –Shannon Farrell
1620	Summarize Day 1, Discussion, Capture Action Items	NRC & Participants
1630	Time Allowed for Public Comments	Public & NRC
1700	Adjourn for Day	NRC

Table 2 Agenda for Additive Manufacturing Presentations at November Public Workshop, (cont.)

Wednesday, November 29, 2017		
Government Agency Initiatives		
Time	**Presentation (#)/Title**	**Organization - Presenter**
(Session 3 Moderator: Christopher Hovanec, NRC)		
0800	Summary of Day 1; Objectives & Guidance for Day 2	NRC
0815	(3.1) Rolls-Royce Nuclear Developments in AM.	Rolls-Royce – Dave Poole
0835	(3.2) Additive Manufacturing Initiatives.	DOE-NE AMM - Alison
0900	(3.3) GAIN Gateway for Accelerated Innovation in Nuclear.	ORNL- Andrew Worrall
0920	(3.4) AM Qualification Paradigm Similarities for Fuel & Components.	INL - Isabella van Rooyen
0945	Break	
1000	(3.5) Comparisons between 316L SS made using Multiple LPBF Systems.	NSWC – Sam Pratt
1030	(3.6) Qualification & Certification of Metallic Components for NAVSEA.	NAVSEA – Justin
1100	(3.7) Informatics in AM Qualification: Incorporating Databases, Simulation & Analysis.	NIST – Paul Witherell
1130	(3.8) Ultrasonic Additive Manufacturing & other AM Processes for Nuclear Component Manufacture.	ORNL/UTK – S. Suresh Babu
1200	Lunch	
(Session 4 Moderator: Rob Tregoning, NRC)		
1300	(4.1) Standardization in Additive Manufacturing: Challenges in Structural Integrity Assurance.	NASA-MSFC – Doug Wells
1330	(4.2) NDE & Inspection Challenges for Additively Manufactured Components.	NASA-WSTF – Jess
1400	(4.3) Measurement Science for Metals-Based Additive Manufacturing.	NIST – Kevin Jurrens
1430	(4.4) America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC).	ANSI - Jim McCabe
1500	(4.5) ASME Additive Manufacturing Standards.	ASME-Kate Hyam
1520	Break	
1530	(4.6) BPTCS/BNCS Special Committee on Use of Additive Manufacturing.	NRC – Dave Rudland
1545	(4.7) The Status of Global Additive Manufacturing Standardization to Support Q&C.	ASTM - Mohsen Seifi
1615	(4.8) Topics of Interest for AM of Reactor Materials & Components.	NRC – Allen Hiser
1630	Discussion	Participants
1645	Time Allowed for Public Comments	Public and NRC
1700	Adjourn Meeting	NRC

3 SELECTED HIGHLIGHTS FROM PAPERS AND DISCUSSIONS

On November 28-29, 2017, the Office of Nuclear Regulatory Research (RES), Division of Engineering (DE), hosted the first Nuclear Regulatory Commission (NRC) Workshop on Additive Manufacturing (AM) for Reactor Materials and Components (RMC). As shown in Section 2, the NRC AM-RMC Workshop included a keynote address by the RES Office Director, Michael Weber, as well as presentations by representatives from American and international industry, members of the NRC staff, the American National Standards Institute (ANSI) and its Additive Manufacturing Standardization Collaborative (AMSC), the American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM), the Electric Power Research Institute (EPRI), the Department of Defense (DoD) facilities, Department of Energy (DOE) and National Laboratories, the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the Nuclear Energy Institute (NEI), and the National Institute of Standards and Technology (NIST).

This was the first NRC AM-RMC workshop. It included discussions on such issues as: (1) The state-of-the-art of AM, (2) Industry activities in AM, (3) Irradiation testing and effects on AM, (4) AM qualification, (5) Standards for AM, (6) Nondestructive evaluation of components fabricated using AM, (7) American AM activity in international context, (8) cybersecurity of the manufacturing process, (9) Regulatory perspectives on AM, (10) Computer modeling, and (11) AM in nuclear fuel. Proceedings of presentations are included in Section 4. All presentation materials are also available in the NRC's Agencywide Documents Access and Management System (ADAMS) at accession number ML17338880.

The audience included approximately 120 attendees representing companies and organizations from 5 countries, including vendors, industry groups, Government regulatory agencies, and both foreign and domestic utilities (see Section 6).

<u>Tuesday Morning Session</u>

Amy Hull, Senior Materials Engineer, Corrosion and Metallurgy Branch (RES/DE/CMB) moderated the first session and introduced the speakers of the morning session (see Section 4, presentations 4.1-4.8). The first speaker, Michael Weber, Director of RES, mentioned that representatives of the nuclear industry, including licensees and vendors, had notified NRC that parts made using direct metal laser melting/sintering may be used in the operating nuclear power plant fleet as early as 2018 and he remarked that NRC was interested in understanding industry plans and the opportunities that industry sees for the use of additive manufacturing in civilian nuclear applications. NRC's collective objective is to ensure that if such parts and materials are used in NPPs, they are used safely and securely. To accomplish this objective, NRC needs to have sufficient information about the safety characteristics and associated monitoring of parts and materials manufactured using additive manufacturing.

Rob Tregoning, Technical Advisor for Materials Engineering, next gave an overview of the meeting logistics and objectives. The primary objectives were to (1) understand the nuclear industry's near-term and long-term strategy and plans for implementing additive manufacturing; (2) discuss opportunities, challenges, and approaches for utilizing additive manufacturing for safety-critical components in other (non-nuclear) industries in both near and long-term; and (3) identify current standardization activities, recognized gaps, and future plans.

Mark Richter, Senior Project Manager-Fuel and Decommissioning Programs at the Nuclear Energy Institute (NEI), gave an industry perspective on additive manufacturing for reactor materials and components. Dr. Richter noted that additive manufacturing has established a decade-long track record serving secondary side and balance of plant (BOP) component needs. He reviewed the National Nuclear Energy Strategy (NNES) and its objectives to preserve, sustain, innovate, and thrive. Within the objective to innovate, commercialize, and deploy new nuclear, the possibility exists to deploy low-risk AM fuel assembly components in a reactor by 2018. He concluded by saying the industry challenge was to develop innovative approaches to refine the manufacturing process, minimize investment and production costs, and work collaboratively with regulatory and consensus standards bodies to achieve acceptance for broad use. Efficiency gained today supports a platform for future new nuclear deployment. In response to a question about the existence of a list of components where the nuclear industry has begun work and any operating experience (OE), Dr. Richter said he did not know of such. He mentioned that he expects fuel applications to come much sooner than pressure-retaining parts.

Dave Gandy, Technical Executive in EPRI's Nuclear Materials area, discussed integrated computational materials engineering (ICME) & process monitoring for qualification of nuclear components of laser powder bed (LPB) AM. He discussed the results of the first year of a 3-year project funded by DOE Advanced Methods for Manufacturing (AMM) [working collaboratively with the ORNL Manufacturing Demonstration Facility (MDF, https://www.ornl.gov/mdf)]. Examples Dr. Gandy presented for nuclear applications for AM focused on reactor internals and fuel assembly components. A major anticipated deliverable is developing ICME process analytical methods to fuse the modeling, process, *in-situ* and *ex-situ* characterization data through Dream3d architecture. If the ICME and in-situ process monitoring qualification methodology for AM components are proven effective, these methodologies will be documented for ASME Code and NRC acceptance. During the discussion, mention was made of controlling defects and the use of hot isostatic pressing (HIP) to treat open and closed voids.

Michael Gorelik, FAA Chief Scientific and Technical Advisor for Fatigue and Damage Tolerance, led the effort to develop the agency's first strategic roadmap for AM. He mentioned that risk factors for AM deployment included surface quality, microstructure variability, powder control, process control, and HIP effectiveness. AM challenges to be addressed include limited understanding of acceptable ranges of variation for key manufacturing parameters, limited understanding of key failure mechanisms and material anomalies, lack of industry databases/allowables, development of capable NDE methods, lack of industry specifications and standards, and new design space. He used the Wohlers Report as a 'sanity check' for the AM Roadmap content and emphasized that collaboration among industry, agencies, and technical societies (such as ASTM, AWS, etc) is needed to ensure safe introduction of AM in major industry sectors. FAA does not anticipate rule changes for AM, but specific guidance documents & policies are expected to be needed. Dr. Gorelik also mentioned DOT/FAA/TC-18/3, "Proceedings from the Joint FAA – Air Force Workshop (FAA CSTA Workshop) Qualification/Certification of Metal Additively Manufactured Parts" as a helpful reference.

Scott Zimmerman, the Chief Information Security Officer / Principal Cybersecurity Engineer at Concurrent Technologies Corporation (CTC) discussed the main AM security challenges as being related to loss or theft of intellectual property, compromised process and/or product integrity, productivity disruption, and damage to reputation. The main message was to build in cybersecurity, don't bolt it on at the end. NIST issued cyber safeguards (Special Publication 800-171) in June 2015 to protect controlled unclassified information (CUI) in non-federal information systems. A “General FAR Rule” is in development that will obligate all federal agencies to require cyber protection of CUI, per SP 800-171, in all contracts and agreements.

Mr. Zimmerman also gave an overview of CTC’s new Center for Advanced Nuclear Manufacturing (CANM) established in Johnstown, PA in 2017 to utilize existing metalworking capabilities to establish a self-sustaining global resource to develop and deploy applied metalworking and manufacturing capabilities to advance design, fabrication and operation for Small Modular Reactors (SMRs) and Advanced Reactors (ARs). CANM will provide manufacturing and demonstration facilities to support the fabrication and testing of functional prototype systems.

Bill Mohr, a Principal Engineer in the Structural Integrity Group of EWI (https://ewi.org/, formerly known as the Edison Welding Institute), discussed the issue of fatigue for AM components. He showed that testing of additively-manufactured metal pieces has shown a wide variety of results for many investigators. Categorizing the results according to general, surface, and sub-surface flaws allows the data to be put in more coherent groups and compared across processes. This method also allows better estimation of the effect of post fabrication treatments, such as machining, HIPing, and heat treatment. Optimization of the deposition method to limit pores and regions of incomplete fusion is needed to allow further substantial improvements due to surface finishing and PWHT. While HIPing can overcome some of these imperfections, it is not a cure-all. If initial deposition procedures are optimized to avoid general flaws and surface flaws, then HIPing may provide little or no benefit.

Frank Medina, the EWI technology leader for AM and Director of the Additive Manufacturing Consortium (AMC), gave a detailed presentation on selecting the correct material and technology for metal AM applications. He noted that the ASTM F42 Committee on Additive Manufacturing Technologies was formed in 2009 and categorized AM technologies into seven categories: powder bed fusion, sheet lamination, directed energy deposition, binder jetting, material extrusion, material jetting, and vat photopolymerization. Only the first four are appropriate for metal AM. Tooling and metal part prototyping are common applications. Direct manufacturing of novel designs, compositions, and geometries are being actively pursued. Direct approaches are becoming increasingly available and reliable, but remain expensive for many types of geometries and volumes. Knowing the technology limitations is key for success.

Tuesday Afternoon Session

Carol Moyer, Senior Materials Engineer, (RES/DE/CMB) moderated the second session and introduced the speakers of the afternoon session (see Section 4, presentations 4.9-4.16).

The first speaker, Myles Connor, the GE-Hitachi Lead Materials Engineer responsible for direct metal laser melting (DMLM) AM development, discussed the evaluation of additively manufactured materials for nuclear plant components.   He noted that fabrication & unirradiated testing results were shared during the GE-H visit to NRC in June 2017 (ADAMS ML17136A042). He discussed his DOE NEET CFA-15-8309 project with ORNL and University of Michigan to evaluate the SCC susceptibility, corrosion fatigue (CF), and irradiation resistance of the AM 316L stainless steel in nuclear environments. The laser process can have a strong influence on microstructure, even after HIP and high temperature surface annealing have been used to improve SCC resistance. In summary, he found that unrecystallized grains after annealing do not have a significant negative influence on mechanical, SCC, and CF performance and that HIP may not be needed if the laser properties yield low porosity.

Zeses Karoutas, Westinghouse Electric Company (WEC) Chief Engineer, discussed what is driving AM for nuclear. WEC believes that to deliver the nuclear promise of "advancing safety, reliability, and economic performance," the industry needs innovation. AM is innovation in the form of a disruptive technology. The Westinghouse goal is for AM to help transform the nuclear industry and support the nuclear promise.

Bill Cleary, WEC Nuclear Fuels (NF) AM Technical Lead, presented the WEC key areas of AM interest including global technology development efforts, tooling and replacement parts, nuclear fuel components efforts, and the thimble plugging device (TPD) project. The TPD project was not intended for large-scale production but rather for testing and proof of principle. Mr. Cleary noted that the benefit of AM for tooling and replacement parts, radiation exposure and mechanical testing of 316L, A718, and Zr products look promising. WEC plans to insert the first AM part in reactor in 2018 to gain experience and next wants to focus on building AM parts to obtain benefits in performance, economics and manufacturing relative to current methods.

Paula Freyer, Fellow Engineer/Metallurgist at WEC Global Technology Office Churchill Laboratory Services, discussed her results from laboratory testing and evaluation of unirradiated and neutron irradiated AM alloys. She found that unirradiated and irradiated AM 316L tensile properties exceed ASTM AM 316L specifications, and generally significantly exceed minimum property requirements. The 316L powder that they tested was "medical" 316, not exactly the same chemistry as rolled 316 from certified mill test reports (CMTRs). Preliminary 1-month corrosion studies had been conducted comparing AM and wrought 316L samples.

George Grabis, Principal Engineer at NovaTech, supported by Craig Gramlich, Mechanical/Fluids Engineer at NovaTech, discussed his small company, founded in 1994, and the work it is doing via Small Business Innovative Research (SBIR) funding to develop AM techniques of powder bed fusion, and laser sintering to manufacture Alloy 718 bottom nozzles and holddown springs. Nozzles can be modified to tune the pressure drop, thus to control the coolant flow to various elements. They partnered with Areva to outfit and test future fuel assembly designs. Further, they are working with ORNL to do material irradiation testing.

Steve Wolbert, Manufacturing Engineer at NuScale Power, presented potential applications for AM in the NuScale nuclear plant module (NPM) including reactor vessel internals, integral safe ends, and sub-supplier components. He anticipates that a NuScale module will include traditional forgings, powder metallurgy- hot isostatic pressing (PM-HIP) complex shapes, AM parts, traditional welds, advanced joining techniques, and laser clad components. NuScale Power is the developer of a 50-MWe light-water SMR. In 2017, it filed the first application with NRC for the design certification of an SMR. NuScale Power's advanced manufacturing cooperation includes EPRI, CTC's CANM, NovaTech, and AddiTec, among others.

Brian Matthews, with a background in reactor physics and nuclear safety, founded AddiTec in 2015, and has focused on reducing cost and expanding of additive technologies beyond current limitations. Of the five technologies in use for metal AM (electron beam melting, direct metal deposition (DMD), direct metal laser sintering (DMLS), binder jetting, and investment casting) AddiTec focused on going beyond the shortcomings of DMD and DMLS. AddiTec's objective is to develop and reduce the cost of advanced DMD and DMLS systems by a factor of >10; innovate system design and capabilities; and mass produce AM parts using ultra-low cost AddiTec AM systems. There was discussion in the room about exploring hybrid delivery of wire plus powder with the vision that, by changing the chemistry, it may be possible to increase the corrosion resistance of AM material with a particular powder on the surface. For example, the concept was raised of building a spent fuel rack with low-cost stainless steel wire, with selective powder application of neutron absorbers as needed.

Shannon Farrell, Canadian Department of National Defence, Defense Research and Development, discussed the analysis of seeded defects in laser AM (LAM) 300M steel. Canada's Department of National Defence is developing AM to reduce cost of maintenance and improve operational readiness. Their focus is parts-on-demand and repair and refurbishment of legacy parts. In conclusion, he noted that densification of 300M steel specimens was controlled through modification of LAM fabrication parameters, and that specimens appeared to have a threshold limit of porosity. The Archimedes' principle was shown to be an effective tool for simple, rapid assessment of bulk density. Radiography was capable of seeing the 500-1000 µm defects in the 97.5% density specimens. UT ultrasonic gain is promising for estimation of through-thickness density in LAM materials.

Wednesday Morning Session

Christopher Hovanec, Materials Engineer (NRR/DMLR/MVIB), moderated the Wednesday morning session and introduced the speakers (see Section 4, presentations 4.17 - 4.24).

The morning session began with a presentation by Dave Poole of Rolls-Royce (RR) on nuclear developments in additive manufacturing. Rolls-Royce began its AM program in 2008 and has a robust program for production of AM components, using both PBF and DMD systems. No AM components are currently used in pressure boundary applications at nuclear facilities, however. The lead products are manual globe valves and pipework tee fittings, both of which are class 1 fittings designed to ASME Section III code. Rolls-Royce plans to continue development and increase production using AM equipment. They are progressing from less- to more-critical applications, first substituting for existing manufacturing processes, then enhancing, then designing using AM capabilities. Surface finish is a big concern; parts they have made so far are fully finish machined. Partly, this is for corrosion fatigue performance, and also internal flow performance. In-process NDE is especially important for 1-way choice components (see pg. 4-180). Parts that are designed for AM may be difficult or impossible to inspect with conventional techniques (e.g. RT), so RR needs to consider in-process inspection from the start.

Next, Alison Hahn of the Department of Energy's Office of Nuclear Energy (NE) presented additive manufacturing initiatives being pursued by her Office. Currently, their main focus is improving methods for the fabrication of nuclear components by reducing cost and lead time and increasing reliability. The NE Advanced Methods for Manufacturing (AMM) program was established in 2012. Projects are selected from competitive solicitations. She noted that more samples are being irradiated in the DOE Nuclear Science User Facilities (NSUFs) than can be post-irradiation-examined (PIE'd) under existing work. Those samples will be available in the sample library for work by others. The earlier presentation on near-net-shape forming via PM/HIP (an AMM supported project) generated much interest. PM/HIP samples are to be irradiated through NSUF starting in 2018. NRC staff proposed a follow-up action to have larger/longer discussions examining all the 'new' manufacturing techniques proposed for SMRs including PM/HIP programs.

Andrew Worrall of Oak Ridge National Laboratory (ORNL), and Deputy Director of DOE's "Gateway for Accelerated Innovation in Nuclear" (GAIN) program talked about the work being done under this private-public partnership (emphasizing reverse focus from public-private partnership) dedicated to accelerating innovative nuclear energy technologies' time to market. DOE provides support where industry wants to lead. Often additive technologies and irradiation testing are expensive, especially for start-up companies. DOE and the GAIN program are trying to address this, to move the technology forward, by providing access to national laboratory facilities and expertise. GAIN targets both the industry and the supply chain with its 3 ‘pillars’ of support: modeling & simulation, expertise, and unique facilities. GAIN is intended to be a conduit to everything DOE is doing to support the industry. GAIN, working with NEI and EPRI, has facilitated three technology working groups (TWG): MSR, HTGR, fast reactors. AM might potentially be used for printing metal fuels and TRISO fuels. In discussions, NRC staff noted the importance of inspectability from the start and during service life. NRC staff further noted that a follow-up action would be to discuss NRC participation in the Fall 2018 GAIN workshop on Advanced Manufacturing.

Next, Isabella J. van Rooyen, Distinguished Staff Scientist and Principal Investigator in the Fuels Design and Development Department at Idaho National Laboratory (INL) presented on Additive Manufacturing Qualification Paradigm Similarities for Fuel and Components. She discussed the potential use of additively manufactured components in the nuclear industry. Dr. van Rooyen discussed the following elements of an AM development program: design (thin-thick, gradient composition, integrated systems), prototyping, fabrication, cladding, welding, novel alloy development, measurement, and repair. Additive Manufacturing as an Alternative Fabrication Technique (AMAFT) was discussed as an integrated modular technique to transform U-based material into accident tolerant fuel. Her work is now focusing on uranium silicide (U_3Si_2), experiments that have been conducted on U-surrogates (similar properties & laser absorption of U3Si2). She also discussed other new technologies being tested and the path forward for INL’s research in AM.

Sam Pratt of the Naval Surface Warfare Center (NSWC) Carderock Division gave a presentation, written by Caroline Scheck and Bryan Kessel, on the comparisons of components made with 316L SS material using multiple Laser PBF machines. There are multiple original equipment manufacturers (OEMs) for PBF systems and each OEM utilizes its own unique software, system controls, processing parameter options, etc. that can result in material and mechanical variation. This project focused on the results from using three different OEM PBF systems to fabricate 316L austenitic SS. The purpose is understanding variability when a reasonable attempt is made to maintain consistency between build files, and using OEM-recommended system processing parameters and raw materials. Results were analyzed to determine the variability between identical components manufactured with different AM machines. Results include powder feedstock characterization, mechanical and corrosion testing, and microstructural feature comparisons between fabricated coupons from each system. Process qualification is a focus area for the Navy. It is interested in understanding how usage of different AM systems impacts results. Jointly, NSWCs maintain four laser powder bed fusion systems from three different manufacturers.

Justin Rettaliata, the Additive Manufacturing Technical Warrant Holder of Naval Sea Systems Command (NAVSEA), presented on the Qualification and Certification (Q&C) of Metallic Components for NAVSEA. The goal of the NAVSEA program is to develop the ability to qualify and certify AM parts for NAVSEA ships, with the end state ultimately being accelerated qualification and certification of components at a much reduced cost. This will require the establishment of processes, specifications, and standards across NAVSEA and the US Navy Fleet. NAVSEA is preparing a ‘tech pub” that will discuss how to implement AM, including metals such as 316L, Ti, Ti 6-4, and a few Inconel alloys. Largely the spec will be “material agnostic” (independent of material composition). The current focus at NAVSEA has been on replacement components; steam valves and replacements for obsolete trash compactor handles will be the first metal AM in service.

Paul Witherell, a Mechanical Engineer in the Systems Integration Division of the Engineering Laboratory at the National Institute of Standards and Technology (NIST), discussed Informatics in AM Qualification: Incorporating Databases, Simulation, and Analysis. Paul manages a project on Systems Integration for Additive Manufacturing and serves as the Associate Program Manager of the Measurement Science for Additive Manufacturing program in the Engineering Laboratory. The main aim of the presentation was to show that, when used and applied correctly, databases, modeling, and simulation have a large role to play in AM part qualification. To use predictive modeling, it is necessary to understand sources of uncertainty, especially when changing processes. Reference models are needed. The "AM Bench" model is under development by another NIST group and will be the focus of a June 2018 workshop. Qualification is in the "eye of the beholder" and subject to the criticality of the part and risk of functional failure. Dr. Witherell addressed the main questions of determining when a part is satisfactorily 'qualified.' What is necessary to qualify against the customers' (functional) needs? What part/process characteristics are most likely to lead to failure? What are the failure modes that will determine how the performance of the part is measured? What data is necessary to "establish pedigree"? What is good data or an established/quality dataset? Does this have to be done for all parts? Only for different geometries? Only for different maintenance cycles? Only for different machines? Various AM materials databases were discussed including the NIST Additive Manufacturing Materials Database (AMMD). Other participants mentioned that the Metallic Materials Properties Development and Standardization (MMPDS), the primary source of statistically-based design allowable properties for metallic materials and fasteners used in many different commercial and military aerospace applications around the world, does not yet have AM materials, but is waiting for the public standards to be sufficiently mature.

In the final presentation of the morning session, S. Suresh Babu, the UT/ORNL Governor's chair of advanced manufacturing at the University of Tennessee, Knoxville, TN, spoke about Ultrasonic Additive Manufacturing (UAM) and other AM Processes for Nuclear Component Manufacture. Dr. Babu acts as a bridge to the ORNL's expertise and infrastructure including the ORNL MDF to develop a collaborative research and education ecosystem locally and to deploy engineering solutions to manufacturing industries. Dr. Babu noted that AM has emerged as a potential route for manufacturing nuclear power components with dissimilar materials. Other applications include control rods, spray nozzles, cooling channels, and instrumentation. The laser direct energy deposition (DED) process allowed ORNL to fabricate transition joints with controlled compositions and phase variations. UAM was successfully used for prototypes with embedded neutron absorbers. It is possible to develop ICME models and to extend in-situ and ex-situ characterization to develop rapid qualification methodologies for both fusion and solid-state AM processes. Building on the existing knowledge base, he said he believed we can get to a nuclear-qualified component within two years.

Wednesday Afternoon Session

Rob Tregoning, Senior Technical Adviser for Materials Engineering Issues (RES/DE), moderated the Wednesday afternoon session and introduced the presenters (see Section 4, presentations 4.15 - 4.232).

The first presentation of the afternoon session was given by Doug Wells, a senior structural engineer at NASA's Marshall Space Flight Center. He noted that he has been peripherally involved with additive manufacturing for all of his 25 years at NASA. In the past five or so years, he has been heavily involved in the transition of additive manufacturing from a prototyping technology to a flight hardware technology with all the ensuing qualification and certifications challenges. The subject of his presentation was Standardization in Additive Manufacturing: Challenges in Structural Integrity Assurance. Mr. Wells presented on the need for a standardized, qualified AM process and consensus on definitions of AM quality for consistency. He mentioned that NDE standardization in AM is high priority and would be enhanced by creating a defect catalog for AM. It would be analogous to references used to identify defects in castings or welds and contain correlation of defect type to AM process, NDE method, and reliability of detection, as well as correlation of defect risk to structural integrity.

Jess Waller, a materials scientist from Office of Safety and Mission Assurance's (OSMA) NDE program at NASA's White Sands Test Facility presented on NDE and Inspection Challenges for Additively Manufactured Components. Dr. Waller noted that important technology gaps include: (1) integrated process control (in-situ monitoring during build) (2) material property controls (input materials, qualified material processes) (3) mature process-structure property correlations (design allowables data) (4) mature effect-of-defect (includes fracture mechanics) (5) mature quality control measures (includes NDE tailored to AM). In-process and post-process NDE are vital to qualifying AM components for use in NASA equipment and will also be extremely necessary for the nuclear industry. Standardization across industries will allow for faster time to market and a better understanding of defects in AM components. He discussed key NASA AM Qualification and Certification documents as well as the Additive Manufacturing Roadmap and NDE-Related Technology Gaps documents. Dr. Waller is the POC for government-industry round-robin testing.

Next, Kevin Jurrens, Deputy Chief of Intelligent Systems Division, Engineering Laboratory of NIST presented on Measurement Science for Metals-Based Additive Manufacturing. The AM field has grown dramatically over the past six years alone, and this is amplifying the need for measurement science and standards for the industry. The NIST Roadmap for Measurement Science for Metal AM, written in 2012, became the input to America Makes, and the basis for the ANSI Additive Manufacturing Standardization Collaborative (AMSC) Roadmap. Currently, no unified standardized process exists and there is no standardized path for Q&C. NIST wants standards that are non-contradictory, not overlapping, and avoiding duplication of effort. For AM to continue to grow and become a major contributor, it is vital for NIST to collaborate with industry partners to develop these standards for many industries.

Jim McCabe of the American National Standards Institute (ANSI) presented on the America Makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC). The AMSC "Standardization Roadmap for Additive Manufacturing, Version 1.0, February 2017, listed 89 knowledge gaps - many are in design, process control, and Q&C. He emphasized the importance of the many standards developing organizations (SDOs) to coordinate and create a "consistent, harmonized, and non-contradictory set of AM standards and specifications." AMSC's purpose is to facilitate AM growth across industry and drive standardization among the SDOs.

Kate Hyam of the American Society of Mechanical Engineers (ASME) presented on ASME's development of Additive Manufacturing Standards. A special committee on the use of additive manufacturing for pressure equipment has been developed by the Board on Pressure Technology Codes and Standards (BPTCS) and the Board on Nuclear Codes and Standards (BNCS) to create standards and requirements for AM pressure-boundary components.

Immediately following, Dave Rudland, Senior Technical Advisor for Nuclear Power Plant Materials at the NRC (NRR/DMLR), presented on the BPTCS/BNCS Special Committee on Use of Additive Manufacturing. The objective of this committee, as defined in their charter, is "to develop a technical baseline to support development of a proposed Boiler and Pressure Vessel standard or guideline addressing the pressure integrity governing the construction of pressure retaining equipment by additive manufacturing processes." Currently, the board is preparing the future ASME requirements and meeting on a regular basis to discuss these requirements. A member of the NRC staff will be included in the committee.

Next, from ASTM International, Mohsen Seifi presented on The Status of Global Additive Manufacturing Standardization to Support Q & C (qualification and certification). The presentation included information on ASTM International and its progress into standardization of AM processes as well as the partnerships ASTM has created across the industry. Dr. Seifi discussed the competition for the ASTM Additive Manufacturing Center of Excellence (COE). The objective is to facilitate collaboration & coordination among stakeholders, to develop better standards. An ASTM survey noted that much good R&D is being done in industry and universities, but not captured in standards. The AM COE is to work to transition R&D to stakeholders.

In the final presentation of the day, Allen Hiser, NRC Senior Technical Advisor for License Renewal Aging Management (NRR/DMLR), spoke on Topics of Interest for AM of Reactor Materials and Components. During this presentation, the topic areas identified and discussed were the quality of AM materials and components, codes and standards for AM, properties and structural performance of AM components, service performance and aging degradation, and cyber security of the AM process. Addressing all of these areas will be vital to the use of AM components in nuclear power plants.

The public meeting concluded with a group discussion and time for public comments and questions and was adjourned around 1700.

4 PROCEEDINGS

4.1 Opening Remarks (Michael Weber, NRC)

Opening Remarks

Michael Weber, NRC Public Meeting on

Additive Manufacturing for Reactor Materials & Components

November 28-29, 2017
8:00 AM – 5:00 PM

- Good morning, thank you for coming, and thank you for your interest in participating in this meeting. I am Michael Weber the Director of Nuclear Regulatory Research and it is a privilege to welcome you to this meeting today.

- One of the aspects that I thoroughly enjoy in working on research is the opportunity to learn about and understand cutting edge scientific and engineering information in partnership with our regulatory counterparts to accomplish NRC's nuclear safety and security mission. This meeting is a prime example.

- Welcome to this first NRC public meeting about plans for using additive manufacturing to produce systems, structures, and components for nuclear power reactors and other potential applications. For example, representatives of the nuclear industry, including licensees and vendors, have notified NRC that parts made using direct metal laser melting/sintering may be used in the operating nuclear power plant fleet as early as next year. We are working with our colleagues in NRR and NRO to make sure that the NRC will be ready to review such submittals for safety-significant regulatory applications. Therefore, we would like to understand your plans and the opportunities that you see for the use of additive manufacturing in civilian nuclear applications.

- I have great expectations for the success of this meeting. We are building on the catalyst created when a team from GE-Hitachi arranged a public meeting with NRC in June of this year to discuss general aspects of additive manufacturing. We are aware that other vendors are also considering similar applications. Our collective objective is to ensure that if such parts and materials are used in nuclear power plants that they are used safely and securely. To accomplish this objective, we need to have sufficient information about the safety characteristics and associated monitoring of parts and materials manufactured using additive manufacturing.

- We had the opportunity to meet with many of you at the ANSI Additive Manufacturing Standardization Collaborative Forum in September, at the meetings in Idaho sponsored by the US Nuclear Infrastructure Council (NIC) and Department of Energy (DOE) early October, at the Westinghouse Churchill facility later in October, at ASME meetings, and at the ASTM Symposium on Additive Manufacturing this month. We recognize and appreciate these interactions. Your willingness to share insights and plans with the NRC at this stage of deployment help us prepare and be ready to review.

- Our meeting during the next couple of days provides another opportunity to interact with you regarding additive manufacturing. We look forward to listening to presentations and discussing such topics as qualification and quality control, Non-Destructive Examination, and inspection, materials properties, cybersecurity, and reverse engineering to the extent that we can have these discussions in a public forum while protecting sensitive information.

- The first day of our meeting will mainly focus on industry activities and perspectives; during the second day, we will explore complementary government agency initiatives.

- We are excited to hear from the many organizations involved in Additive Manufacturing, including ANSI, ASME, ASTM, Concurrent Technologies, DOD Labs, DOE Labs, EPRI, EWI, FAA, GE-Hitachi, NASA, NEI, Novatech, NuScale Power, and Westinghouse, to mention a few.

- So engage, collaborate, share to the extent that you can and thank you again for your active participation. Together we achieve nuclear safety and security

4.2 Introduction (Rob Tregoning, NRC)

U.S.NRC

NRC's Additive Manufacturing Workshop: Meeting Logistics

- Category-Two Public Meeting
  - Questions at designated points in the agenda
  - Presentations and public meeting summary in ADAMS
    - Email to amy.hull@nrc.gov
  - Attendance list
  - Public meeting feedback
    - Hardcopy forms (back of the room)
    - Link to public meeting: https://www.nrc.gov/pmns/mtg?do=details&Code=20171391
    - Direct link to form: https://www.nrc.gov/docs/ML1412/ML14125A005.pdf
      - Title: Additive Manufacturing for Reactor Materials and Components
      - Meeting Contact: Amy Hull, MS T-10 A36
      - Meeting Dates: 11/28 – 29/2017

U.S.NRC

NRC's Additive Manufacturing Workshop: Meeting Logistics

- Room Layout
  - One representative from each organization at table behind placard
  - Speakers at head table
- Webinar

	Webinar Info (matthew.hiser@nrc.gov; ACRS Tel: 301-415-5464)	Bridge line
Day 1	https://attendee.gotowebinar.com/register/7397322203895099905	call in 888-437-3094, passcode 6447957
Day 2	https://attendee.gotowebinar.com/register/6092926479888081409	

- Lunch (1 hour) and Breaks (10 – 30 minutes)
- Fire Exits
- Bathrooms

4.3 **<u>AM for Reactor Materials & Components: Industry Perspective (Mark Richter, NEI)</u>**

Overview

- Industry Challenges and Current Landscape
- Industry Responds
- Sustain and Innovate
- Additive Manufacturing and Nuclear Energy
- M o ve Forward

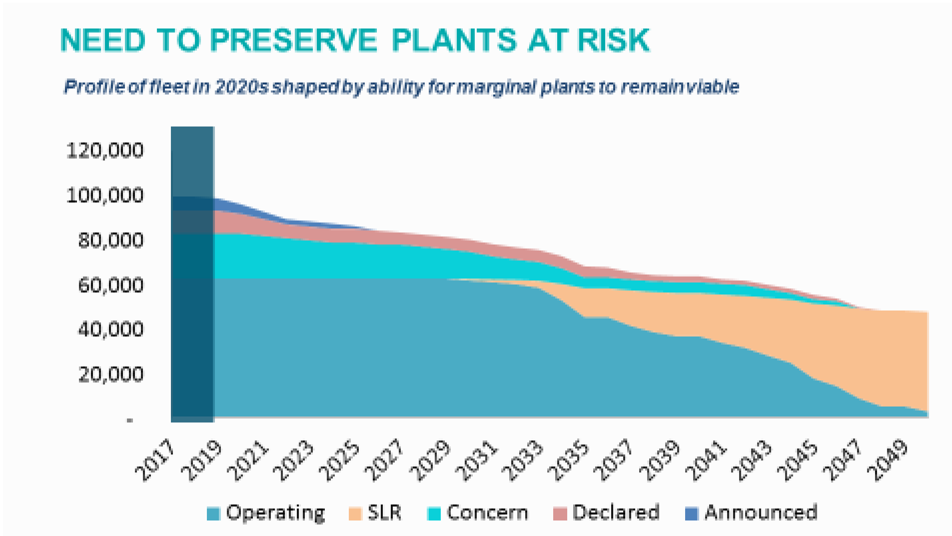
NEI

Early Plant Shutdowns

Plant	MWe	Closure Year	Latest Electricity Generated (billion kWh per year)	Latest CO2 Emissions Avoided (million tons/year)
Crystal River 3	860	2013	7.0	5.3
San Onofre 2 & 3	2,150	2013	18.1	8.8
Kewaunee	566	2013	4.5	4.8
Vermont Yankee	620	2014	5.1	2.7
Fort Calhoun	479	2016	3.5	3.7
Pilgrim	678	2019	5.0	2.6
Oyster Creek	610	2019	5.3	4.4
IPEC 2 & 3	2,083	2020/21	16.6	8.5
Palisades	811	2022	5.8	5.0
Diablo Canyon	2,240	2025/26	18.5	8.5

11,101 MWe of baseload capacity
54.3 million short tons of CO_2 avoided
13% of Clean Power Plan's 2030 414-million-ton target
Over 9,200 direct jobs

NEI


NEED TO PRESERVE PLANTS AT RISK
Profile of fleet in 2020s shaped by ability for marginal plants to remain viable
120,000
100,000
80,000
60,000
40,000
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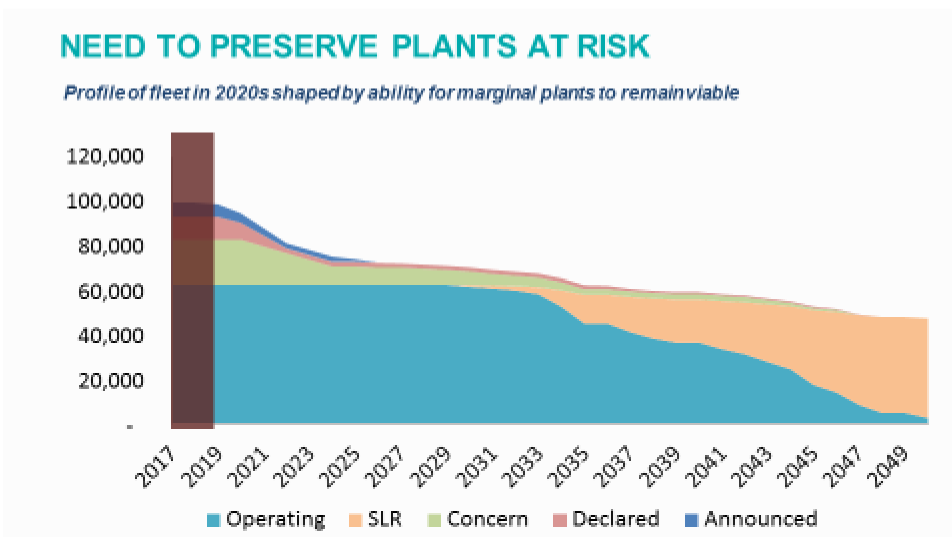
Operating
SLR
Concern
Declared
Announced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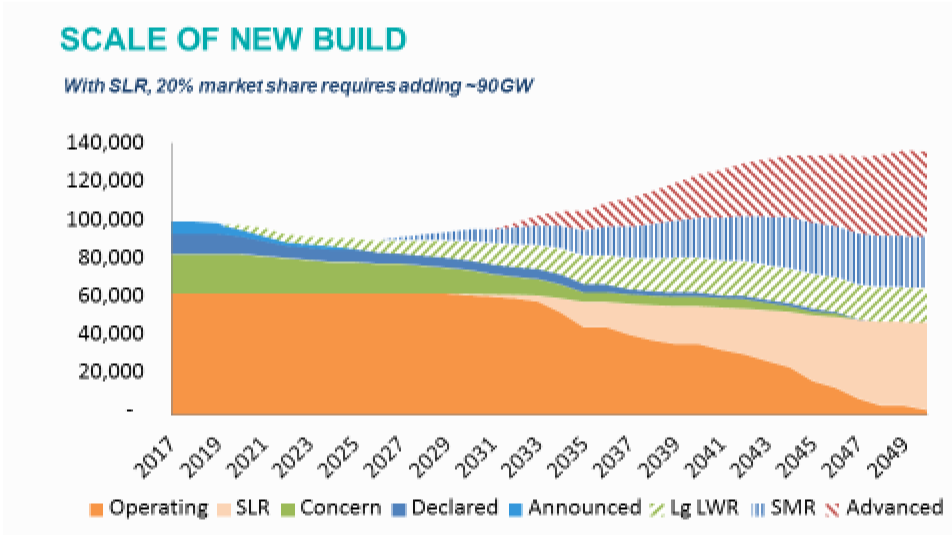
SCALE OF NEW BUILD
With SLR, 20% market share requires adding ~90GW
140,000
120,000
100,000
80,000
60,000
40,000
20,000
-
2017
2019
2021
2023
2025
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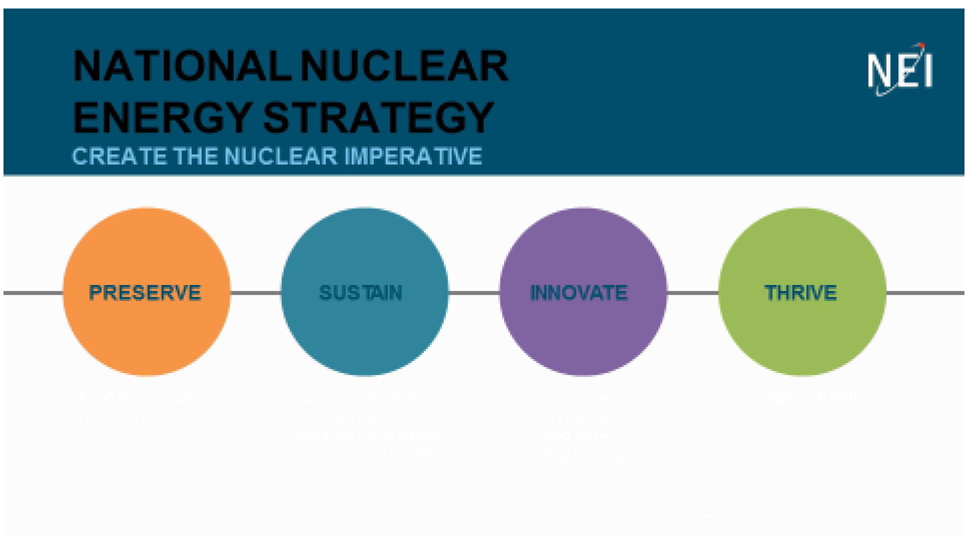
Concern
Declared
Announced
Lg LWR
SMR
Advanced


NATIONAL NUCLEAR ENERGY STRATEGY
CREATE THE NUCLEAR IMPERATIVE
NEI
PRESERVE
SUSTAIN
INNOVATE
THRIVE

Additive Manufacturing Strengths

- Build 3D objects by layering materials-plastics, metals, living tissues-endless potential
- Enable rapid prototyping
- Integrates sophisticated technologies
- Compliments materials removal processes in manufacturing to achieve final shape and dimensions

Create Sustainability NOW

- Preserve reliability and support long term operation
- Sustain the viability of the operating fleet
  - Re-create non-OEM parts or OEM parts where design drawings are unavailable, e.g. pump impeller
  - Improve part performance by removing design limitations
  - Reduce manufacturing lead times and costs
- Additive manufacturing has established a decade long track record serving secondary side and BOP component needs

Innovate, Commercialize and Deploy New Nuclear

- Demonstrate cost-benefit and establish regulatory acceptance with current applications through ASME and other codes and standards
- Strong collaboration between U.S. industry, national labs and universities
- Opportunities in new plant components, new products, and fuel components
- Production of 316 SS and Inconel demonstration parts
- Low risk fuel components in a reactor by 2018

Moving Forward

- High equipment costs versus *potential* industry savings
- Part size limitations
- Lack of process standardization
- Process development ongoing
- Final products are near-net-shape
- Finishing steps required to meet dimensional and surface finish requirements

NEI

Industry Challenge

Develop innovative approaches to refine the manufacturing process and minimize investment and production costs, work collaboratively with regulatory and consensus standards bodies to achieve acceptance for broad use. Efficiency gained today supports a platform for future new nuclear deployment.

NEI

4.4 **ICME & Process Monitoring for Component Qualification via LPB-AM (Dave Gandy, EPRI)**

ELECTRIC POWER RESEARCH INSTITUTE

ICME & Process Monitoring for Qualification of Nuclear Components via LPB-AM

D. Gandy and C. Stover
Electric Power Research Institute
S. Babu, F. List III
ORNL Manufacturing Demonstration Center

NRC/Industry AM Technical Information Exchange Meeting
November 28-29
North Bethesda, MD

Parts of Presentation previously made at:

- US DOE Advanced Manufacturing Methods Workshop in Idaho Falls, October 2017
- And at ASME BPVC on Additive Manufacturing, November 2017

AMM
Advanced Methods for Manufacturing

2

Presentation Outline

- Introduction to DOE Project on AM
- Interest by Nuclear Industry and Applications
- Project Tasks & Progress
- What We Have Learned…
- Summary

3

Introduction—DOE Project

- ASME, NRC, and industry continue to look to identify strategy/approach for "nuclear quality components" manufactured by AM.
- Current approach requires manufacture of multiple parts followed by destructive testing of several parts
  - Properties (microstructural/mechanical) are still difficult to predict
- Objective: ORNL/EPRI are working on an approach that incorporates *Integrated Computational Materials Engineering (ICME)* and *In-situ Process Control* aimed at demonstrating **properties reproducibility** for nuclear applications using LPB-AM.

There has to be a better way to qualify AM parts for nuclear applications.....

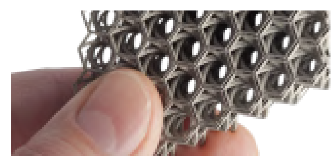
4

Why Is Industry Interested in Laser Powder Bed-AM?

1. Produce replacement parts for the **existing fleet** with a very short turn around
   - Obsolete parts—remember some units are over 40 years old
2. Produce new or complex parts for the **new fleet** of ALWRs, SMRs and Gen IV applications
3. Design to include improved flow characteristics or special features that can't be done through casting/forging/ machining
4. Introduce favorable properties via unique microstructures
5. Design for performance

Chamber size: 250mm x 250mm x 300mm (~10x10x12) (courtesy of Renishaw)

Examples: Nuclear Applications for AM --Reactor Internals and Fuel Assemblies



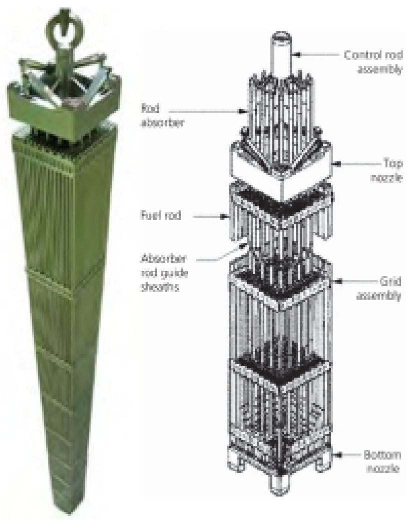
- **Smaller parts (<100 lbs, 45kgs)**

Potential Reactor Internals

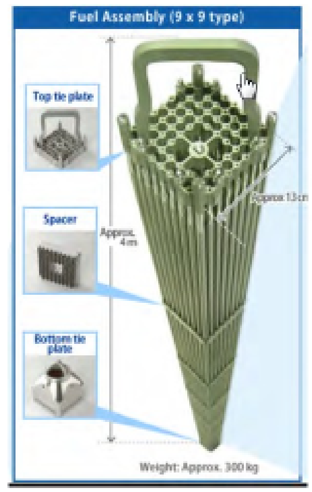
- Small valves, tees, wyes
- Fuel assemblies (next slide)
- Control rod drive internals
- Alignment pins & springs
- Small spray nozzles
- Instrumentation brackets
- Stub-tube/housing
- Steam separator inlet swirler
- Flow deflectors
- GEN IV—cooling channels

PWR Control Rod Assembly

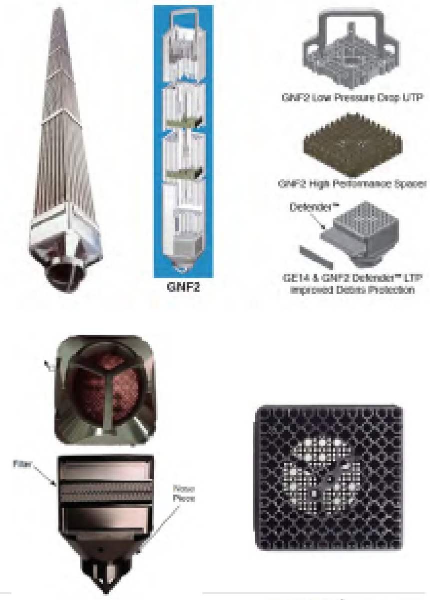
Fuel Assemblies--Examples



Courtesy of WEC



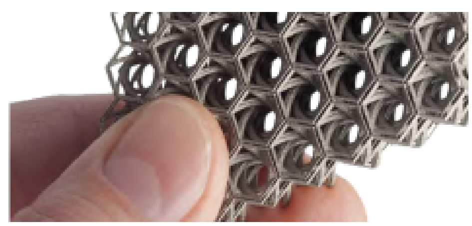
Courtesy of Hitachi



Current AM Limitations--Metallics

6 Key Limitations

- Chamber size
- Deposition rates, single laser or EB
- Porosity or lack of fusion
- Residual stresses/distortion
- Post processing required, HIP
- Layer-by-layer qualification (nuclear)



Project Tasks

1. Demonstrate Artifact Design and Baseline Properties
2. Process Design, Processing and In-situ Monitoring & Validation
3. Deploy and Validate High Performance Computational Models
4. Ex-situ Non Destructive Microstructure Characterization
5. Scale up to Full Size Components
6. Develop ASME and Regulatory Acceptance

Rolls-Royce | Oak Ridge National Laboratory | Westinghouse

Task 1: Demo Artifact Design and Baseline Properties

- Produce two demonstration components (simple and complex).
- Measure/document static (yield strength, tensile strength, elongation) and dynamic (Charpy toughness & fatigue) properties.
- WEC and RR provide components/data for existing technologies (forging, casting, etc.) for comparison.

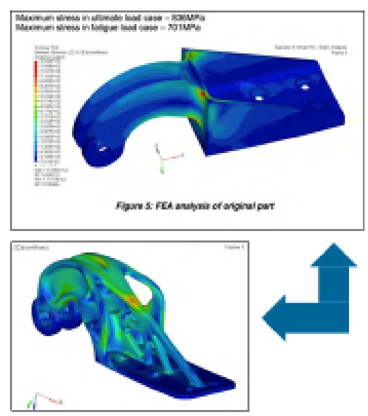
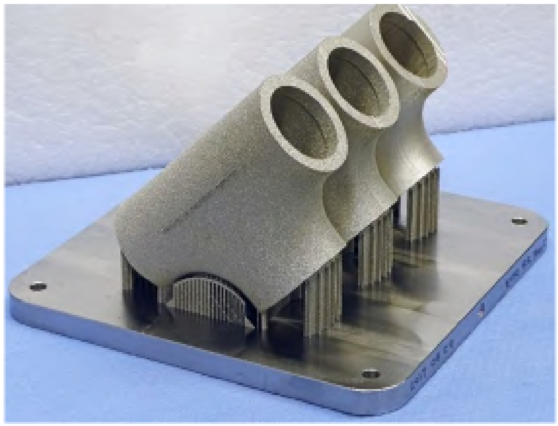


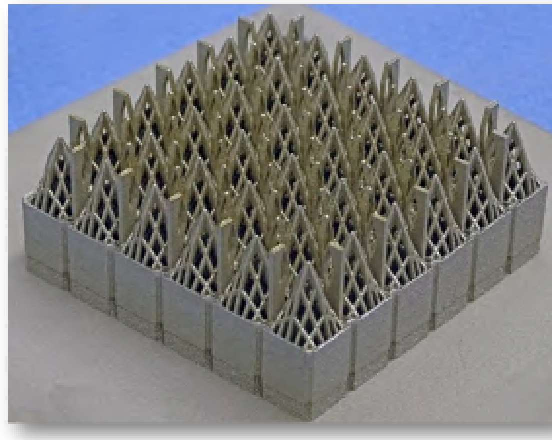
Figure 5: FEA analysis of original part

Application of Topology, Sizing and Shape Optimization Methods to Optimal Design of Aircraft Components

Additive Manufacturing (AM) of Reactor Internals



Rolls-Royce 2" diameter 316L SS Pipe
Tee-Sections, Build Time ~67 hrs

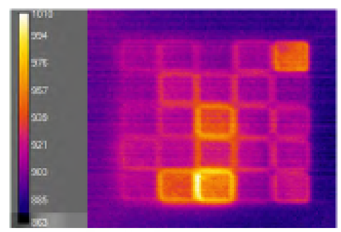


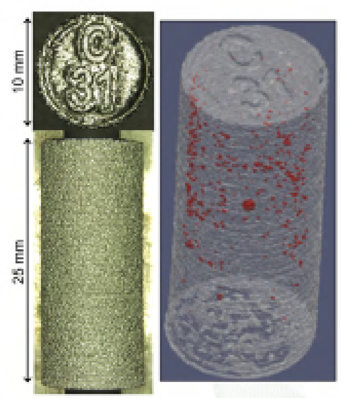
Westinghouse 3" x 3" Inconel 718
Fuel Nozzle, Build Time ~10.5 hrs

DOE/EPRI/Westinghouse/Rolls-Royce

Task 2: Process Design

- Components manufactured using **Renishaw® laser powder bed AM** processing equipment.
- The simple and complex geometries from Task 1 to be scaled & appended
- The process variables including: laser power, scanning speed, scanning strategy, preheat temperature, and powder characteristics will be recorded
- Three different qualities of build: poor, medium and high quality (intentionally) and compared.
  - Random defects, engineered defects, & with HIP.





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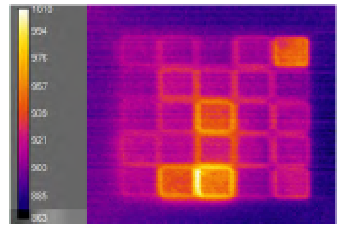
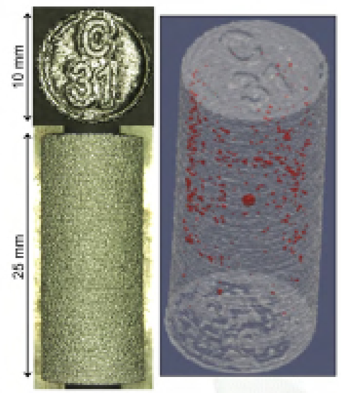
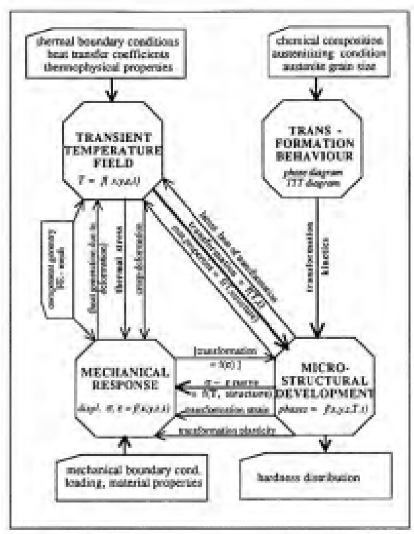




Task 3: Deploy and Validate High Performance ICME Computational Models (1)

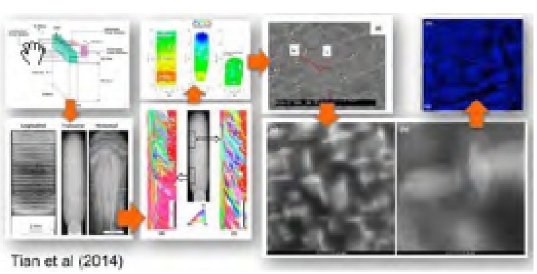
- Process parameter data and boundary conditions will be used as input for ICME models for heat transfer and mass transfer
- Models will be used to predict spatial variations of temperature, liquid metal flow, and liquid solid interface velocity.



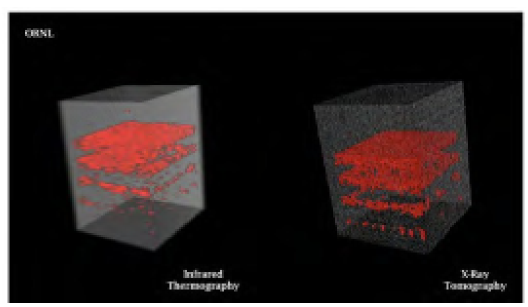
Task 3: Deploy and Validate High Performance ICME Computational Models (2)

- From these characteristics, models will be used to predict:
  - Defect formation
  - Columnar vs equiaxed grain deformation
- Predicted results will be validated from in-situ monitoring (Task 2)
- Data in turn will be loaded into 3D framework
- ICME models will be used to predict the debit of static, dynamic, corrosion properties

Task 4. Ex-situ NDE and Microstructural Characterization

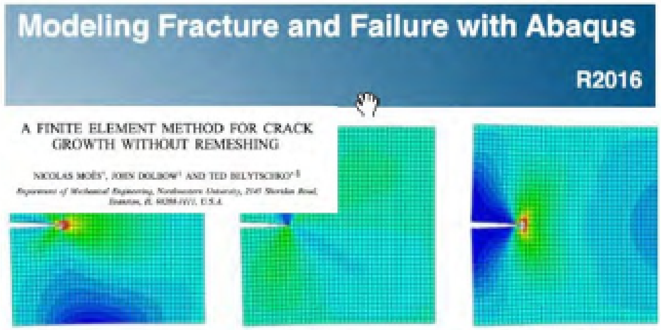


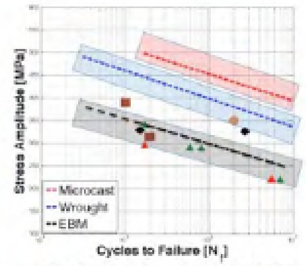
Multi-scale Characterization Methods (Optical, SEM, EBSD, TEM, etc



Comparison of Infrared Thermography and X-Ray Tomography Results

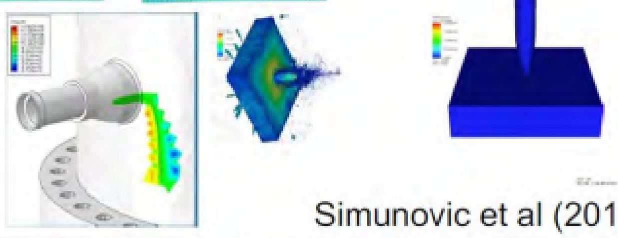
Task 5: Scale Up To Full Size Components





Kirka et al (2016)

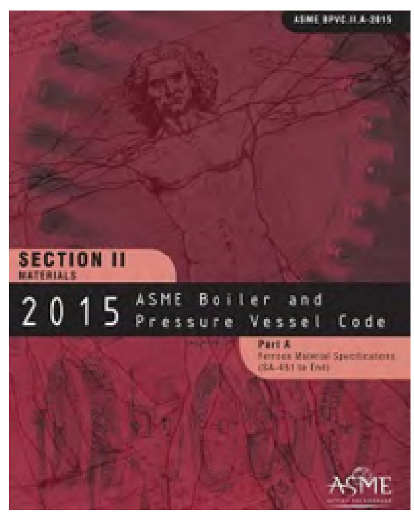
- What can we do with this multitude of experimental and modeling datasets?



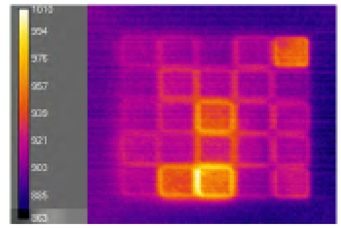
Simunovic et al (2013)

Task 6: Develop ASME Code Acceptance & Project Management

- If the ICME and in-situ process monitoring qualification methodology for AM components is proven correct, these methodologies will be documented for ASME Code and NRC acceptance.



Project Progress: Task 2: Process Design



- Components manufactured using **Renishaw® laser powder bed AM** processing equipment.
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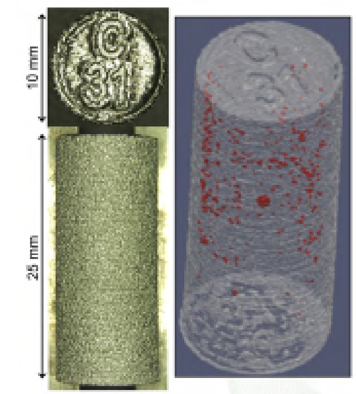

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Three Cylindrical Samples Produced for CT Scanning

- Each sample contains both engineered and random defects
- IR data exists for each sample
- Goal: compare layer-by-layer IR data to the CT data.

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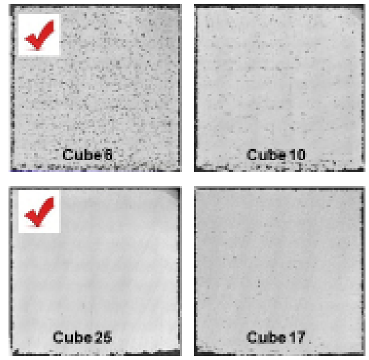
Task 2: Process Design

- Developed a methodology to extract the defect generation probability from in-situ thermal imaging and analyses.
- **Key-factors:** time and spatial resolution
- **Key-findings:** There are critical data from maximum intensity, integrated area, pulses and time-decay
  - no need for IR to temperature conversion!

x-y plane cross-section

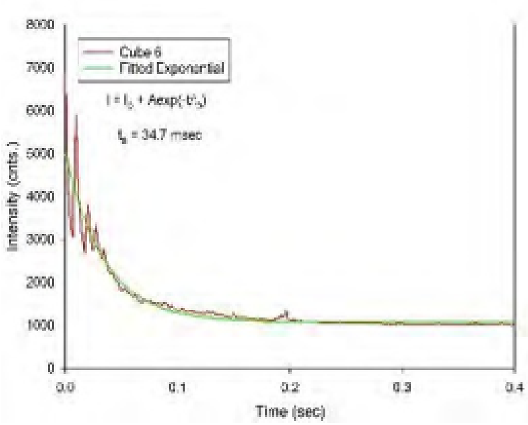


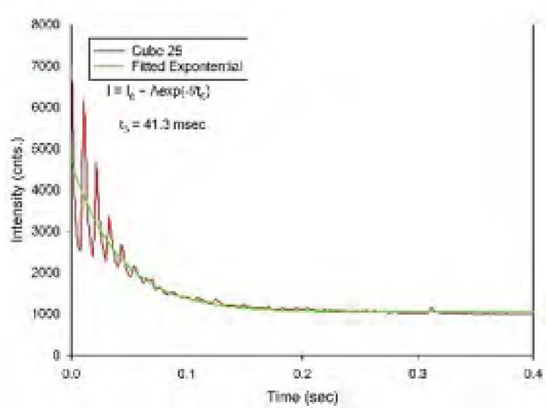
An Analytical Approach to Defect Mapping

- Over 1,000 frames are recorded for each layer.
- Cooling curves for each pixel within a layer are calculated from these frames.
- Comparison of cooling curves for each pixel are used to identify neighboring defects.

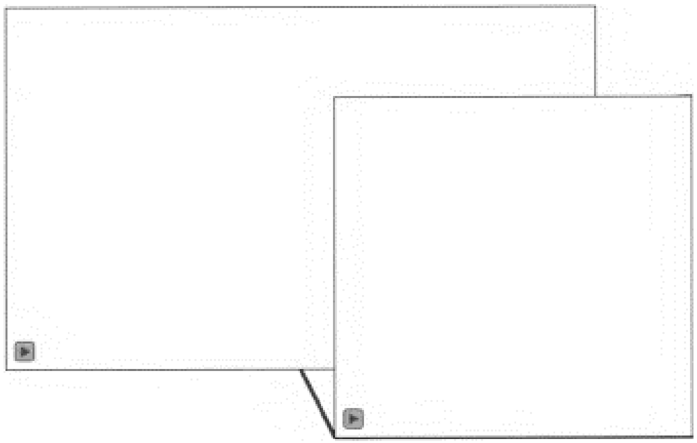
Task 2: Process Design

$$I(t) = I_0 + Ae^{-t/\tau_0}$$



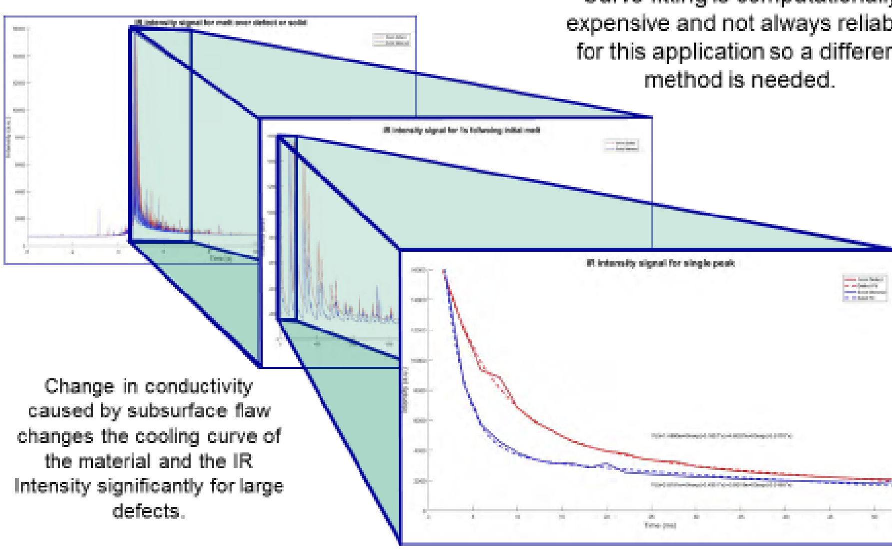


Raw IR Data



Data Analysis

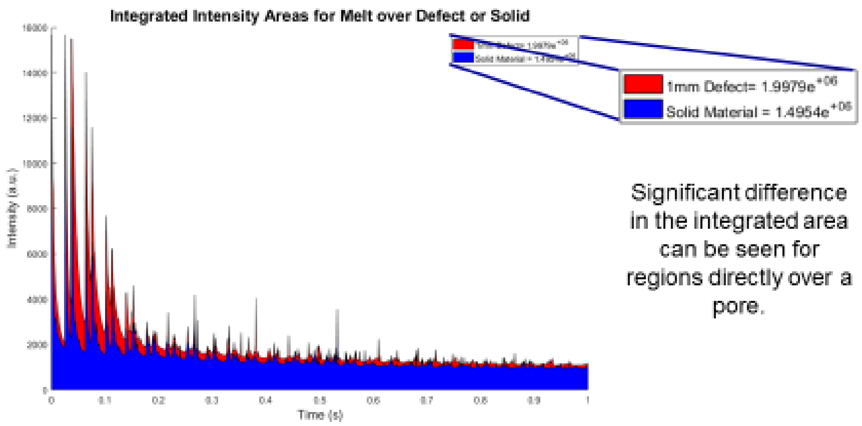
Curve fitting is computationally expensive and not always reliable for this application so a different method is needed.



Change in conductivity caused by subsurface flaw changes the cooling curve of the material and the IR Intensity significantly for large defects.

Integrated Intensity

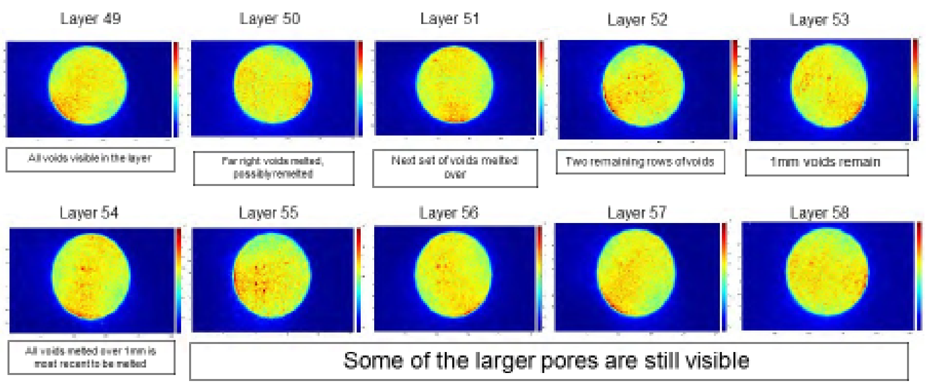
- Taking the Area under the signal curve through integration allows for all of this information to be quantified by a single number. Showing any region where the signal has longer decay.



Significant difference in the integrated area can be seen for regions directly over a pore.

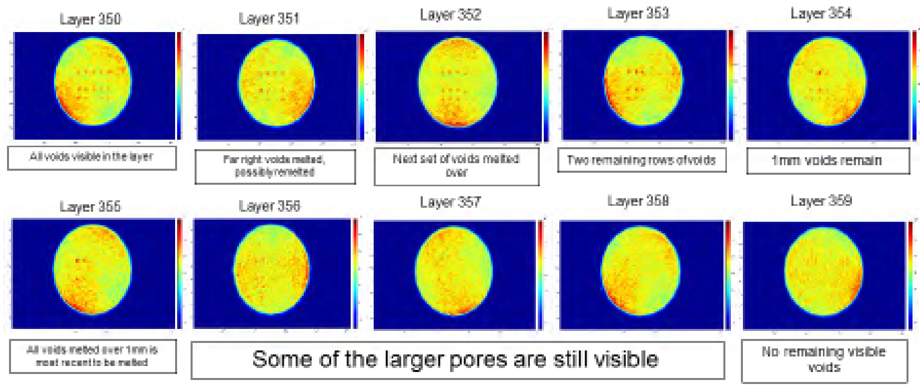
Thermal signature of porosity layers early in build process

- Mapping Integrated intensity over entire surface reveals in-layer and subsurface flaws.

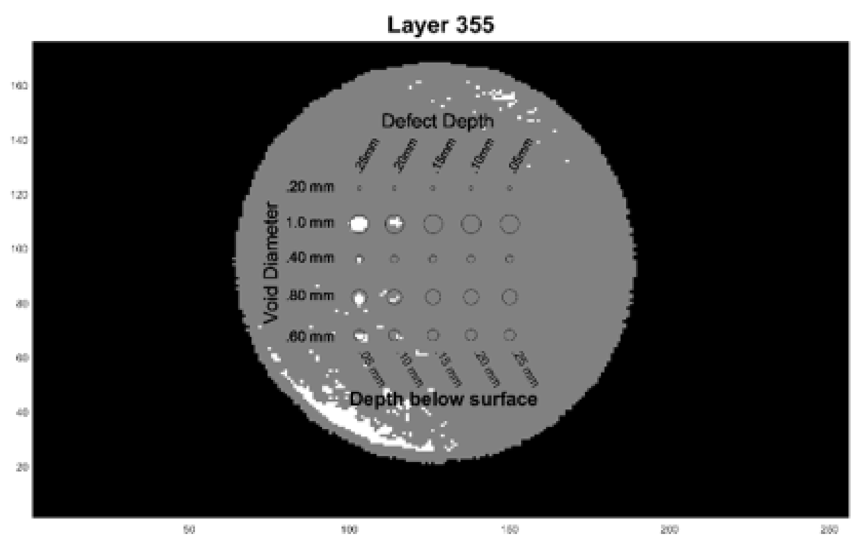


- 200μm defects are not able to be detected because they are 1 pixel in measurement, 400μm defects can be detected in some layers depending on the thermal conditions.

Thermal signature of porosity layers late in build process



Detecting Potential Material Voids



Binarized images show the potential defect regions within the part

3D Visualization of Defects

What Have We Learned So Far…

- Using IR thermography and Data Analysis can provide a method to detect "in-layer" and "subsurface" defects that are sufficiently large enough for the camera resolution to pick up.
  - Beginning and end of melt path seem to show large increase as well
    - Not indicating defects however
  - Noise in the data caused by spatter also needs to be removed
    - Current impact of spatter is not as significant as beginning and ending melt regions
  - Produces terabytes of data
- Further analysis of high-resolution data is continuing.

Major Deliverables Anticipated from the Project

1. Designs that will allow for LPB-AM of complex components
2. Fabrication of 3 components by AM, as well as, a traditional manufacturing processes
3. ICME process analytical methods to fuse the modeling, process, *in-situ* and *ex-situ* characterization data through Dream3d architecture
4. Data and ICME and *in-situ* process monitoring qualification methodology package to support ASME & regulatory qualification/acceptance.

Project Summary

- Completed 1st year of 3-year project
- Believe we have developed IR monitoring method to capture defects (in-layer and subsurface).
  - Performing CT scans to fully characterize
  - 200μm flaw detectable
- Just starting the ICME computational modeling part of the project and ex-situ characterization.
- Beginning engagement with ASME and Regulators
- Terrific engagement by industrial partners: WEC and Rolls-Royce.

Acknowledgement

- Acknowledgment: *"This material is based upon work supported by the Department of Energy under Award Number DE-NE0008629."*

- Disclaimer: *"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."*

Together…Shaping the Future of Electricity

Project Schedules and Milestones Status

Task	1	2	3	4	5	6	7	8	9	10	11	12	Org.
1. Design													OEM
2. Processing & In-Situ Analyses													Nat Lab
3. Computational Modeling													Nat Lab
4. Ex-situ Characterization													OEM
5. Scale Up													OEM
6. Regulatory & Code Acceptance													PI

Project Milestones will include: 1). Fabrication of three nuclear parts via AM; 2). Collection of ICME and in-process monitoring data (data package); 3). Transfer of monitoring technology directly to the two participating OEMs for immediate implementation and use; 4). Ex-situ characterization assessment data along with scale up information; and 5). ASME Code Case submittal for nuclear qualification of AM.

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4.5 Regulatory Considerations for AM Qualification and Status of FAA AM Roadmap (Michael Gorelik, FAA)

Disclaimer

The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration position, rules interpretation or policy

Outline

- **Industry Trends**
- **Regulatory Considerations**
- **Recent FAA Developments**

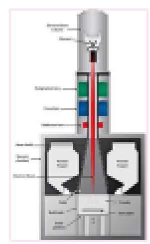
AM is Not a Single Process…

… a *partial* list of metal AM technologies

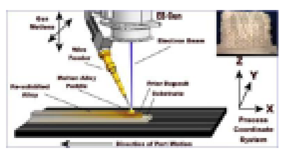
- 3-D Printing
- Powder Bed Fusion (PBF)
- Electron Beam Melting (EBM)
- Additive Layer Manufacturing (ALM)
- Directed Energy Deposition (DED)
- Direct Metal Laser Sintering (DMLS)
- Selective Laser Melting (SLM)
- Rapid Plasma Deposition (RPD)
- Laser Engineered Net Shaping (LENS)
- Laser Freeform Manufacturing Technology (LFMT)
- Laser Cladding Technology (LCT)
- Laser Deposition Technology (LDT)
- Wire + Arc AM (WAAM)
- Ultrasonic Additive Manufacturing (UAM)

- Different physics → different Q&C considerations
- Lack of common terminology (e.g. L-PBF / SLM / DMLM / DMLS)

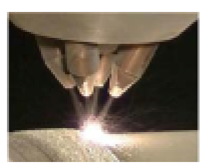
Diversity of AM Processes and Certification Domains

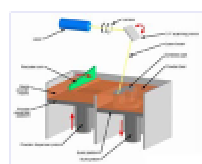


By Source of Material:
Powder vs. Wire



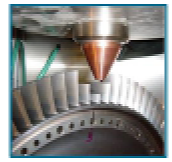
By Source of Energy:
Laser vs. e-Beam vs. Plasma Arc





New Type and Production Certificates	Repair and Overhaul (MROs)	Aftermarket Parts (PMAs)

Business Drivers for AM



- Part count reductions
- Producibility / machinability issues
  - *e.g. thin-wall castings*
- More complex geometric designs
  - *Weight reduction*
  - *Design optimization*
- Single Source alternatives
- Production of low volume / legacy parts
- PMA business model (reverse engineering)
- Low barrier to entry for smaller businesses

Business Drivers Can Be Good *Predictors* Of *Technology Trends*

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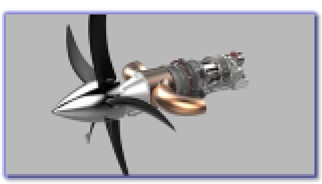
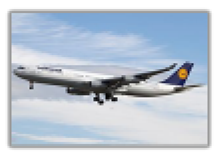
Examples of Expanding Use of AM

- "GE *Advanced Turboprop* is the first Aviation product to fully utilize additive tools…"
  - It has 30% fewer parts (from 800+ to *15 parts*), and will be completed with a 50% reduction in cycle time

From GE 2016 Annual Report



"By 2018 Airbus expects to print about ***30 tons of metal AM parts every month***, according to a company statement…"



http://www.3dcadworld.com/manufacturers-turn-additive-made-metal-parts/

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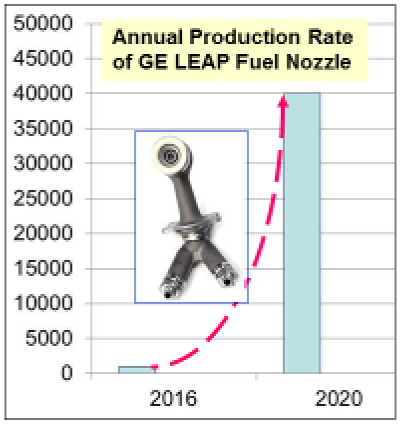
Example: Moving Towards Full-Scale Production

"GE Aviation Selects Auburn, AL for High Volume Additive Manufacturing Facility"



"Production will ramp up quickly over the next five years, going from 1,000 fuel nozzles manufactured annually to more than 40,000 by 2020".

Reference: http://www.geaviation.com/press/other/other_20140715.html

Example: Moving Towards "Part Family" Qualification

Families for qualification

Successful qualification can be used to qualify a number of similar parts

Separate qualification of each AM part is not necessary.

To be considered as a 'family', the parts shall satisfy the following criteria:

- Same material and post processing conditions
- Same classification of part and part function
- Same manufacturing and inspection programme
- Similar geometry and section thickness

Qualification of a number of similar parts = qualification by 'families'

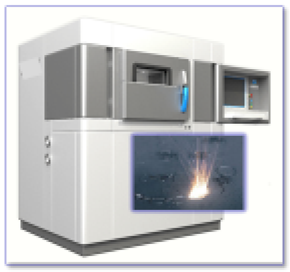
AIRBUS

Presented by J. van Doeselaar (Airbus) at the 2017 Joint FAA – AFRL AM Qual & Cert Workshop, Dayton, OH.

Additive Manufacturing – New Paradigm:

Manufacturing Capabilities Ahead of Design Vision..?

> **"Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas…"**
> *Mr. David Joyce, GE Aviation President and CEO*



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Regulatory Considerations for AM

- **New Material and Process Space**
  - *Common consideration for new material or manufacturing technology introduction*
- **New Design Space**
  - *Unique to Additive Manufacturing..?*

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Topological Optimization Using AM

Common Claim: "*Complexity is Free…*"

- ***… But is it really?***
  - High number of Kt features
  - Inspectability challenges
  - Location-specific properties
  - Surface quality of hard-to-access areas
    - may need to live with as-produced surface

Need a Realistic Assessment of Technical Challenges / Risks Associated with a Business Case

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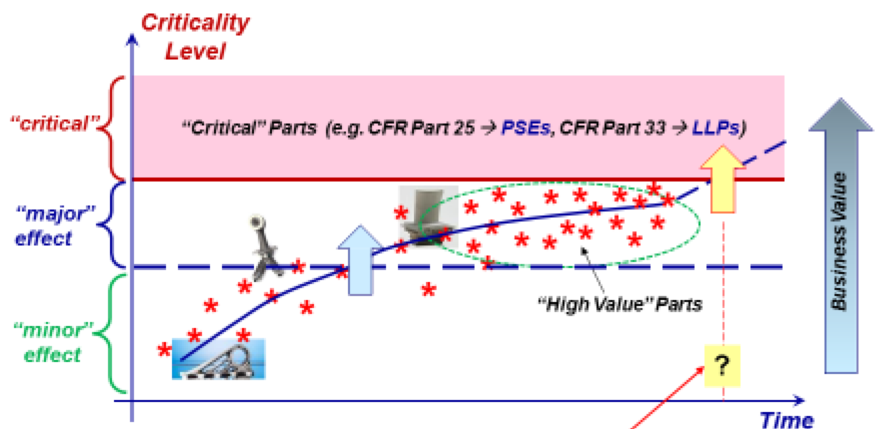
Evolution of Criticality of AM Parts



Transition to "safety-critical" applications in aviation will occur sooner than initially expected

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NAVAIR News Release
NAVAIR Headquarters
Patuxent River, MD

July 29, 2016

NAVAIR marks first flight with 3-D printed safety-critical parts

Safety-Critical AM Parts are Coming…

An MV-22B Osprey equipped with a 3-D printed titanium link and fitting inside an engine nacelle maintains a hover as part of a July 29 demonstration at Patuxent River Naval Air Station, Maryland. The flight marked Naval Air System Command's first successful flight demonstration of a flight critical aircraft component built using additive manufacturing techniques. (U.S. Navy photo)

F-15 Pylon Rib Insertion Success Story

Courtesy of AFRL

Issue: -7075 Al Forging, Pylon Rib, Corrosion Fatigue Cracking
-Decision to move to Ti 6-4 forging already made
Long lead time for Ti forging ~1 year

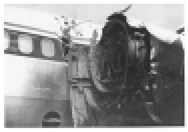
Solution: -Replace with Ti 6Al-4V Additive
-To meet urgent need for aircraft in depot
- Quality issues lessened because of high margin for Ti in this application.

RX Role: -Provided Technical Leadership to Acquisition
-Executed Technology Demonstration Project
-Worked Attachment Issues (bushings, fasteners,etc...)

Results: -Additive Substitution Certified for use in Structural …
-Parts Manufactured and Qualified …
-Prior to Insertion … Provided Forgings
-Ti forging cost … competition

First structural AM part introduced in 2003

Distribution A: Cleared for Public Release Case No. 88ABW-2015-2477 19 May 2015

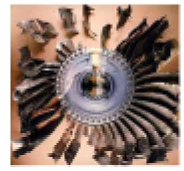


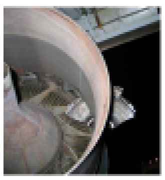
What Causes Aircraft Failures?

Frequency of Failure Mechanisms *)

(mechanical failures only)

Failure Mechanism	% Failures *(Aircraft Components)*
Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%





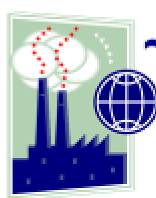
*) *Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

➢ **Some of the most challenging requirements *for new material systems such as AM* are related to F&DT**

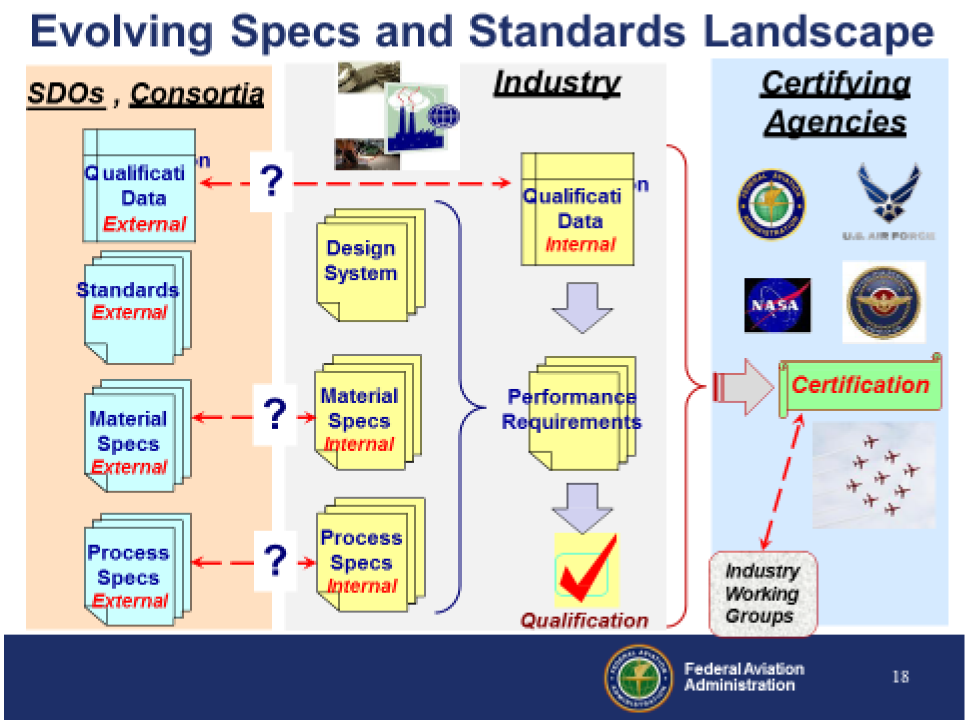
AM - "Barrier to Entry"

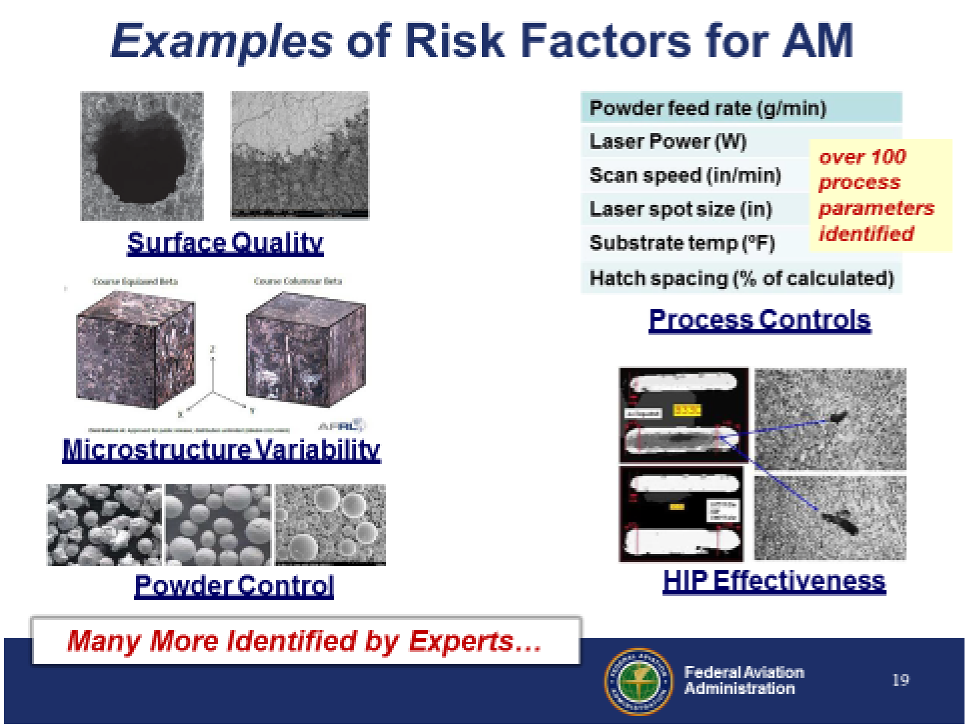
Optimistic →  **~ $1M** 

Equipment acquisition

Realistic →  **~ $10's of M** 

- **Process development**
- **Process qualification**
- **Process controls**
- **Material characterization**
- **Design data**
- **QA / NDI**
- **etc.**


Evolving Specs and Standards Landscape
SDOs , Consortia
Industry
Certifying Agencies
Qualification Data External
?
Qualification Data Internal
Design System
Standards External
Material Specs External
?
Material Specs Internal
Performance Requirements
Certification
Process Specs External
?
Process Specs Internal
Qualification
Industry Working Groups
U.S. AIR FORCE
NASA
Federal Aviation Administration
18


Examples of Risk Factors for AM
Surface Quality
Microstructure Variability
Powder Control
Powder feed rate (g/min)
Laser Power (W)
Scan speed (in/min)
Laser spot size (in)
Substrate temp (°F)
Hatch spacing (% of calculated)
over 100 process parameters identified
Process Controls
HIP Effectiveness
Many More Identified by Experts…
Federal Aviation Administration
19

AM Challenges To Be Addressed

- **Limited understanding of acceptable ranges of variation for key manufacturing parameters**
- **Limited understanding of key failure mechanisms and material anomalies**
- **Lack of industry databases / allowables**
- **Development of capable NDI methods**
- **Lack of industry specs and standards**
- **New design space**

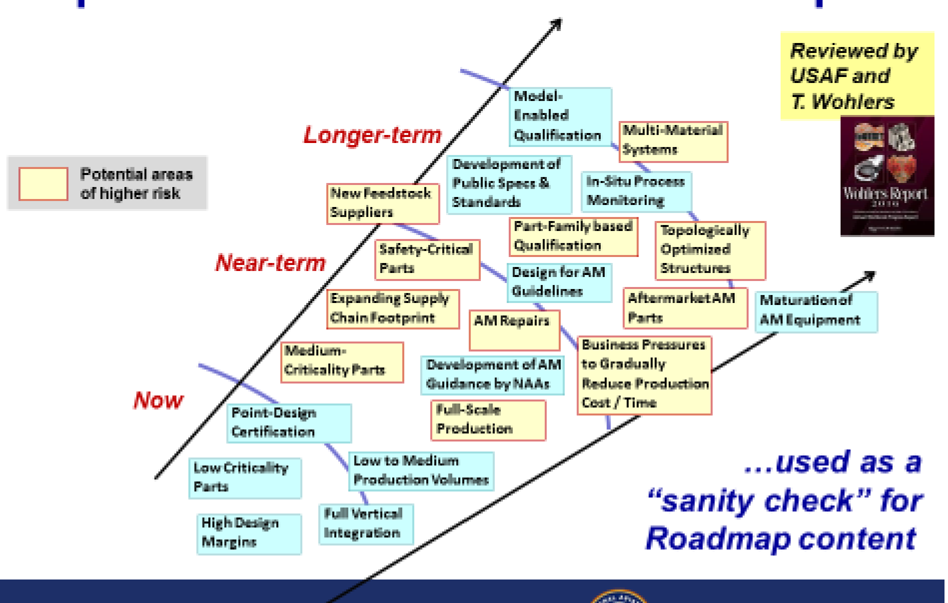
Additional level of complexity – some of these areas are inter-dependent…

Other considerations

- ***Lack of robust powder (feedstock) supply base***
- ***OEM-proprietary vs. commodity type technology path***
- ***Low barrier to entry for new (inexperienced?) suppliers***

Federal Aviation Administration 20

Expected Evolution of AM Landscape…



…used as a "sanity check" for Roadmap content

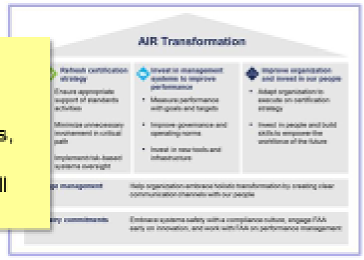
Federal Aviation Administration 21

AIR Transformation *(effective 7-23-17)*

Aircraft Certification Service (AIR)

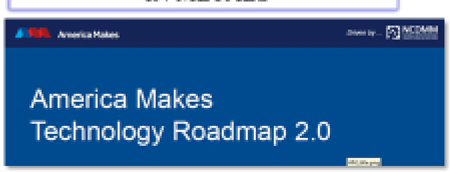
- Policy and Innovation
- Compliance and Airworthiness
- System Oversight
- Organizational Performance
- Foundational Business

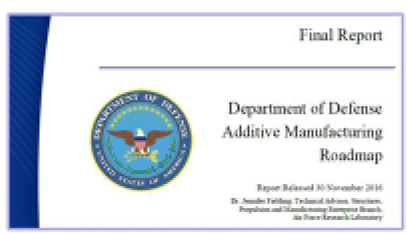
The **Policy & Innovation Division** *supports aerospace innovation* by creating novel means of compliance, develops and maintains AIR regulations, manages the CSTA (chief scientists) program and overall fleet safety, as well as educational outreach.



Public-facing AIR Transformation Web Site:
https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/air/transformation/

Examples of *External* Benchmarking



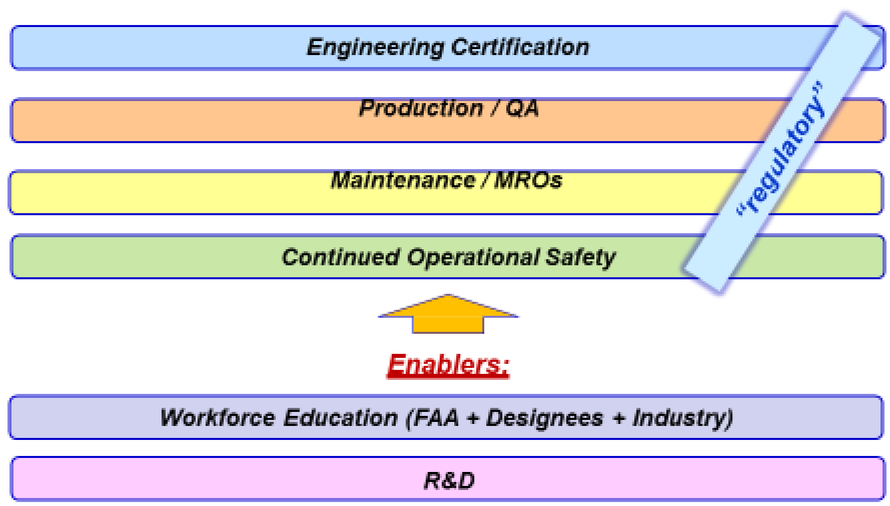


Benchmarking of Composites ACs

(AC – Advisory Circular)

- **Parallels between Composites and AM:**
  - Process-intensive technology subject to manufacturing variability
  - Material is being created at the same time as the part is being built
- **Three ACs from the "Early Days" of Composites**
  - Composite aircraft structure → AC 20-107A (1984)
  - Composite manufacturing quality control → AC 21-26 (1989)
  - Repair Stations for Composite and Bonded Aircraft Structure → AC 145-6 (1996)

AM Certification – Main Strategic Focus Areas



Will be mapped out in the FAA AM Roadmap

Mechanisms to Address Knowledge Gaps

- **Industry engagement (AIA, GAMA, MARPA, other..?)**
- **Engagement with SDOs (SAE, ASTM, AWS, …)**
- **Government engagement (USAF, NAVAIR, NASA, NIST, America Makes, …)**
- **R&D (internal / external)**
- **CSTA and other targeted workshops, e.g. DER conferences, ARSA, …**
- **FAA AM certification projects benchmarking**
- **Coordination with foreign certification authorities**

Collaboration and Technical Interchange are Key Enablers

Federal Aviation Administration 26

Prioritization Considerations

- **Safety impact**
  - Expected increase in criticality of applications
    - "minor effect" → "major effect" → "safety-critical" / timeline?
  - Various industry segments (e.g. OEMs, Tier 1, PMAs, MROs…)
- **Certification process**
  - Breadth of application (e.g. multiple categories of parts / multiple product types)
  - Industry deployment timeline (e.g. current TRL / MRL levels)
  - Regulatory gaps (applicability of current policies / advisory materials)
  - Current experience level (development / full-scale production / field)
- **Other considerations**
  - Availability of industry specs and standards (materials, processes)
  - Availability of industry design / properties data

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Summary

- Expect rapid expansion of AM in Aviation and increase in the levels of AM parts criticality
- Appropriate regulatory framework is a key enabler
- FAA AIR Transformation → new P&I Division
  - *Big focus on developing certification approaches for new technologies (Innovation) and collaboration with industry*
- FAA is working on developing strategic AM certification roadmap
  - Will include a sequence of regulatory documents (e.g. policy, guidance, …) to be developed over the next few years
- ***Industry, agencies and societies collaboration is needed to ensure safe introduction of AM in the National Airspace***

Federal Aviation Administration 28

References


Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Additive manufacturing in the context of structural integrity

Michael Gorelik

https://doi.org/10.1016/j.ijfatigue.2016.07.005


Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification

Mohsen Seifi, Michael Gorelik, Jess Waller, Nik Hrabe, Nima Shamsaei, Steve Daniewicz & John J. Lewandowski

JOM

Additive Manufacturing

https://link.springer.com/article/10.1007/s11837-017-2265-2

Federal Aviation Administration 29

4.6 Industry Insights - Cybersecurity for Additive Manufacturing (Scott Zimmerman, CTC)

Agenda

- Introduction
- Threat Update - FUD
- Cybersecurity for Direct Digital Manufacturing (DDM)
- Cybersecurity Regulations
- Supply chain
- Recommendation

CTC Concurrent Technologies Corporation

2

CTC - Leading Innovation through Engineering, Technology and Services

Concurrent Technologies Corporation (CTC) is an independent, nonprofit, applied scientific research and development professional services organization.

Enterprise Ventures Corporation (EVC) is CTC's technology commercialization arm and is organized as a wholly owned for-profit affiliate of CTC.

CTC and EVC provide full lifecycle support services to clients, from innovative concepts through production and deployment.

30 YEARS OF INNOVATION

600 EMPLOYEES

25 LOCATIONS

CTC Concurrent Technologies Corporation

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Center for Advanced Nuclear Manufacturing

- With the advent of the next generation of SMRs and AR's there is a clear need for advanced manufacturing technologies to support the efficient fabrication of complex modular systems
- In 2017 CTC made the decision in 2017 to establish the Center for Advanced Nuclear Manufacturing (CANM) with support from the US Nuclear Infrastructures Council's
- Leverages CTC's experience in operation of the Navy Metalworking Center (NMC) helps to facilitate an efficient start-up and operation of the Center

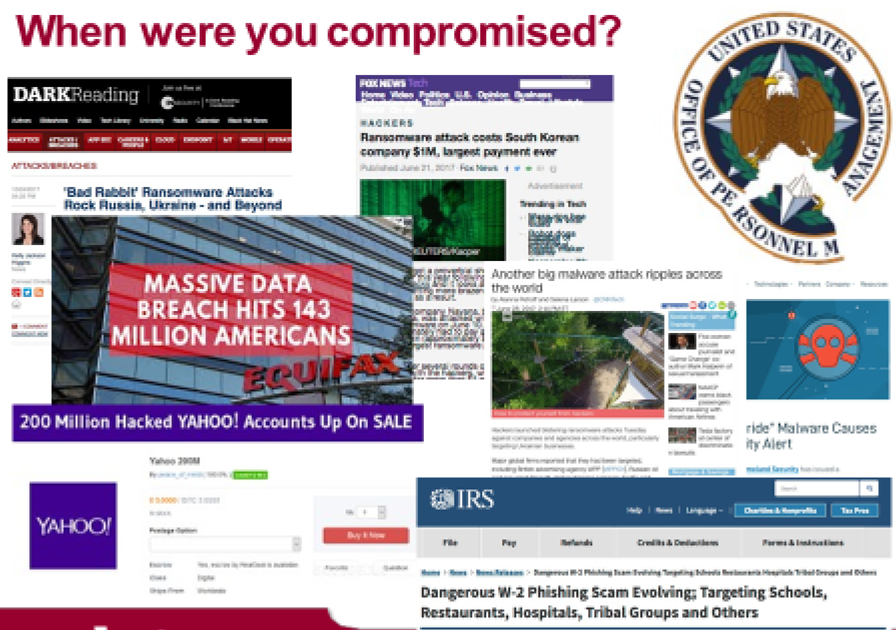
CANM™ Center for Advanced Nuclear Manufacturing
Operated by Concurrent Technologies Corporation

Cyber Threat Update

Threat update

- Verizon Breach Report (November 10, 2017)
  - 75% of breaches were from external actors, 25% involved internal actors
  - 62% featured hacking, 51% included malware, 81% were **stolen or weak passwords**
  - 66% of malware **installed via email**
  - 73% were financially motivated with **21% being espionage**
  - 61% of the victims were businesses **under 1,000 employees**
- Manufacturing specifics results
  - 90% of data stolen during a breach were considered "**secrets**" by the owner
  - **Strategic gains** were the number one motive
  - The majority were conducted by **state-affiliated sponsored actors**
  - Internal espionage was present as well

When were you compromised?



Why are we still failing?

- We have big budgets for security…
- We are focusing on the right things, I think…
- There is a shortage of talent but is that really the reason…
- Is the adversary that motivated or smarter…
- Are our workforce the issue…
- Do we not train enough or the right way…
- Is this just the new norm…

Cybersecurity for DDM

Cybersecurity: A Practical Perspective

Can you connect our new printer?

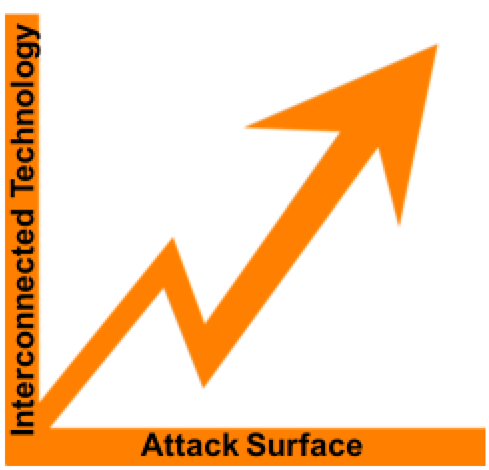
Direct Digital Manufacturing

- *"The fabrication of components in a seamless manner from computer design to actual part in hand"- Brookings Institute*
- A disruptive technology with similar communication challenges as with Control Systems and IOT sensors
- Air gapped cybersecurity approach cutting the "Digital Thread"

Industrial Control System Cyber Issues

- ICS-CERT 2016 Report ICS Findings
  - Boundary protection
  - Least functionally
  - Authenticator management
  - Identification and authentication 5. Least privilege
  - Allocation of resources

Advanced Manufacturing Security Challenges

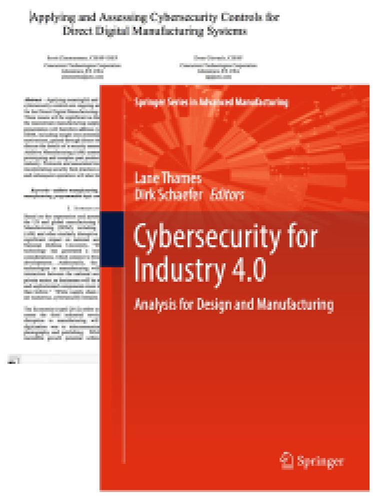


RISK

- Loss or theft of intellectual property
- Compromised process and/or product integrity
- Productivity disruption
- Damage to reputation

Additional Research

- CTC cyber risk assessment
- NIST Symposium on DDM
  - https://www.nist.gov/publications/proceedings-cybersecurity-direct-digital-manufacturing-ddm-symposium
- Textbook chapter
  - "Cybersecurity for Industry 4.0"
  - http://www.springer.com/us/book/9783319506593



DoD Cybersecurity Requirements

DoD Information Assurance Framework Evolution

- DoD Information Technology Security Certification and Accreditation Process (DITSCAP), mid 1990s
  - Standardized approach, did not take into account evolving threat landscape
- DoD information Assurance Certification and Accreditation Process (DIACAP), 2006
  - Recognized an acceptable operational risk level to support mission
- DoD Information Assurance Risk Management Framework (DoD RMF), 2013
  - Risk based approached to managing cybersecurity

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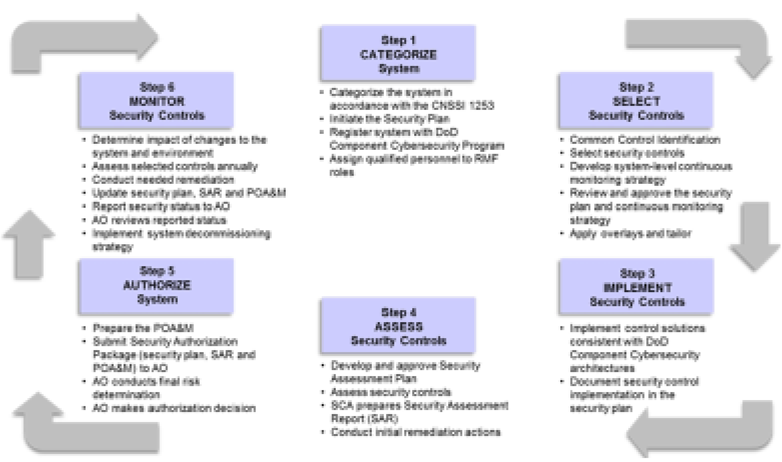
DoD Risk Management Framework



https://aida.mitre.org/cyber-rmf/

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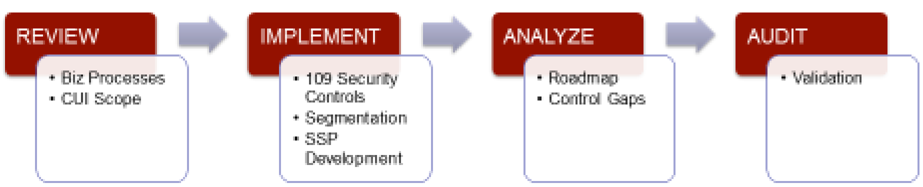
USG/DoD Contractor Cyber Requirements

- NIST issued cyber safeguards (Special Publication 800-171) in June 2015 to protect CUI in non-federal information systems.
- DoD issued the "Network Penetration" DFARS in Aug. and Dec. 2015 and these were revised on Oct. 21, 2016.
- Federal civilian agencies issued a new FAR "Basic Safeguarding" clause, effective June 15, 2016, requiring all contractors to protect "Federal Contract Information" on "Information Systems."
- NARA issued the Final Rule on "Controlled Unclassified Information" (CUI) on Sep. 14, 2016.
- A "General FAR Rule" is in development that will obligate all federal agencies to require cyber protection of CUI, per SP 800-171, in all contracts and agreements. Expect this Rule to be final in 2017.

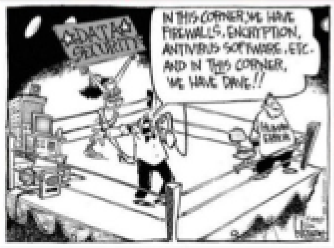
Path to NIST SP800-171 Compliance



SMB Supply Chain Cybersecurity Issues

- Small suppliers/businesses have become a prime target for attackers and act as a stepping stone to primes
  - From janitorial services to software engineering-- with physical or virtual access to information systems, software code, or IP
- Small businesses are spending less on cyber security while large businesses are spending more
- Small businesses generally don't have formal cyber security awareness efforts for their employees

Supply chains cyber risk ..



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Recommendations

- Learn lessons from past industry digitization
  - Telecom with the Internet of Things (IOT) to digital photography
- Now is the time to build cybersecurity into the process
  - Corporate leadership tends to be reactionary, we must get ahead of disruptive technology
  - Address cybersecurity concerns throughout the component lifecycle
  - Create active defense, don't wait to respond
  - Don't bolt it on at the end…

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Cybersecurity Recommendations

Architecture
Consistency throughout the architecture, you are only as strong as your weakest link

Authentication
Strong, multifactor authentication is imperative for all critical systems

Access Control
Always start with least privilege rule set

Audit
Consistent log retention and auditing to enable continuous monitoring

Digital Signatures
Enables non-repudiation of message transfer between two parties

Timestamps
Important in attack forensics and investigation

Secure Communication Infrastructure
Where appropriate encrypt only protocols essential to operation are present

Redundancy
Promotes system availability

Defense in Depth
A layered security approach

Separation of Duties
... or privileges of operators and users

Intrusion Detection Prevention Systems
Host based

Removal of unneeded applications

Security Management Process
... for system updates/ upgrades

Adversary & Trust Models
Importance of understanding who is an adversary and who is a partner

QUESTIONS?

Center for Advanced Nuclear Manufacturing

- With the advent of the next generation of SMRs and AR's there is a clear need for advanced manufacturing technologies to support the efficient fabrication of complex modular systems
- Two organizations have recently developed models for a manufacturing technology center for U.S. nuclear industry -
  - DOE NE vision for a nuclear advanced manufacturing technology center
  - USNIC's concept for a U.S. Virtual Advanced Manufacturing and Research Center (VNAMRC)
- Leveraging CTC's experience in operation of the Navy Metalworking Center (NMC) helps to facilitate an efficient start-up and operation of the Center -
  - Transferrable experience and capabilities
  - Extensive experience in managing project identification and development efforts
  - Experienced management and technical staff with "right mix" of skills.

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CANM Operation

- With USNIC's support, CTC made the decision in 2017 to establish the Center for Advanced Nuclear Manufacturing (CANM)
- CANM will utilize existing metalworking capabilities to establish a self-sustaining global resource to develop and deploy applied metalworking and manufacturing capabilities to advance SMR / AR design, fabrication and operation
  - Bring together the right mix of technologists, engineers and solution providers from industry and academia to develop and demonstrate cost effective and implementable technical solutions
  - Provide manufacturing and demonstration facilities to support the fabrication and testing of functional prototype systems
- CANM is initially being operated as an industry-funded organization
- DOE is working to establish an advanced manufacturing technology center with an industry cost-share requirement for awarded projects.

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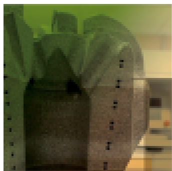
4.7 Reflections on Fatigue for AM Components (Bill Mohr, EWI)



Additive Manufacturing Consortium
Operated by EWI

Reflections on Fatigue for AM Components

Rockville, MD
November 28, 2017

William Mohr
Principal Engineer, EWI
614.688.5182
bmohr@ewi.org

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Resume: William Mohr

- EWI engineer in Structural Integrity for over 24 years.
- Supporting a wide variety of industries:
  - From pipelines to auto transmissions to heart valves.
- Design chair for AWS D1.9 Structural Welding Code—Titanium.
- Second vice chair for AWS D20 Specification for Fabrication of Metal Components using Additive Manufacturing.
- Bachelors from MIT and graduate degrees from Stanford.

Additive Manufacturing Consortium

Outline

- Fatigue Data for Laser Powder Bed Fusion
- Categorizing the Data
- Correlation with Imperfections and Inspection
- AWS D20

Additive Manufacturing Consortium

Fatigue Data Compilation

- Collect published literature data on fatigue of additively manufactured metal pieces.
- Materials:
  - Largest group – Ti6Al4V
  - Next largest – stainless steel
- S-N data rather than fatigue crack growth rate.

Additive Manufacturing Consortium

Publications in Data List

	Laser – Powder Bed	EB – Powder Bed	Laser – DED Powder	Laser – DED Wire	EB – DED Wire	GTAW – DED Wire
Ti6Al4V	20	5	3	1	1	1
SS – PH Grades	6					
SS – 316	3					
Other Ti	1		1			
718	2		1			
625	2					

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Wide Variety, Little Duplication

- **Variety of orientations (x, y, z, etc.).**
- **Variety of deposition conditions.**
- **Variety of post-deposition heat treatments.**
- **Variety of specimen shapes and sizes.**
- **Two primary test methods and others:**
  - Tension R=0.1 K_t = 1 specimen
  - Rotating Bending R = –1
  - Others include strip specimens.

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Plotting Fatigue Data

- **My preferences are based on structural weld fatigue rather than base metal fatigue.**
- **Log-log plot (stress parameter on vertical axis).**
- **Stress range (maximum to minimum) is the stress variable:**
  - Some plot maximum stress alone
  - Others plot stress amplitude (half of range).
- **Cycles of lifetime is the lifetime variable:**
  - Runout (RO) means no failure at end of cycles.

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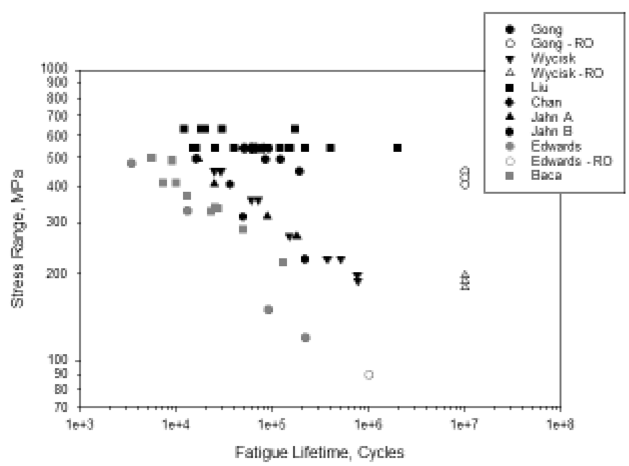
Ti6Al4V – Z Direction: Untreated



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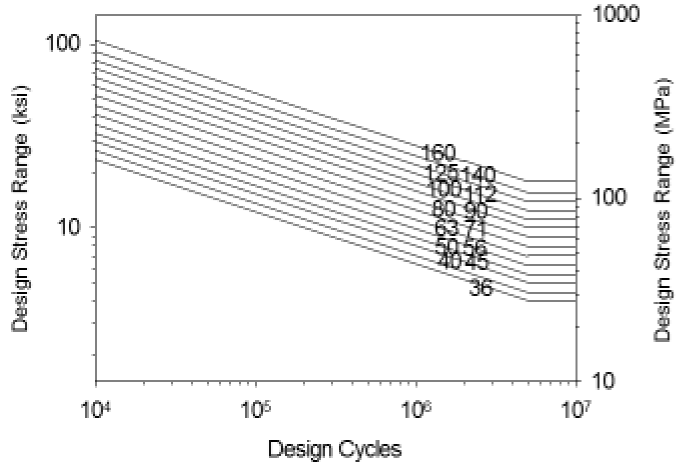
AWS D1.9 Design Curves



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Approach to Grouping

- **Four groups:**
  - Fails from defects throughout part:
    - Removing as-deposited surface not much improvement.
  - Fails from defects on the surface
  - Fails from sub-surface defects:
    - Sensitive to material between defect and surface.
  - Fails from no defect at all.

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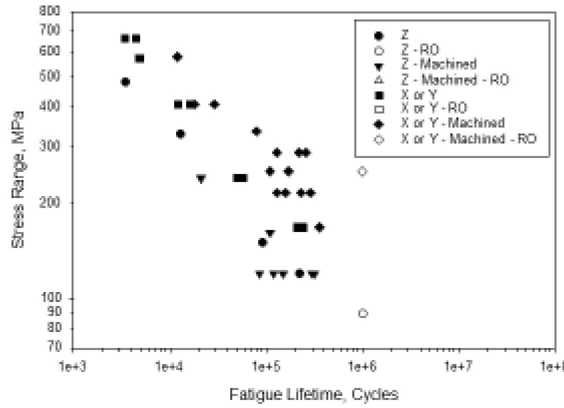
Defects Throughout

- **Ti-6Al-4V powder bed.**
- **Not much difference by orientation or surface finish.**



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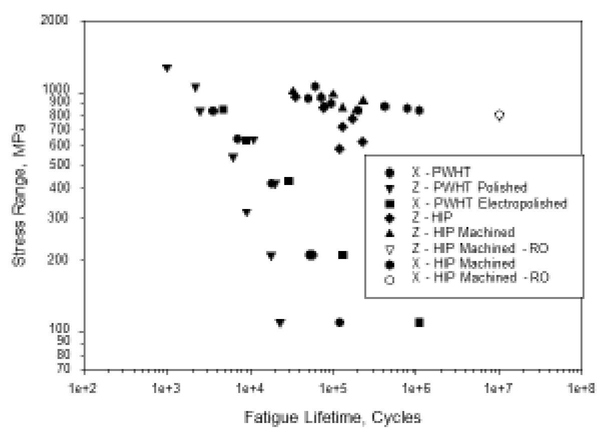
Improvements to Defects Throughout

- **Limited improvement from:**
  - PWHT
  - Surface finish
  - Direction.
- **HIP has more improvement.**



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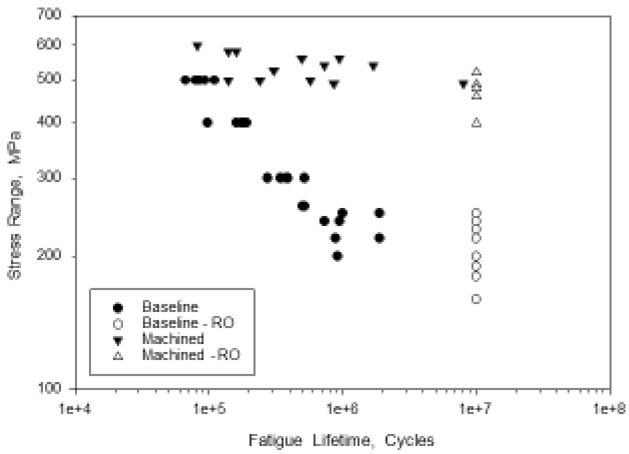
Surface Flaws Removed

- Big effect of machined surface.
- Stoffregen et al. on 17-4PH.



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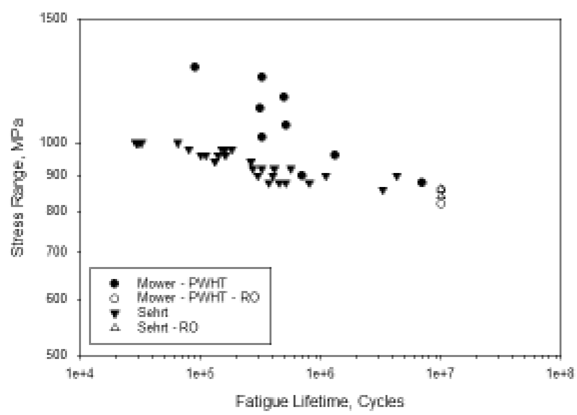
Subsurface Flaws – 17-4PH

- PWHT by Mower and Long improved performance at high stress range.
- R = –1 bending.



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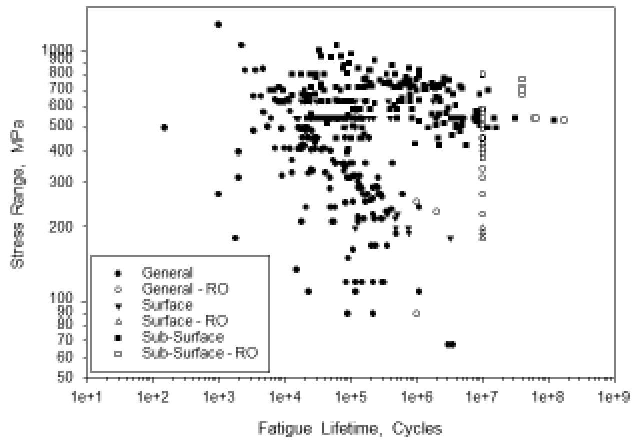
Ti-6Al-4V – Data Characterized



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Still a Lot of Variability

- **General:**
  - Severity of flaws
  - Types of flaws (porosity vs. lack of fusion).
- **Surface:**
  - Size of flaws
  - Size of specimen.
- **Subsurface:**
  - Strength from heat treatment
  - Orientation.
- **Microstructure:**
  - Heat treatment and microstructure.
- **Different effects based on behavior mode.**

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How to Improve Performance

- **General flaws:**
  - Procedure development to eliminate deposited flaws
  - HIP to close up deposited flaws.
- **Surface flaws:**
  - Optimize travel at surface to avoid flaws
  - Machine or surface treat.
- **Subsurface flaws:**
  - Heat treat to increase strength at surface
  - Minimize flaws and maximize their distance from the surface.
- **Microstructure:**
  - Generally choose higher strength structure.

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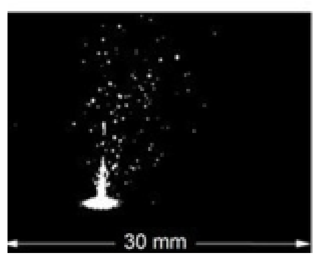
Effect of Material

- **Variability among results for Ti-6Al-4V is greater than for stainless steel.**
- **The lower density of the powder particles may make them easier to move during laser passage.**

Metal vapor micro-jet controls material redistribution in laser powder bed fusion additive manufacturing

S. Ly, A. M. Rubenchik, S A. Khairallah, G. Guss and M. J. Matthews, Nature 2017



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Inspection of Fatigue Failures

- **Common imperfection sizes associated with failures in fatigue tests:**
  - Less than 1 mm but greater than 0.1 mm.
- **Common shapes:**
  - Irregular outlines
  - Unfused powder particle surfaces.

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AWS D20

- **Currently in committee drafting.**
- **Includes clauses on:**
  - Design
  - Procedure qualification
  - Personnel qualification
  - Fabrication
  - Inspection.
- **Includes both PBF and DED.**
- **Full range of metals allowed.**
- **Three levels of service: A, B, and C (non-critical).**

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D20 Inspection

- **Procedure qualification includes tensile tests (A, B) and microstructure examination:**
  - Acceptance criteria will be set by the engineer.
- **Procedure qualification includes inspection (A, B).**
  - PT, MT, RT, or CT depending on situation
  - Acceptance criteria are adapted from AWS D17.1.
- **Inspection for built parts (A, selection of B).**

D20 Inspection and Fatigue

- **Flaw size acceptance criteria from D20 are much larger than the flaw sizes found on fatigue test fracture surfaces.**
- **Acceptance criteria are based on comparing to welds rather than trying to meet wrought metal properties.**

Additive Manufacturing Consortium

4.8 Selecting the Correct Material and Technology for Metal AM Applications (Frank Medina, EWI)

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D20 Inspection and Fatigue

- Flaw size acceptance criteria from D20 are much larger than the flaw sizes found on fatigue test fracture surfaces.
- Acceptance criteria are based on comparing to welds rather than trying to meet wrought metal properties.

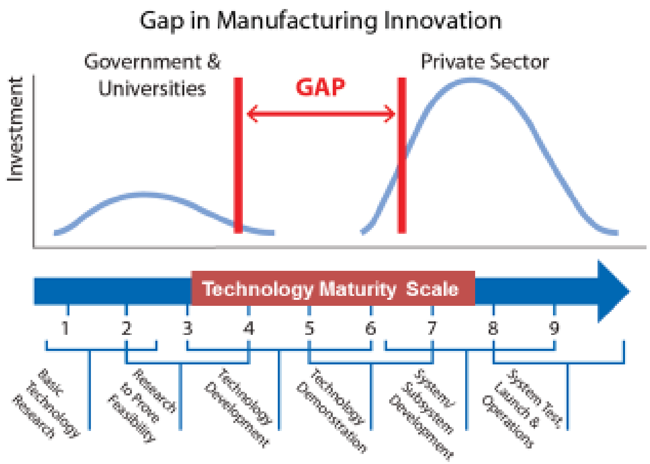
Additive Manufacturing Consortium

About EWI

- Non-profit applied manufacturing R&D company
  - Develops, commercializes, and implements leading-edge manufacturing technologies for innovative businesses
- Thought-leader in many cross-cutting technologies
  - >160,000 sq-ft in 3 facilities with full-scale test labs (expanding)
  - >$40 million in state of the art capital equipment (expanding)
  - >170 engineers, technicians, industry experts (expanding)

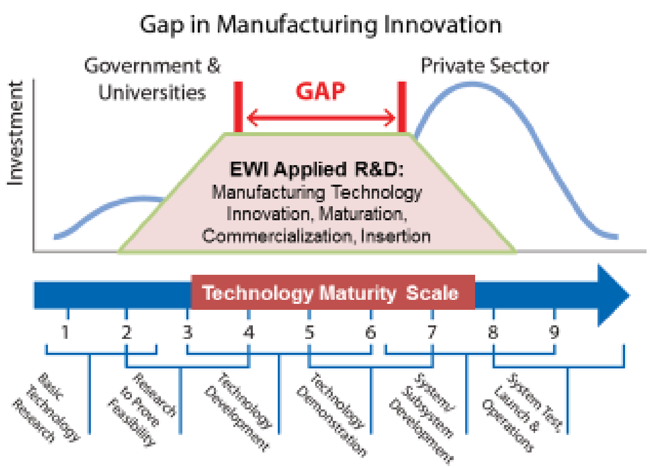
EWI

Structural Gap between Research and Application



Source: NIST AMNPO presentation Oct 2012

EWI Applied R&D Bridges the Gap Between Research and Application



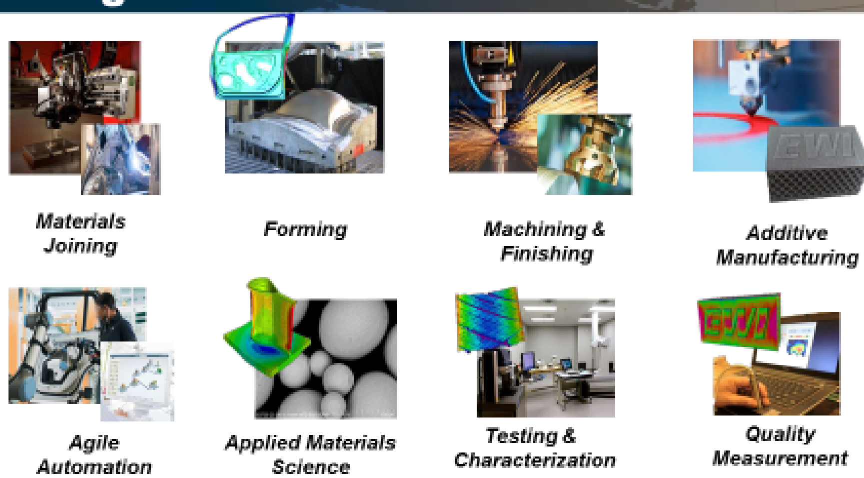
Source: NIST AMNPO presentation Oct 2012

Connecting Colorado to EWI's Capabilities Nationally

- EWI Colorado opened in 2016
- Customers have access to EWI capabilities nationally
- Among the broadest range of metal AM capabilities

EWI
We Manufacture Innovation

Growing Range of Cross-Cutting Manufacturing Technologies



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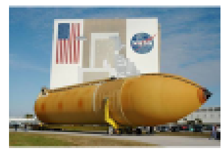
AM is Materials Joining

Manufacturing of complex 3D parts by *joining* successive beads and layers

675 feet of weld
(Audi R8)

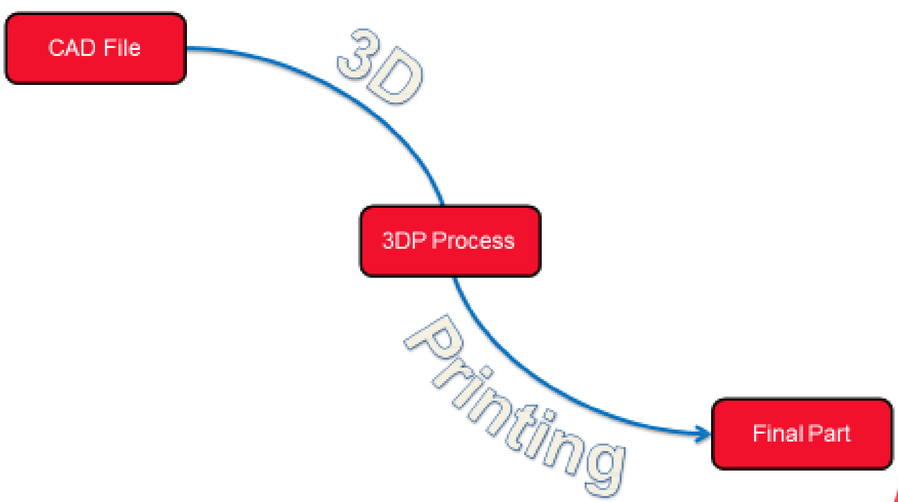
1-inch L-PBF Cube

5 miles of weld

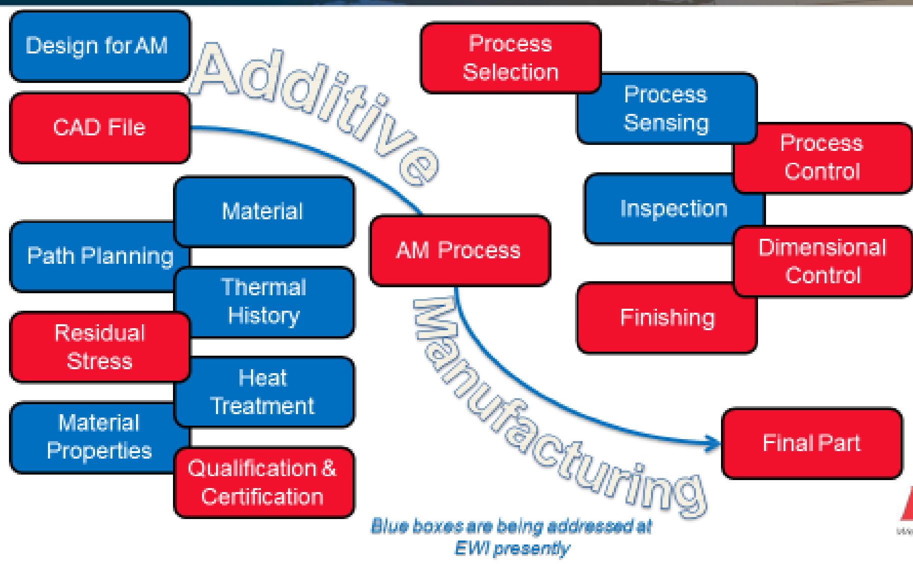


3,400 feet of weld

A Holistic View of Additive Manufacturing Process Chain



Additive Manufacturing Supply Chain



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EWI's Focus Areas are Aligned with the Needs of Industry

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Seven AM Technologies

In order to help standardize additive manufacturing in the United States the ASTM F42 Committee on Additive Manufacturing Technologies was formed in 2009 and categorized AM technologies into seven categories

- **Powder Bed Fusion**
- **Sheet Lamination**
- **Material Extrusion**
- **Directed Energy Deposition**
- **Material Jetting**
- **Vat Photopolymerization**
- **Binder Jetting**

EWI has all Seven AM Technologies

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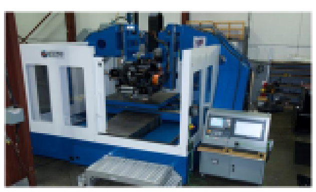
EWI AM Capabilities Overview

Laser PBF
EOS M280

Laser PBF – Open Architecture
EWI-Designed and Built

Electron Beam PBF
ArcamA2X

Sheet Lamination UAM
Fabrisonic



Laser DED
RPM 557

Electron Beam DED
Sciaky EBAM 110

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Key Considerations for an AM Part

- **Every part is not an ideal candidate for AM!**
- **Critical questions to ask before considering AM:**
  - Do current manufacturing constraints limit parts performance?
  - Can sub-components be merged to avoid assembly?
  - Can number of joints be minimized?
  - Can weight & material be reduced and achieve the same function?
  - Is extensive tooling needed to manufacturing part?
  - Can new material combinations increase part performance?
  - Can part durability be maximized?

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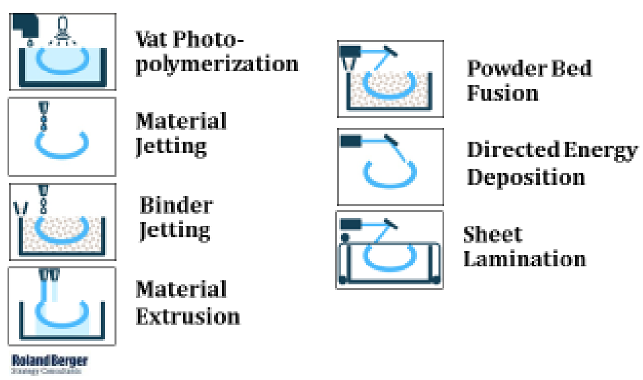
Types of Additive Manufacturing

ASTM International:
Technical Committee F42 on Additive Manufacturing



Types of Additive Manufacturing

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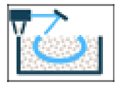
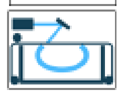


Powder Bed Fusion

Directed Energy Deposition

Binder Jetting



Sheet Lamination

RolandBerger

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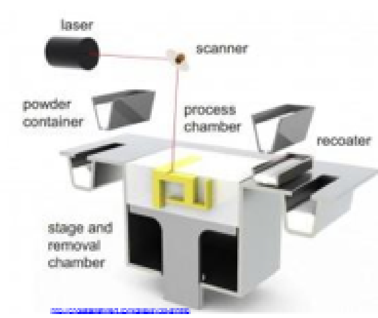
Powder Bed Fusion Processes

- **Laser powder bed fusion:**
  - Laser selectively melts and consolidates fine powder layer-by-layer
  - Systems operate at room temperature under Nitrogen or Argon environment depending on build material.
  - Maximum build chamber size: 31.5"X16"X20"
  - Deposition rate: ~ 0.02- 0.2 lbs/hr
  - Materials: AlSi10Mg,CoCr, Ni alloys, Steels, titanium alloys and some refractory metals.
  - Surface Roughness: 10-20μm Ra



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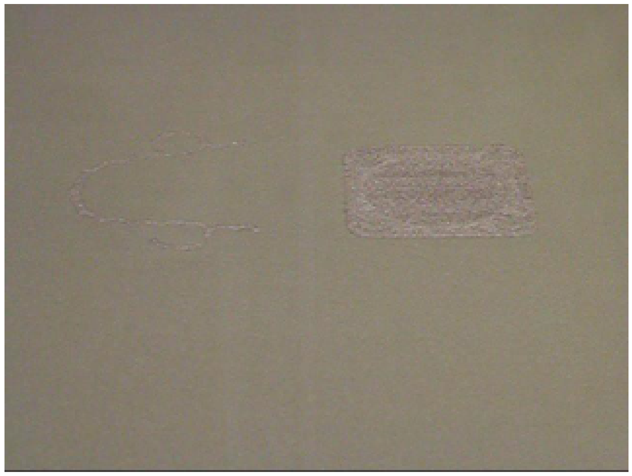
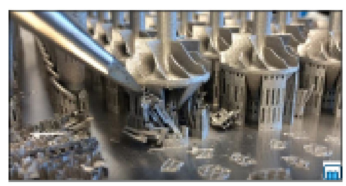
Powder Bed Fusion Processes



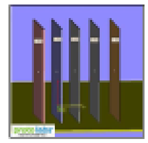
Laser Powder Bed Fusion Processes

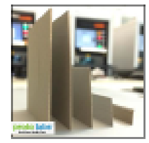
- **Design Considerations:**
  - **Overhang features:**
    - Most materials are able to build features 45^0 off vertical.
    - Support structures need to be added for greater overhanging features.
    - Supports not only act as mechanical structures but are required to mitigate internal stress build u in parts
    - Circular/rectangular features can be redesigned into tear drop shape (self-supporting) to avoid use of supports.
  - **Surface roughness:**
    - Surface roughness is dependent on material, layer thickness and part orientation.
    - Vertical side walls usually have a better Ra than horizontal or angular surfaces.



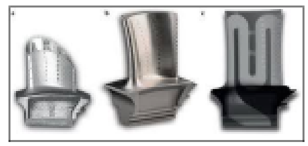
Laser Powder Bed Fusion Processes

- **Design Considerations:**
  - **Minimum feature size:**
    - The minimum feature size is dependent on the spot size of the laser beam.
    - Best possible spot size is ~50 μm.
    - Important to consider while support removal.
  - **Aspect ratio:**
    - Typically a height to width ratio of 40:1 is considered as a rule of thumb for laser powder bed systems.



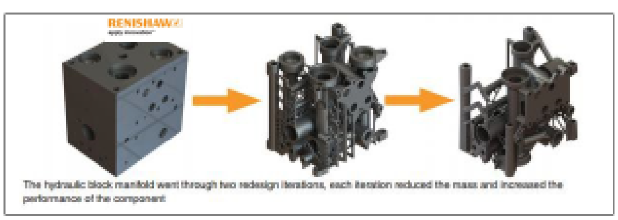


  - **Internal channels:**
    - Complex internal channels are possible as long as overhang lengths and self-supporting angles as considered.
    - If channels need support, support accessibility for removal should also be considered.
    - Design should also account for powder removal before stress relief.



Laser Powder Bed Fusion Processes

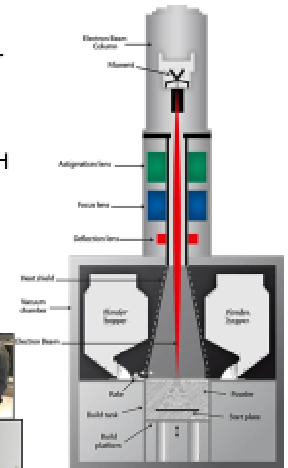
- **Some Examples:**



Powder Bed Fusion Processes

- **Electron beam powder bed fusion:**
  - High energy electron beam melt layers of powder to create the desired geometry under controlled vacuum.
  - Maximum build chamber size: 13.7380" dia. X 15" H
  - Deposition rate: ~ 0.1- 0.5 lbs/hr
  - Materials: Titanium alloys, CoCr, Ni alloys, TiAl, Cu, Niobium, Mg, Steels, Nb, Tantalum
  - Surface Roughness: 15-30μm Ra

Build setup in Magics | Machine Setup | Build Completed | Powder Recovery System | Final Part



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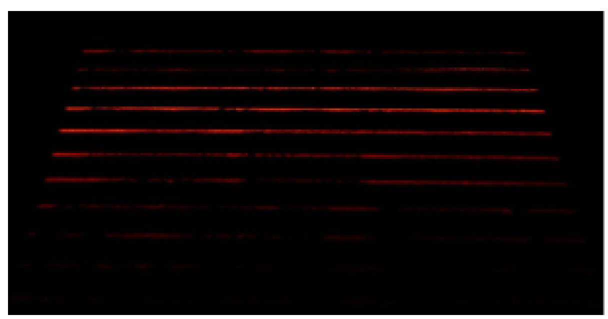
Electron Beam Melting



CAD TO METAL Arcam AB

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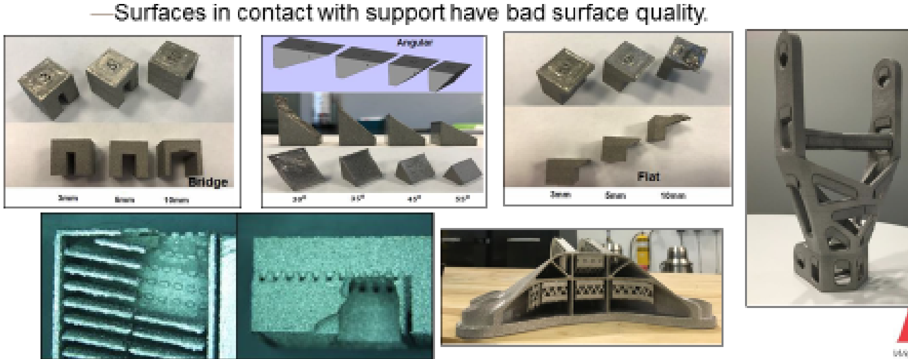
EB Powder Bed Fusion Processes

- **Design Considerations:**
  - **Overhang features:**
    - Most materials are able to build features 45^0 off vertical.
    - Support structures need to be added for greater overhanging features.
    - Most alloys can build with free hanging supports.
    - Surfaces in contact with support have bad surface quality.



Surface in contact with supports

Free hanging supports

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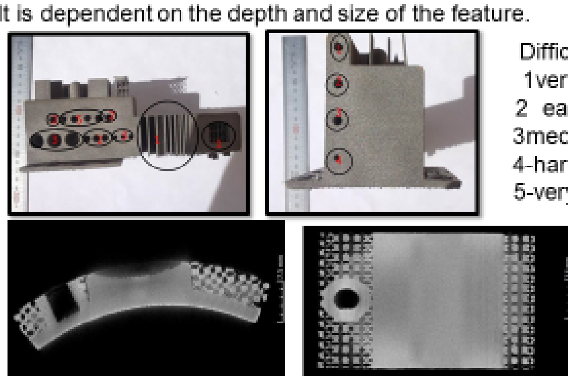
EB Powder Bed Fusion Processes

- **Design Considerations:**
  - **Semi-sintered powder removal:**
    - Powder removal becomes difficult in case of mesh structures, blind holes and internal channels.
    - Pore size of ~ 400 μm is possible
    - It is dependent on the depth and size of the feature.



Difficulty scale
1very easy (PRS)
2 easy (PRS)
3medium
4-hard
5-very hard

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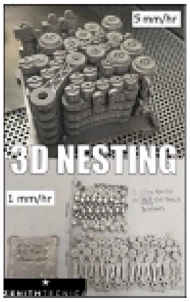
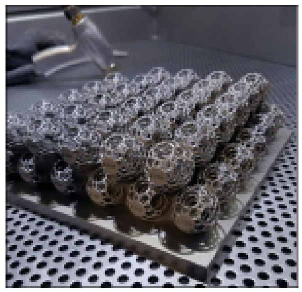
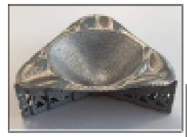
Powder Bed Fusion Processes

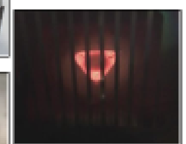
- **Design Considerations:**
  - **Part nesting:**
    - EBM technology allows us to stack parts through out the height of the build chamber.
    - Ensure that parts are in contact with each other through supports
    - Distribute parts evenly across a the build plate to avoid heat build up and deformation.





Part Nesting





Heat build up

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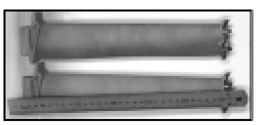
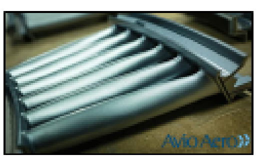
Powder Bed Fusion Processes

- **Some Examples:**





Turbine blades

Acetabular cups with trabecular structures

Race car gear box

Housing combining lattice structures and solid sections

Custom cranial implant

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Direct Energy Deposition Processes

- **Laser Direct Energy Deposition:**
  - High power laser is fired at a target to create a localized melt pool.
  - A stream of metal powder is delivered into the melt pool and a weld bead is created.
  - Maximum build chamber size:
    - 5'X5'X7'
  - 5 axis motion – non coordinated motion
  - Deposition rate: ~ 5 lbs/hr
  - Materials:
    - Titanium alloys, steel alloys, aluminum, nickel alloys, cobalt alloys, tungsten carbide
  - Surface Roughness
    - ~30 μm+

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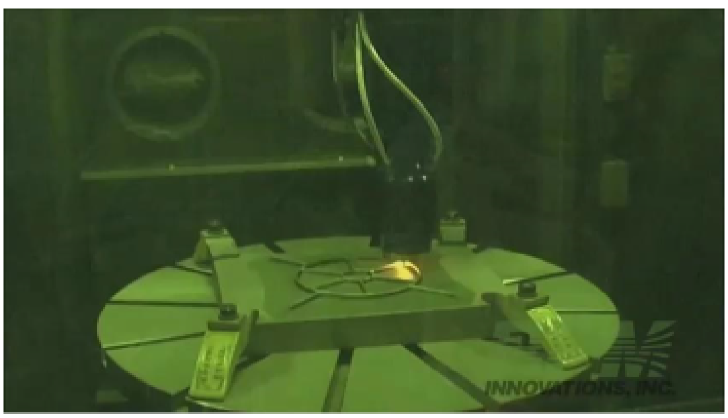
RPM Innovation



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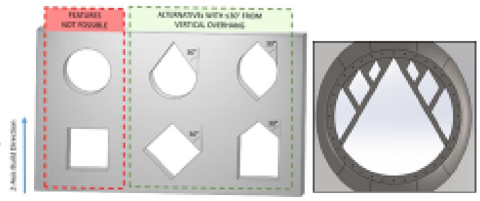
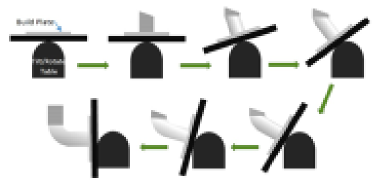
Laser Direct Energy Deposition Processes

- **Design Considerations:**
  - Holes and channels:
    - Holes and channels normal to the build direction need to be modified to tear drop, lemon shaped, diamond shaped or by adding angled support into the design.
  - Ducts:
    - Bend-like features are made possible by utilizing the tilt/rotate table in incremental steps.
    - Each section is designed as a separate CAD file.



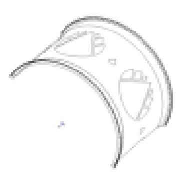


Laser Direct Energy Deposition Processes

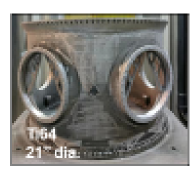
- **Design Considerations:**
  - The technology favors thin walled parts.
  - Single walled parts have to be redesigned as surface models.
  - Different features of the part require different parameters and thus have to designed as separate files and arranged accordingly.
  - Additional supporting structures need to be added to the part to minimize part distortion due to stresses.

Secondary payload adapter

Modified part



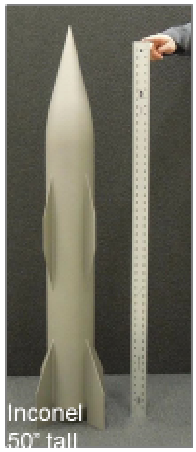
Surface Model

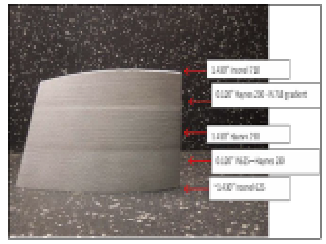


Final part

Laser Direct Energy Deposition Processes

- **Some Examples :**





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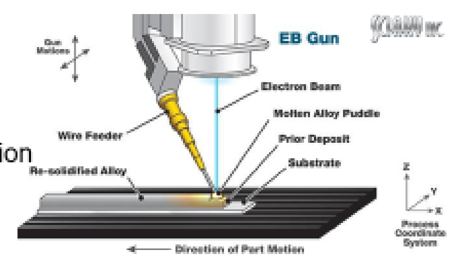
Direct Energy Deposition Processes

- **Electron Beam Direct Energy Deposition:**
  - Wire fed DED process derived from EB welding.
  - Near net shape manufacturing
  - Maximum build chamber size:
    - 8.8'X4'X5'
  - 5-7 axis motion coordinated motion
  - Deposition rate: 7-20 lbs/hr
  - Materials:
    - Titanium alloys, Nickel alloys, Tantalum, Tungsten, Niobium ,Stainless Steels, Aluminum (2310,4043),Magnesium
  - Surface Roughness
    - Irrelevant for near net shape



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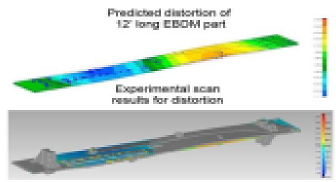
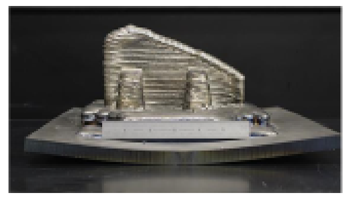
EB Direct Energy Deposition Processes

- **Design Considerations:**
  - **Overhanging features:**
    - All tool path must be supported by either the substrate or a previous deposit.
    - This limitation can be compensated for through 4+ Axis part manipulation, and / or secondary set-up operations.
  - **Feature size v/s deposition rate:**
    - Increase in deposition rate (wire size, travel speed) = decrease in feature resolution
  - **Thermal Distortion**:
    - High deposition rates and large melt pools generate significant thermal stresses which require substrate and fixture considerations in some circumstances





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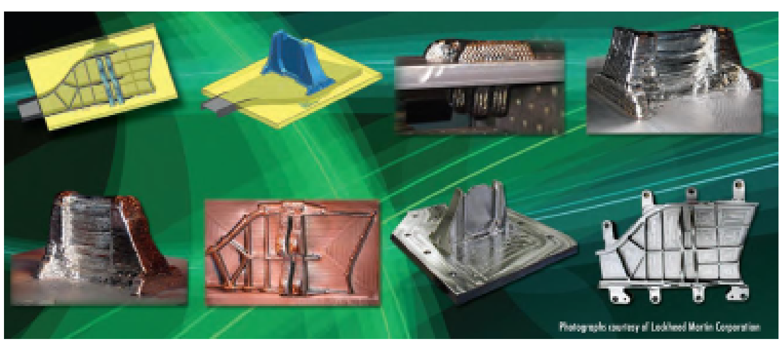
EB Direct Energy Deposition Processes

- **Design Considerations:**
  - **Time / material constraint:**
    - Limit of filament life is approximately 9hrs
    - Limit to material that can be placed on a spool / in the chamber for deposition



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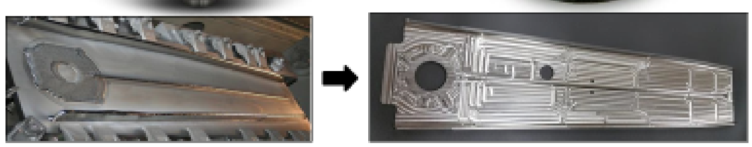
EB Direct Energy Deposition Processes

- **Sample Examples:**

Satellite propellant tank ~60" dia.

Variable ballast tank



Airbus rear upper spar

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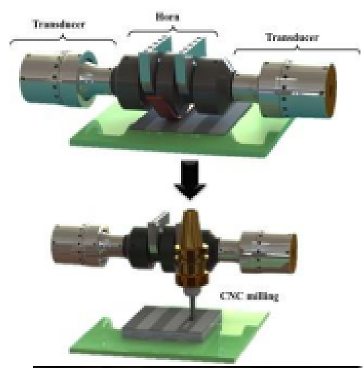
Sheet Lamination

- **Ultrasonic Additive Manufacturing**
  - A solid state bond is created between metal foils by using high frequency sound waves.
  - Waves are transmitted through a steel 'horn' causing the metal foils to vibrate and exposes the virgin material on the face of the foil creating a solid state bond.
  - Embedding electronics and sensor
  - Maximum build chamber size:
    - 6'X6'
  - Materials:
    - Steels, Aluminum, Nickel alloys, precious metals



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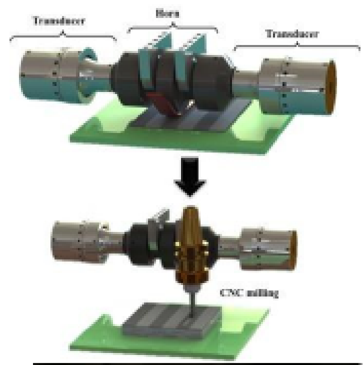

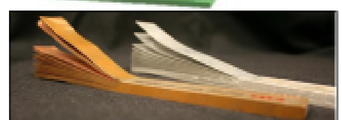

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Sheet Lamination

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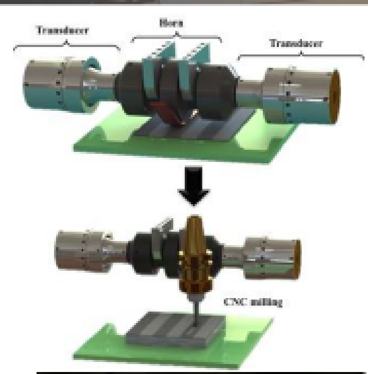

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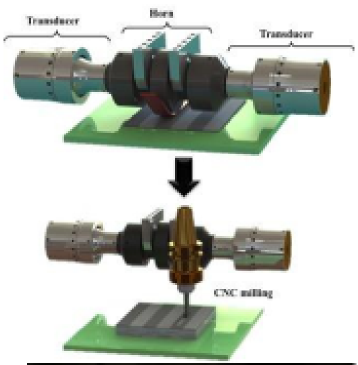

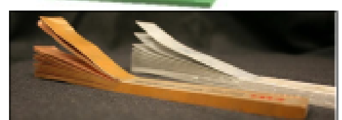

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Ultrasonic Consolidation Process

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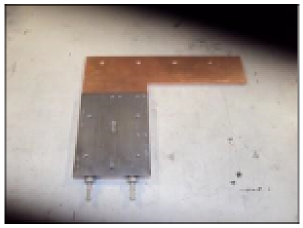
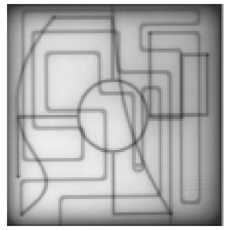
Sheet Lamination

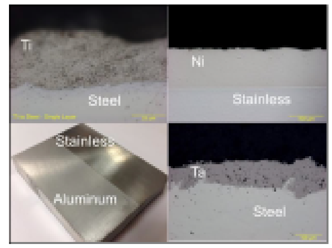
- **Some Examples:**



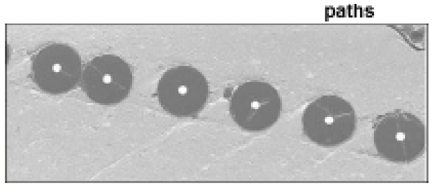
Multi-material heat exchanger



x-ray image of complex internal flow paths



Dissimilar metals joining



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SiC fibers in aluminum laminate

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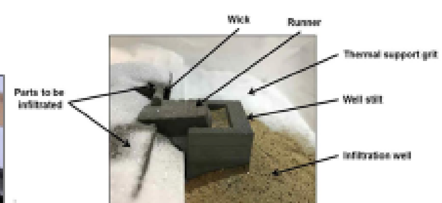
Binder Jetting

- **Binder jetting :**
  - Liquid binder is deposited on metal powder layers as per the desired geometry to set the part together.
  - This part is then cured followed by either direct sintering or infiltration to get the final part.
  - Maximum build chamber size: 31”X19”X15”
  - Materials: Steels, Ni alloys, Tungstens, Sand, Ceramics, CoCr, Iron, Carbon, SiC
  - Surface finish: ~15 μm



Infiltration process

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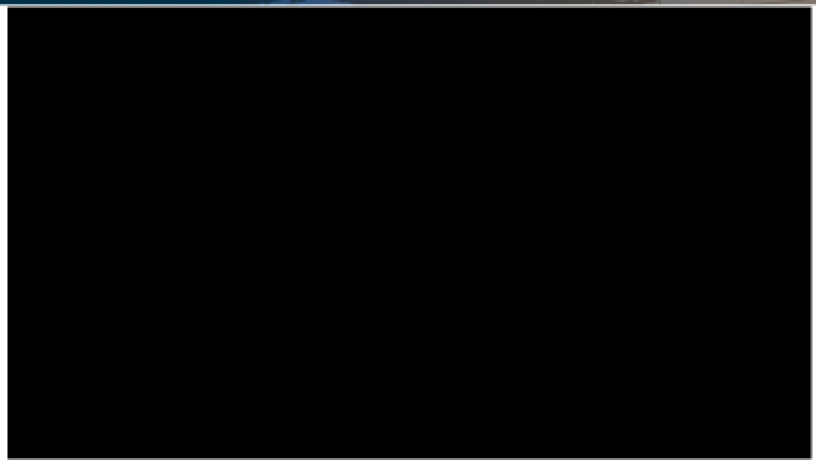
Binder Jetting



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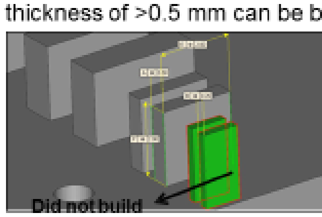
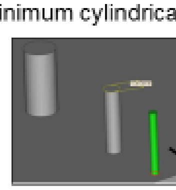
Binder Jetting

- **Design Considerations:**
  - —**Overhanging feature**:
    - —Can build overhanging features without support structures
  - —**Minimum feature size**:
    - —Minimum wall thickness of >0.5 mm can be built and infiltrated



    - —Minimum cylindrical feature >0.5 mm dia. can be built and infiltrated



Did not build

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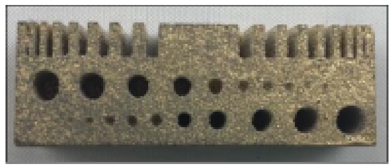
Binder Jetting

- **Design Considerations:**
  - **Wick and Runner design**
    - In case of infiltration, the wick and runner could be designed into the part itself.
  - **Minimum feature size**:
    - Minimum through hole > 2.5mm, blind hole > 3mm and min. gap between walls >1mm can be built after infiltration.
    - These values are also dependent on the size of thermal support grit used during infiltration.



  - **Shrinkage factor:**
    - Incase of direct sintering, shrinkage has to be accounted for during sintering based on the build material.

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Binder Jetting

- **Some Examples:**

Prosthetic hand
Stainless steel/bronze matrix

Stator(3"- 5")
Stainless steel/bronze matrix

Strainer plates

ExOne

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Overall Summary & Conclusions

- **Metal Part Manufacture is now possible using many different AM techniques**
  - Tooling and Metal Part prototyping are common applications
  - Direct Manufacturing of Novel Designs, Compositions and Geometries is being actively pursued
  - Direct approaches are becoming increasingly available and reliable, but remain expensive for many types of geometries and volumes
  - Knowing the technology limitations is a good key for success

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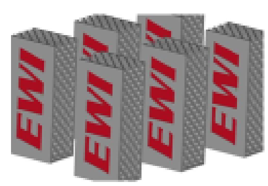
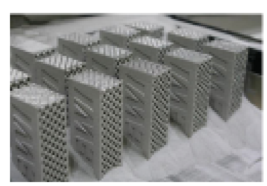
Questions





Francisco Medina, Ph.D.
Technology Leader, Additive Manufacturing
Director, Additive Manufacturing Consortium
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http://ewi.org/technologies/additive-manufacturing/

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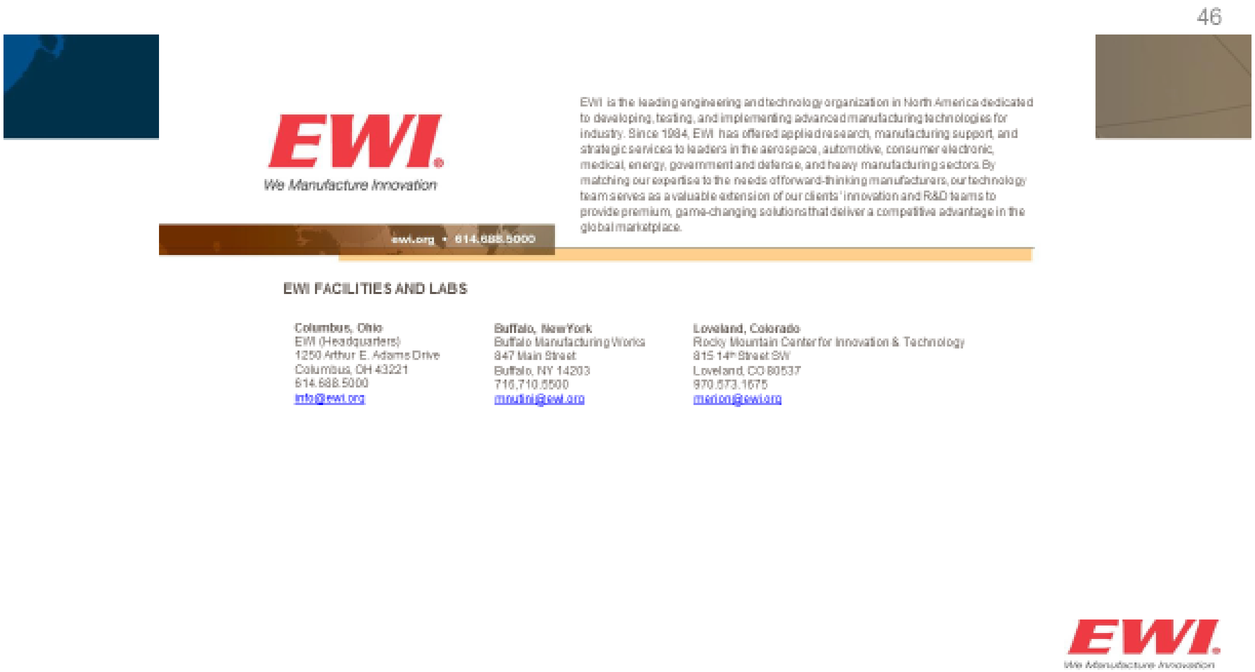

4.9 **Evaluation of Additively Manufactured Materials for NPP Components (Myles Connor, GEH)**

Additive Manufacturing for Nuclear

Topics of Discussion

- DMLM Description (if needed)
- Overview/Status of GEH DOE AM Programs
- Recent SCC and Irradiation Results
- Discussion on DMLM Application in Nuclear Industry

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DMLM Description

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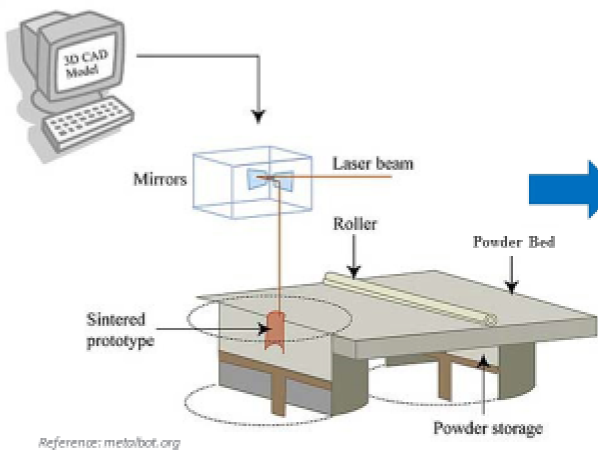
Additive (3D Printing) Process

Direct Metal Laser Melting (DMLM)



Reference: metalbot.org

Intricate Designs that conventional manufacturing processes <u>cannot achieve</u>

Reference: Within Labs, UK

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Overview/Status of GEH/DOE AM Programs

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NSUF CFA-16-10393 Project

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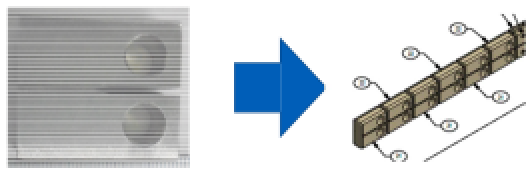
Irradiation Testing of LWR Additively Manufactured Materials

- Objective: Perform full irradiation / PIE on structural materials produced by DMLM
- Participants: GEH (Connor - PI), INL (Jackson)
- Activities: Obtain microstructural characterization, mechanical properties, stress corrosion crack growth data for un-irradiated **Type 316L and IN 718** (GEH) and corresponding irradiated data to ~0.7 dpa (INL at the ATR)



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CFA-16-10393 Project

Timeline

2016-2017 — Fabrication and Unirradiated Testing (GEH)
- Fabricate 316L and IN718 samples ✓
- Mechanical Testing (tensile, toughness, fatigue, SCC) ✓

2017-2019 — ATR Irradiation (INL)
- SCC testing for unirradiated IN718
- Irradiation – 3 cycles starting in August, 2017
- Complete May, 2018

2019 — PIE (INL)
- Initiate in August, 2018
- IASCC, Fracture Toughness, Tensile, TEM

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NEET CFA-15-8309

Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing

- Objective: Support commercialization of AM for nuclear. Evaluate the SCC susceptibility, corrosion fatigue, and irradiation resistance of the additively manufactured 316L stainless steel in nuclear environment
- Participants: GEGR (Rebak - PI), ORNL (Muth), U of M (Was), GEH (Connor)
- Activities:
  Evaluate/Optimize commercial AM SS
  Advanced AM SS for SCC and Radiation
  Component demonstration and evaluation

NEET CFA-15-8309

Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing

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  Evaluate/Optimize commercial AM SS
  Advanced AM SS for SCC and Radiation
  Component demonstration and evaluation

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Detailed Tasks of the Program

Task 1: Evaluating commercial AM stainless steel (GEGR, ORNL, UM, GEH)

- ❑ Four different manufacturers (machine, powder, process variabilities)
- ❑ Roles of laser and heat treatment on microstructure and surface
- ❑ Stress corrosion crack (SCC) growth behavior
- ❑ Corrosion fatigue (CF) crack growth behavior
- ❑ Irradiation and irradiation assisted stress corrosion cracking (IASCC)

Task 2: Optimizing commercial AM stainless steel (GEGR, GEH)

- ❑ Laser process and heat treatment optimization
- ❑ Hot isostatic pressing (HIP) vs. Non-HIP
- ❑ Stainless steel chemistry optimization
- ❑ Process optimization for surface properties (roughness and microstructure)

Completed On-going Not started

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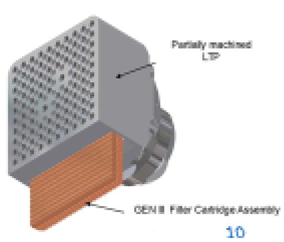
Detailed Tasks of the Program

Task 3: Advanced AM stainless steel for SCC and radiation (GEGR, ORNL, UM)

- ❑ Heat treatment study and grain boundary structure modification
- ❑ Chemistry adjustment (effects of high Cr or high Ni)
- ❑ SCC, IASCC, mechanical properties

Task 4: Component demonstration and nuclear specification (GEGR, GEH, ORNL)

- ❑ Complex geometry component fabrication using optimized process
- ❑ Component evaluation (material and performance)
- ❑ Post inspection technique (laser scan & CT)
- ❑ Cost evaluation
- ❑ Contributions to nuclear specification



Completed On-going Not started

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Material Microstructure, Properties, and SCC Performance

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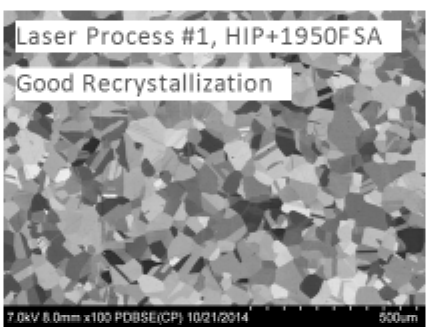
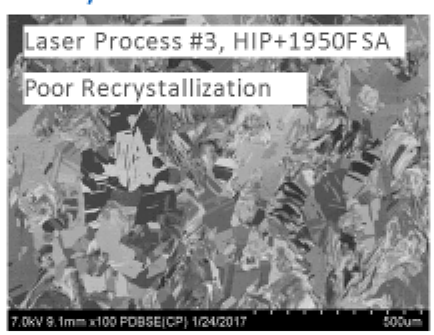
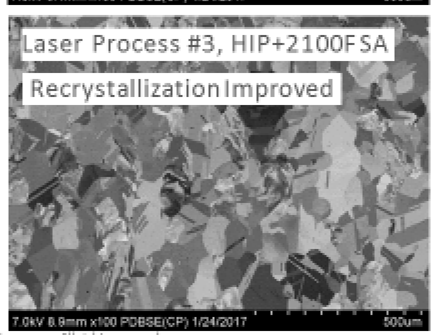
Heat Treatment and Recrystallization



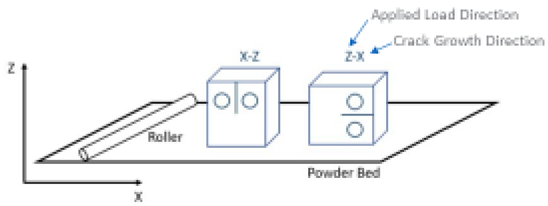


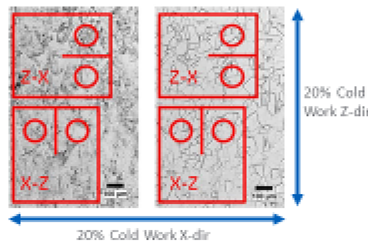


- ❑ Laser process can strongly influence the recrystallization microstructure.
- ❑ Having some unrecrystallized grains is unavoidable in AM parts even after high temperature annealing.

SCC Test Specimens and Conditions

Stress Relief Only and HIP + Solution Anneal





- Compact tension specimens
- BWR testing conditions:
  - ❑ 288^{0}C water
  - ❑ 2 ppm O_2 or 63 ppbH_2
  - ❑ K=22, 27.5, 33 MPa√m
- 5000-8000 hours tested per sample

25ksi√in, 20%CW, 20 ppb SO_4^{2-}

Sample	2ppm O_2 (mm/s)	63ppb H_2 (mm/s)
HIP + SA, Z-X Orientation	3.4 X 10^{-7}	1.1 X 10^{-8}
Wrought	~3 X 10^{-7}	~1 X 10^{-8}

SCC crack growth rate:
AM 316L ≤ wrought 316L

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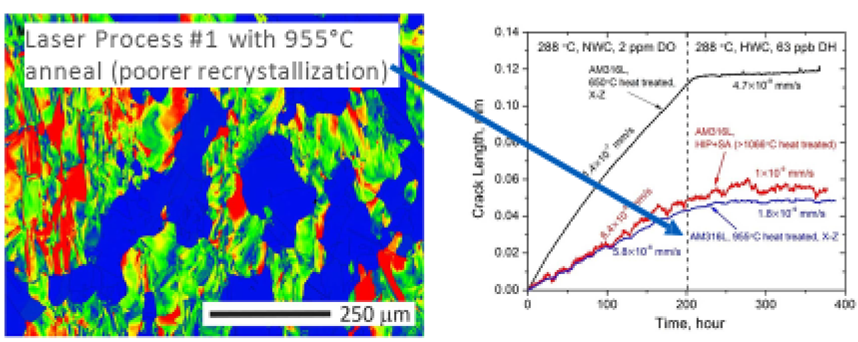
Impact of the Unrecrystallized Grains on SCC



After high temperature annealing (above stress relief), retained unrecrystallized grains in the material may not significantly affect SCC behavior.

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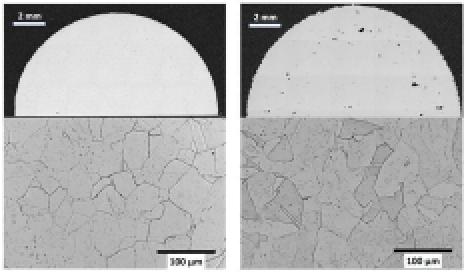
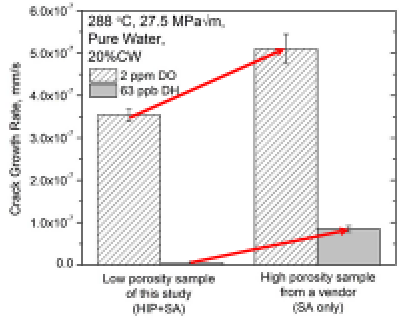
HIP vs. Non-HIP (Porosity Effect)

Laser Process #1 | Laser Process #2



Mean Porosity: 0.08 %
Mean Pore Size: 2.8 µm

Mean Porosity: 0.3 %
Mean Pore Size: 16 µm



Tested Materials	CGR (mm/s)
Laser Process #3, HIP+SA, 2ppm DO	3.6 X 10^{-7}
Laser Process #3, SA only, 2ppm DO	3.8 X 10^{-7}

- ❑ High porosity increases SCC growth rate in both NWC and HWC
- ❑ For reasonably low porosity heat, HIP does not make significant difference on SCC behavior.

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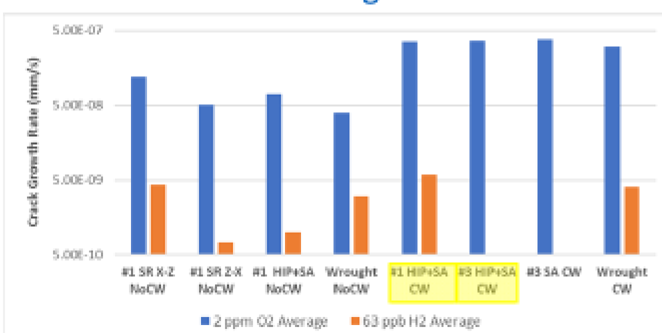
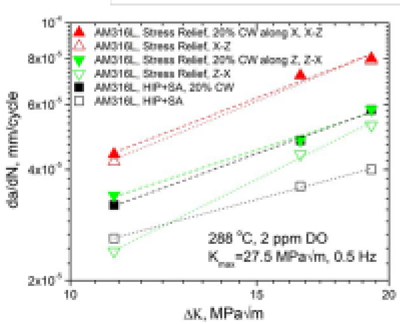
SCC and Corrosion Fatigue Crack Growth





- ❑ High-temperature HIP and Annealing yield reasonable SCC and corrosion fatigue growth behavior
- ❑ Stress relieved (only) material is not recommended.
- ❑ HIP+SA improves corrosion fatigue

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Effect of irradiation on microstructure, mechanical properties and IASCC

Experimental work by Mia Song and Mi Wong

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Effect of irradiation on microstructure, mechanical properties and IASCC

Experimental work by Mia Song and Mi Wong

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Heat treatment of GE 3D materials

Material Label	Laser Process	Stress Relief	HIP	Solution Anneal
QCAM316L-AM	#1	Yes	No	No
QCAM316L-HIP	#1	Yes	Yes	1950F 1hr
GEAMW-AM316L-HIP	#3	Yes	Yes	2150F 1.5 hr
QCA800-HIP		Yes	Yes	2200F 1.5 hr

Heat treatment of GE 3D materials

Material Label	Laser Process	Stress Relief	HIP	Solution Anneal
QCAM316L-AM	#1	Yes	No	No
QCAM316L-HIP	#1	Yes	Yes	1950F 1hr
GEAMW-AM316L-HIP	#3	Yes	Yes	2150F 1.5 hr
QCA800-HIP		Yes	Yes	2200F 1.5 hr

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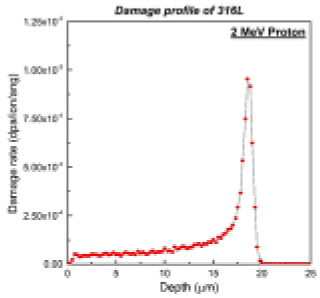
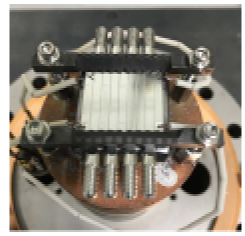
Experiment

- Irradiation

Parameter	2 MeV Proton	5 MeV Fe++ (QCAM316L only)
Dose (dpa)	5	100
Temperature (°C)	360	400
Damage rate (dpa/s)	1.6×10^{-5}	3.6×10^{-4}
Current (µA)	37	0.618

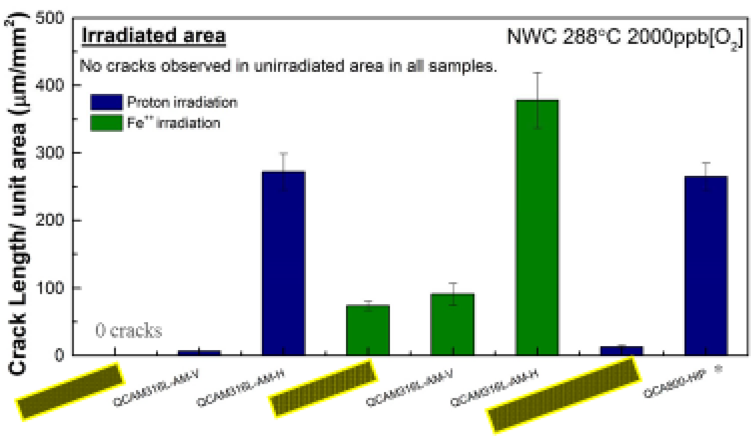




Irradiation stage

- Constant Extension Rate Tensile (CERT) test in BWR (NWC) environment
  - 288°C, 2000 ppb $[O_2]$
  - Slow strain rate: ~ $1 \times 10^{-7} s^{-1}$
  - Plastic deformation: ~ 4 %

Cracking susceptibility of GE materials



* combined cracking data from two specimens.

- Overall, HIP 316 shows better irradiation tolerance compared with the stress relieved condition.
- IASCC susceptibility is higher for the case where the printing direction was perpendicular to the loading direction.
- High IASCC susceptibility correlated with the degree of radiation damage.

Applications and Challenges

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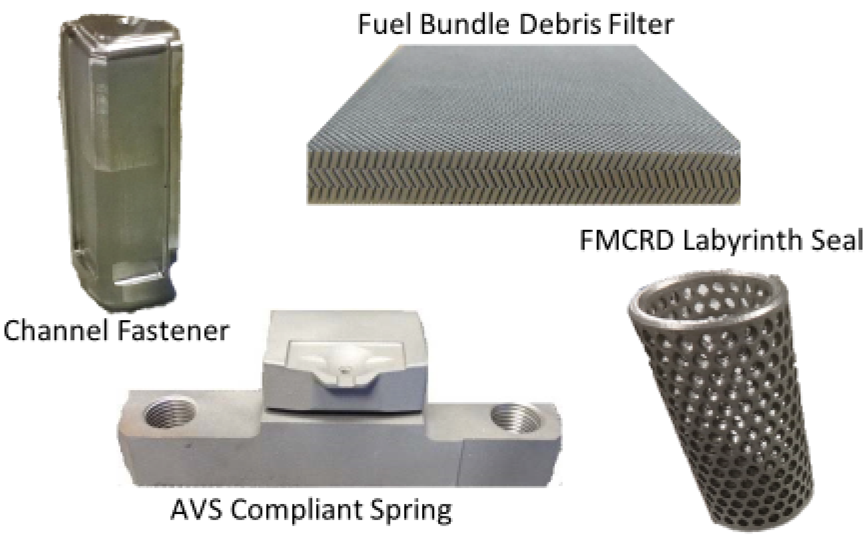
Application Examples



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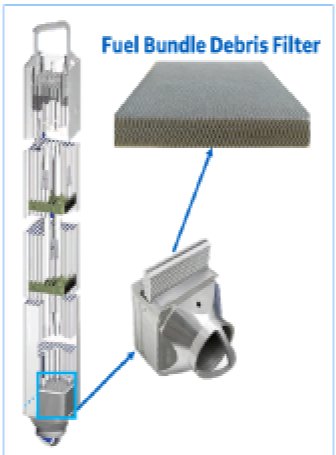
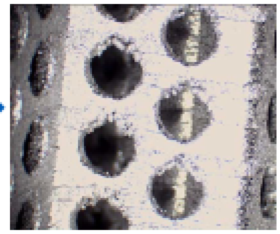
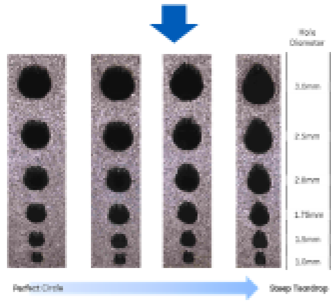
Nuclear Part Design - Iteration Process

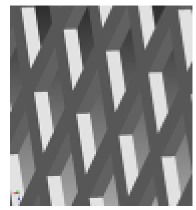




Challenge with hole size smaller than model. Pressure drop too high.

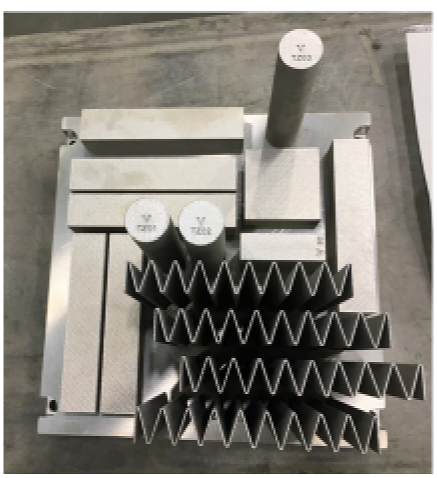


Studied teardrop shapes for rounder small holes



Settled on diamond pattern

Nuclear Part Design – Final Build Plate



Small-scale production run, with additional materials testing samples:

- Production parts
- Tensile bars in X,Y,Z direction
- Extra material specimens

Intended Purpose:

- Material testing
- Microstructure analysis
- Performance requirement testing
- Manufacturing and inspection process development

Challenges for Additive

Powder Bed Laser Fusion Process

- Nuclear industry has more difficulty in incorporating new materials, designs
  - Costly validation, limited facilities, speed of change/innovation
- Developmental/Technical challenges
  - "design for additive" learning curve, surface roughness, qualification, NDE/inspection, size constraints (build envelope)
- Collaboration will facilitate more rapid use of Additive Manufacturing

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Summary

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Summary

Material Microstructure

- Unrecystallized grains after annealing do not have a significant negative influence on mechanical, SCC, and CFG performance
- HIP may not be needed if the laser properties yield low porosity

IASCC

- Stress relieved only samples show unfavorable. HIP and annealed 316L AM shows favorable irradiation tolerance.
- Direct comparison to wrought 316L coming soon.

Application Readiness

- Clear understanding of how to qualify and deploy 316L AM material (challenges do exist). Will become more cost effective with experience.

Questions?

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4.10 The 'Big Picture' Vision for AM in Nuclear Industry (Zeses Karoutas, WEC)

Westinghouse Non-Proprietary Class 3

The 'Big Picture' Vision for AM in Nuclear Industry

Zeses Karoutas
Westinghouse Electric
Chief Engineer, Fuel Engineering & Safety Analysis
Meeting at NRC, November 28 & 29, 2017

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What is Driving Additive Manufacturing for Nuclear

Delivering the Nuclear Promise:
"Advancing Safety, Reliability and Economic Performance"

In order to facilitate this industry initiative Westinghouse believes the industry needs innovation.

Additive is innovation in the form of a disruptive technology.

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Additive and Nuclear

Additive is a disruptive technology

- Harvard Business School professor Clayton M. Christensen coined the term disruptive technology.
- A disruptive technology is one that displaces an established technology and shakes up an industry or a ground-breaking product that creates a completely new industry

Some examples of disruptive innovation include:

Disruptor	Disruptee
Personal computers	Mainframe and mini computers
Mini mills	Integrated steel mills
Cellular phones	Fixed line telephony
Community colleges	Four-year colleges
Discount retailers	Full-service department stores
Retail medical clinics	Traditional doctor's offices

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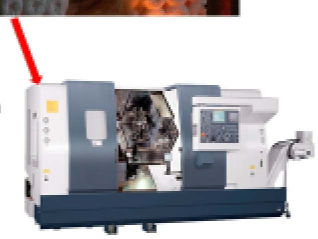
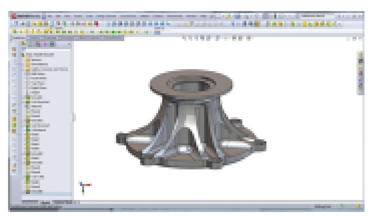
Additive and Nuclear

Additive is a disruptive technology

1. CAD Model
2. Die
3. Wax pattern
4. Mold
5. Casting
6. Machining





1. CAD Model
2. Printed part

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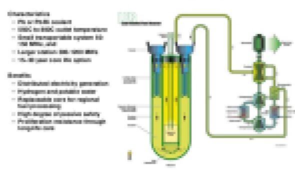
Additive and Nuclear

Additive shaking up the Nuclear industry

- **Potential to facilitate:**
  - Small Modular Reactors
  - Micro Reactors
  - Advanced Reactors
- **Improved safety**
  - Accident tolerant fuel
  - Sensors

Lead-Cooled Fast Reactor (LFR)



- **Improved economic performance**
  - New design enhancements
  - Flexibility
- **Improved reliability**
  - Replacement parts

Potential to facilitate multi nuclear industry initiatives

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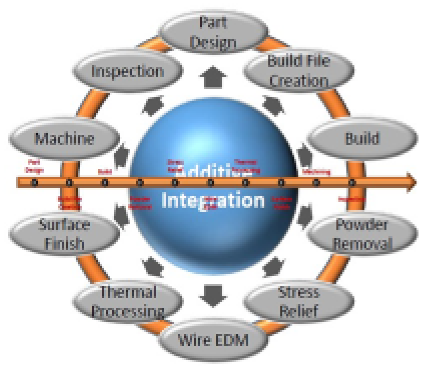
Full Integration is the Key to Success

- Additive Manufacturing cannot be treated as standalone
  - 3D printers are "**just**" another machine tool
  - no one machine tool can do it all
- Design for Additive Manufacturing (DFAM) must be employed
- All aspects of the production process are interdependent
- 3D printers must be combined with traditional manufacturing processes



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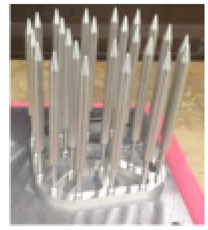
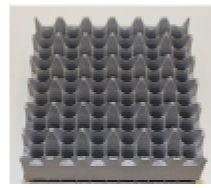
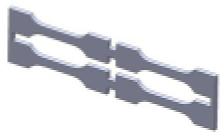
Additive Manufacturing - 3D Printing for Nuclear

- Develop and test critical nuclear materials: 316L, Alloy 718, and Zirconium
- Produce a reactor ready test component
- Exploit the benefits of Additive Manufacturing
  - Producing components with: Powder Bed Fusion, Binder Jetting, and Directed Energy Deposition AM technologies
  - Obsolete and high value / lead time components
  - Next gen plant components - SMR, LFR, …
  - Prototypes, mockups, jigs / fixture, tooling, etc.
- Support the development of codes and standards
  - Participating on ASTM F42 subcommittees
  - DOE funded project: Qualification of AM for Nuclear
- Development Needs:
  - Additional material development and testing to support the development of code & standards
  - Cost effective, large scale equipment
  - AM suppliers with Nuclear programs







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Summary

- Will Additive Manufacturing have a big impact in Nuclear ?
  - Be Cost Effective
  - Improve Performance and Reliability
  - Improve Delivery and Schedule
- In Westinghouse we have started to move in the AM direction:
  - Utilize 3D printing now for tooling
  - Implement a 3D part in reactor to gain experience
  - Perform mechanical tests on 3D parts (with and without radiation effects)
  - Investigate what parts make sense to build with AM

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Our Goal is for AM to Help Transform the Nuclear Industry and Support the Nuclear Promise

8

4.11 Current Westinghouse Efforts (Bill Cleary, WEC)

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Current Westinghouse Efforts

William Cleary
Westinghouse Electric
NF Additive Manufacturing Technical Lead
Meeting at NRC, November 28 & 29, 2017

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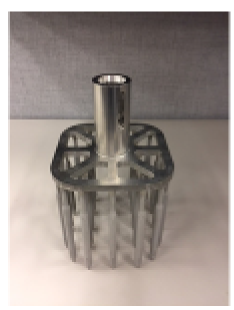
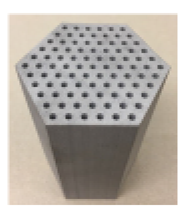
Key Areas of Additive Manufacturing Interest

- Global Technology Development Efforts
- Tooling and Replacement Parts
- Nuclear Fuel Components Efforts
- Thimble Plugging Device (TPD) Project





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Global Technology Efforts

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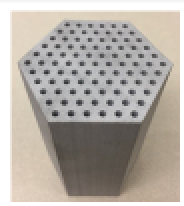
Global Technology Development Efforts (R&D)

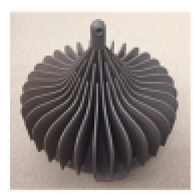
OVERVIEW

- Prototype components for SMR, advanced reactors and AM manufacturing / design demonstration
- Material development for next generation applications
- Support the development of codes and standards (ASTM & ASME)



BENEFITS

- Design freedom: complex geometries, internal passageways, etc.
- Reduced design time: fast prototyping & mold production
  - Little to no tooling required
  - Design complexity at minimal cost
- Near net shape: reduced material, machining & welding
- Reduced lead-time / reduced supply chain



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Tooling and Replacement Parts

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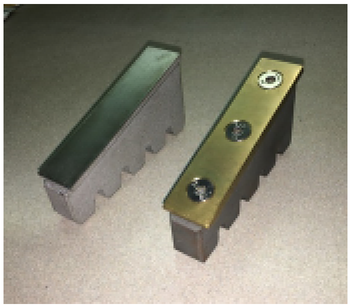
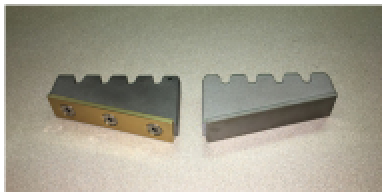
Blairsville Site Tooling Application

- Original was five piece design with brass wear plate - heat treated to 36-44 Rc
- AM part printed in one build using tool steel – heat treated to 42 Rc
- Reduced need for replacement as the tool steel work hardens increasing useful life





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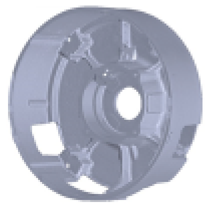
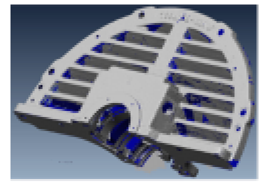
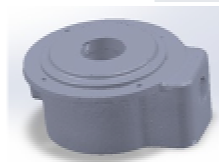
Replacement Parts Development Efforts



- **OVERVIEW**
  - **Demonstrating Reverse Engineering Process:**
    - 3D laser scanning → CAD Models → AM sand molds → traditional casting
  - **Multiple replacement castings have been identified**
    - Difficult to procure replacement castings



- **BENEFITS**
  - **AM complexity with traditional sand casting**
  - **Significantly reduced cost and lead-time**
  - **Conversion to modern, digital design information and manufacturing**



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Replacement Parts Development Efforts

- **Worn out shaft repaired using plasma spray coating**
- **Nickel and molybdenum deposited onto the worn surfaces and part ground back into engineering specifications**
- **Able to return the part to service for about a third of the price of a replacement**

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Nuclear Fuel Efforts

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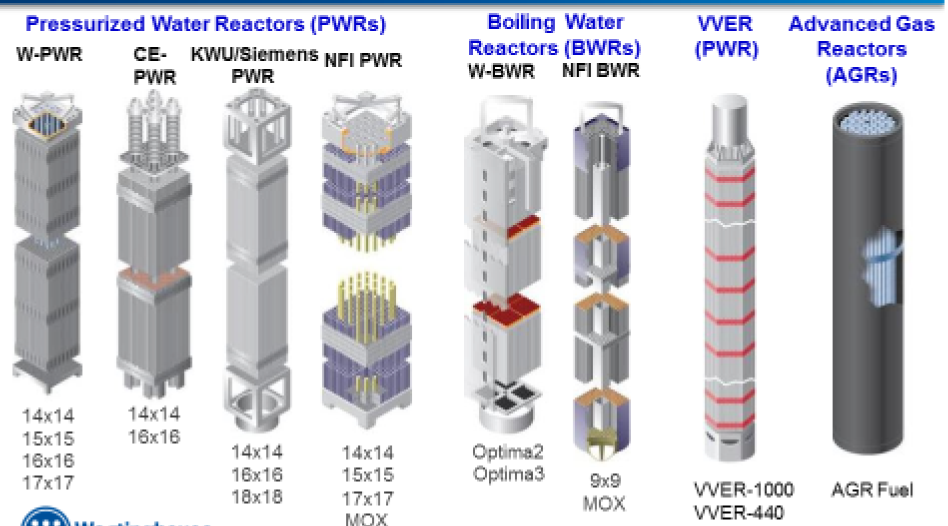
Westinghouse Fuel Manufactured Products



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Potential Benefits to Nuclear Fuel

- Lower fuel assembly pressure drop
- Better flow mixing and greater heat transfer ability
- Less potential for leakers
- Greater accident tolerance
- Better fuel margins
- Extended fuel cycles
- Customizable fuel assemblies
- Less supply chain dependence
- Fewer overall suppliers
- Reduced time from concept to market
- Flexibility

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Shatter Paradigms for Fuel Design Constraints Based on Traditional Materials and Manufacturing Limitations

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Additive Manufacturing and Nuclear Fuel

WEC Nuclear Fuel is pursuing the use of Additive Manufacturing (AM) in a variety of manners:

- Design of Advanced Debris Filtering Bottom Nozzle
- Advanced spacer grids optimized utilizing design freedom
- Evaluating available AM metal powders for use in fuel components
- Radiation exposure testing of 316L, A718, and Zr products

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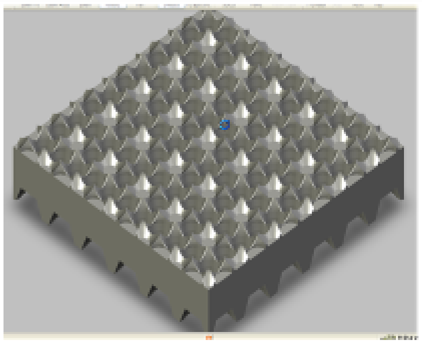
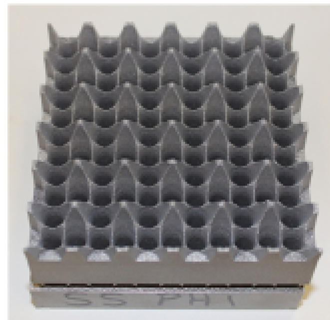
Preliminary efforts to develop AM designs and alloys

Advanced Debris Filtering Bottom Nozzle



Additively manufactured and achieved a substantial pressure drop reduction.



This effort resulted in 24 unique plastic designs each tested in the "Vista" loop for hydraulic performance

Used to quickly "optimize" designs for improved hydraulic performance

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Prototyping to evaluate and optimize performance of concepts

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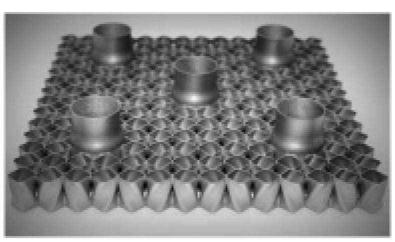
Advanced Spacer Grids

Prototype grid printed using AM

- Grid (not printed) did not perform as expected in DNB testing
- Potential "fixes" could be realized using AM
- Possible opportunity to expand testing capabilities to enable prototype screening greatly reducing costs and improving development cycle times



Prototyping to improve results and shorten development cycle time

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Thimble Plugging Device

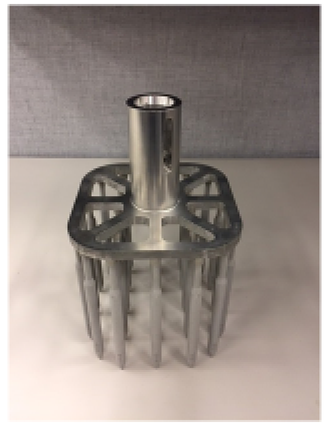
Thimble Plugging Device (TPD) Project

- Why the Thimble Plugging Device
  - **Low risk component for which consequences of failure minimal**
  - Fairly complex design promoting enhanced understanding of the AM design and building process
  - Constructed of material that has been previously tested in MIT reactor
  - Located in reactor region with fluence rate comparable to region of ADFBN placement in the core.
- The AM TPD is intended to be produced for technology development and will not be produced in typical production QTYs. AM TPD has not been redesigned to utilize AM benefits.

Improve our understanding of AM materials in radiation environment

TPD Project

- Current Status:
  - Prototype builds have been completed and proof of concept demonstrated
  - Concepts and Issues meeting completed
  - Design and Manufacturability meeting held
    - Qualification Plans, CDI's, PO's in place for qualification pieces
    - Four qualification pieces have been built
    - Testing of qualification pieces complete



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Summary of Vision

- We see immediate benefit of AM for tooling and replacement parts
- Radiation exposure and mechanical testing of 316L, A718, and Zr products look promising
- Plan to insert first AM part in reactor in 2018 to gain experience
- Next want to focus on building AM parts to obtain benefits in performance, economics and manufacturing relative to current methods

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4.12 Laboratory Testing & Evaluation of Unirradiated and Neutron Irradiated Additively Manufactured Alloys (Paula Freyer, WEC)

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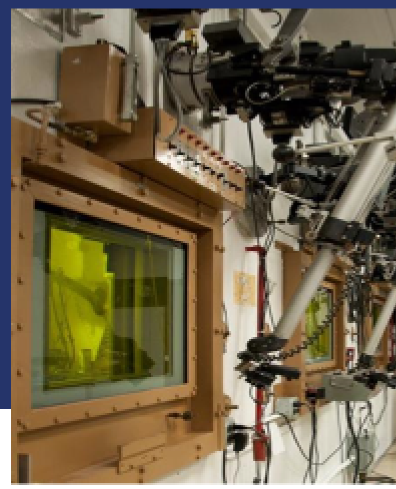
Laboratory Testing and Evaluation of Unirradiated and Neutron Irradiated Additively Manufactured Alloys

Paula Freyer
Fellow Engineer/Metallurgist
Westinghouse Electric Company LLC
Global Technology Office
Churchill Laboratory Services

NRC Public Meeting
Additive Manufacturing for Reactor Materials & Components

North Bethesda, MD
November 28-29, 2017



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Laboratory Testing and Evaluations
– Additively Manufactured (AM) Alloys –

AM 316L

- Completed significant testing and evaluation of unirradiated and 0.8 dpa irradiated samples
- All work performed under WEC* sponsorship
- Samples in storage in Westinghouse Hot Cells
- Additional work on these samples not currently being pursued
- Objective: thimble plugging device insertion into commercial PWR(s) in late 2018

AM Alloy 718

- Completed significant testing and evaluation of unirradiated and 0.8 dpa irradiated samples
- All work performed under WEC* sponsorship
- Samples in storage in Westinghouse Hot Cells
- Aggressively pursuing additional funding (DOE NSUF#) to perform further work

AM Zircaloys

- Samples irradiated to 1, 2 and 3 dpa under WEC* sponsorship
  - 1 dpa irradiations completed
  - 2 dpa irradiations completed 2018
  - 3 dpa irradiations completed 2019
- PIE work will initiate in early 2018 under DOE NSUF# sponsorship
- Aggressively pursuing additional funding to perform further work – likely award in Jan 2018

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* WEC = Westinghouse Electric Company LLC
\# NSUF = Nuclear Science User Facilities

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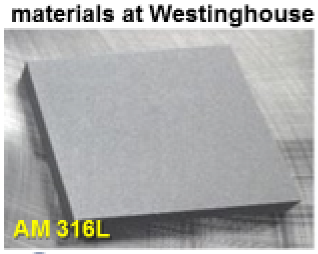
Laboratory Testing and Evaluations
– Typical Approach –

- DMLS block
- Microstructural analysis of as-printed material
- EDM wire cut AM 'quads' from X, Y, Z directions and conventional quads from T, L directions
- Heat treat quads
- Neutron irradiate subset of heat treated quads
- Laboratory testing and evaluations of unirradiated, irradiated, AM and conventional materials at Westinghouse



~106 x 106 x 16 mm

~108 x 90 x 56 mm

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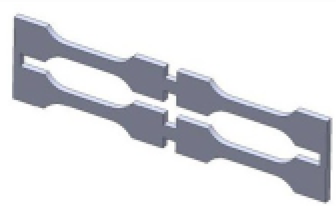
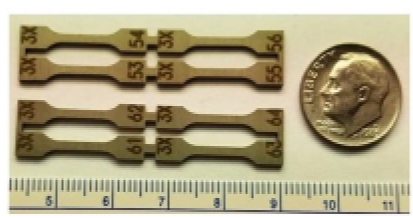
Laboratory Testing and Evaluations
– 'Quad' Miniature Tensile Specimen Geometry –

- Specimens wire EDM cut from test materials as four connected miniature tensiles = 'quads'
- EDM surfaces not polished prior to tensile testing
- Nominal dimensions of individual miniature tensile specimens:
  - L = 23 mm (~ 0.91 inch)
  - W_{gauge} = 1.52 mm (~ 0.06 inch)
  - T = 1 mm (~ 0.04 inch)
- Specimens irradiated in MIT reactor as quads and subsequently separated into individual miniature tensile specimens inside Westinghouse's hot cell





Miniature tensile specimen quads.
Scale in centimeters.

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Scope of Laboratory Testing and Evaluation

- Slight variations for each of the 3 alloys however significant portions of the testing/evaluations are identical
- Includes but not limited to:
  - Radiation measurements
  - Chemistry evaluations (ICP-MS and/or ICP-OES)
  - Immersion density measurements
  - Microhardness
  - Light optical and scanning electron microscopy (unetched and etched)
  - Electron backscattered diffraction (EBSD)
  - Transmission electron microscopy
  - Room and elevated temperature tensile testing with digital image correlations/advanced video extensometry
  - Fractography
  - Hydrogen content analysis
  - Autoclave corrosion testing
  - FIB analysis of surface deposits

Significant materials evaluations completed for AM 316L and AM Alloy 718.

Significant evaluations for AM Zircaloy are funded and will begin Jan 2018.

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Example: AM 316L Testing Program Overview

- Utilized both conventional 316L plate and AM DMLS printed 'blocks'
  - AM blocks used to reduce/eliminate potential influence of part geometry on material microstructure and tensile properties
- Miniature tensile specimens wire EDM cut from:
  - plate material in transverse (T) and longitudinal (L) directions
  - AM printed block in 'X' and 'Y' directions (two directions in build plane)
- Miniature tensile specimens irradiated in MIT reactor for a ~5 months to a damage dose of ~0.8 dpa
- Analysis included: tensile testing, chemical analysis, corrosion testing, focused ion beam cross sectional analysis of surface deposits, light optical microscopy, scanning electron microscopy, fractography, and hardness testing, etc.
  - We have published some microstructural results and a majority of the tensile results

Tensile:
P.D. Freyer, W.T. Cleary, E.M. Ruminski, C.J. Long, P. Xu, *"Hot Cell Tensile Testing of Neutron Irradiated Additively Manufactured Type 316L Stainless Steel,"* 18th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Aug 2017, Portland, Oregon.

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AM 316L Testing Summary

- Tensile testing performed at both room and elevated temperature
- 12 different tensile test conditions evaluated (next table)
- Conventional plate material
  - Standard annealed condition (i.e., 1038°C (1900°F))
  - ASTM A479/A479M – 17
  - ASTM A240/A240M – 16a
  - Certified material test report (CMTR) - compliant with all applicable ASTM chemistry and mechanical property requirements
- AM material
  - Produced as block using DMLS process and 316L (UNS S31673) powder
  - Mean build layer thickness of 20 μm (~0.8 mil)
  - Standard anneal performed on quads cut from block

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AM 316L Testing Summary

Summary of 5 material conditions evaluated, including 10 material orientations, and tensile results presented

Number	Irradiation Condition	Conventional or AM	Condition	Orientation Evaluated	Tensile Results Summarized Herein
1	Unirradiated	Conventional Plate	Annealed	L and T	✓
2		AM	Printed (microstructural characterization only)	X and Y	Some microstructural results provided
3		AM	Printed + annealed	X and Y	✓
4		AM	Printed + annealed + long term thermally exposed	X and Y	
5	Irradiated	AM	Printed + annealed + irradiated	X and Y	✓

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AM 316L Testing Summary

Summary of 12 tensile test conditions evaluated

Data Set	Number	Material Condition Description
A	1	L Conventional Unirradiated Room Temperature
	2	T Conventional Unirradiated Room Temperature
B	3	L Conventional Unirradiated Elevated Temperature
	4	T Conventional Unirradiated Elevated Temperature
C	5	X AM Unirradiated Room Temperature
	6	Y AM Unirradiated Room Temperature
D	7	X AM Unirradiated Elevated Temperature
	8	Y AM Unirradiated Elevated Temperature
E	9	X AM Irradiated Room Temperature
	10	Y AM Irradiated Room Temperature
F	11	X AM Irradiated Elevated Temperature
	12	Y AM Irradiated Elevated Temperature

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Conventional Plate and AM Powder Compositions

CMTR reported chemical composition (wt%) for conventional plate material and for powder utilized for the DMLS printed block

Element	316L Conventional Plate UNS S31600/31603 (from CMTR)	316L AM Powder UNS S31673 (from powder supplier)
Fe	Balance	Balance
Cr	16.63	17.00-19.00
Ni	10.03	13.00-15.00
Mo	2.01	2.25-3.00
Mn	1.47	2.00 max
Si	0.23	0.75 max
P	0.04	0.025 max
Cu	0.51	0.50 max
S	0.001	0.010 max
N	0.04	0.10 max
C	0.016	0.030 max
Co	0.32	...

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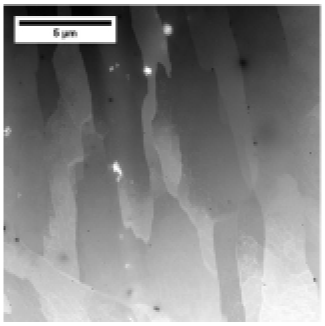
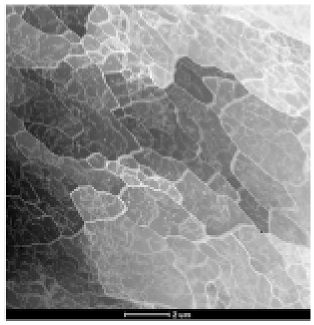
AM 316L Test Material
– As-Deposited Microstructure –



~4,800X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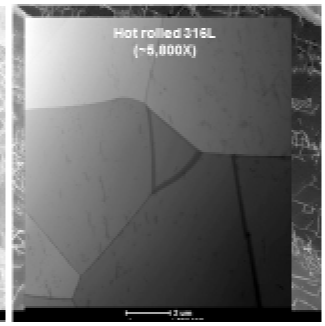

~22,000X

HAADF STEM of columnar grains containing subgrains

ADF STEM of dislocation networks within grains

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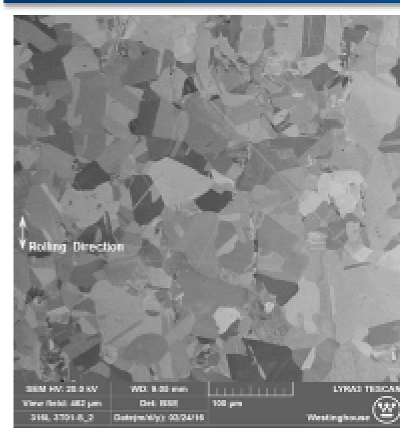
J.J.H. Lim, A.R.C. Malheiros, G. Bertali, C.J. Long, P.D. Freyer and M.G. Burke, "*Comparison of Additive Manufactured and Conventional 316L Stainless Steels,*" Microscopy & Microanalysis, suppl. S3; Cambridge 21, Aug 2015, pp. 467-468.

Conventional and AM 316L Test Material
– Heat Treated Microstructures –



Conventional 316L Plate
Backscattered Secondary Electron SEM Micrograph (~220X)

AM 316L
Light Optical Micrographs (~65X)

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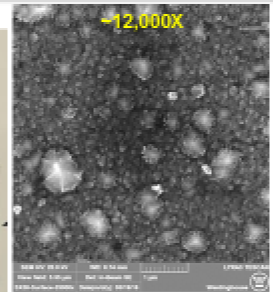
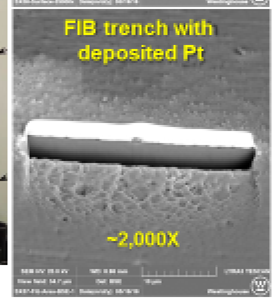
Autoclave Corrosion Testing of Conventional and AM 316L

- 30 days flowing autoclave at simulated PWR primary T, P, and chemistry conditions (per EPRI guidelines)
- Morphology and thickness of resulting oxide characterized using FIB and SEM
- Oxide thickness → estimate corrosion rate

Similar corrosion rates of conventional and AM alloys - base material manufacturing method did not influence corrosion rate.

More in-depth corrosion testing is needed.





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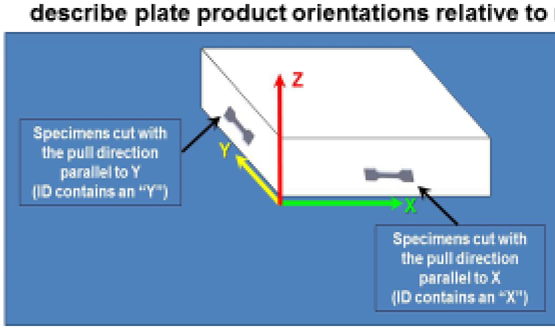
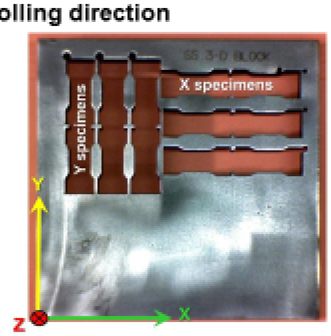
Tensile Specimen Orientations

- X and Y orientations cut from AM block
- No Z tensile specimens (AM block thickness not sufficient to allow for specimens in this orientation)
- For conventional plate material, L and T directions same as typically used to describe plate product orientations relative to rolling direction





Wire EDM cutting of quads from AM 316L test block

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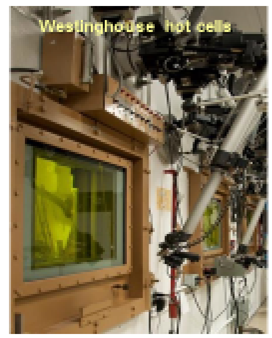
Irradiated Material Description

- 2015 irradiation of AM quads in MIT reactor for ~5 months to fluence:
  - 0.8 x 10^{21} n/cm² thermal
  - 1.2 x 10^{21} n/cm² (E > 0.1 MeV)
  - 6.5 x 10^{20} n/cm² (E > 1.0 MeV)
- Damage dose of ~ 0.8 dpa
- Irradiated close to core center (peak flux)
- Irradiated ~298°C (568°F)
- Quads cooled at MIT for ~5 months prior to shipment to Westinghouse Hot Cells
- Total of 6 AM quads irradiated, 3 were AM 316L quads (12 miniature tensiles)



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Radiation Measurements of Irradiated Quads

- Measurements for three irradiated AM 316L quads
- Near contact dose rates of ~150 R/hr
  - all work performed inside Westinghouse hot cells

Quad Identification Numbers	Measured and Calculated Dose Rates			
	At ~1 m (39")	At ~0.3 m (12")	At ~2.5 cm (1")	At ~1.3 cm (0.5")
	Measured Value	Measured Value	Calculated Value	Calculated Value
	mR/hr		R/hr	
SX01-SX04	36	260	37	150
SX49-SX52	35	230	33	132
SY25-SY28	38	250	36	144

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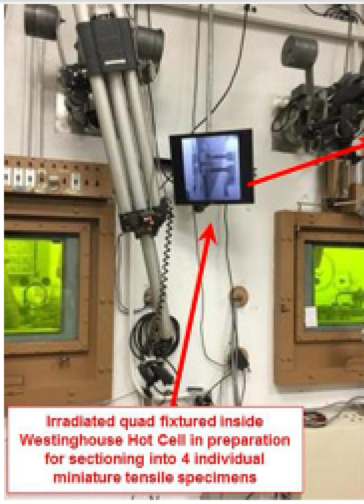
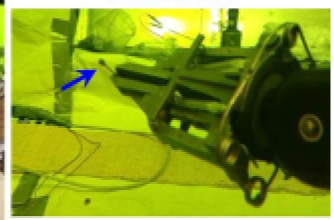
In-Cell Sectioning of Irradiated Quads



Irradiated quad fixtured inside Westinghouse Hot Cell in preparation for sectioning into 4 individual miniature tensile specimens

Close up view of irradiated quad shown on video monitor



Individual miniature tensile specimen (blue arrow) held by manipulator

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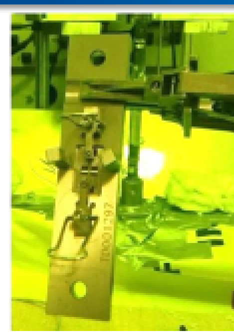
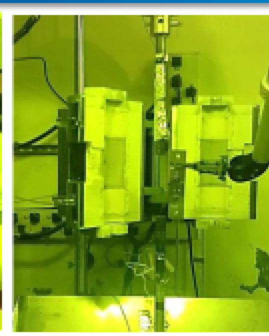
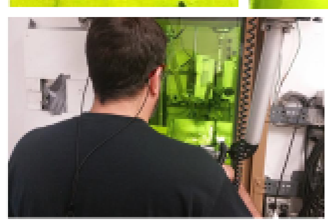
Tensile Testing Approach

- Instron screw driven tensile machine with:
  - Instron Digital Image Correlation/Advanced Video Extensometer (DIC/AVE)
  - Instron 5 kN load cell
- Custom designed and fabricated specimen holding fixture
  - optimized to specifically be used with hot cell manipulators
- Specimens first loaded into fixture and then fixture installed onto pull rods of in-cell tensile machine
- DIC not utilized for elevated temperature tests







Alignment of pin holes on specimen holding fixture with pin holes on tensile machine pull rod clevises inside Low Level Hot Cell

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In-Cell DIC/AVE

- First must speckle contrast mark specimens
- DIC camera captures images during test
- DIC software follows movement of speckle points located within gauge length
- Images collected during testing and processing of strain data occurs after test
- DIC and load cell calibrated in accordance with ASTM specifications

DIC system inside Low Level Hot Cell (marked with yellow arrow)

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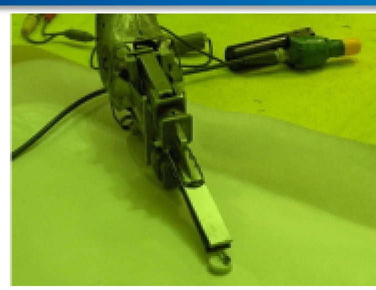
Speckle Marking for DIC

- Optimum approach developed for speckle marking
- Numerous different paints and application techniques initially evaluated
- Optimum: spray white paint ~0.3-0.6 m (1-2 feet) above specimen and allow paint mist to settle down onto specimen surface
- Repeatedly produced miniature tensile specimens with excellent speckle patterns



Placement of individual irradiated miniature tensile specimen onto small raised platform and example of good speckle pattern

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Tensile Test Results

Reference Document or Data Set	UTS, MPa	0.2% YS, MPa	EL, %	RA, %
Room Temperature ASTM Specification Minimums and CMTR Values				
Conventional Unirradiated ASTM Spec A479	485	170	30	40
Conventional Unirradiated ASTM Spec A240	485	170	40	Not specified
Conventional Unirradiated CMTR for 316L	577	260	57	74
AM Unirradiated ASTM Spec F3184-16	515	205	30	40
Room Temperature Test Results				
Data Set A: Conventional Unirradiated	618	282	63	85
Data Set C: AM Unirradiated	605	357	48	77
Data Set E: AM Irradiated	652	427	43	75
Elevated Temperature Test Results				
Data Set B: Conventional Unirradiated	452			
Data Set D: AM Unirradiated	450			
Data Set F: AM Irradiated	493			

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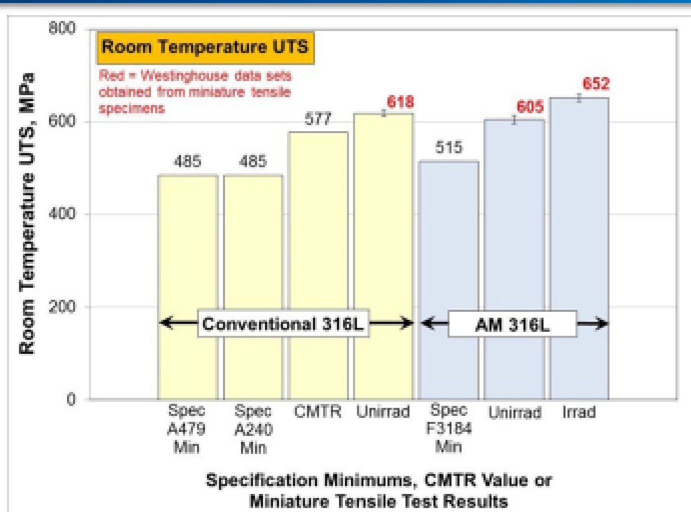
Tensile Test Results - UTS



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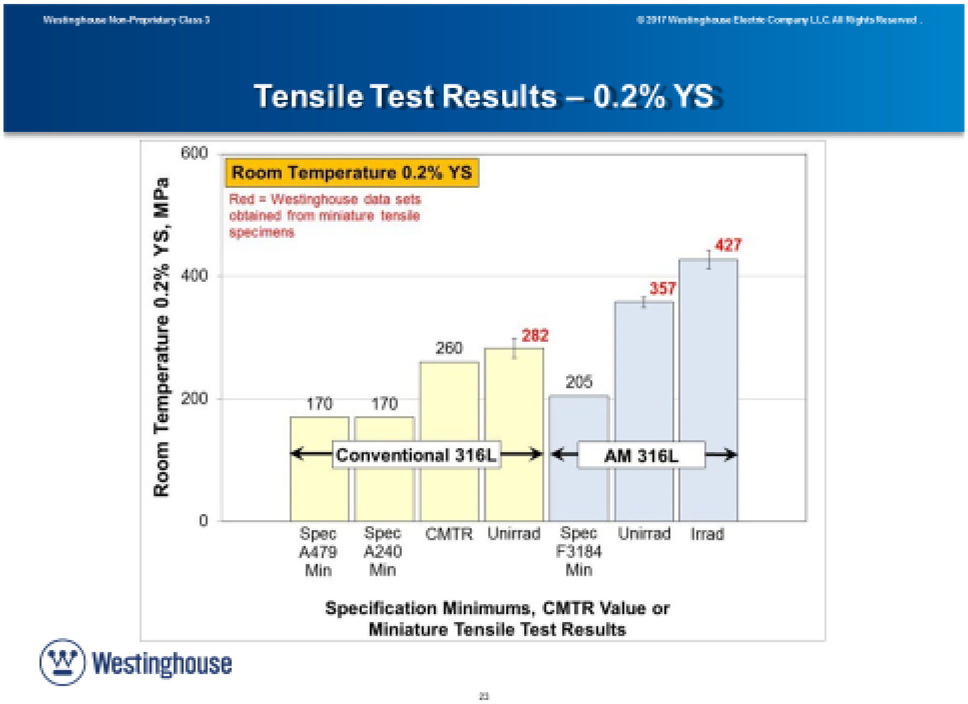
Westinghouse Non-Proprietary Class 3
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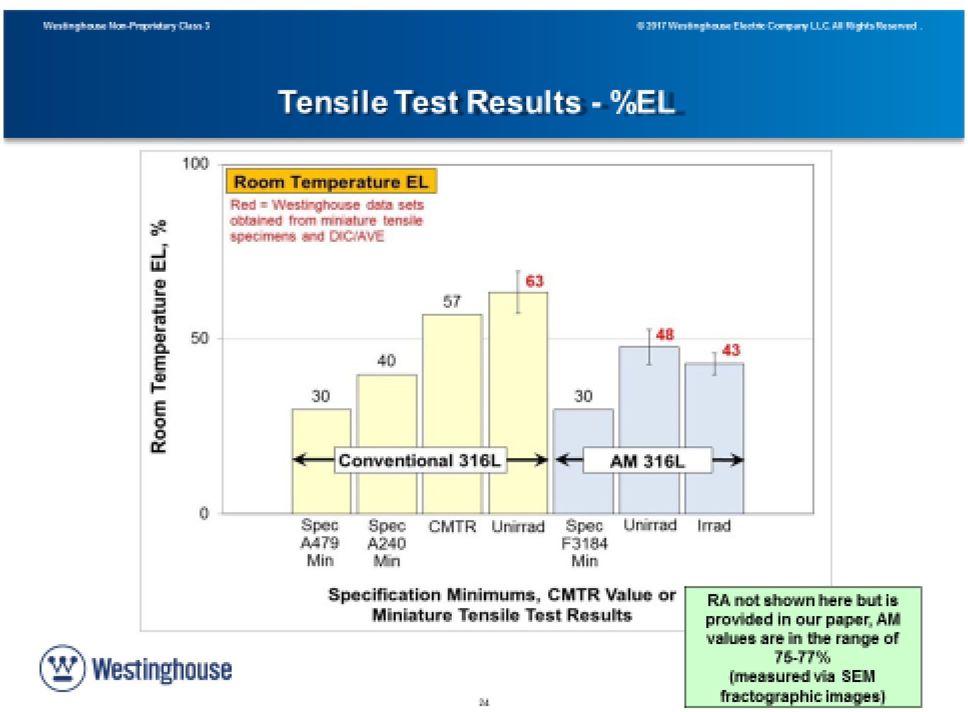
Tensile Test Results – 0.2% YS
Room Temperature 0.2% YS
Red = Westinghouse data sets obtained from miniature tensile specimens
Room Temperature 0.2% YS, MPa
600
400
200
0
170
170
260
282
205
357
427
Conventional 316L
AM 316L
Spec A479 Min
Spec A240 Min
CMTR
Unirrad
Spec F3184 Min
Unirrad
Irrad
Specification Minimums, CMTR Value or Miniature Tensile Test Results
Westinghouse
23


Westinghouse Non-Proprietary Class 3
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Tensile Test Results - %EL
Room Temperature EL
Red = Westinghouse data sets obtained from miniature tensile specimens and DIC/AVE
Room Temperature EL, %
100
50
0
30
40
57
63
30
48
43
Conventional 316L
AM 316L
Spec A479 Min
Spec A240 Min
CMTR
Unirrad
Spec F3184 Min
Unirrad
Irrad
Specification Minimums, CMTR Value or Miniature Tensile Test Results
RA not shown here but is provided in our paper, AM values are in the range of 75-77% (measured via SEM fractographic images)
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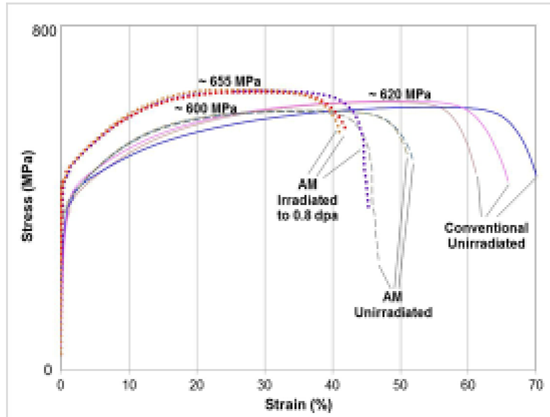
24

Examples of Stress Strain Curves

- Good reproducibility
- Unirradiated conventional
  - highest strain to failure of ~60-70%
  - maximum stress of ~620 MPa
- Unirradiated AM 316L
  - lower strain at fracture values of ~48-52%
  - slightly lower maximum stress of ~600 MPa
- Irradiated AM 316L
  - further decrease in strain to ~40-45%
  - increase in maximum stress to ~655 MPa



Stress strain curves for nine miniature specimens tested at room temperature

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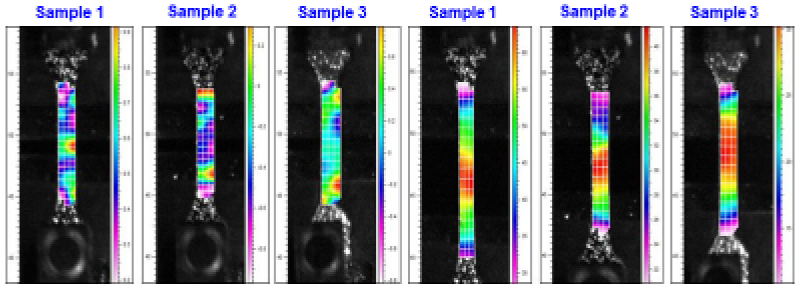
Examples of DIC Axial Strain Distribution Maps

- Maps at 345 MPa (50 ksi) and UTS
- Note speckled grip ends can be seen in most images
- Maps at same dimensional scale but not same strain scale

Sample 1 | Sample 2 | Sample 3 | Sample 1 | Sample 2 | Sample 3



Unirradiated Conventional | Unirradiated AM | Irradiated AM | Unirradiated Conventional | Unirradiated AM | Irradiated AM

605 MPa EL = 68.3% | 599 MPa EL = 47.6% | 649 MPa EL = 45.3%

← At 345 MPa → ← At UTS →

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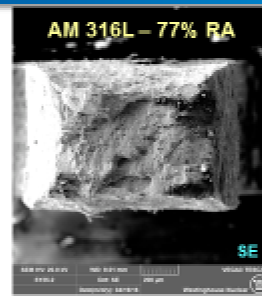
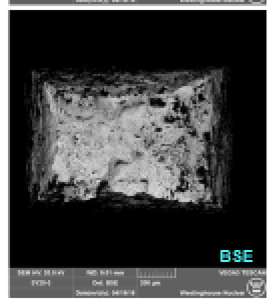
Summary and Conclusions - 1

General Observations

- Highly activated miniature tensile specimens successfully tested in-cell utilizing custom designed and fabricated specimen holder and DIC/AVE
- Total of 46 conventional and AM 316L specimens tested at both room temperature and 300°C (572°F)
- Results obtained are encouraging - work continues towards development of AM technologies for fuel-related components
  - including testing of higher damage dose materials in 2017-2019
- Significant near term goal: fabrication and delivery of lead test component to Westinghouse nuclear utility customer for in-reactor insertion
- Tensile test data from Z direction is needed
- Data sets show relatively low standard deviations





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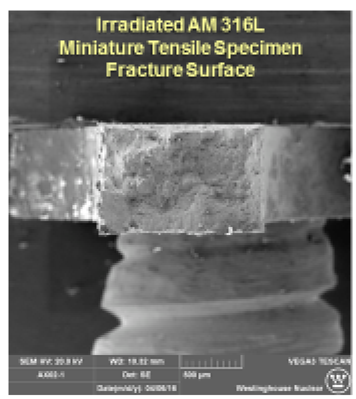
Summary and Conclusions - 2

Room Temperature Tensile Results

- Unirradiated and irradiated AM 316L tensile properties exceed ASTM AM 316L specifications, and generally significantly exceed minimum property requirements
- Unirradiated AM 316L (compared to conventional 316L)
  - UTS value nearly identical
  - YS higher by approximately 75 MPa
  - EL and RA lower by ~8-15%
- Irradiated AM 316L (compared to unirradiated AM 316L)
  - UTS and YS higher by ~50 MPa and 70 MPa, respectively
  - EL and RA lower by ~2-5%

Elevated Temperature Tensile Results

- Unirradiated AM 316L UTS essentially identical to conventional 316L
- Irradiated AM 316L UTS higher than unirradiated AM 316L by ~45 MPa



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Acknowledgements

- Westinghouse Nuclear Fuels, and specifically Mr. Zeses Karoutas, Chief Engineer, for his unwavering support of this work
- Westinghouse Supply Chain Management for their outstanding assistance
- Mr. Gordon Kohse of MIT for exceptional assistance regarding irradiation of test specimens
- Mr. Jason Boyle of Westinghouse Hot Cell Facility for excellent work performing the tensile tests
- Westinghouse Hot Cell technicians and Radiation Safety Officer for outstanding laboratory evaluations and radiological support

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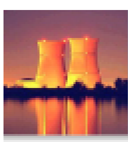
4.13 Additive Manufacturing for Nuclear Components (George Pabis and Craig Gramlich, Novatech)



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Additive Manufacturing for Nuclear Components

George Pabis
Craig Gramlich

November 28, 2017

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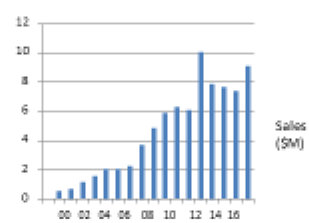
Agenda

- NovaTech Overview
- Additive Manufacturing (AM) Technology Overview
- Ideology
- Accomplishments
- Results
- Future Tasks

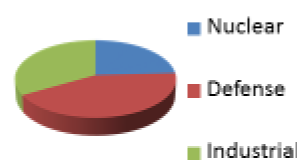
NOVATECH

OVERVIEW – General Information

- Founded in 1994, NovaTech is located in Lynchburg, Virginia
- 35 Employees, 27,500 ft² Facility
- Sales of \$9.3 M (2016), Small Business Classification, S-Corporation
- Quality Assurance Program Compliant with ASME NQA-1 and 10CFR50 App. B
- Registered with US Dept. of State (ITAR) and US/Canada Joint Certification Office



Sales



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NUCLEAR – Engineering

Our Services Includes All Aspects Of Nuclear Engineering: From Space Reactors To Commercial Plants

- NSSS Engineering
- Commercial Reactors Design and Analysis
- Criticality Safety Analysis
- Control Component Design and Analysis
- Reactor Internals Design, Inspection, and Repair
- Quality Assurance Support
- Steam Generator Services
- Fuel Element Consolidation
- Fuel Assembly (Design, Analysis, and Development)
- New Fuel Transport / Shipping Containers

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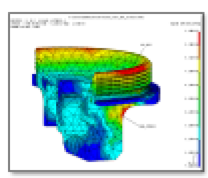
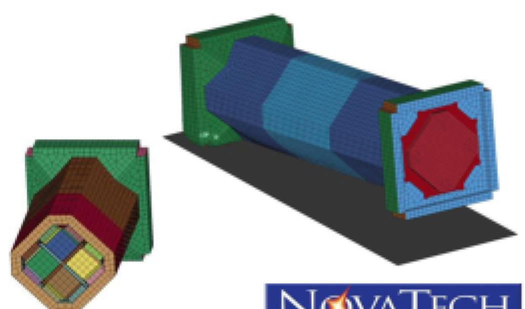
NUCLEAR – Engineering

FINITE ELEMENT ANALYSIS

- Software
  - ANSYS®, LS-DYNA®, and SDRC I-DEAS® and Run Locally
  - NASTRAN®, FEMAP®, and COSMOS® Trained Personnel
- Static, Dynamic, Buckling, Transient
- Thermo-Mechanical and Fluid-Mechanical Interactions





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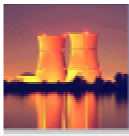

NUCLEAR – Engineering

PACKAGE DESIGN

- New Package Design (Traveller, BWR, SMR Package, MAP-13)
  - NovaTech contracted for $7M+ since 2001 and continuing today
  - Conceptual Trade Studies
  - Structural and Mechanical Design, Analysis, and Drafting
  - Manufacturing Studies
  - Project Management (NT Engineers led the design team and testing efforts)
  - Licensing support and SAR preparation
  - Led the Regulatory Testing (both Drop and Burn)
  - Transport and Tie-down equipment
  - Conveyance modifications
  - Custom enclosures and Packaging
  - Generating responses to US and international RAI's

Fresh Fuel Shipping Packages is a Core Competency – from clean sheet design to service, inspections and maintenance

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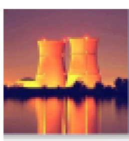
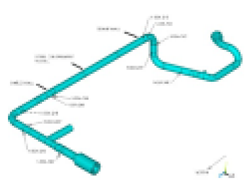
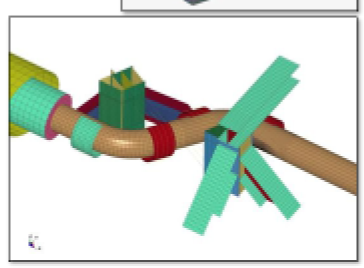


NUCLEAR – Engineering

PIPE WHIP ANALYSIS

- Whip restraint design for all postulated break scenarios
- Interfaced with design team to determine correct placement of restraints
- Pipe sizes from 3" to 36" diameter
- Up to 2250 psi
- Actions:
  - Analysis and modeling LS-DYNA & ANSYS
  - Calc note preparation & verification





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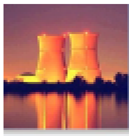

NUCLEAR – Engineering

SMALL MODULAR REACTOR SYSTEM DESIGN

- Contract lasted 4 years
- Support the initial design studies beginning in 2008
  - Provided conceptual and preliminary design
  - Safety and support system design, analyses and documentation
  - Fuel mechanical design and testing
  - Fabrication and testing of fuel assembly and CRA prototypes
  - Component design and seismic analyses
  - Provided economic assessment for non-electric power applications
  - Provided design support for non-utility applications
  - NRC technical briefings during pre-application
  - Technical and topical reports
  - Drafting DCD sections
  - Review of specific licensing issues (10 CFR 50.62, 10 CFR 50.54(hh)(2), EA-12-049, etc)

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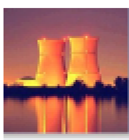
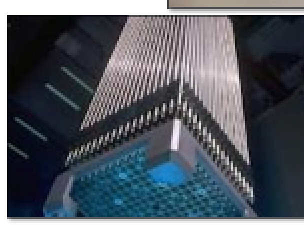


NUCLEAR – Engineering

FUEL DESIGN

- Contract lasted 2 years
- Varied from 5-10 engineers
- Work preformed remotely at NovaTech but travelled to support testing and meetings
- Work included
  - Design and analysis of skeleton
  - control rod assemblies
  - axial power shaping rods
  - burnable poison rods
  - primary and secondary neutron sources
- Generated and checked production drawings
- Supported the final design review.



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NUCLEAR – Design & Build

LIFT BEAMS

- Design
  - Complete design packet
  - Full Structural Analysis
  - NUREG Requirements
  - ANSI N14.6, 1978
- Manufacturing
  - NQA-1
  - Material Certs
  - Charpy testing
  - AWS Certified welders
  - Complete Data Pack provided
- Load Testing
  - Test Process Plan
  - NDT Pre and Post load testing
  - NIST calibrated dynos
  - Experience up to 450,000 lb.

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NUCLEAR – Design & Build

UPENDING EQUIPMENT

- Design
  - Up to 50,000 pound load
  - No overhead crane required
  - Hydraulic and electric
  - Pendent control
  - Carbon steel construction
  - Optional storage containers
- Manufacturing
  - NQA-1
  - AWS Welding
  - 125% Load testing
  - Functional testing
  - Complete Data Pack provided
  - Operational Manual

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NUCLEAR – Design & Build

AUXILLIARY WORK PLATFORMS

- Design
  - Complete design packet
  - Full Structural Analysis
  - Powered and non-powered
  - Monorail and Jib Crane incorporated
  - Welded aluminum construction
  - Units can be anodized
  - OSHA compliant railings with toe plates
  - Sectioned assembly or continuous span
  - Seismic analysis can be provided

- Manufacturing
  - NQA-1
  - Material Certs
  - AWS Certified welders
  - Complete Data Pack provided
- Load Testing
  - Test Process Plan
  - NDT Post load testing
  - Deflection requirements checked

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MAJOR CUSTOMER LIST

- Aerojet
- American Ordnance
- AREVA
- BWXT
- BAE Systems
- Battelle Memorial Lab.
- Cadence Medical
- Day & Zimmermann
- DE Technologies
- Department of Defense
- Department of Energy
- Dominion Power
- Duke Energy
- EPRI
- Flowserve
- TVA
- NASA
- Nuclear Fuel Services
- NuScale
- Sandia National Lab.
- Savannah River Company
- Siemens Energy
- Southern Company
- TerraPower
- US Army – ARDEC
- Vagts Engineering Inc.
- Westinghouse Electric

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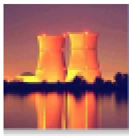
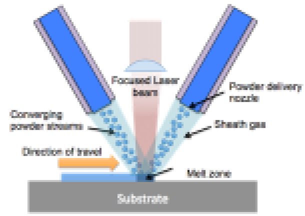
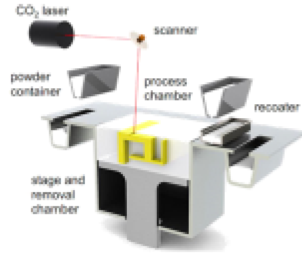


AM Overview

- Plastic
- Metallic (SLS, DMLS, SLM)
  - Powder Bed
    - Laser sintered layers of atomized material
  - Direct Deposition
    - Powder Fed
    - Wire Fed
  - Hybrid
    - Direct Deposition + Iterative CNC machining





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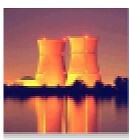

Ideology

- Use 3D Printing as if it was a common tool
- Increase component performance
  - Debris Capture
  - Pressure Drop
  - Spring Rates
- Design geometries that were formerly not manufacturable
  - Fuel Rod Locking
  - Torturous Path
- Part Consolidation

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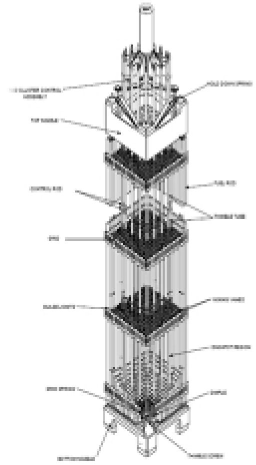
Ideology

- Start with components that have commercially available powder materials (Stainless Steel and Inconel)
  - Top & Bottom Nozzles
  - Holddown Springs
- Define design requirements
- Rapidly fabricate prototypes that show potential based on analysis
- Test designs



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Accomplishments

- Won Phase I and Phase II SBIR contracts to develop bottom nozzles
- Won Phase I SBIR contract to develop holddown springs
- Partnered with AREVA to outfit and test future fuel assembly designs
- 3D printed eight bottom nozzle 5X5 prototypes out of Inconel-718
- Age hardened and inspected Inconel-718 parts
- Designed and fabricated a prototype fuel rod lower end cap
- Successfully tested the fuel rod locking mechanism
- Performed tensile tests, flow tests, and debris filtering tests
- Submitted Technical report summarizing 2016 Phase I Research

Final Technical Report

Preliminary Research into the Viability of 3D Printing Nuclear Fuel Assembly Components

Prepared for

Office of Science, U.S. Department of Energy

Submitted by

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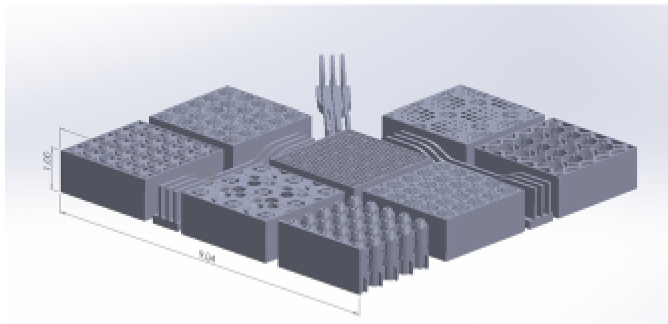
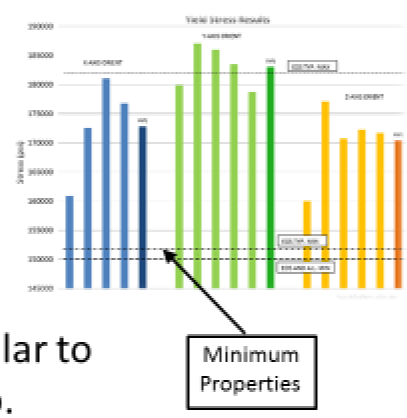
Completed SBIR Work

- Phase I – Bottom Nozzle

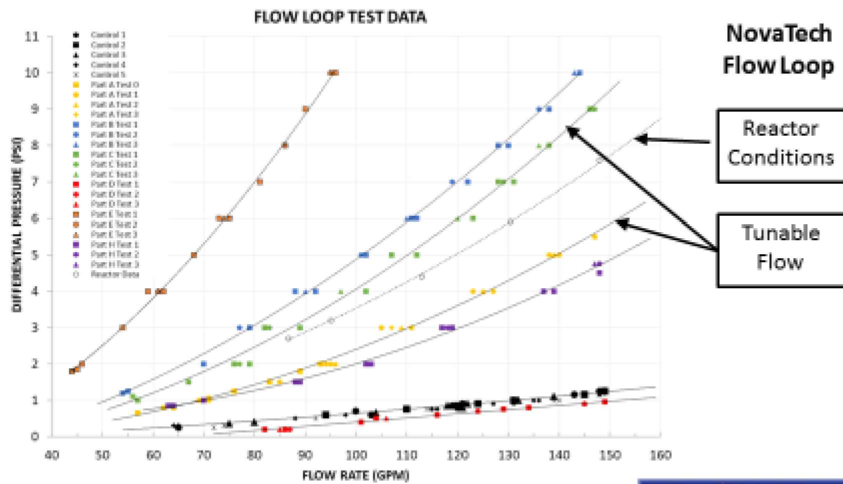


Results – Tensile Tests

- Yield Strength
- Ultimate Strength
- Elongation
- Conclusion: Material properties of 3D printed Inconel-718 are very similar to Inconel-718 bar and strip.



Results – Flow Tests



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Results – Fuel Rod Locking

- Designed to replace the lower end grid
  - Removes lower end grid and a fuel rod failure initiation point
- Integral to the bottom nozzle grillage
  - Allows for longer fuel rod
    - Room for more fuel or plenum volume
- Locks fuel rod axially
- Provides anti-rotation feature
- Reconstitutable
- Designed for internal fuel rod weld
  - Reduced starting Zircaloy barstock diameter to save money
- Designed for single setup machining
  - Lathe turning + wobble broaching
- Successfully tested to 30 lb pull force – no failure

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Results – Debris Tests

- Tested all filter designs twice for debris resistance
- Small holes and torturous paths are the most effective filters
- AM fabricated designs are highly effective at debris filtering

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Current SBIR Work

- Phase I – Holddown Spring
- Phase II – Bottom Nozzle

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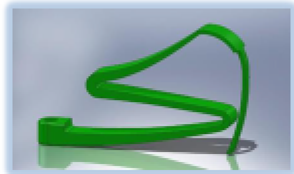
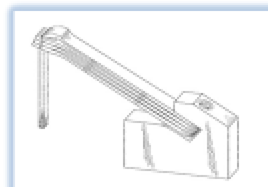
Holddown Spring Design

- 3-Leaf Westinghouse 17x17 spring replacement
- Tunable to different fuel assembly and reactor designs
- Minimize Upper Core Plate wear
- Reduce rework
- Evaluate potential Upper Nozzle / Holddown Spring Design Interface
- Reduce number of parts





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Holddown Spring Testing

- Mechanical Tests at NovaTech
  - Fabricate custom fixtures
  - Load-Deflection
  - Fatigue
- 1,000-hour life and wear testing
  - Coinciding with bottom nozzle life and wear

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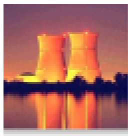

Bottom Nozzle Design

- 17 X 17 Westinghouse Full Size Bottom Nozzle Design
  - Features TBD
    - Debris Filtering
    - Pressure Drop Tuning
    - Fuel Rod Capture
- Material Irradiation Testing

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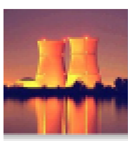

Bottom Nozzle Testing

- 1000 Hour Life and Wear Testing of Design Changes
  - AREVA Facility
  - Full Scale
  - 100% Flow
  - Reactor Temperature
  - Reactor Water Chemistry
- Pressure Drop Testing
- Load-Deflection Testing

NQA-1 COMPLIANT

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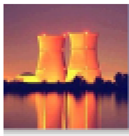

Material Irradiation Testing

- Inconel-718
- Irradiate samples at Oak Ridge National Laboratory
  - HFIR (High Flux Isotope Reactor)
- 60×10^{19} n/cm^2 fluence (~6 dpa)
- Testing on-site at ORNL
  - Tensile Tests
  - Relaxation (TBD)
  - Microstructure (TBD)

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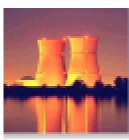

Summary

- NovaTech is excited to be involved with this transformative technology.
- We are using additive manufacturing to fabricate:
  - Bottom Nozzles with debris filtering
  - Bottom Nozzles with tuned pressure drops
  - Bottom Nozzles with fuel rod locking features
  - Top Nozzles with one-piece Holddown Springs
- As we look to the future, we see:
  - More fuel assembly components being additively manufactured
  - Part consolidation
  - Faster fabrication times
  - Reduced costs

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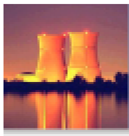
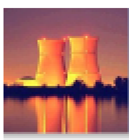
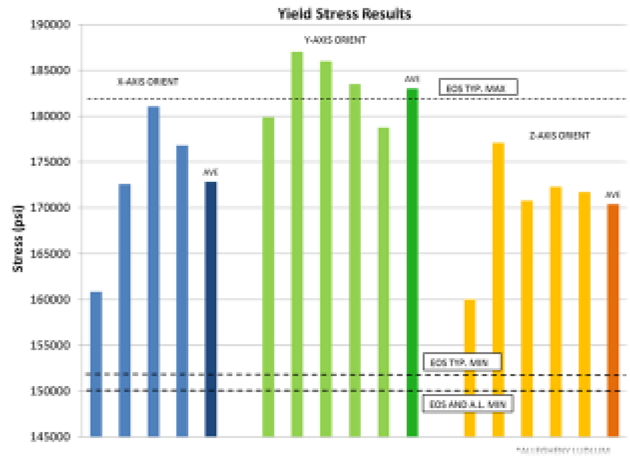


Questions?

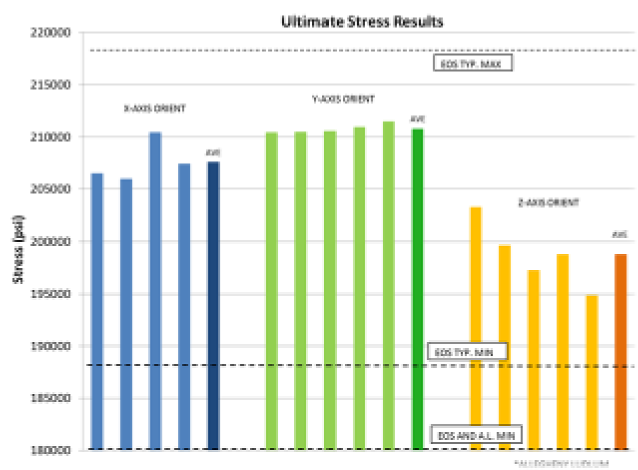


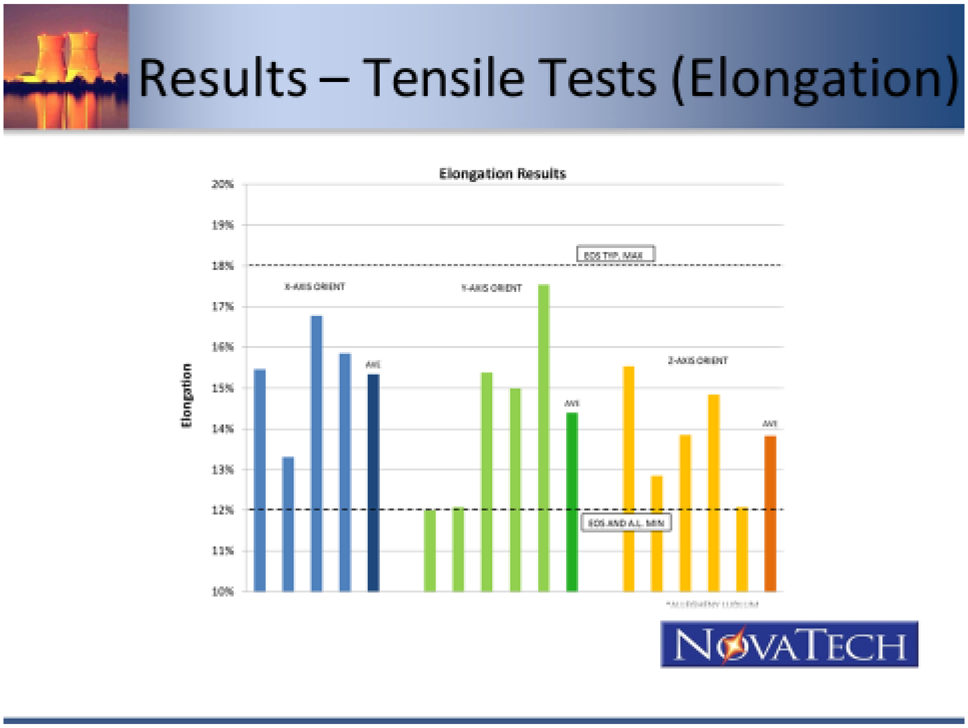
Additional Slides

Results – Tensile Tests (Yield)



Results – Tensile Tests (Ultimate)





4.14 Additive Manufacturing for Reactor Materials and Components (Steven Wolbert, NuScale Power)

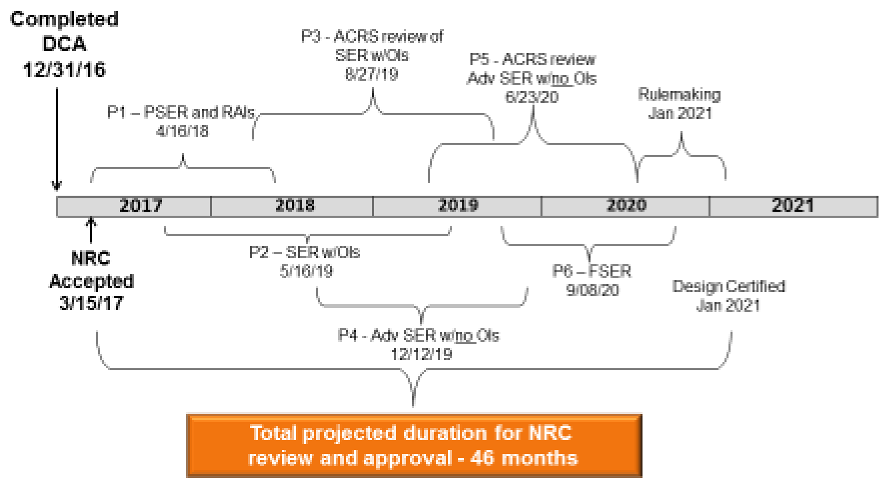
Acknowledgement & Disclaimer

This material is based upon work supported by the Department of Energy under Award Number DE-NE0000633.

Blazing the Trail to Commercialization

Achieving a Successful Review

NuScale Baseline DC Review Schedule



NuScale Supply Chain Characteristics

- Unique—not like a traditional power plant
- Steady-state manufacturing vs. construction job
- Select and develop a set of supplier partners for all NuScale plants, not a bid list for one plant
  - close partnerships are critical
  - pricing models and terms negotiated in advance
  - suppliers are vested in the long term viability of NuScale
  - standard specifications

Supply Chain Focus Areas

- Selection of Fabrication Partners
- Design for Manufacturing, Assembly, Transport
  - Iterative Design (listening to suppliers)
  - Component prototyping
  - Maintain Standardization (GD&T windows, interfaces)
- Sustaining a long term supply chain
- Maintaining focus on the goal of a purpose built factory
- Uniquely positioned to take advantage of advanced manufacturing techniques (shop based fab)

NuScale Nonproprietary

NuScale Power

Manufacturing Related Activities





NuScale Nonproprietary

NuScale Power

Manufacturing Related Activities

Advanced Manufacturing Cooperation

CANM Center for Advanced Nuclear Manufacturing
Operated by Concurrent Technologies Corporation

EPRI ELECTRIC POWER RESEARCH INSTITUTE

NuScale Power

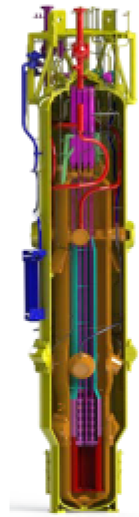
Solutions Through Advanced Technology
MAINSTREAM ENGINEERING

ADDiTEC

NovaTech Innovative Technologies International

Potential Applications for AM in the NPM

- Reactor Vessel Internals
  - HCSG Tube Supports
  - CRDS Supports
  - CRA Cards
  - Fuel Pins
- Integral Safe Ends
- Sub Supplier Components
  - Fuel Assembly
  - Valve Internals
  - Latch Mechanisms



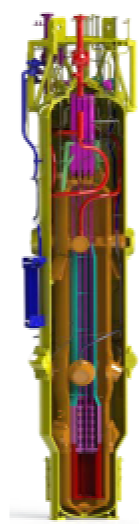
NuScale Nonproprietary

Advanced Manufacturing Mandate

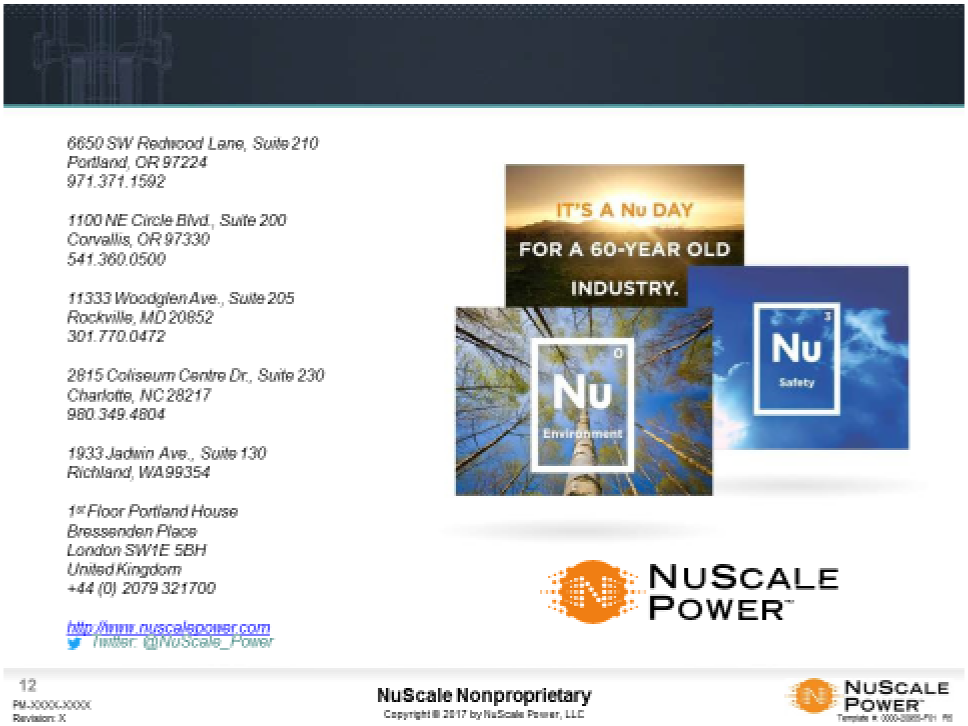
- Does NuScale need advanced manufacturing?
  - Reduced production schedules ✓
  - Reduced module cost ✓
  - Reduced module weight ✓
  - True Nth-of-a-kind production ✓

~~*"That's the way we've always done it"*~~

- What's a NuScale Module look like in 10 years?
  - Traditional forgings
  - PM-HIP complex shapes
  - Additive Manufactured parts
  - Traditional welds
  - Advanced joining techniques
  - Laser clad components



NuScale Nonproprietary



4.15 Metal Additive Manufacturing Innovations (Brian Matthews, AddiTec)

ADDITIVE MANUFACTURING WITH METAL

METAL AM BACKGROUND

FIVE TECHNOLOGIES IN USE

MOST CAPABILITY & DEMAND

ELECTRON BEAM MELTING

Uses electron beam as power source instead of laser.

Melts metal powder layer by layer with electron beam in high vacuum.

Fully melts metal powder creating full density parts.

Can only process one material in a single part.

Limited to small parts.

DIRECT METAL DEPOSITION

Deposits metal powder or wire onto a substrate which is instantly melted using a laser, electron beam or arc process.

Capable of creating functional gradients using multiple materials in the same part.

Can repair existing parts and apply coatings to extend life of new parts.

No inherent limit on the size of parts produced.

DIRECT METAL LASER SINTERING

Uses one or more lasers to sinter powder metal layer by layer in an inert atmosphere.

Fully melts metal powder creating full density parts.

Produces very high resolution parts with intricate details.

Can only process one material in a single part.

Limited to small parts.

BINDER JETTING

Metal powders are bonded with a binding agent and subsequently fused in a sintering furnace, melting the metal into a solid homogeneous mass.

Requires a sintering furnace.

Cannot create full density parts.

Limited to small parts.

INVESTMENT CASTING

Wax pattern is created from a 3D printed mold and filled with molten metal alloy.

Used for prototypes and short production runs.

Expensive process requiring extensive labor compared to alternatives.

Can only process one material in a single part.

Cannot achieve fidelity of other processes.

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PROBLEM

HIGH COST & COMPLEXITY OF METAL AM

CURRENT LIMITATIONS

Current AM systems are very expensive:

- $0.5m to $3.5m for DMD Systems
- $0.5m to $2.5m for DMLS Systems

Generally requires in-depth process knowledge

No custom solutions

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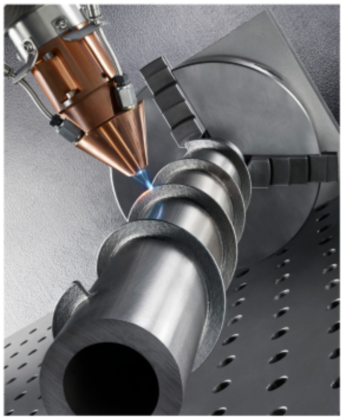
DIRECT METAL DEPOSITION

HIGH COST & COMPLEXITY OF METALAM



DMD BACKGROUND

Several companies offer DMD equipment for commercial applications

- $200k to $400k price range

DMD equipment is typically integrated with industrial robots, gantry systems or CNC mills to create complete DMD systems

- $0.7m to $3.5m price range

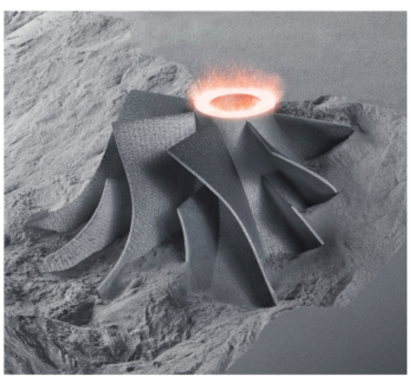
Majority of DMD systems use metal powder. No commercial DMD systems process both metal powder and wire

ADDiTEC ADDITIVE TECHNOLOGIES

4

DIRECT METAL LASER SINTERING

HIGH COST & COMPLEXITY OF METALAM



DMLS BACKGROUND

Several companies offer mature medium-large DMLS systems for commercial applications

- $0.5m to $2.5m price range

Most systems attract expensive maintenance contracts

- $50k to $100k annual fees typical

Most systems require use of only vendor approved powder, increasing consumables cost

ADDiTEC ADDITIVE TECHNOLOGIES

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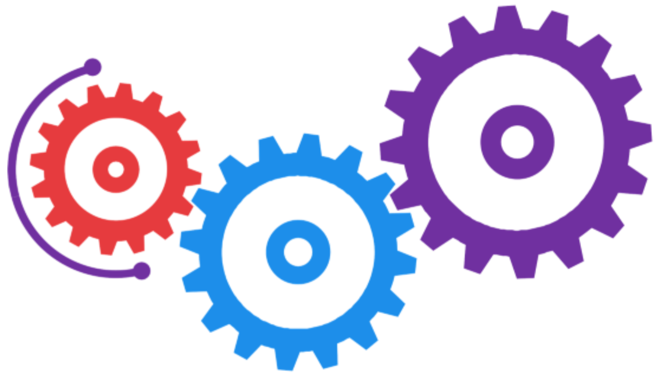
OUR SOLUTION

SYSTEMS – PRODUCTS – SERVICES

OUR VALUE PROPOSITON

- Develop and reduce the cost of advanced DMD and DMLS systems by a factor of >10
- Innovate system design and capabilities
- Mass produce AM parts using ultra-low cost AddiTec AM systems



ADDITEC

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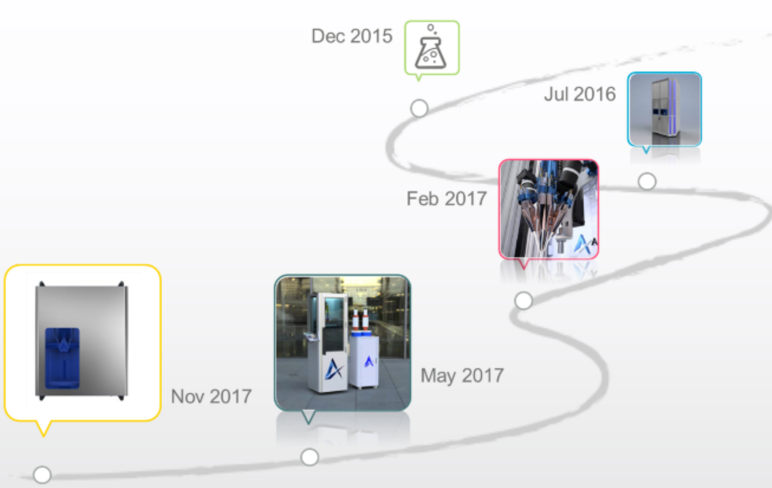
TIMELINE

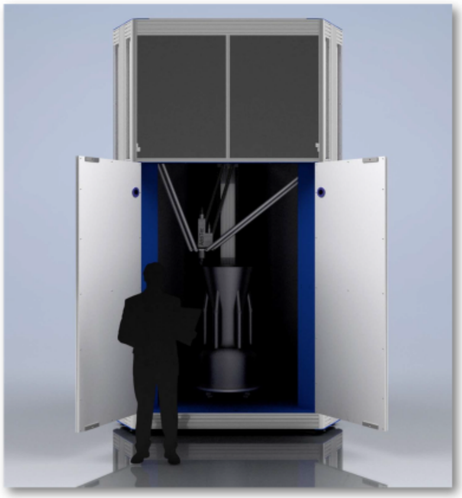
OUR HISTORY



1. Company formed. Established initial team & facilities. Selected DMD technology.
2. Designed, built & commissioned 1st large DMD printer. Established QA programs for Aerospace & Nuclear industries.
3. Started design of an ultra-low cost TriAx 3D system to power 3D printers, hybrid systems & robotic/gantry applications.
4. Unveiled prototype TriAx 3D tech. Started design of office friendly TriAx 3D printer & ultra-low cost DMLS printer.
5. Submitted design concepts for 1st metal printer for the ISS using TriAx 3D tech. Started testing office-friendly TriAx 3D printer & DMLS printer.

DIRECT METAL DEPOSITION

LARGE DIRECT DEPOSITION SYSTEMS



CUSTOM LARGE DMD PRINTER

- Superior build volume - much larger than powder-bed systems:
  - ✓ Up to 12-ft height
  - ✓ Up to 5-ft diameter
- Flexible and scalable platform
- Multi-material capability
- Low operating cost
- Low system cost

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TRIAX 3D MODULE

DIRECT DEPOSITION DEVICE

INNOVATING DMD

q TriAx 3D is an innovative DMD system for 3D printers, CNC Hybrid systems, and robotic/gantry applications

✓ Uses a patent-pending arrangement of multiple off-axis diode lasers and on-axis material feeds

✓ The only commercially available dual mode deposition system allowing use of both metal wire and powder feedstock through a common nozzle

✓ Accommodates multiple material feeds with automatic in-process switching

✓ Sophisticated in-line process control

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TRIAX 3D MODULE

DIRECT DEPOSITION DEVICE

INNOVATING DMD

INTEGRATED CUSTOM DIODE LASERS

ON-BOARD WIRE FEED SYSTEM

- The TriAx 3D module comprises an industrial-grade supply unit and deposition head
  - ✓ The supply unit contains powerful diode lasers, wire feed system, powder feeders, HMI, integrated chiller, PSUs & on-board Nitrogen generator option
  - ✓ The supply unit is connected to the dual-mode deposition head via 10m supply lines
  - ✓ All major components are designed and built in-house
- Internal production costs significantly lower than competing systems, while offering both wire and powder deposition capability, including simultaneous printing of wire and powder using same head

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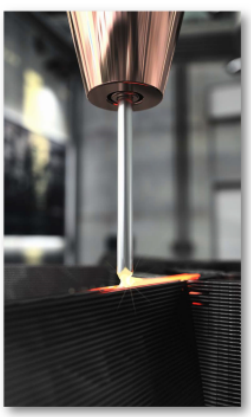
10

TRIAX 3D

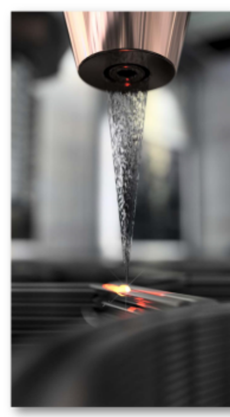
ADVANCED DUAL-MODE DEPOSITION

INNOVATING DMD



WIRE DEPOSITION

- AddiTec is currently testing dual-mode deposition where metal wire and powder feedstock is deposited simultaneously
- ✓ Provides capability to automatically apply coatings to printed parts to improve thermal and corrosion characteristics
- ✓ Allows generation of complex nuclear materials at very low cost (e.g., structures containing neutron absorbing materials)
- ✓ Early results indicate improved deposition efficiency and lower surface roughness



POWDER DEPOSITION

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TRIAX 3D PRINTERS

CUSTOM DMD PRINTERS

INNOVATING DMD

- AddiTec has developed a range of custom 3D printers powered by the TriAx 3D Module
  - ✓ Office-friendly applications afforded by clean and safe wire deposition mode
  - ✓ Custom print envelope
  - ✓ Unique product with no competitor equivalent
  - ✓ Low price point
  - ✓ Attractive product for companies and universities new to AM

ADDITEC 12

TRIAX 3D HYBRID SYSTEMS

HYBRID MANUFACTURING

INNOVATING DMD

- AddiTec offers a wide range of hybrid manufacturing systems powered by the TriAx 3D Module
  - ✓ Customers select from a wide-range of CNC mills
  - ✓ AddiTec performs integration at its facility and delivers the resulting hybrid system to the customer as a fully integrated unit
  - ✓ AddiTec offers high specification hybrid systems starting at two to ten times less than the cost of competing systems
  - ✓ Competing hybrid systems range between $0.7m and 3.5m

ADDITEC 13

TRIAX 3D CUSTOM SOLUTIONS
OTHER APPLICATIONS: ISS

- AddiTec has developed a conceptual design for a custom rack-mounted DMD printer for the International Space Station (ISS)
  - ✓ Currently under consideration by NASA
  - ✓ Uses the AddiTec patent-pending TriAx 3D deposition head
  - ✓ Will allow up to two independent wire feeds facilitating multi-material capabilities
  - ✓ Major design components already proven

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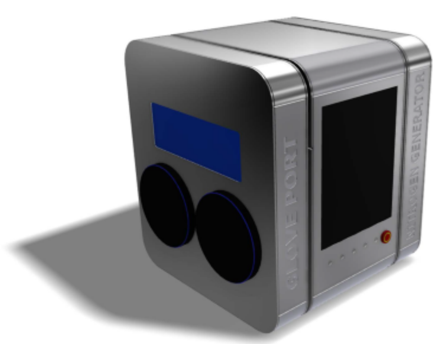
DIRECT METAL LASER SINTERING
ULTRA-LOW COST DMLS

INNOVATING DMLS



- AddiTec is currently testing a prototype DMLS printer, proving the feasibility of ultra-low cost DMLS
  - ✓ Leverages AddiTec Diode Laser technology developed for the TriAx 3D modules
  - ✓ High degree of vertical integration of key components, including custom in-house designed atmosphere control system, chiller, diode laser driver, optical assembly & software
  - ✓ Features integrated glove ports and on-board nitrogen generator
  - ✓ Internal production cost is < 1/10th the price of commercial equivalent systems

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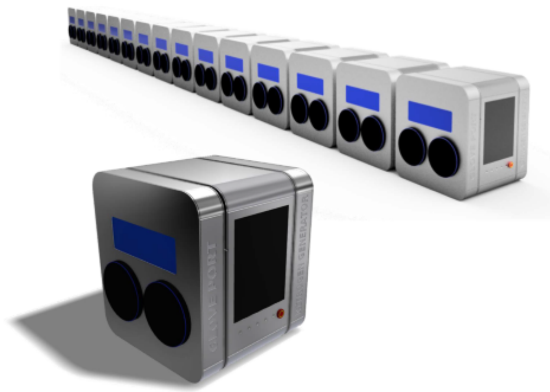
DIRECT METAL LASER SINTERING

ULTRA-LOW COST DMLS



INNOVATING DMLS

- AddiTec is designing a large DMLS printer array that utilizes its ultra-low cost DMLS technology
  - ✓ Each DMLS printer will facilitate automatic production runs via robotic loading and unloading
  - ✓ The array size will be expandable, starting with 10 printers and expanding to 100+ printers
  - ✓ Enables mass production of high value parts at very low cost

CAPABILITIES SUMMARY

4.16 Analysis of Seeded Defects in Laser Additive Manufactured 300M Steel (Shannon Farrell, DRDC)

Defence Research and Development Canada | Recherche et développement pour la défense Canada

Analysis of Seeded Defects in Laser Additive Manufactured 300M Steel

Additive Manufacturing for Reactor Materials and Components
NRC Headquarters, North Bethesda MD
28-29 November 2017

Dr. Shannon Farrell

Department of National Defence,
Defence Research and Development Canada – Atlantic

DRDC | RDDC

Canada

Outline

- Motivation
- Specimens
- Microstructure
- Density
- Traditional Non-Destructive Characterization
    - Radiography
    - Ultrasonics
- Conclusions & Future Work

DRDC | RDDC 1

Importance

- Canada's Department of National Defence is developing AM to reduce cost of maintenance, improve operational readiness
  - Parts-on-demand
  - Repair and refurbishment of legacy parts

- Challenges with respect to integration include
  - Naval materials are not commonly made with AM
  - Acceptance criteria

DRDC | RDDC

Research Goals

1: Establish AM fabrication parameters and post processing treatments to produce metallurgically sound materials

2: Ascertain the quality of AM materials

– limits for conventional non-destructive techniques to identify defects

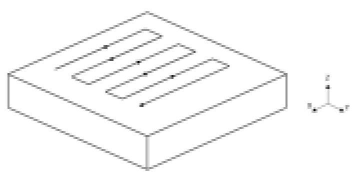
3: Assess mechanical properties, fatigue and performance of AM materials

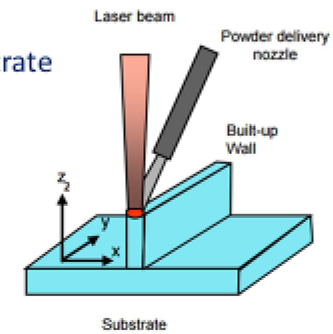
DRDC | RDDC

3

Additive Manufacture

- National Research Council of Canada developed a blown powder laser AM system
  - 500W Lasag Nd:YAG laser coupled with a fibre-optic processing head
  - Pulse mode, average power 200-250 W
  - Powder delivery via Sultz-Metco 9MP feeder at a rate of 8-9 g/min
- Flat specimens, deposited onto steel substrate
  - Built in the Z (through thickness) direction
  - Varied hatch spacing to produce voids





Xue, L. & Islam, M.U., "Free-Form Laser Consolidation for Producing Metallurgically Sound and Functional Components", Journal of Laser Applications, Vol. 12, 2000, pp. 160-165

300M Specimens

- Commercially available 300M powder
  - 300M high strength steel alloy similar to AISI 4340
  - Praxair gas atomized powder with a chemical composition conforming to specifications for wrought 300M steel
  - 16-45 µm powder diameter

C	Ni	Cr	Si	Mn	Mo	V	Fe
0.387	1.98	0.84	1.64	0.86	0.43	0.08	Bal.

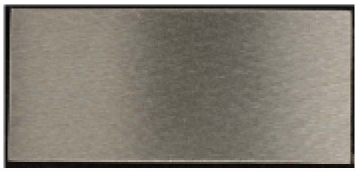
- Six specimens with intentional homogeneously distributed defects
  - Target density of 99%, 97.5%, and 96%

300M Specimens

- Heat treatment
  - Austenized at 871°C for 1 hour & oil quenched
  - Double Tempered at 302°C for 2 hours & air cooled

- Machined and polished
  - 4 machined to 150 mm x 60 mm x 3 mm
  - 2 specimens as built, 150 mm x 60 mm x 4.5 mm
    - With 0.75mm thick full density overlayers

Reference Specimen	Target density (%)	Target defects (%)
A	99	1
B	99	1
C	97.5	2.5
D*	97.5	2.5
E*	96	4
F	96	4



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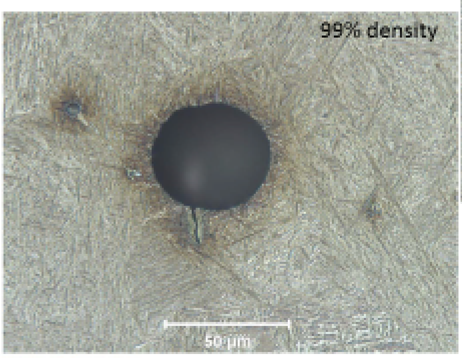
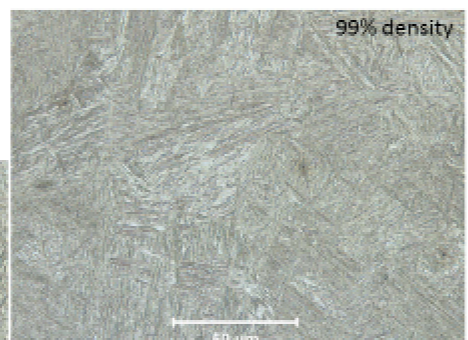
6

Microscopy

- Lath tempered martensite (bainite?) grains with isolated defects
- Spherical pores
  - 5 to 50 µm diameter
  - appear random
  - similar amount in each specimen





- Pores represent residual gases trapped in the powder during manufacture

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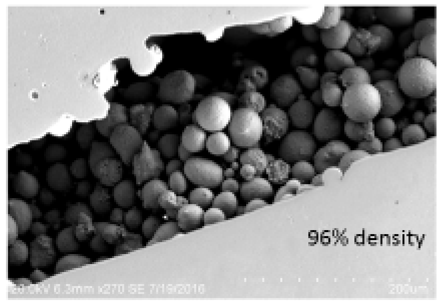
7

Microscopy

- LOF defects propagate in the x-y plane of the build
  - number and size increase as the net density decreases
  - from 500-1000 µm in length

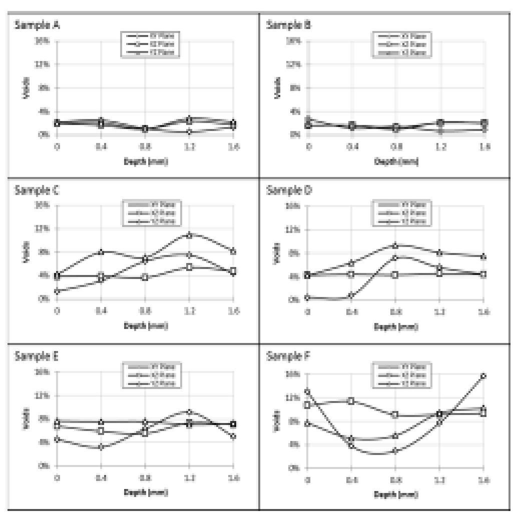
- A typical LOF void with unsintered powder (10-50 µm diameter)
  - voids were larger than gas bubble porosity (5-50 µm)



Microscopy

- Through-thickness density measurements as a function of depth and plane orientation

- More voids within XY plane than the XZ and YZ planes
  - Clear evidence of intentional seeding of defects through modifying of in-layer build parameters (ie. hatch spacing or scan speed)



Microscopy

- Average measured densities from optical microscopy as a function of three planes

Reference Specimen	Target density (%)	Target defects (%)	XY plane		XZ plane		YZ plane	
			Density (%)	St.Dev. (%)	Density (%)	St.Dev. (%)	Density (%)	St.Dev. (%)
A	99	1	98.5%	0.6%	97.5%	1.1%	99.0%	0.2%
B	99	1	98.1%	0.3%	97.8%	1.2%	99.2%	0.1%
C	97.5	2.5	99.9%	1.2%	95.8%	1.0%	97.5%	0.0%
D*	97.5	2.5	97.2%	0.6%	96.2%	0.4%	97.1%	0.1%
E*	96	4	96.8%	0.1%	95.6%	0.4%	95.8%	0.1%
F	96	4	97.7%	0.9%	93.3%	0.8%	95.9%	0.2%

- Specimens D and E were built with a ~0.75mm thick full density outer layer.

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10

Direct dimensioning approaches

- The part densities were calculated from the mass measured with an analytical balance and the volume measured with two surface dimension measurement approaches

- A metrology system (Nikon MMDx 3D laser scanner)

- Mitutoyo coordinate measuring machine (CMM, model #BHN715)

- Results were compared with the average OM results

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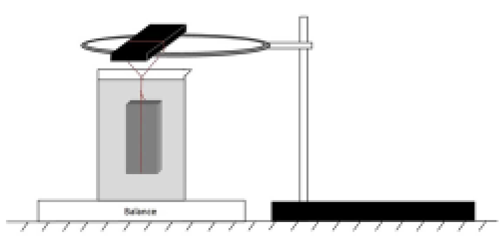
Laser Metrology and CMM

- Both measurement approaches produced unsatisfactory results

Reference Specimen	Target density (%)	Target defects (%)	Metrology		CMM		Microscopy	
			Density (%)	St.Dev. (%)	Density (%)	St.Dev. (%)	Density (%)	St.Dev. (%)
A	99	1	98.5%	0.6%	97.5%	1.1%	98.2%	0.6%
B	99	1	98.1%	0.3%	97.8%	1.2%	98.4%	0.5%
C	97.5	2.5	99.9%	1.2%	95.8%	1.0%	94.5%	2.5%
D*	97.5	2.5	97.2%	0.6%	96.2%	0.4%	94.9%	2.4%
E*	96	4	96.8%	0.1%	95.6%	0.4%	93.5%	1.5%
F	96	4	97.7%	0.9%	93.3%	0.8%	91.3%	3.4%

Archimedes' Principle

- The buoyant force acting on a submerged body is equivalent to the weight of fluid displaced by the body
  - Buoyant force dependent on specimen *volume* rather than *mass*



  - ASTM Standard B311-08: Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity

Archimedes' Principle

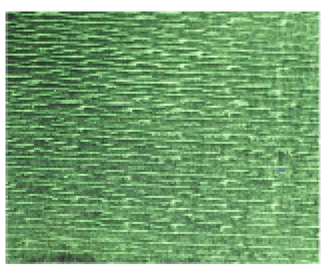
- Measured densities for 300M specimens using Archimedes' principle

Reference Specimen	Target density (%)	Target defects (%)	Deionized Water		Acetone		n-Hexane	
			Density (%)	St.Dev. (%)	Density (%)	St.Dev. (%)	Density (%)	St.Dev. (%)
A	99	1	98.9%	0.2%	98.4%	0.4%	99.0%	0.2%
B	99	1	99.0%	0.1%	98.2%	0.3%	99.2%	0.1%
C	97.5	2.5	97.0%	0.1%	97.0%	0.2%	97.5%	0.0%
D*	97.5	2.5	97.0%	0.1%	96.8%	0.2%	97.1%	0.1%
E*	96	4	95.7%	0.1%	94.8%	0.2%	95.8%	0.1%
F	96	4	95.5%	0.4%	95.2%	0.4%	95.9%	0.2%

- *Specimens D and E were built with a 0.75mm thick full density outer layer

Traditional NDE – Magnetic Particle Inspection

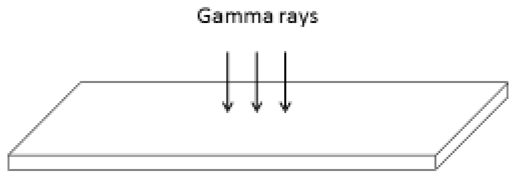
- Application of fluorescent particles (Magnaglo 14AM)
- Surface texture had preferential direction when magnetized
  - Inconsistent over entirety of sample surface
  - No apparent correlation to
    - LAM layering
    - Machining



- Non-conventional electromagnetic techniques will be investigated

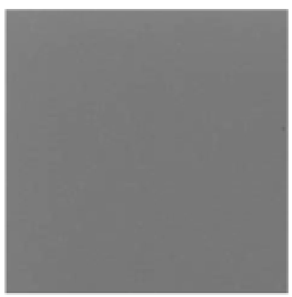
Radiography

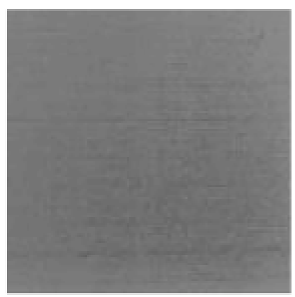
- Irradiated with Ir-192 gamma radiation source
  - Working distance of 20"
  - Radiation time
    - 99% and 96% density specimens: 150 seconds
    - 97.5% density specimens: 210 seconds
  - Reading of around 2.45 on densitometer

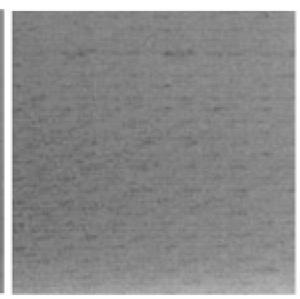


Radiography

- No visible indications for 99% density specimens
- Elongated indications visible for 97.5 and 95% density specimens


Specimen A, 99% density


Specimen C, 97.5% density


Specimen E, 95.8% density

- The LOF defects (~500-1000 µm) were visible
- Suggests a detection threshold between 99 and 97.5% density

Ultrasonic testing

- Researchers have identified relationships between UT signals (e.g., pulse-echo, through-transmission, and immersion) and porosity

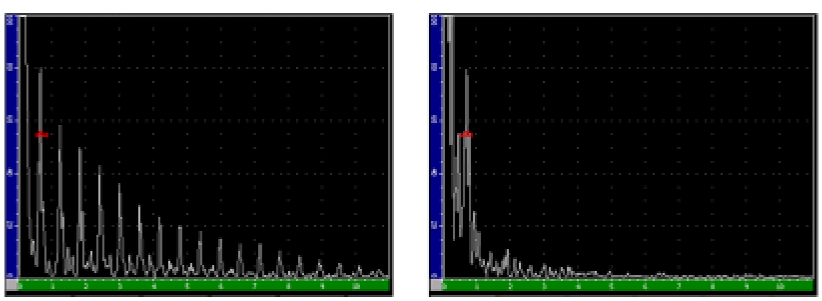
- Slotwinski and Garboczi (2013) had described a linear relationship between the UT pulse-echo velocity and density up to ~99.5%

Slotwinski, J.A. and Garboczi, E.J., "Porosity of Additive Manufacturing Parts for Process Monitoring", *Proceedings of the 40th Review of Progress in Quantitative Non-Destructive Evaluation*, Baltimore, MD, July 22-26, 2013, pp. 1581-1589.

DRDC | RDDC

Ultrasonic testing

- Traces of the ultrasonic transmission backwall reflections of wrought 300M steel (left) and specimen A with 99% density (right)

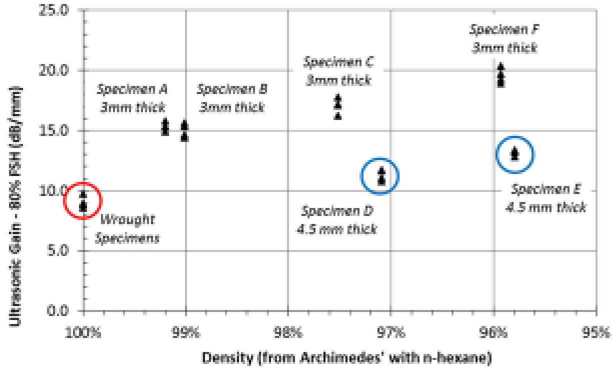


- Wrought specimen shows first seventeen backwall reflections
- 99% density specimen shows a dampening of all but the first backwall reflection

DRDC | RDDC

Ultrasonic testing

- Standardized ultrasonic gain at 80% full screen height (FSH) vs density



- A clear upward trend of increasing gain with decrease in density for similarly-sized specimens

DRDC | RDDC

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Ultrasonic testing

- Average gain to reach 80% FSH for 4.5mm is less than 3mm specimens

- Unclear whether this decrease represents a surface sensitivity of the ultrasonic gain or a sample thickness effect

- More work is needed

DRDC | RDDC

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Conclusions

1. Densification of 300M steel specimens was controlled through modification of LAM fabrication parameters
   - Specimens appeared to have a threshold limit of porosity

2. The Archimedes' principle was shown to be an effective tool for simple, rapid assessment of bulk density

3. Radiography was capable of seeing the 500-1000 µm defects in the 97.5% density specimens

4. UT ultrasonic gain is promising for estimation of through thickness density in LAM materials

DRDC | RDDC

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Current / Future Work

1. Fabrication of 14 specimens over the 100-98% density range
   - Examine sensitivity threshold of UT and RT
   - Examine electromagnetic techniques
   - Computed tomography

DRDC | RDDC

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Acknowledgements

- My co-authors;
  - J. Deering, A. Nolting and K. Avery of Defence Research and Development Canada
  - L. Xue, National Research Council Canada

- Specials thanks to:
  - Nancy Herve
  - Scott Sanford

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Defence Research and Development Canada | Recherche et développement pour la défense Canada

DRDC | RDDC

SCIENCE, TECHNOLOGY AND KNOWLEDGE FOR CANADA'S DEFENCE AND SECURITY

SCIENCE, TECHNOLOGIE ET SAVOIR POUR LA DÉFENSE ET LA SÉCURITÉ DU CANADA

Canada

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4.17 Rolls-Royce Nuclear Developments in AM (Dave Poole, Rolls-Royce)

Rolls-Royce Nuclear Developments in AM
Presentation to the USA Nuclear Regulatory Commission – Nov 2017
Version 2.0

Dave Poole CEng MIET
Chief of Commodity
Additive Manufacturing
Rolls-Royce plc

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RAY-AH-62, PO Box 2000, Raynesway, Derby, DE21 7XX

Presentation slides contribution from John Sulley

Trusted to deliver excellence

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Rolls-Royce

Contents

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Rolls-Royce

AM Equipment & Product Introduction

- First Laser Powder Bed Fusion (L-PBF) capability installed in Rolls-Royce Nuclear in 2008 - 200W, 250x250x250mm system
  - Manufacture of rig components
  - Material and parameter development
  - R&T
- Second L-PBF capability installed in 2013 to meet increasing development work volume – 400W, 250x250x320mm system
- Third L-PBF capability installed in 2015 to establish pre-production cell to go from development into production – 400W, 250x250x320mm system
- 4th, 5th and 6th systems installed in 2017 to meet further increase in R-R programme demands
- 7th system planned for 2018
- No AM components in service in pressure boundary applications
- Current focus on material testing and the manufacture of demonstrator units to support Design Report/Safety Justification

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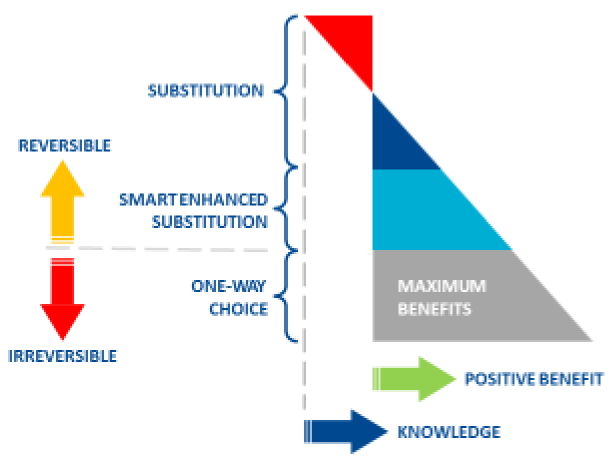
Rolls-Royce

AM Product Introduction



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Rolls-Royce

Lead Applications - General

- Pressure boundary components – various Nuclear systems
- Manual Globe Valves and Piping Tee Fittings
- Stainless Steel
- Direct 'Substitution' – no change to engineering definition
- No 'as-built' surface texture (100% machined or polished)
- Laser Powder Bed Fusion (L-PBF)
- First application (MGV) to be HIPped post AM
- Solution Annealed condition also being developed

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Rolls-Royce

Manual Globe Valve

- Manually operated to open and close to initiate/isolate flow
- Designed to the ASME Code Section III
- Class 1 valve
- Sizes range up to 2"
- Fitted in numerous types of nuclear systems, e.g. coolant make-up, pressure relief
- A high number of valves fitted in each system
- Striving to reduce cost and delivery time in order to satisfy build programmes/customer needs:
  - Convoluted supply chain - raw material, HIPping, machining. Striving for cell manufacture in one facility.
  - Reduce, ideally eliminate HIP cycles – hard facing powder consolidation/HIP bonding of hard facing to main body
  - Reduce, ideally eliminate subtraction machining
  - Reduce amount of raw material usage and waste

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Rolls-Royce

Manual Globe Valve

Rolls-Royce

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Pipework Tee Fittings

- Welded into pipework to provide junctions, e.g. for instrumentation line off-takes
- Designed to the ASME Code Section III
- Class 1 fittings
- Sizes range up to 2"
- Fitted in numerous types of nuclear systems, e.g. coolant make-up, pressure relief
- Eliminating potential for variation and the costs associated in ensuring variation is acceptable:
    - Eliminating hand dressing of the crotch corner - an artisan operation with inherent variability.
    - Must eliminate structural discontinuity, the sharp corners, can't totally eliminate by subtraction machining
    - Reducing the amount of inspection to provide assurance that the crotch corner has been created as required.

Rolls-Royce

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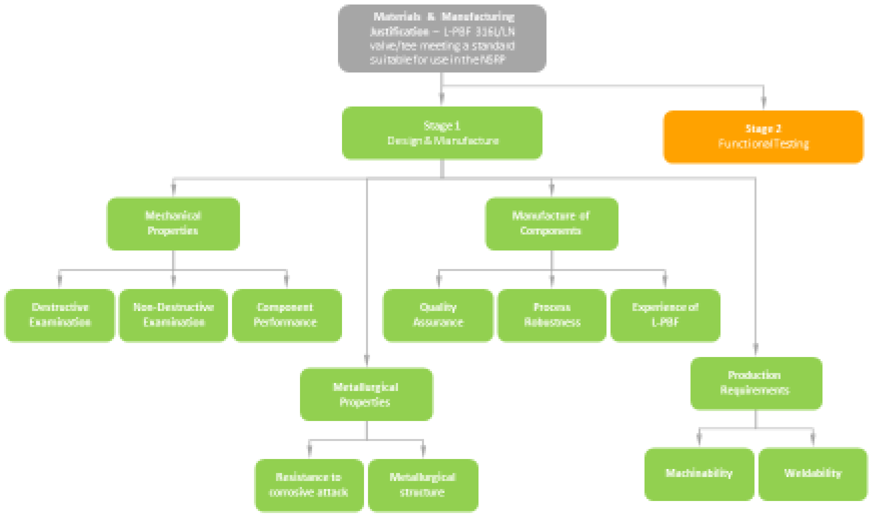
Justification Strategy



Rolls-Royce

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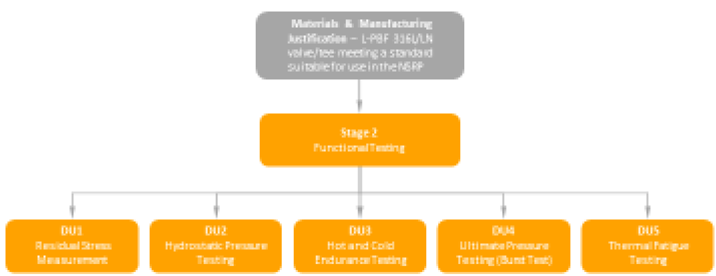
Justification Strategy



Rolls-Royce

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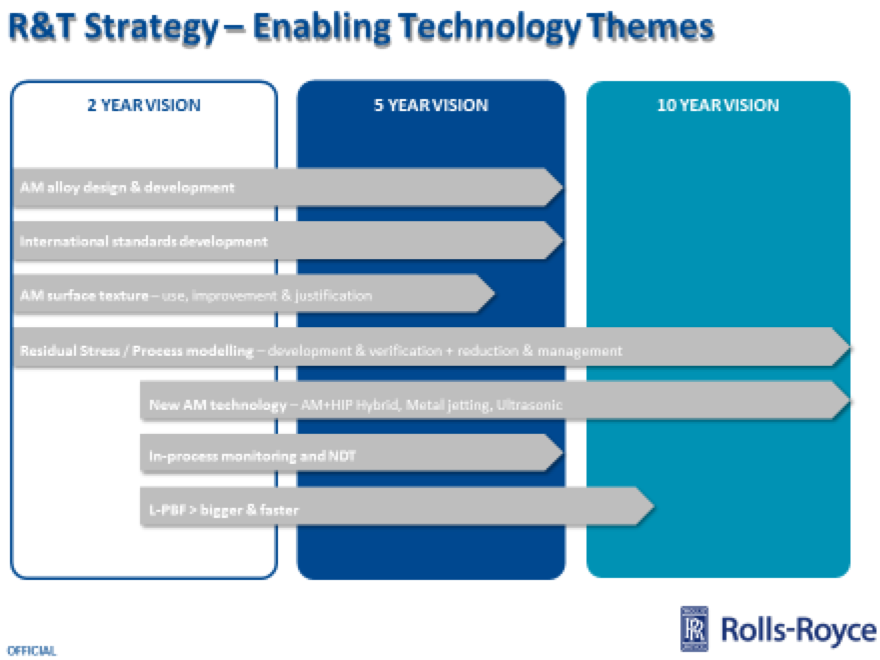


4.18 Additive Manufacturing Initiatives (Alison Hahn, DOE-NE AMM)

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Additive Manufacturing Initiatives

Alison Hahn
Program Manager

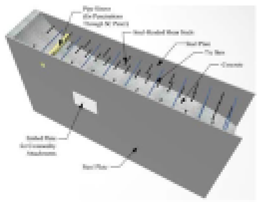
Office of Nuclear Energy
U.S. Department of Energy

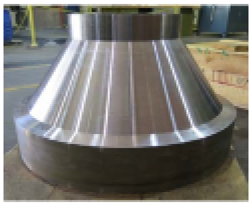
November 29, 2017

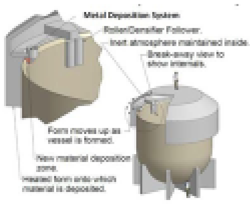
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Advanced Methods for Manufacturing

- **Vision**
  - To improve the methods by which nuclear equipment, components, and plants are manufactured, fabricated, and assembled by utilizing advanced practices including those found in industries such as oil, aircraft, and shipbuilding
- **Goal**
  - To reduce cost and schedule for new nuclear plant construction
  - To make fabrication of nuclear power plant (NPP) components faster, cheaper and more reliable







2

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Current AMM Focus Areas

- Factory and Field Fabrication Techniques
  - High speed, high quality welding technologies
- Assembly and Material Innovation to Enhance Modular Building Techniques
  - Advances and innovation in high strength concrete and rebar
- Advances in Manufacturing Processes
  - **Cladding and surface modification methods**
  - **Additive manufacturing**
- Improved Concrete Inspection, Acceptance and Construction Methods
  - Improved methods to facilitate the curing of concrete
- Data Configuration Management
  - Imaging techniques for as-built design

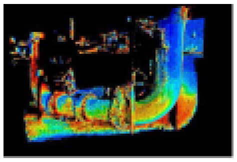


Photo courtesy of TetraVue, Inc.

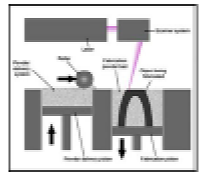
Courtesy of Georgia Institute of Technology

3

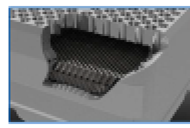
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

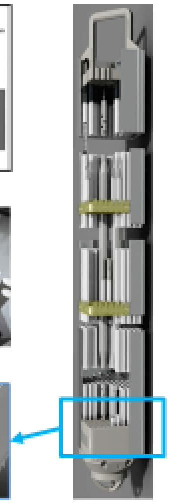
Direct Metal Laser Sintering/Melting

- **Laser Powder Bed**
  - 316L SS
  - Inconel alloys (600, 718, 800)
- **Stress Corrosion Cracking and Corrosion Fatigue are being investigated**
- **Neutron irradiation currently being performed**
- **Strengths:**
  - Can build multiple parts simultaneously
  - Easily fabricate complicated geometries
- **Limitations:**
  - Part size limited by size of chamber
  - Difficult to control microstructure
  - Some heat treatment required



Courtesy of Lockheed Martin





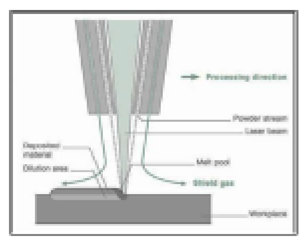
Courtesy of General Electric

4

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Directed Energy Deposition

- **Laser Engineered Net Shaping (LENS)**
  - ODS 316L SS
- **Strengths:**
  - Fabricates large structures
  - Excellent microstructure
- **Limitations:**
  - Difficulty processing complex geometries
  - Requires significant post-processing



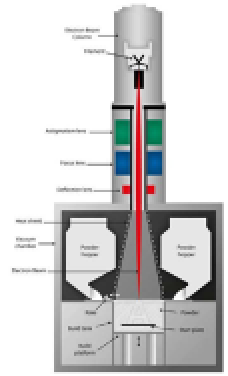
Courtesy of Lockheed Martin

5

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Electron Beam Melting

- **Multi-material components**
  - Ferritic to austenitic steels
- **Ion irradiation was performed in CY 2017**
- **Strengths:**
  - Evacuated processing environment
  - High actual overall power
  - Deflection of beam is possible
- **Limitations:**
  - Part size limited to size of chamber



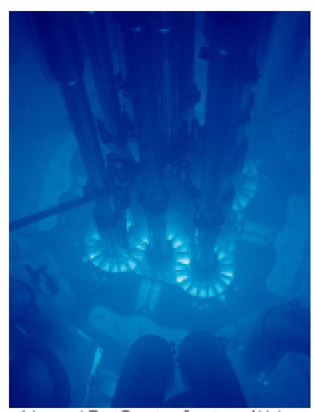
Courtesy of Arcam AB

6

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Irradiation testing

- **Specimens being inserted into the Advanced Test Reactor at the Idaho National Laboratory**
- **Materials being investigated:**
  - 316L SS
  - Inconel 718
- **Potential processes:**
  - Powder Bed Laser Sinter
  - Laser FreeForm
  - E-Beam Wire Fed
  - E-Beam Powder Bed
  - Powder Bed Binder Jet

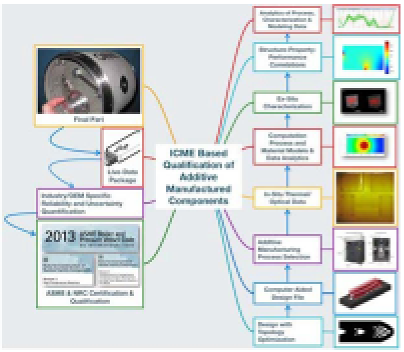


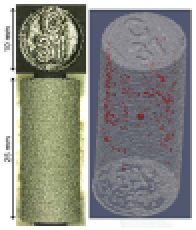
Advanced Test Reactor. Courtesy of Idaho National Laboratory

7

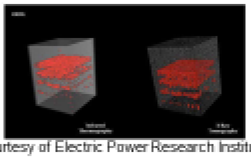
Rapid Qualification for Additive Manufacturing (AM) Processes

- Laser-Based Powder Bed Additive Manufacturing (AM) Processes
- Integrated Computational Materials Engineering (ICME)
- In-situ and ex-situ monitoring:
  - Thermal and optical imaging
  - X-ray and neutron tomography
  - Ultrasonic inspection





Courtesy of Electric Power Research Institute



Courtesy of Electric Power Research Institute

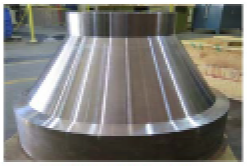
8

Powder Metallurgy/ Hot Isostatic Processing (PM/HIP)

- 316L Stainless Steel has been approved through the ASME Code Cases for use in components such as valves, pump housings, elbows, and flanges
  - Grade 91 has also been approved
- Project also investigated low alloy steels and nickel based alloy
  - SA508
  - Alloy 600M
- Samples expected to be neutron irradiated in FY 2018 at the Advanced Test Reactor at the Idaho National Laboratory

Large 316L SS Valve Body

Steam Separator Inlet Swirler



3700 lb BWR nozzle

9

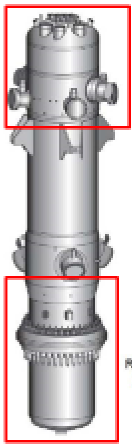
SMR Reactor Pressure Vessel Manufacturing & Fabrication Technology Development

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

- Overall industry goal is to produce a code acceptable SMR Reactor Pressure Vessel (RPV) within 12 months
  - 18 month schedule reduction
  - 40% cost reduction

- R&D project objective is to manufacture the major components for a 2/3 scale (44' long x 6' in diameter) of a NuScale RPV utilizing:
  - **Powder Metallurgy/ Hot Isostatic Processing (PM/HIP)**
  - Electron Beam Welding
  - Diode Laser Cladding
  - Cryogenic Machining

- Partners include EPRI, the UK's Nuclear Advanced Manufacturing Research Center (NAMRC), Carpenter Powder Products, Synertech, TWI, Sheffield Forgemasters, Sperko Engineering and others



Representative Model of NuScale Power Reactor Vessel

10

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Questions?

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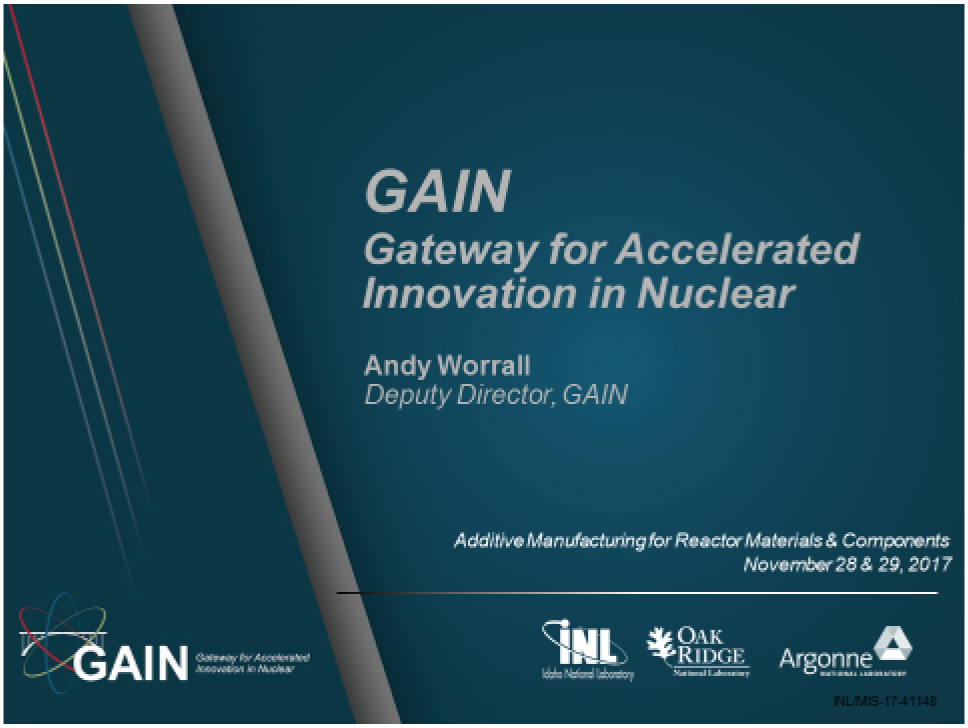
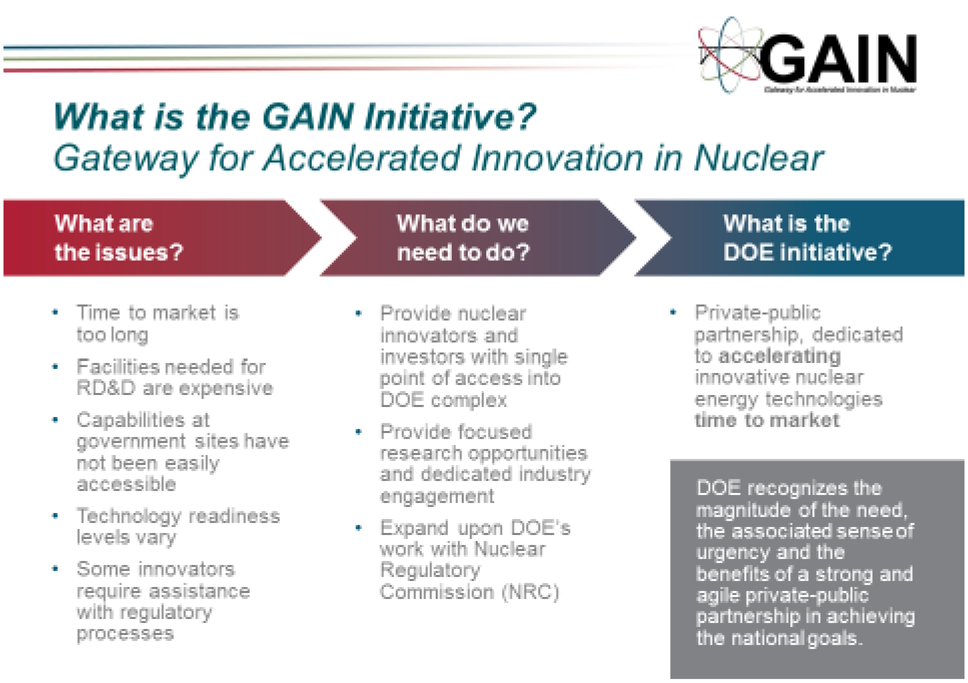
4.19 GAIN Gateway for Accelerated Innovation in Nuclear (Andrew Worrall, ORNL)





GAIN Vision

By 2030,
The U.S. nuclear industry is equipped to lead the world in development of innovative nuclear technologies to supply urgently needed abundant clean energy both domestically and globally.

GAIN is,
A private-public partnership framework aimed at rapid and cost-effective development of innovative nuclear energy technologies towards market readiness.

@GAINnuclear

gain.inl.gov

GAIN Mission

Mission:
Provide the nuclear energy industry with access to technical, regulatory and financial support necessary to move innovative nuclear energy technologies toward *commercialization* in an accelerated and cost-effective fashion

GAIN is:
The organization principle for relevant, federally-funded nuclear energy RD&D programs.

TRISO Fuel Particle

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Where is nuclear innovation needed?

Advanced Reactor Concepts (engineering, licensing, construction, advanced fuels/materials, modular designs, fuel cycle research, etc.)

Components (cables, materials, etc.)

Advanced Methods & Processes

Collaboration (vision driven, trust, learning, etc.)

Safety / Security (Cyber, digitization, control room mods, inspection techniques, passive safety features, etc.)

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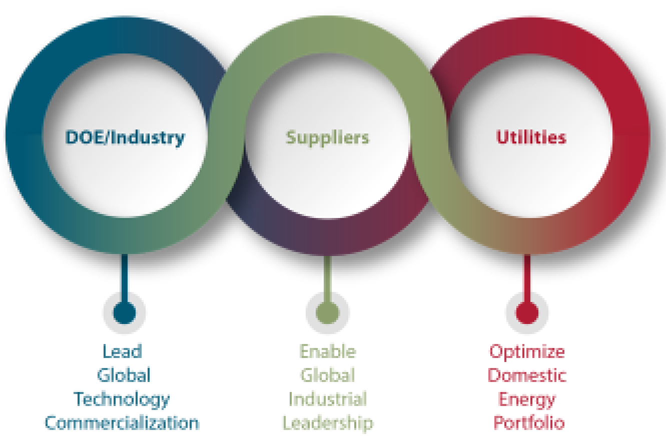
GAIN Initiative: Simultaneous Achievement of Three Strategic Goals

STRATEGIC GOALS



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GAIN: Connecting nuclear innovators to DOE laboratory capabilities and RD&D programs

Modeling & Simulation	Crosscutting Design Support	NRC Interface	Base Reactor and Fuel Cycle R&D Programs	Experimentation
HPC Infrastructure	Nuclear Hybrid Energy	Licensing Framework	Advanced Fuel Cycles	Nuclear Fuels
Verification and Validation	Nuclear Cyber Security	Gradual Risk Reduction	Advanced Reactors	Instrumentation and Sensors
M&S Expertise	Digital I&C Human Factors	Licensing Support Expertise	LW-based Reactors	Materials Science
Reactor physics				Test Reactors

Modeling and Simulation | Expertise | Unique Facilities

Knowledge Management & Integration

– GAIN –

Industry and investor access to DOE capabilities and expertise

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2016 NE Voucher recipients	Proposal	Partner Facility
Creare LLC Hanover, NH	Investigation of Materials for Continuous Casting of Metallic Nuclear Fuel	Idaho National Laboratory
Columbia Basin Consulting Group, LLC Kennewick, WA	Lead-Bismuth Small Modular Reactor (SMR) Licensing Development	Pacific Northwest National Laboratory
Terrestrial Energy USA Ltd. New York, NY	Verification of Molten-Salt Properties at High Temperatures	Argonne National Laboratory
Transatomic Power Corporation Cambridge, MA	Optimization and Assessment of the Neutronics and Fuel Cycle Performance of the Transatomic Power Molten Salt Reactor Design	Oak Ridge National Laboratory
Ceramic Tubular Products Rockville, MD	Robust Silicon Carbide Cladding for LWR Application - Corrosion and Irradiation Proof Test of Low Cost Innovations in MIT Research Reactor	Massachusetts Institute of Technology
Oklo Inc. Sunnyvale, CA	Legacy Metal Fuel Data Exploration for Commercial Scale-Up	Argonne National Laboratory/Idaho National Laboratory
CompRex, LLC De Pere, WI	High Efficiency Heat Exchanger for High Temperature and High Pressure Applications	Argonne National Laboratory
BgtL LLC Laramie, WY	High efficiency and low cost thermal energy storage system	Argonne National Laboratory

GAIN NE Voucher Recipient	Title	Partner Facility
AMS Corp. Knoxville, TN	Radiation Aging of Nuclear Power Plant Components	ORNL
Columbia Basin Consulting Group LLC Kennewick, WA	Methodology for Meeting Containment System Principal Design Criteria for Heavy Metal Fast Reactor Systems	PNNL
DYNAC Systems LLC Del Mar, CA	Dynamic Natural Convection System	INL
Elysium Industries Clifton Park, NY	Synthesis of Molten Chloride Salt Fast Reactor Fuel Salt from Spent Nuclear Fuel	INL / ANL
Fauske & Associates LLC Burr Ridge, IL	Development of an Integrated Mechanistic Source Term Assessment Capability for Lead- and Sodium-Cooled Fast Reactors	ANL
GSE Systems Inc. Sykesville, MD	Human Factors Engineering for the Move to Digital Control Systems – Improved Strategies for Operations	INL
Kairos Power LLC Oakland, CA	NEAMS [Nuclear Energy Advanced Modeling and Simulation] Thermal-Fluids Test Stand for Fluoride-Salt-Cooled, High-Temperature Reactor Development	ANL / INL
MicroNuclear LLC Franklin, TN	Development of the Microscale Nuclear Battery Reactor System	INL
Muons Inc. Batavia, IL	Conversion of Light Water Reactor Spent Nuclear fuel to Fluoride Salt Fuel	ORNL
NuVision Engineering, Inc. Pittsburgh, PA	Evaluation of Power Fluidic Pumping Technology for Molten Salt Reactor Applications	ORNL
Oklo Inc. Sunnyvale, CA	Risk-Informed Mechanistic Source Term Calculations for a Compact Fast Reactor	SNL/ANL
SMR Inventec LLC Camden, NJ	Small Modular Reactor-160 Primary Flow Stability	ORNL
Terrestrial Energy USA Ltd. New York, NY	IMSR® [Integral Molten Salt Reactor] Fuel Salt Property Confirmation: Thermal conductivity and Viscosity	ANL
Transatomic Power Corporation Cambridge, MA	Fuel Salt Characterization	ANL

GAIN
Gateway for Accelerated Innovation in Nuclear

FY 2017 NE Vouchers:

- 41 Letters of Intent
- 32 Voucher requests submitted
- 25 separate small businesses
- 9 "returnees"
- 16 new businesses compared to the 2016 pilot
- ~$4.2M awarded to 14 small businesses

GAIN TECHNOLOGY WORKING GROUPS (TWG)	
Molten Salt Reactor	
Duke Energy	*Charlotte, North Carolina*
Elysium Industries	*Boston, Massachusetts*
Exelon Corporation	*Chicago, Illinois*
Flibe Energy, Inc.	*Huntsville, Alabama*
Southern Company	*Birmingham, Alabama*
TerraPower, LLC	*Bellevue, Washington*
Terrestrial Energy USA Ltd.	*New York, New York*
ThorCon USA	*Stevenson, Washington*
Transatomic Power Corporation	*Cambridge, Massachusetts*
High Temperature Gas Reactor	
AREVA NP, Inc.	*Lynchburg, Virginia*
BWX Technologies, Inc.	*Lynchburg, Virginia*
Duke Energy	*Charlotte, North Carolina*
Kairos Power	*Oakland, California*
StarCore Nuclear	*Montreal, Canada*
X-Energy, LLC	*Greenbelt, Maryland*
Fast Reactor	
Advanced Reactor Concepts, LLC	*Chevy Chase, Maryland*
Columbia Basin Consulting Group, LLC	*Kennewick, Washington*
Duke Energy	*Charlotte, North Carolina*
Elysium Industries	*Boston, Massachusetts*
Exelon Corporation	*Chicago, Illinois*
General Atomics	*San Diego, California*
General Electric-Hitachi	*Wilmington, North Carolina*
Hydromine, Inc.	*New York City, New York*
Oklo, Inc.	*Sunnyvale, California*
Southern Company	*Birmingham, Alabama*
TerraPower, LLC	*Bellevue, Washington*
Westinghouse Electric Co., LLC	*Cranberry Township, Pennsylvania*

Note: GAIN, DOE NTDs, EPRI and NEI participate in all of the TWG teams

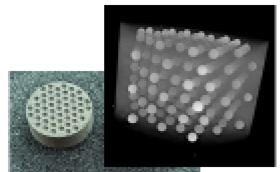
TWGs Solicited for RD&D Needs

- Not all advanced reactor technologies are equally mature, and therefore have different RD&D priorities, as well as material needs

R&D
- Fuels, materials, chemistry
- T-H and safety testing
- Validation of analysis methods
- Advanced modeling & simulation tools

Other
- Vendor development for nuclear grade components
- Reserve of high-assay LEU

- Structures
  - Graphite, ferritic martensitic (HT-9),
- Fuel
  - TRISO, metal (U / U-Pu-Zr), others?
- Cladding
  - SiC composites, FeCrAl
- Components
  - Valves, grids, pipes



K. Terrani (ORNL)

- Demonstration of production, characteristics, and irradiation performance all needed to bring these materials / components to market

Where can GAIN Assist in Additive Manufacturing?

Modeling and Simulation
- *Fundamental (small and macroscale) mod-sim of key phenomena e.g., creep*
- *Materials feedback on performance (neutronics, fuel performance, CFD, chemistry, etc)*
- *Computer-based learning for process optimization & material qualification*

Expertise
- *Material science*
- *Material performance needs*
- *Process development*
- *Material qualification*
- *Licensing*
- *Codes and standards*
- *Experimental design and testing*

Unique Facilities
- *Fuel manufacturing*
- *Material production*
- *Additive manufacturing demonstration facilities*
- *Material properties and characterization*
- *Irradiation testing*
- *Post irradiation examination*

Knowledge Management & Integration
(including business vouchers, TWGs, workshops….)

– GAIN –
Industry and investor access to DOE capabilities and expertise

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GAIN

Nuclear Science User Facilities Provides Access to Unique Facilities Dedicated to Material Science

- Provide irradiation (test reactor), PIE, modeling and simulation
- Co-existence and collaboration with GAIN Initiative
  - GAIN "customers" directed to NSUF as appropriate
  - Advanced nuclear industry needs communicated to NSUF
  - NSUF offers fundamental materials science capability (lower TRL) to support current and advanced reactors
- Awarded Projects on Advanced Manufacturing
  - Enhancing Irradiation Tolerance of Steels via Nanostructuring by Innovative Manufacturing Techniques
  - Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques Irradiation Testing of LWR Additively Manufactured Materials Radiation Effects on Zirconium Alloys Produced by Powder Bed Fusion Additive Manufacturing Processes
  - Additive manufacturing of thermal sensors for in-pile thermal conductivity measurement
  - Radiation Effects on Optical Fiber Sensor Fused Smart Alloy Parts with Graded Alloy Composition Manufactured by Additive Manufacturing Processes

GAIN

Future Activities 2017-2018

Workshops:

- Enabling Advanced Reactors for the Market: March 8-9, 2018
- Molten Salt Reactor Workshop: October 3-4, 2018
- Gap Analysis on Standards and Codes needed for Advanced Reactors
- Follow-on modeling and simulation workshops/demonstrations: TBD
- Advanced Manufacturing: TBD

Database/catalog:

- Develop a list of historical advanced-reactor documents to support knowledge transfer; facilitate access to key documents through OSTI
- Develop and initiate the process to remove AT designation on high priority documents requested by industry

Networking:

- Create directory of advanced nuclear developers

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GAIN
Gateway for Accelerated Innovation in Nuclear

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4.20 AM Qualification Paradigm Similarities for Fuel and Components (Isabella van Rooyen, INL)

Some Content Presented Previously

- CAES Materials Initiative Working Meeting, August 7-8, 2017, Boise State University
- Advanced Manufacturing & Supply Chain Innovation Nuclear Energy Leadership Summit and Showcase, October 3-4, 2017, Idaho Falls, ID
- University of Idaho, October 24, 2017, Idaho Falls, ID
- Energy I-Corps Cohort 6 Graduation 2017, November 14, 2017, Washington DC
- TREAT LEU Conversion Technical Integration Meeting, February 24, 2016
- American Nuclear Society Winter Conference, October 28th – Nov 2nd, 2017, Washington DC

NRC Additive Manufacturing for Reactor Materials & Components, November 29, 2017, NORTH BETHESDA, MD 2

Outline

- Background: Nuclear Fuels and Materials Division
- Applications of Additive Manufacturing in Nuclear Industry
- Benefits of Additive Manufacturing and Technologies
- Example of Conventional Qualification Approach
- Additive Manufacturing Qualification Approach??
- Advanced Manufacturing Research Projects and Selected Results
  - Fabrication of graphite component, UO_2 fuel pellet and UO_2 dispersed in graphite
  - Additive Manufacturing as an Alternative Fabrication technique for Uranium Silicide Fuel
  - Functional Graded Material/Components
- Research Opportunities
- Acknowledgements

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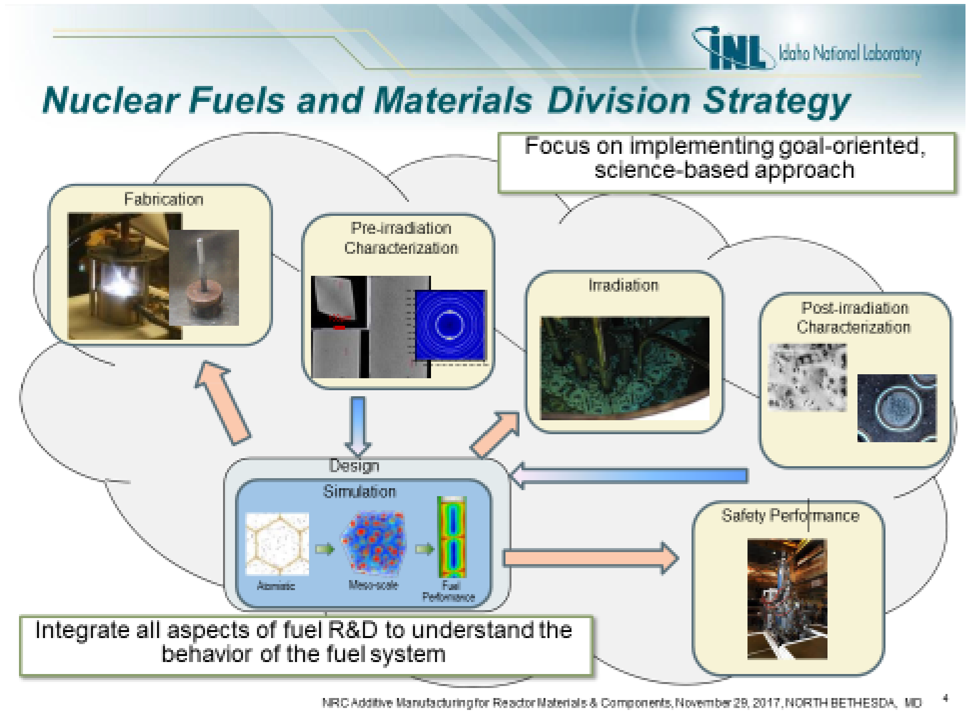
Idaho National Laboratory
Nuclear Fuels and Materials Division Strategy
Focus on implementing goal-oriented, science-based approach
Fabrication
Pre-irradiation Characterization
Irradiation
Post-irradiation Characterization
Design
Simulation
Atomistic
Meso-scale
Fuel Performance
Safety Performance
Integrate all aspects of fuel R&D to understand the behavior of the fuel system
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4


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Applications of "Additive Manufacturing" in Nuclear Industry
Design
Thin-thick
Gradient composition
Integrated systems
Prototyping
Fabrication
Cladding
Welding
Novel Alloy Development
Measurement
Repair
Fuel System
Fuel Container
Structural Parts
Fuel "meat"
Experiment vehicles and components
What is the correct "Additive" process for your product/solution?
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5

Why Additive Manufacturing (AM)?

- ✓ Carefully engineered material properties
- ✓ Repeatable high quality process
- ✓ Reduce
  - Expensive materials
  - Waste
  - Development time & time to market
- ✓ Free complexity
- ✓ Customization
- ✓ Design for function
- ✓ CAD models
- ✓ **Containment of Radiological Material**

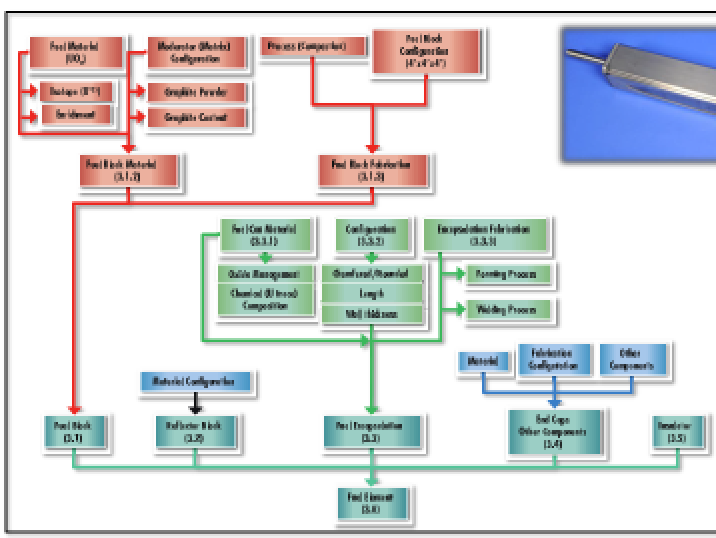
- High Entry Cost
- Powder Supply chain
- Radiologic Controls Paradigm
- Design Paradigm Shift

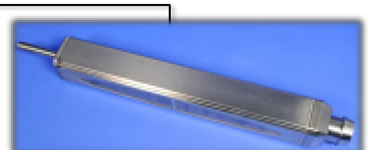
Additive Manufacturing technologies?

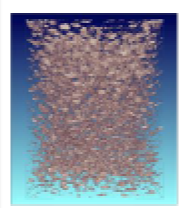
- ✓ Directed Energy Deposition (Powder Feed)
- ✓ Powder Bed Fusion
- ✓ Binder Jet, Aerosol Jet
- ✓ Ultrasonic AM
- ✓ Robocasting or Direct Ink Writing (DIW)

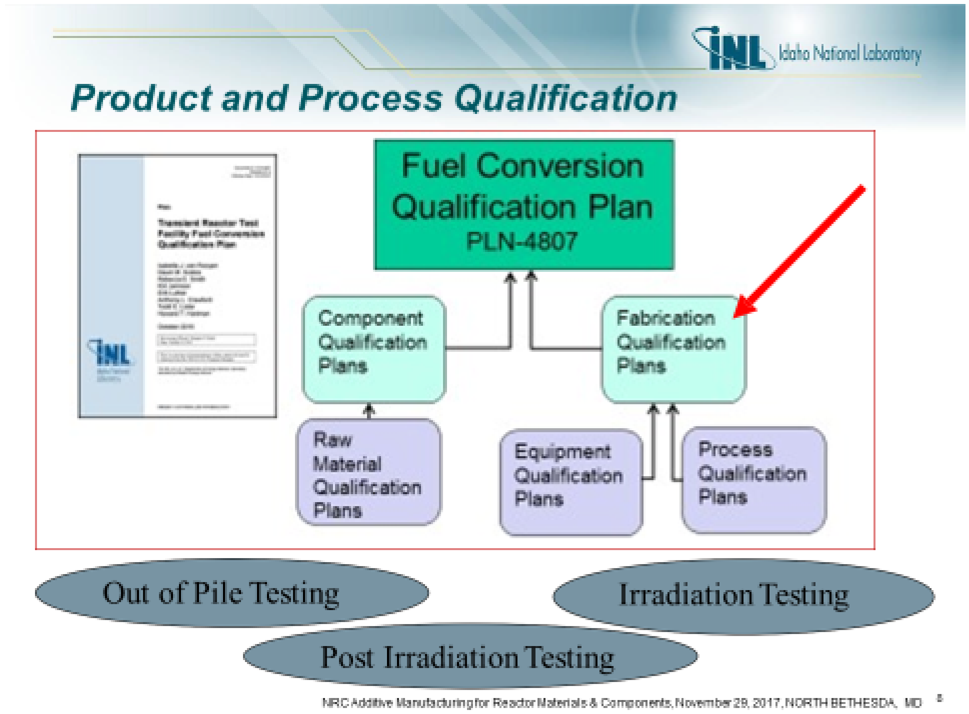
Others

Example of Fuel System Qualification Approach









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Product and Process Qualification
Fuel Conversion Qualification Plan
PLN-4807
Component Qualification Plans
Fabrication Qualification Plans
Raw Material Qualification Plans
Equipment Qualification Plans
Process Qualification Plans
Out of Pile Testing
Irradiation Testing
Post Irradiation Testing
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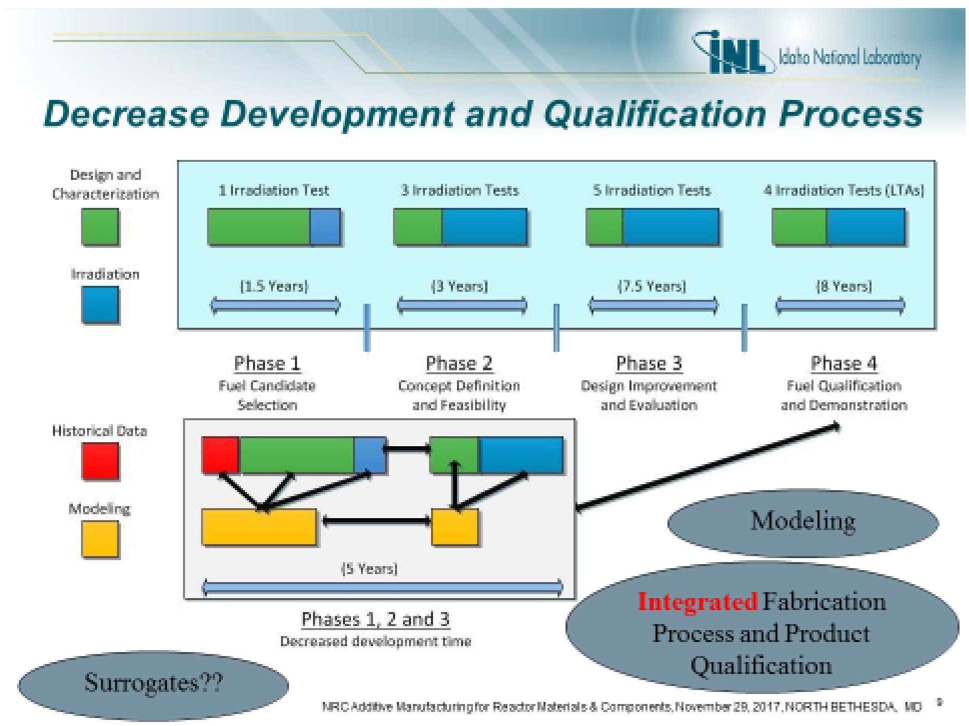

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Decrease Development and Qualification Process
Design and Characterization
Irradiation
1 Irradiation Test
3 Irradiation Tests
5 Irradiation Tests
4 Irradiation Tests (LTAs)
(1.5 Years)
(3 Years)
(7.5 Years)
(8 Years)
Phase 1
Fuel Candidate Selection
Phase 2
Concept Definition and Feasibility
Phase 3
Design Improvement and Evaluation
Phase 4
Fuel Qualification and Demonstration
Historical Data
Modeling
(5 Years)
Phases 1, 2 and 3
Decreased development time
Modeling
Integrated Fabrication Process and Product Qualification
Surrogates??
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Nuclear AM Qualification Approaches??

Fuel

Fuel "Meat":
- Metallic
- Ceramic
- Composite

and

Fuel Clad:
- Metallic
- Ceramic
- Composite

and

Fuel element components:
- Metallic
- Ceramic
- Composite

???

Structural Parts

Material type:
- Metallic
- Ceramic
- Composite

or

Location in Reactor:
- Core
- Low Flux, Temperature
- Gas, Air, Water,
- Fission products

Experiment Vehicles

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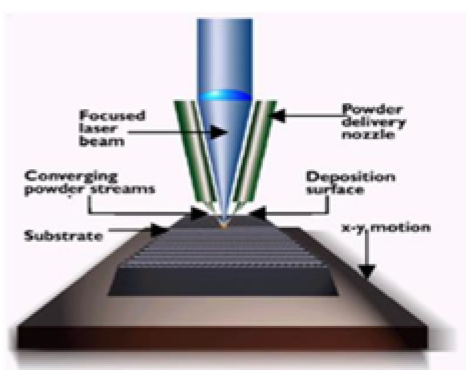
Fabrication Process Parameters for Mechanical - and Property Design



Powder
- Size
- Distribution
- Morphology
- Composition

Laser or EB parameters

Atmosphere

Process
- Speed
- Surface finish
- Properties
- Dimensional
- Raw material
- Availability of facility and powders
- Post fabrication treatment

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Advanced Manufacturing Research Projects and Selected Results

1 — 2015/2016 Funded by TREAT LEU Conversion

- Composite (Graphite-UO_2) Fuel
- UO_2 Pellets
- Graphite components
- Functional graded coatings and fuel components
- Fuel and Clad integrated fabrication

2 — Funded by DOE Commercialization Fund, INL Commercialization, CRADA Westinghouse — U_3Si_2

- Direct Fabrication of U-X fuel using Additive Manufacturing Processes
- Developed Hybrid Additive Manufacturing Technique

3 — Proposal 2018 Funding NEET/NEUP Call

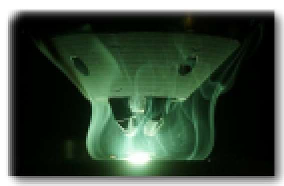
- Functionally Graded Materials

4 — Proposal 2018 Funding NEET/NEUP Call

- Embedded thermocouples in fuel, layers (cladding), fuel clad or structural components using additive manufacturing techniques

1) Fabrication of Graphite component, UO_2 fuel pellet and UO_2 dispersed in Graphite

- Invention disclosure (BA-860): March 2015
- Proof of Principle Surrogate Feasibility: June 2015
- Purchased LENS MR-7: Feb 2016
- Provisional Patent: July 2016
- Patent submitted: July 2017
  (Isabella J van Rooyen, Sean Morrell)



Problem Statement and Novelty

- Increased graphite content improve thermal conductivity and neutronic performance (decreased fuel content): decreased clad temperatures
- LEU fuel designs and fabrication processes, resin additions necessary (both extrusion and compaction processes)

2) Additive Manufacturing as an Alternative Fabrication technique for Uranium Silicide Fuel

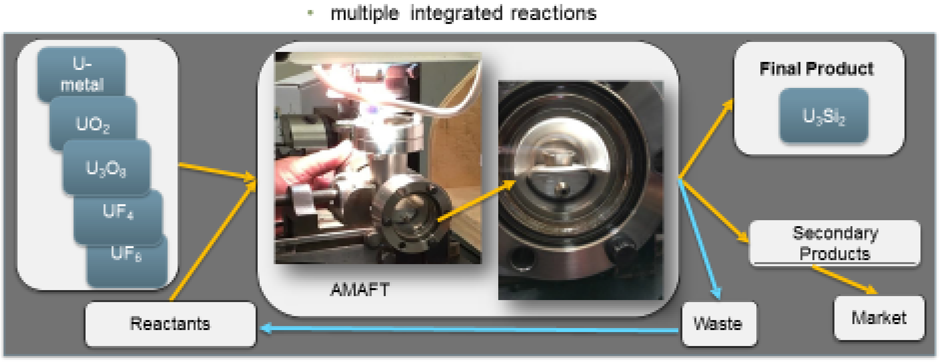
- DOE Technology Commercialization Fund (Awarded July 2016)
- Energy I-Corps Commercialization Fund (Awarded October 2017)
- CRADA with Westinghouse February 2017
- Invention disclosure: BA-894 March 2016,
- Provisional Patent March 2017
- Patent submission in process, November 2017

(Isabella J van Rooyen, Clemente Parga)

AMAFT Technology

AMAFT process: Integrated Modular Additive Manufacturing

- directly transforming various U-based input materials
  - final form accident tolerant nuclear fuel
    - multiple integrated reactions



AMAFT Value Proposition

- Reduce cost of nuclear fuel for fabricators 20%
- End user receives benefits from: Fuel efficiency, reduced operating costs, reduced capital costs

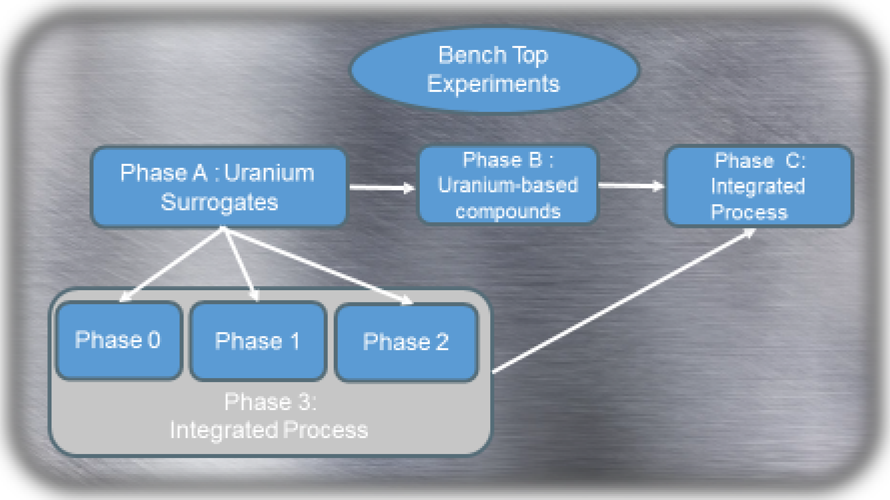
AMAFT Process: Direct Fabrication of U_3Si_2

- Advantages of U_3Si_2
  - High atomic density[1]
  - Improved thermal conductivity[2]
  - Irradiation stability limiting fuel swelling[3]

Property [1]	UO_2	U_3Si_2
Theoretical density (g/cm^3)	10.96	12.2
Theoretical uranium number density (atom/cm^3)	2.44×10^{22}	2.86×10^{22}
Thermal conductivity (W/m K 400–1,200°C)	6–2.5	13–22.3
Melting point (°C)	2,847	1,665

- Conventional method to produce U_3Si_2 — powder metallurgical method
  - Arc melting
  - Challenging to achieve a pure phase (U_3Si, USi, and U_3Si_2)
  - Extensive preparation process with laborious work.

Experiments to Establish Process to Fabricate U_3Si_2



Experiments with U-surrogates

	U_3Si_2	Ce_3Si_2	Zr_3Si_2
Atomic Mass	770.25 [7]	476.5 [11]	329.84 [16]
Crystal Structure	Tetragonal [6]	Tetragonal [11]	Tetragonal [15]
Melting Point (°C)	1665 [5]	1390 [10]	2,325 [14]
Density (g/cm^3)	12.2 [5]	5.96 [10]	5.88 [13]
Enthalpy of Formation @ 25 °C (KJ/mol)	-33.86 [4]	-60.9 [12]	384.56 [8]
Gibbs Free Energy of Formation@ 25 °C (KJ/mol)	-180,121 [4]	-11.1 [12]	*
Heat Capacity (J/mol·K)	150 [5]	*	118.74 [9]

*Data not available

- Ce_3Si_2 and Zr_3Si_2: Crystal Structure
- Ce_3Si_2: Melt point
- Ce_3Si_2 melt congruently like U_3Si_2

- Zr-Si and Ce-Si binary phase diagrams share many similarities with the U-Si: e.g. multiple intermediate phases, multiple eutectic points
- ZrF_4: Thermodynamic stability closely resembles UF_4

Progress on Experiments

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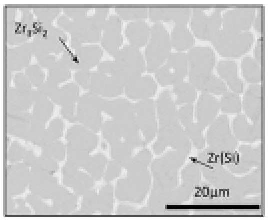
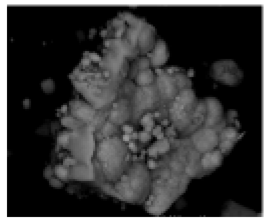
Surrogate

TRL 2

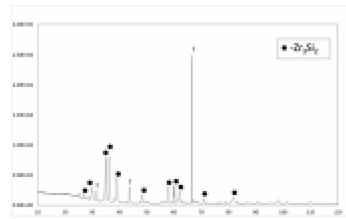
- Phase 0: Objective to verify laser intensity, test experimental set-up
- Phase 1: Successfully formed Zr_3Si_2 by means of laser synthesis
- Phase 2: Direct formation of Zr_3Si_2 by means of laser synthesis
- Phase 3: Planned October 2017 – January 2018



Back-scatter electron micrograph displaying the formation of Zr_3Si_2. Data validated by X-ray diffraction.



Back-scatter electron micrograph displaying the formation of Zr_3Si_2. Data validated by X-ray diffraction.



XRD analysis displaying the formation of Zr_3Si_2 (includes resin mount)

U-based: Planned November/December 2017 – January 2018

TRL 4

AMAFT Current Status and Partnership Needs

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Current status

- Technology Commercialization Fund Topic 1 (2016/2017) will submit Topic 2 in 2018 with Westinghouse
- Converting provisional patent into a non-provisional patent (in process).
- Input into developing INL's rapidly growing advanced manufacturing strategy
- Highlighted other products (included in provisional patent) now being further explored (Zr_3Si_2).
- Invited speaker:
  - Advanced Manufacturing and Supply Chain Innovation Nuclear Energy Leadership Summit and Showcase, October 3–4, 2017, Idaho Falls,
  - University of Idaho, October 24, 2017
  - Lawrence Livermore National Laboratory, 2018
  - Invited by NRC November 2017
- Four Publications

Key partnership needs

- Powder Supplier Collaborator
- Modular Integrated Equipment Manufacturer (Concept to Production Equipment)
- Qualification Process Methodology
- AMAFT Process Modeling & Property Modeling
- Other Advanced Fuel Fabricators

New Collaborators??

AMAFT Publications

- Featured in an article by Joseph Campbell, INL's Nuclear Science and Technology communications, on 19 September 2017, INNOVATIVE FUEL MANUFACTURING PROCESS MOVES CLOSER TO MARKET; https://www.inl.gov/article/industry-laboratory-team/.
- Presented a paper at the American Nuclear Society Winter Conference, October 28th – Nov 2nd, 2017, Washington D.C., Jhonathan Rosales, Isabella van Rooyen, and Clemente Parga, "Characterization of U_3Si_2 Surrogates along the Development of an Additive Manufacturing Process."
- Invited to publish article in JOM, a publication of the Minerals, Metals and Material Society, Jhonathan Rosales, Isabella J van Rooyen, Subhashish Meher, Rita Hoggan, Clemente Parga, and Jason Harp, "Effect of High Si content on U_3Si_2 Fuel Microstructure," accepted for publication October 2017.
- Drafting Ph.D. thesis, Jhonathan Rosales, "Characterization of Direct Additive Manufactured U_3Si_2 Surrogates to Predict U_3Si_2 Microstructures," Nuclear Engineering Sciences, University of Florida, Supervisor Dr. Isabella J van Rooyen (estimated completion February 2018).

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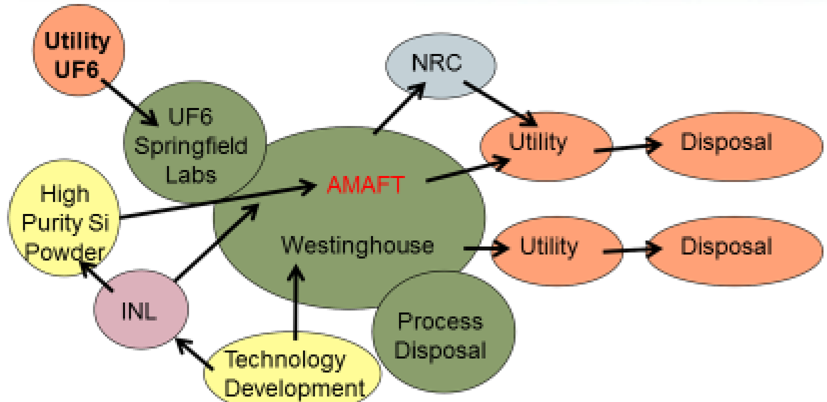
Energy I-Corps Cohort 5: Team 4 AMAFT

- Allow the fuel vendor to decrease capital and production costs by directly transforming easily available input materials into final form accident tolerant nuclear fuel
  - Isabella van Rooyen (Principle Investigator)
  - Ed Lahoda (Industry lead: Westinghouse)
  - George Griffith (Entrepreneurial Lead)

*"It was a surprise to learn how critical **partnerships** would be to the overall commercialization process. **We need partners to help with qualification, standards, process development, and characterization**," Van Rooyen said. "Energy I-Corps was an opportunity to think outside the box from our normal everyday research mindset."*

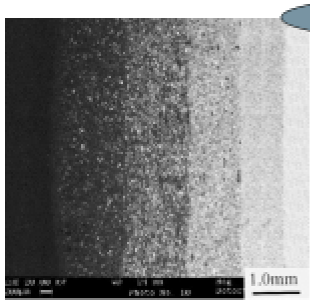
Customer Discovery: Energy I-Corps

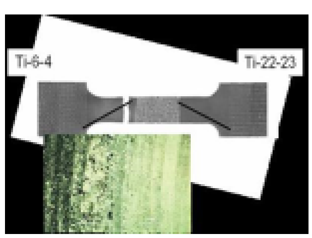


Customers
Westinghouse based on accident tolerant fuel investment
High value fuel fabrication is an re-opening market for fuel fabricators (other fuel)

Partners
Powder supplier cooperation
Equipment Developer

3) Functional Graded Materials/Components





Fuel enrichment gradients

Coatings

Graded interface approach:
- ✓ No gap for accuracy
- ✓ Fine balance for expansion differences
- ✓ Carefully engineered material properties
- ✓ Repeatable high quality process

Examples:
- ✓ SiC/Cu graded material
- ✓ Ti

[Y. –H. Ling, Journal of Nuclear materials, 303 (2002): 188-195]
[Advances in Laser Deposition Technology and Applications R. Grylls, T. Marchione, D. Keicher; ALAC Conference Proceedings, 2006.]
[U Van Rooyen LDRDFY13]

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Current Research & Collaboration Opportunities

- New process modelling
- Surrogate applicability and property behavior
- Irradiation behavior prediction
- Process parameter optimization
- Process automation (novel hybrid processes)
- Energy Source
- Handling of U-compounds in the novel hybrid processes
- Scale up optimization
- Supply chain of powders

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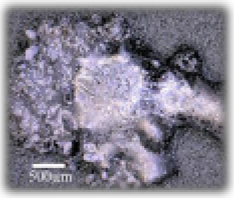
Additional Qualification Challenge Questions

- Role of Surrogates in Qualification Process
- Integrated Product and Process Qualification
- Gradient Material Qualification
- Novel Integrated process Hybrid Equipment Qualification
- Capturing of lessons learned from other industries
- Relevancy of other industries' development and qualification processes
- Embedded Products (sensor) Qualification

Acknowledgements

- This work was sponsored by the U.S. Department of Energy Idaho Operations Office Contract DE-AC07-05ID14517, and as part of the Technology Transitions Commercialization Fund, DOE-NE, NEET, NNSA
- Transmission electron microscopy and Focused ion beam work was carried out at the Center for Advanced Energy Studies –Microscopy and Characterization Suite
- Contributors to the U_3Si_2 AMAFT Development and/or Energy I-Corps Projects:
  - Clemente Parga, Jhonathan Rosales, David Swank, DC Haggard, Ed Lahoda, George Griffith
- Contributors to the TREAT LEU conversion AM team for development, funding or facilities:
  - Sean Morell, Optomec, Jatu Burns



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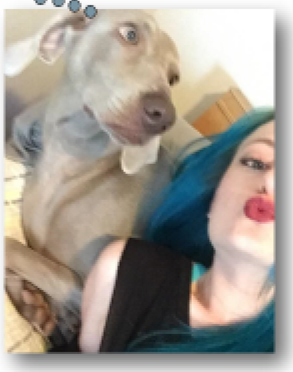
Questions??

What now??



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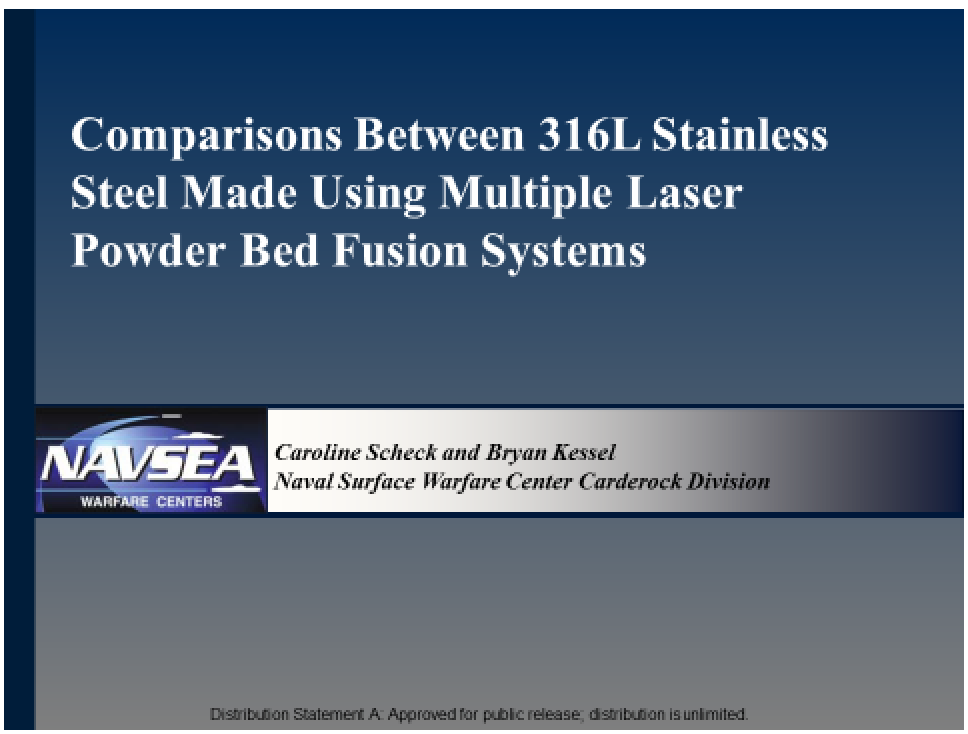
4.21 **Comparisons Between 316L SS Made Using Multiple LPBF Systems (Sam Pratt, NSWC)**



Acknowledgements

Funding

- Department of Navy Innovation Sustainment Group (DISG)
- NAVSEA Technology Office Cross Platform Systems Development (CPSD) Program
- Defense Logistics Agency (DLA)

Collaborators

- Naval Surface Warfare Center Indian Head Explosive Ordinance Division
- Naval Surface Warfare Center Dahlgren Division
- ARL Pennsylvania State University

Background

- Process qualification is a focus area for the Navy
  - Interested in understanding how usage of different additive manufacturing systems impacts results
  - Naval Surface Warfare Centers maintain four laser powder bed fusion systems from three different manufacturers
- Project purpose was to, when a reasonable effort was made to maintain general consistency across systems, examine:
  - Mechanical, microstructural, and corrosion variation
  - Identify issues in set-up across systems
- Scope was not intended to keep parameters consistent across systems or control variation
- Results to inform process qualification and Navy knowledge

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Laser Powder Bed Fusion Systems

Machines

- System A
- System B
- System C

Processing Parameters

- Default parameter sets for 316SS were used on all systems, no attempt was made to correlate parameters between systems
  - Raster patterns, power, travel speed, etc. were unique to each system
- Argon environment

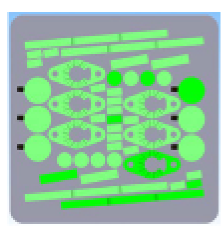
3 Powder Suppliers

- System B and System C used the recommended original equipment manufacturer (OEM) powders (powder B and powder C)
- System A used powder B and an a non-OEM alternate powder (powder X)
- 316SS argon atomized powders, sizing varied
- Powders bought in single lots, virgin powder used for all builds

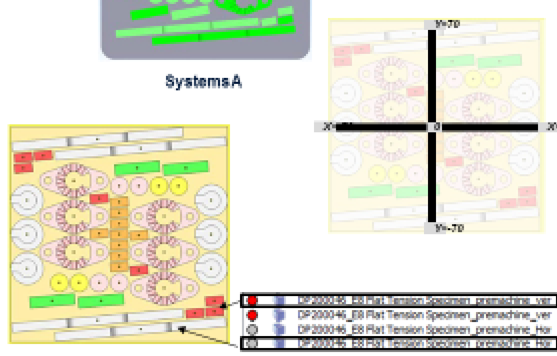
Build Design

Primary Specimens

- Tensile *(to be tested machined and as-built)*
  - Round, vertical, net shape
  - Round, vertical, pre-machine
  - Flat, vertical, net shape
  - Flat, vertical, pre-machine
  - Flat, horizontal, pre-machine
- Corrosion
- Torsion



Systems A

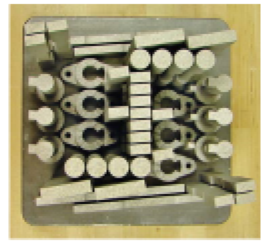


While specimens have same dimensions, different CAD files were designed for each specimen to aid in placement

System B

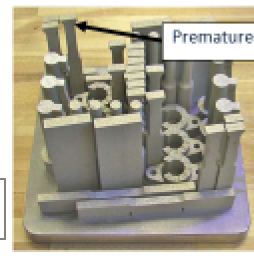
Build Design

- Specimens were designed to fit on the smallest build platform (System A)
- Larger systems located specimens in center of build platforms
- Solid support structures necessary to prevent build failures
- 2 build cycles/system
- Specimen removal
  - Band saw
  - EDM



Small build platform

Large build platform



Partial build

Machined Verses As-Built (Strength)

As-Built	Average 0.2% YS	Stdev
System A (powder X)	388	13
System A (powder B)	452	8
System B (powder B)	516	4
System C (powder C)	585	33

Machined	Average 0.2% YS	Stdev
System A (powder X)	397	40
System A (powder B)	445	62
System B (powder B)	519	11
System C (powder C)	588	26

Difference (As-Built to Machined)	Average 0.2% YS	Stdev
System A (powder X)	9	27
System A (powder B)	-7	54
System B (powder B)	3	6
System C (powder C)	4	-6

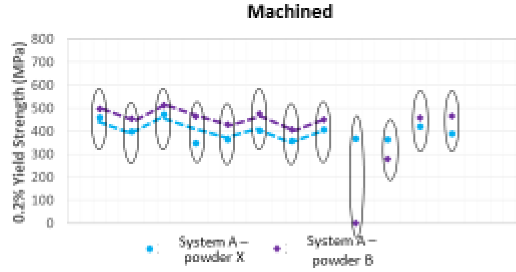
Of Note

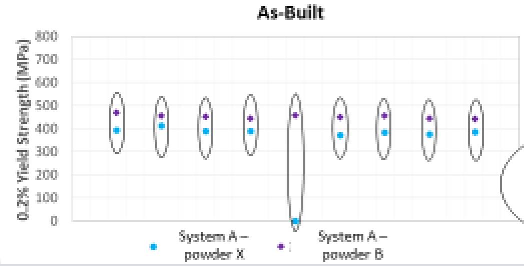
- Figures show machined and as-built properties disregarding relative location on build platform between systems and build cycles
- Machined specimens were designed with extra material to achieve same dimensions as as-built specimens post machining

Results

- System A showed more variability in machined specimens verses as-built
- System B shows consistent properties regardless of machined or as-built surface

Repeatability by Location (Strength)





Each group of specimens were made at the same build platform location

Of Note

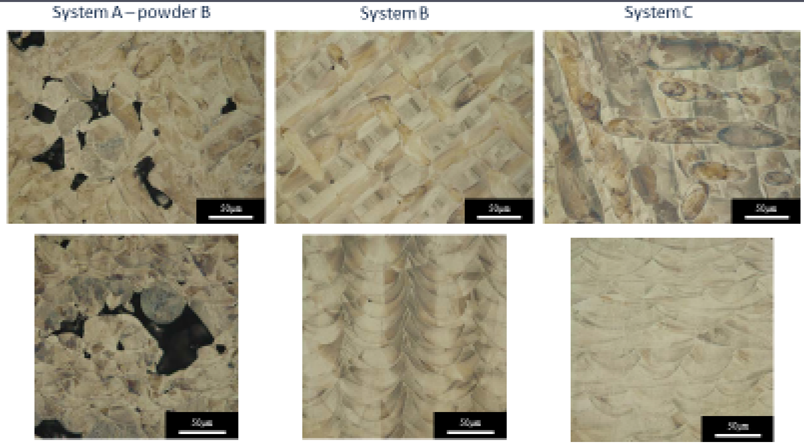
- Results are from two different build cycles on System A
- Each build cycles used identical processing parameters
- Only change was powder (powder X verses powder B)

Results

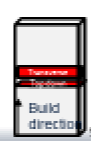
- Reduction in properties due to impact of powder variability only
- Results indicate system has repeatable processing ability based on location

Microstructure

	System A – powder B	System B	System C
Top-down			
Transverse			



- Significant variation in macrostructures observed across systems
- Various indications (incomplete fusion, cracks, unmelted powder, etc.) seen in System A - indicates non-optimized processing parameters

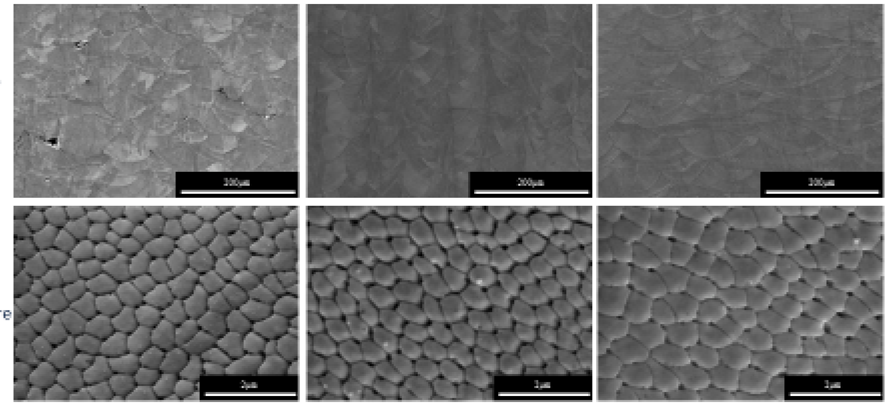


Microstructure

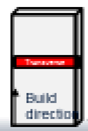
System A – powder B | System B | System C

Macro

Sub structure

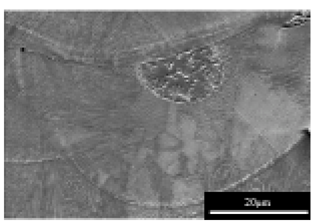


- Images taken from center of specimen
- Transverse orientation

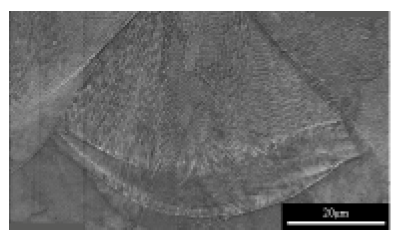


10

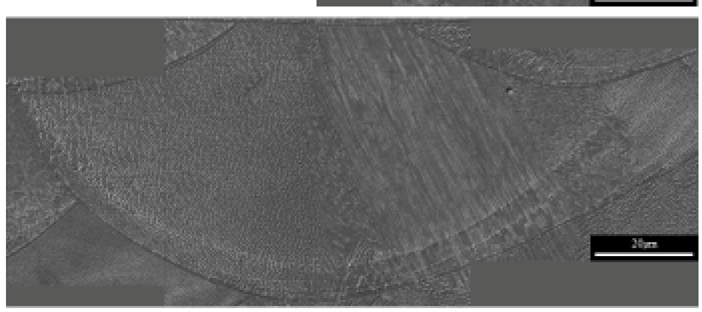
Microstructure



System A – unmelted powder



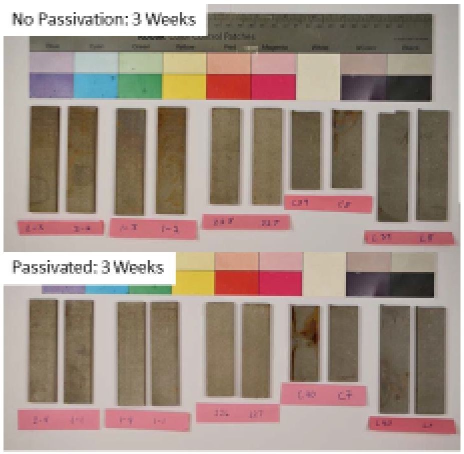
System A



System C

11

Corrosion – Initial Results



Salt Fog Testing

Results

- Results in-progress
- Preliminary results indicate accelerated corrosion on System A samples (non-optimized parameters)

Conclusions

- Purpose of project was to examine major differences across AM laser powder bed fusion systems when default processing parameter sets were used
  - Default system parameters may not be optimized for material properties
  - Even when not processing parameters are not optimized, tested specimens indicate general consistency over multiple build cycles

Continuing Work

- Mechanical property variation across systems
- Mechanical property variation within systems (two build cycles) by location
- Scanning electron microscopy evaluation
- Powder characterization

Distribution Statement A: Approved for public release; distribution is unlimited.

ABSTRACT: Abstract: Metal powder bed fusion (PBF) additive manufacturing (AM) systems fabricate material layer-by-layer using an energy source that selectively melts or sinters raw powder feedstock. There are multiple original equipment manufacturers (OEMs) for PBF systems and each OEM utilizes its own unique software, system controls, processing parameter options, etc. that can result in material and mechanical variation. This project focuses on the results from using three different OEM PBF systems to fabricate 316L austenitic stainless steel; the purpose is understanding variability when a reasonable attempt is made to maintain consistency between build files and using OEM recommended system processing parameters and raw materials. Results include powder feedstock characterization, mechanical and corrosion testing, and microstructural feature comparisons between fabricated coupons from each system.

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4.22 Qualification and Certification of Metallic Components for NAVSEA (Justin Rettaliata, NAVSEA)

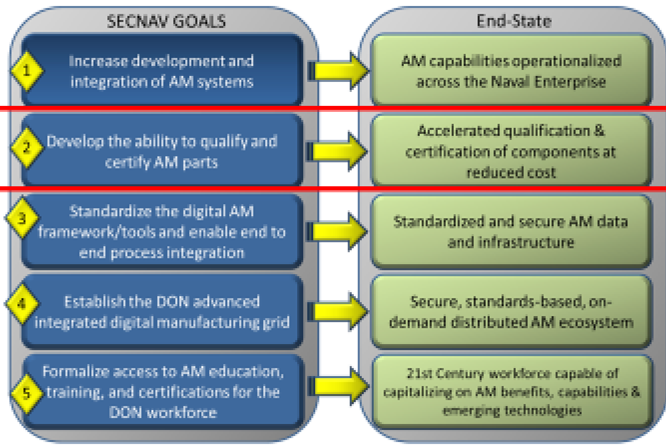
NAVSEA
NAVAL SEA SYSTEMS COMMAND

Qualification and Certification of Metallic Components for NAVSEA

Dr. Justin Rettaliata
Additive Manufacturing Technical Warrant Holder
NAVSEA 05T
29 November 2017

Department of the Navy Additive Manufacturing Implementation

- Maintain momentum and broaden our efforts across the NR&DE
- Assist, accelerate, and enable AM implementation to all naval communities (Operational, Logistics, technical, etc)



2

NAVSEA AM Strategy

- Develop & align engineering and acquisition competency and expertise to:
  - Ensure AM ship and weapon system components are safe, reliable and effective
  - Leverage AM as another manufacturing technique 'in the tool box'
    - Grow AM knowledge base through investments and collaboration
    - Push AM capabilities and authorities to waterfront (depots and shipyards), afloat, etc.
  - Employ AM in maintenance & repair
  - Expand the current use of AM for rapid design development, prototyping & tooling
  - Identify necessary S&T/R&D investment to enable AM capabilities for the NAVSEA enterprise
  - Connect AM digital backbone application with cybersecurity strategy
- Work with Directorates and PEOs to identify areas for application that improve capability and/or reduce cost
- Establish the processes, specifications and standards for use of AM for ship acquisition, design, maintenance, and operational support.
- Coordinate & collaborate with NAVAIR and other SYSCOMs for DoN AM objectives and investment

Operationalize AM in support of the Fleet where it makes sense.

Distribution Statement A – Approved for Public Release

3

Enabling AM Utilization Shipboard

- Current Fleet Memo (Jan 2015) specifies that no AM printed component can be installed shipboard w/o Departure from Specification (DFS)
- Design, Practice and Criteria Manual for AM – FY18 release
- Establish a "Green Box" Category for AM components
  - "Category" of components that are low-risk/low criticality
  - Approval Authority delegated down to CHENG (Waterfront or Ship).
  - Materials:
    - Polymer (substitute w/ like materials or better)
    - Metal
  - Criticality (as defined by NAVSEA S9800-AB-MAN-010, section E.3, NAVSEA-Tailored System Safety Risk Matrix):
    - Level 7: Could result in injury/illness resulting in no lost work days; or damage exceeding $10,000 but less than $100,000; or minimal environmental damage, requiring no restoration.
    - N/A: Could results in injury/illness requiring only first aid or less; or damage less than$10,000; and no environmental damage.
  - Fire/Smoke/Toxicity Consideration
    - AEL items
    - COSAL items
    - Volume Limitation
    - Storage requirements

NAVSEA Laser Powder Bed Fusion Process Specification

NAVSEA Laser Powder Bed Fusion Requirement *Draft Specification* requirements include:

- Identification of essential elements
- Process qualification through standard test array(s) and first article fabrication
- Process control plans to include: 1) digital file handling procedures, 2) build fabrication and feedstock handling procedures, 3) AM equipment maintenance control plan
- Performance qualification

Informed by:

- Platform specific requirements (such as for Friction Stir Welding)
- Leveraging industry and outside the DOD specifications where possible
  - Current specs/standards are immature
  - Some NAVSEA requirements may not be applicable outside of the Navy (SUBSAFE; Fire, Smoke, Toxicity (FST), etc.)
- Leveraging existing NAVSEA specs (NAVSEA Tech Pub 300 -Casting, NAVSEA Tech Pub 248 - Welding and Brazing)

Emphasis on leveraging ongoing work while ensuring requirements are suited to NAVSEA operating environments: 'Getting to yes' with qualification and certification

Naval Sea Systems Command Qualification Efforts

Part Demonstrations

- NAVSEA is currently working through 2 part demonstrations for parts produced utilizing the powder bed fusion process
  - 316L stainless steel and 17-4 PH stainless steel
- Part demonstrations are being used as an opportunity to test/exercise the requirements in the draft PBF process specification
- It is anticipated that the number of PBF/DMLS parts that are proposed as engineering changes to the fleet will continue to increase; current part demos provide the opportunity to explore the unique path to qualification and certification of AM parts from the standpoint of the NAVSEA Tech Authority process

Development of Industry Standards

- NAVSEA has representation on Standard Development Organization committees to aid in the incorporation of Naval specific requirements into industry standards
  - AWS D20 PBF specification
- Participation in the America Makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC)
  - Co-chair for Process Control working group
  - Participation in Qualification/Certification working group

Long Term Goal: Rapid Qualification of Metallic AM parts

Long term goal for qualification of AM parts:

Utilization of a tiered qualification approach to achieve **rapid**, **reduced cost qualification** of AM parts by leveraging in-situ monitoring and process modeling.

What does NAVSEA need to accomplish this goal?

Technical:

- Validated in-situ monitoring
  - Specs for how to validate and limitations of use
- Validated process models
  - Specs for how to validate and limitations of use
- Acceptable material properties for a given material and process
- Material and Process specifications for all AM Materials and Processes
- Tiers of criticality for invoking different qual requirements

Cultural:

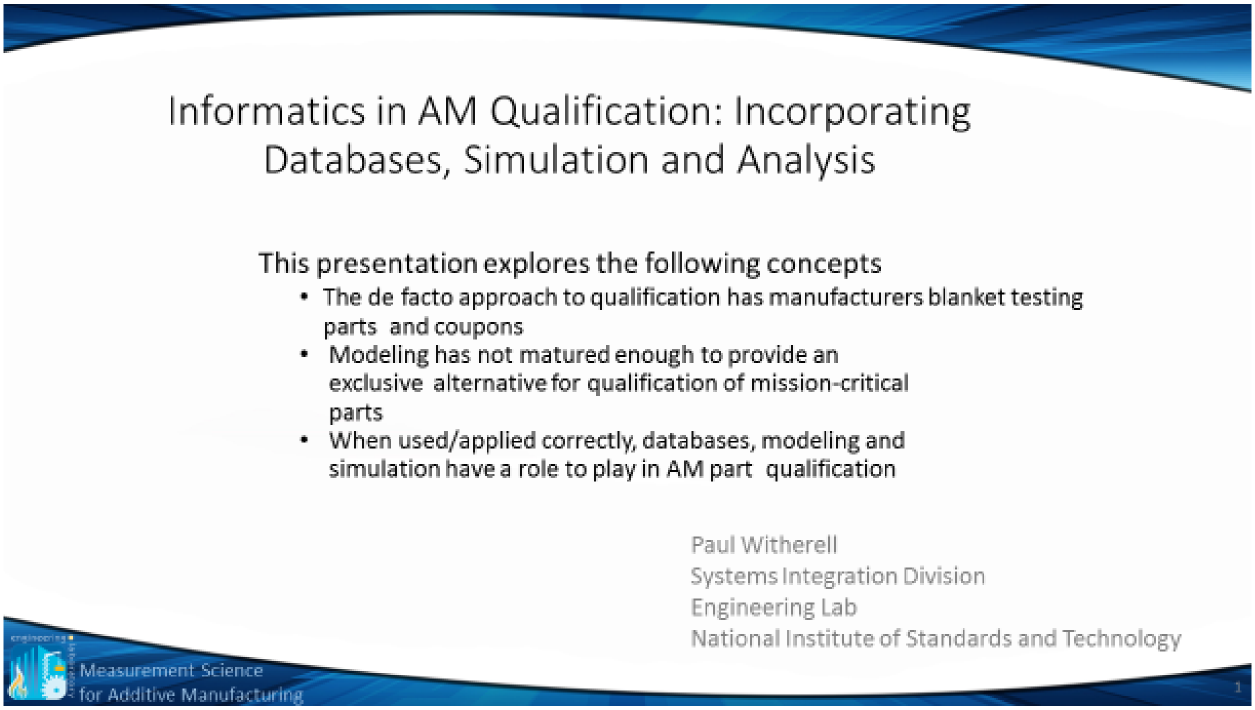
- Use of model based qualification
- Use of in situ monitoring in place of traditional NDE
- Drive for agility and adaptability within a traditionally rigid system/framework

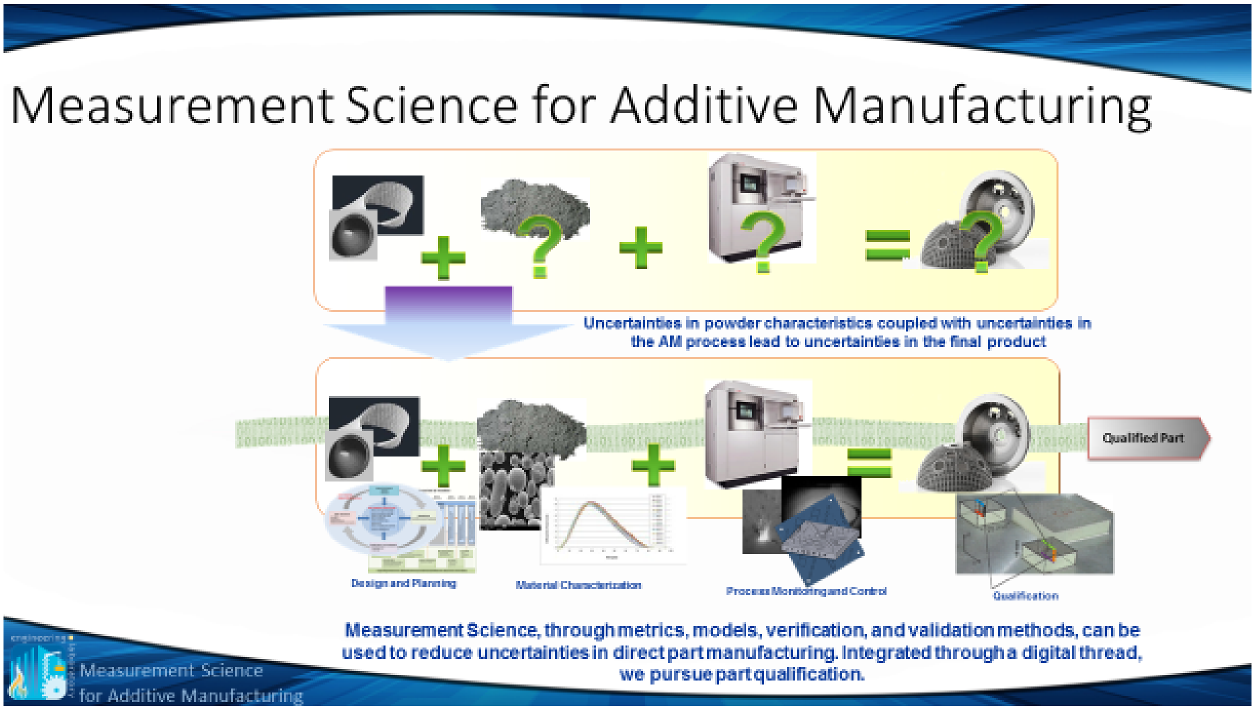
Contracting/Approval Mechanism:

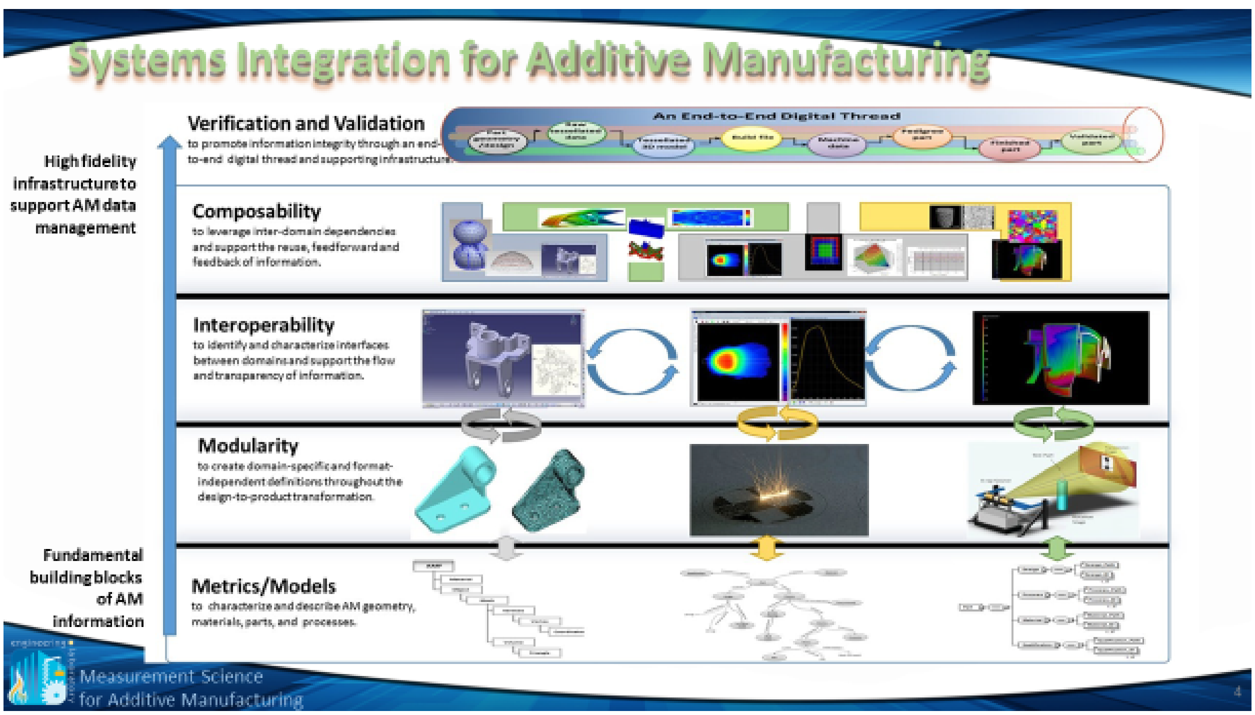
- What is the approval process for different criticality tiers?
  - Identify gaps
  - Identify areas that can be accelerated
  - Remove any roadblocks

Questions?

4.23 **Informatics in AM Qualification: Incorporating Databases, Simulation, & Analysis (Paul Witherell, NIST)**




Measurement Science for Additive Manufacturing
Uncertainties in powder characteristics coupled with uncertainties in the AM process lead to uncertainties in the final product
Qualified Part
Design and Planning
Material Characterization
Process Monitoring and Control
Qualification
Measurement Science, through metrics, models, verification, and validation methods, can be used to reduce uncertainties in direct part manufacturing. Integrated through a digital thread, we pursue part qualification.
Measurement Science for Additive Manufacturing


Systems Integration for Additive Manufacturing
High fidelity infrastructure to support AM data management
Fundamental building blocks of AM information
Verification and Validation
to promote information integrity through an end-to-end digital thread and supporting infrastructure
An End-to-End Digital Thread
Composability
to leverage inter-domain dependencies and support the reuse, feedforward and feedback of information.
Interoperability
to identify and characterize interfaces between domains and support the flow and transparency of information.
Modularity
to create domain-specific and format-independent definitions throughout the design-to-product transformation.
Metrics/Models
to characterize and describe AM geometry, materials, parts, and processes.
Measurement Science for Additive Manufacturing
4

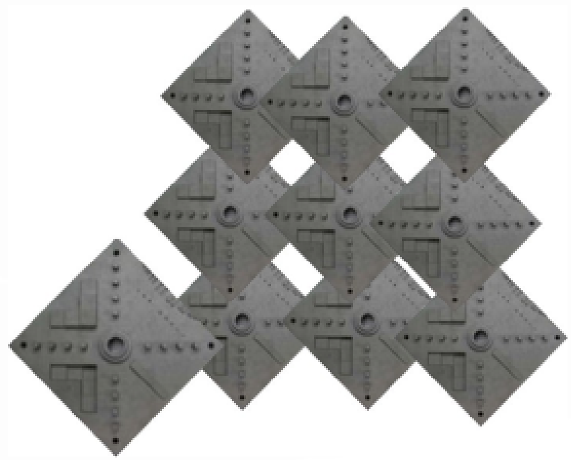

What am I designing for, what am I qualifying for?
AM Information can be classified into
– Design/Geometry
– Material
– Process
– Part
Topological optimization
Support structure
Lattice structure
<Design/Geometry>
Powder composition ratio
Powder geometry
Powder type
<Material>
Powder bed system
Powder feed system
Feedback control system
Sensors
Actuator
AM machine
<Process>
Generated part
Coupon/test
Virtual inspection
<Part/Qualification>
A qualified part is one that falls within the range of all ***critical*** design tolerances, has the specified surface attributes, and maintains part integrity and *stability during any functional tests*, ***as determined by the customer***.
http://www.moldmakingtechnology.com/articles/
a-modern-moldmaking-trend
Measurement Science
for Additive Manufacturing
5


Measurements for Qualification
Information includes any process measurements and mechanical testing or *NDE on the manufactured part and the results of these tests
Fraunhofer
<Build parameters>
<Grain morphology>
<Tensile strength>
<Industrial CT scanning>
<Ultrasonic testing>
*NDE (Non-Destructive Evaluation)
Measurement Science
for Additive Manufacturing
6

Qualification through Brute Force

Current Mindset

- We need test specimens for each direction to ensure we are getting the properties we desire.
- I've calibrated this machine for this part, now don't touch it!
- I've developed this model that almost exactly predicts my part's performance.



Measurement Science for Additive Manufacturing 7

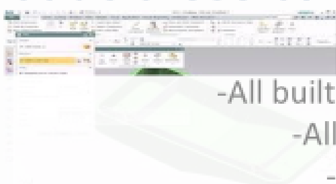
Do all parts need the same rigor?

Measurement Science for Additive Manufacturing 8

When is a part satisfactorily "qualified"?

- What is qualification?
  - What is necessary to qualify against the *customers' (functional) needs*
    - What part/process characteristics are most likely to lead to failure?
    - What are the failure modes that will determine how the performance of the part is measured?
  - What data is necessary to "establish pedigree"?
    - What is good data or an established/quality dataset?
  - Does this have to be done for all parts? Only different geometries? Only different maintenance cycles? Only different machines?

What do these builds have in common?



Lid

-All built by an aerospace manufacturer

-All built using AM processes

-All require qualification

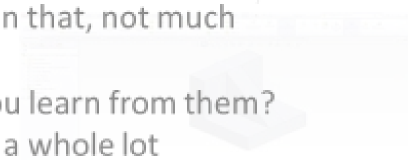
-All in a database

Other than that, not much

What can you learn from them?

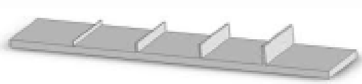
Not a whole lot

Structural Support
Titanium (Internal Features)
Sciaky



Fuel Line
Cobalt Chrome
EOS

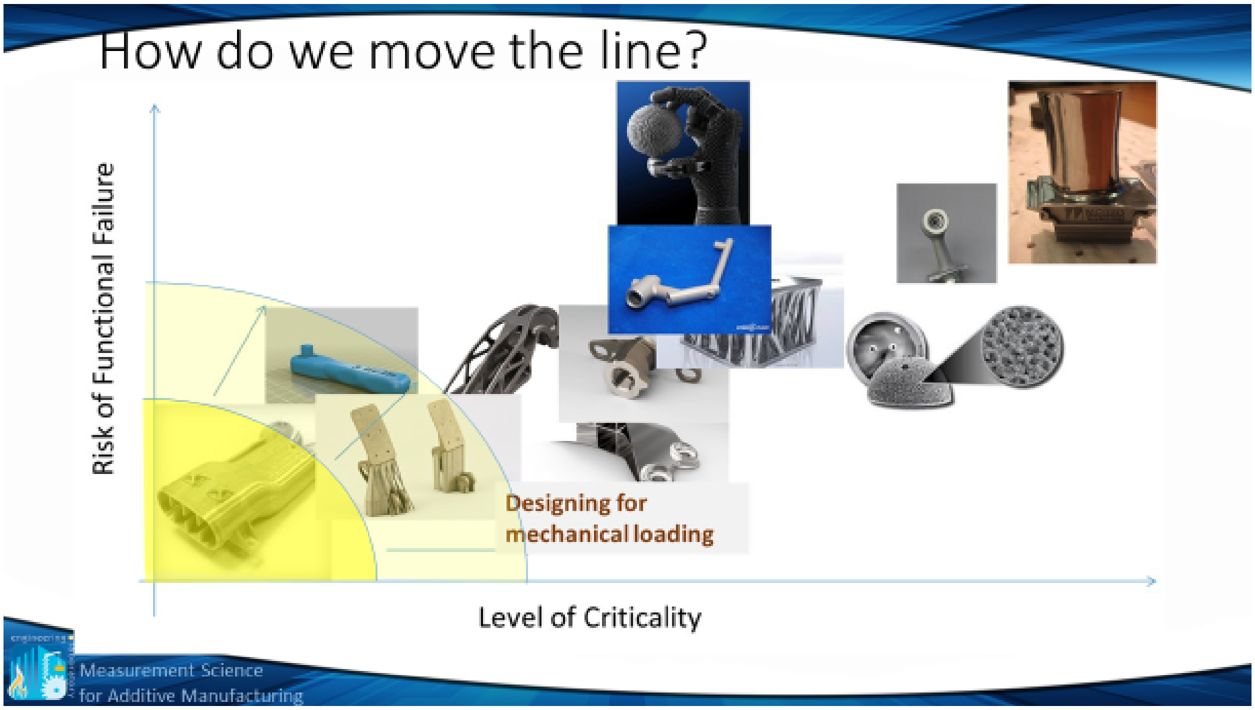
Clip
ABS Plastic (Honeycomb)
3D Systems Cube



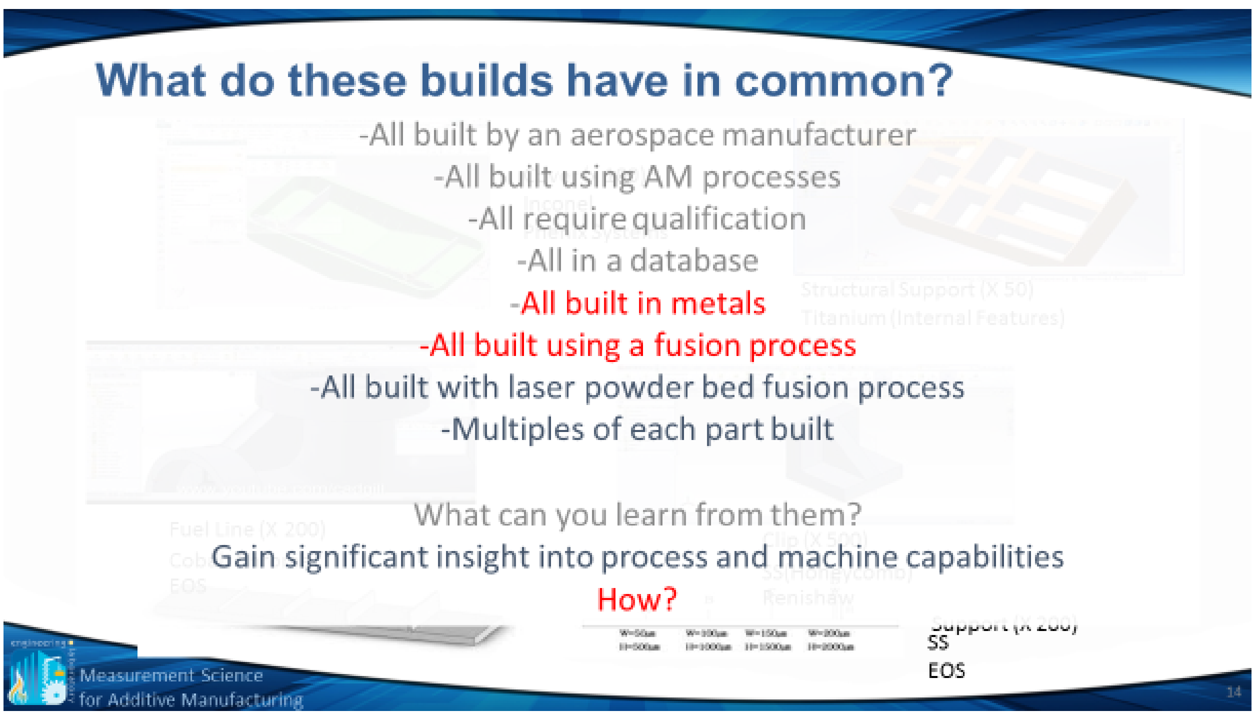
Support
Graded SS
Optomec


What do these builds have in common?
-All built by an aerospace manufacturer
-All built using AM processes
-All require qualification
-All in a database
-All built in metals
-All built using a fusion process
What can you learn from them?
Some insight into how metals are processed differently
Support
Graded SS
Optomec
Measurement Science
for Additive Manufacturing
11


Various AM Material Database Efforts
GRANTA
ARL
MSAT
SENVOL
Battelle
The Business of Innovation
Celebrating over 60 Years
Measurement Science
for Additive Manufacturing
12



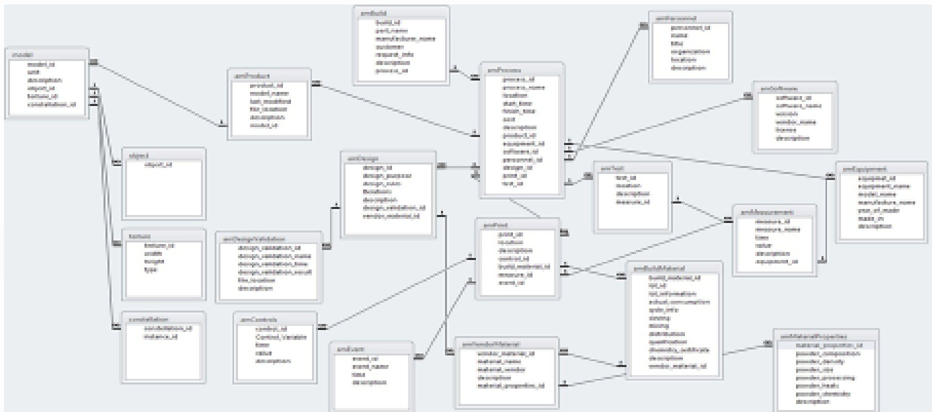
How do we move the line?
Risk of Functional Failure
Level of Criticality
Designing for mechanical loading
Measurement Science for Additive Manufacturing



What do these builds have in common?
-All built by an aerospace manufacturer
-All built using AM processes
-All require qualification
-All in a database
-All built in metals
-All built using a fusion process
-All built with laser powder bed fusion process
-Multiples of each part built
What can you learn from them?
Gain significant insight into process and machine capabilities
How?
SS
EOS
Measurement Science for Additive Manufacturing

Design Allowables in AM: Establishing Material-Process-Structure Relationships

- Look to establish repeatable correlations between processed material and:
  - surface finish
  - microstructure
  - tensile strength
  - etc.



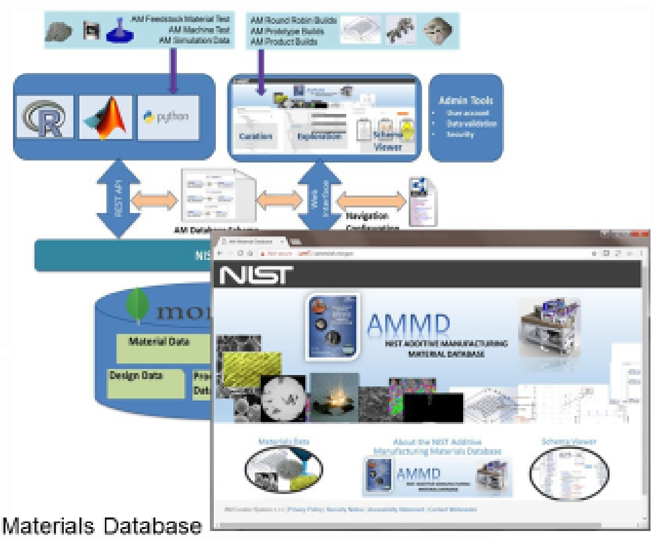
NIST Additive Manufacturing Material Database - AMMD

Goal: To develop an open database system set for:

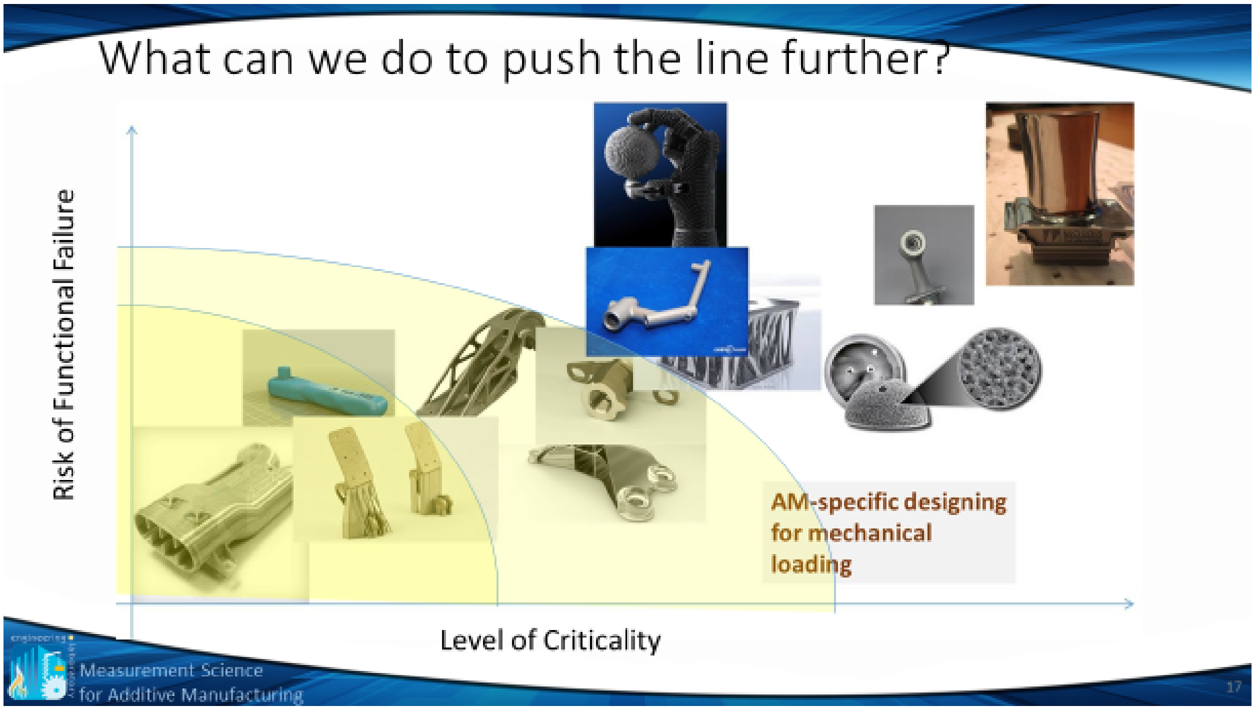
- *—deep understanding of AM geometry-material-process-property relationships*
- *—better AM process control and optimization*

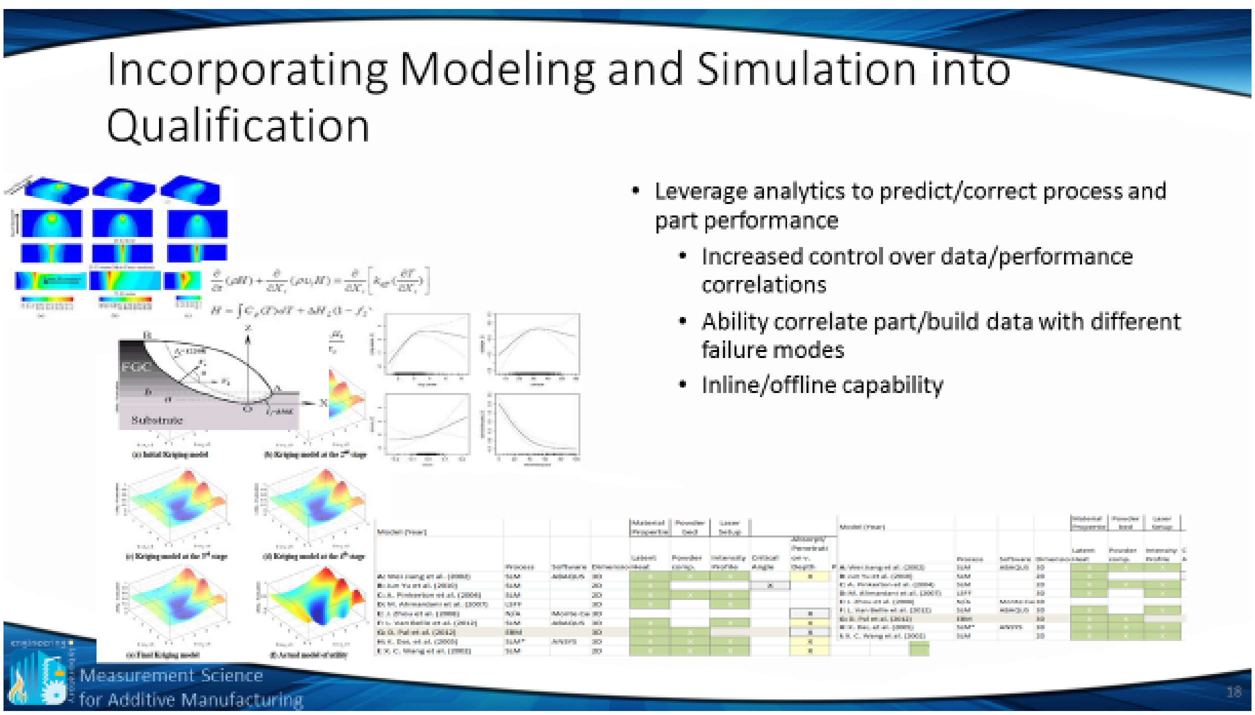
Features:

- *— Lifecycle and value chain data*
- *— Openly accessible*
- *— Community effort of data curation*
- *— Consensus/ co-developed schema*
- *— Integration support for data analytics*



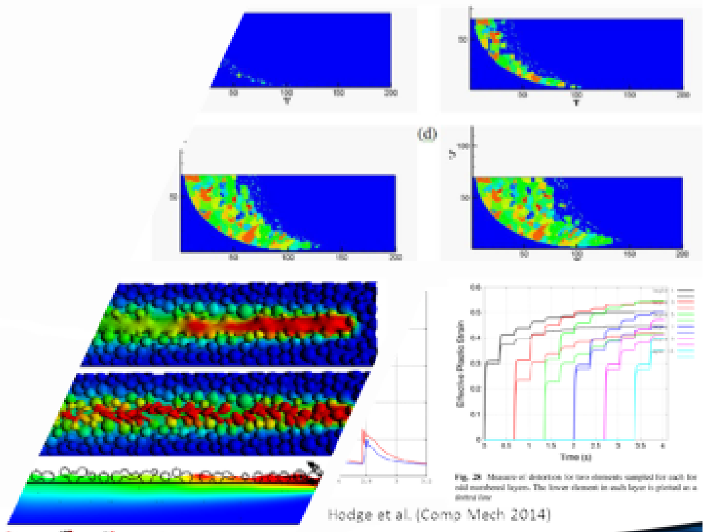
AM Materials Database
https://ammd.nist.gov


What can we do to push the line further?
Risk of Functional Failure
Level of Criticality
AM-specific designing for mechanical loading
Measurement Science for Additive Manufacturing
17


Incorporating Modeling and Simulation into Qualification
• Leverage analytics to predict/correct process and part performance
• Increased control over data/performance correlations
• Ability correlate part/build data with different failure modes
• Inline/offline capability
Measurement Science for Additive Manufacturing
18

Predictive and Performance Modeling

- Information-centric models to represent advanced process
  - Physics-based models
  - Empirical models
  - Statistical models
- Use analytics to predict/correct process performance
  - Increased control over data
  - Ability correlate part/build data with different failure modes
  - Inline/offline capability

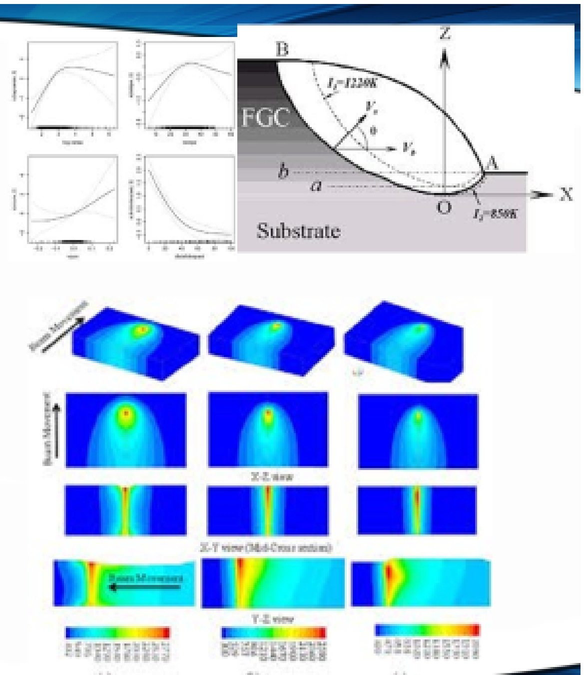


Hodge et al. (Comp Mech 2014)

Measurement Science for Additive Manufacturing

Feedback for Process Planning and Control

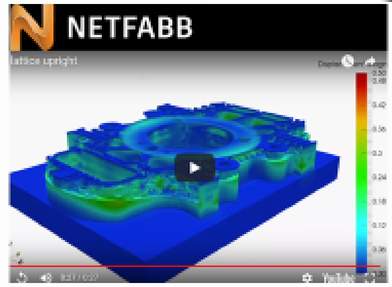
- Data analytics allows observations to be made based on previous parts
  - Design of Experiments-Adjust process parameters where appropriate based on observed trends
  - Optimization- Identify best parameter values based on evaluated data sets
  - Trial and Error- Adjust accordingly based on measured results and observed magnitudes
- Feedback control loops beginning to emerge
  - Leverage measured data during process time



Measurement Science for Additive Manufacturing

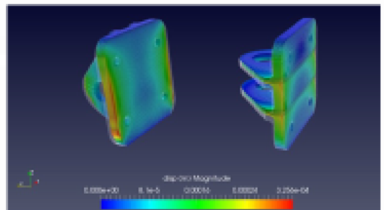
Deployment of Simulation Tools

- Simulation increasingly used by manufacturers
- Models incorporated into design and analysis tools
  - Distortion Prediction
  - Residual Stress Prediction



AUTODESK

Pan Computing
Process Simulation for Additive Manufacturing

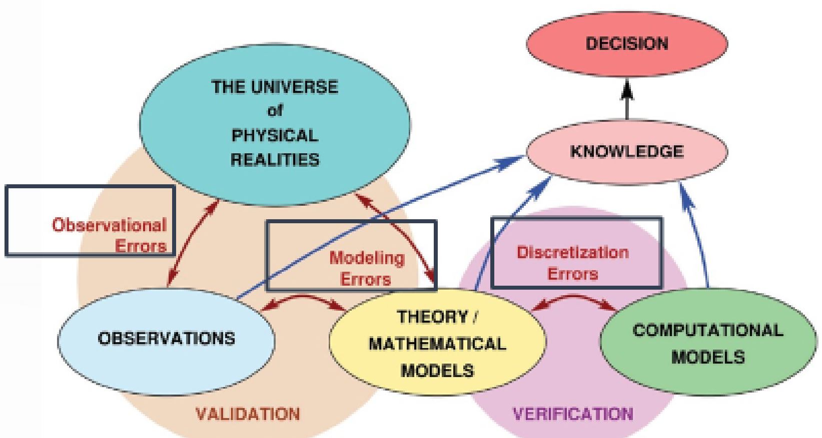


3DSIM ANSYS

Characterization, UQ, & Composability of Powder Bed Fusion Process Models

Addressing Uncertainty in Models

How large is the error in these models and where does it come from?



T. Oden, R. Moser, O. Ghattas, Computer predictions with quantified uncertainty, Part I, SIAM News, 2010, 43(9), pp. 1-3

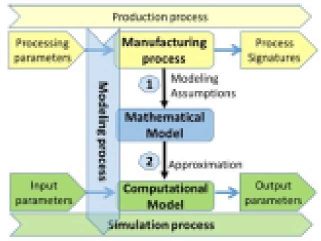
Characterizing Predictive Models

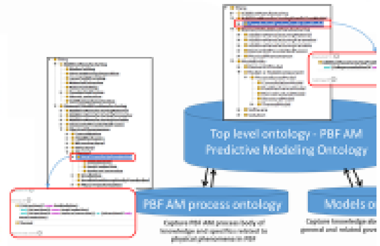
Characterization of predictive models can increase utility

- Uncertainty Quantification to better characterize unknowns
  - Feed in new datasets
- Global surrogates can be derived from local surrogates across design spaces
  - Allow neighboring events, and additional data, to provide further context
- Well-defined domains support composability
  - New analysis capabilities

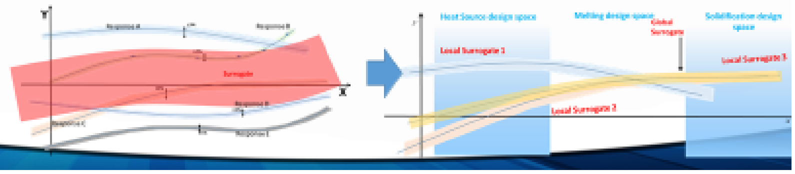
Reference Models still needed

- AM Bench





Lopez, Felipe F.; Witherell, Paul W. (2016); Lane, Brandon M.; "Identifying uncertainty in laser powder bed fusion additive manufacturing models," Journal of Mechanical Design, v138, 2016



Model Appropriateness

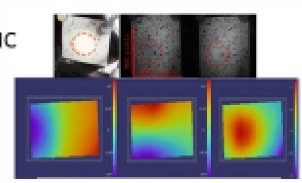
Emerging Theme:

"Model appropriateness was defined by stating the problem to be solved, with the intended use of the model being the pivotal event. The elements of model appropriateness were identified with the type of model (descriptive vs. predictive) determining which elements of model appropriateness need to be executed."

Ette EI, Williams PJ, Kim YH, Lane JR, Liu MJ, Capparelli EV, «Model appropriateness and population pharmacokinetic modeling," J Clin Pharmacol. 2003 Jun;43(6):610-23.

- What is a "critical" part? What is failure?
- What is its "critical" function? What am I testing for?
- Qualify the material, qualify the process, or qualify the part?
- How and when can I use my data to help?
- How and when can I use my models to help?

DIC



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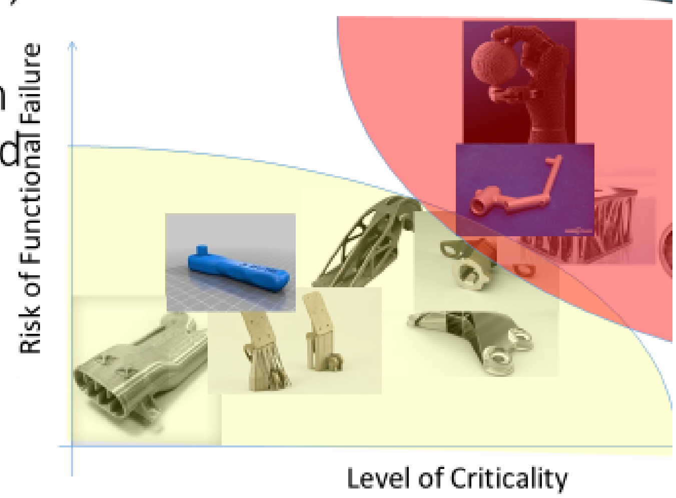
Takeaways

- Qualification is in the "eye of the beholder" and subject to the criticality of the part and risk of functional failure
- Databases are coming, but they can only offer so much
- There is something to be said for consistency in model development
  - Expanded sampling by incorporating other models
  - Larger data sets
- There is a role for modeling and simulation in qualification, but
  - Context must be understood
  - Limitations must be properly observed
  - Uncertainty must be embraced

There is a role for analysis, and that role is highly dependent on application context, risk of failure, and level of criticality



This role can be satisfied with material databases, design allowables, and modeling and simulation

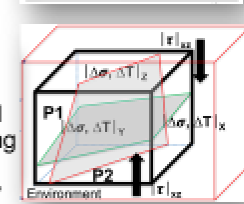
4.24 **<u>Ultrasonic Additive Manufacturing & other AM Processes for Nuclear Component Manufacture (S. Suresh Babu, ORNL/UTK)</u>**

Outline: 17+3 mins Q/A

- Motivation
- Ultrasonic Additive Manufacturing (UAM)
  - Case Study 1: HFIR Control Plates
- Direct Energy Deposition Process
  - Case Study 2: Dissimilar Material Joints
- Future Directions
- Summary

AM Process Flow

Fundamental Understanding Science & Technology



Babu (2017)

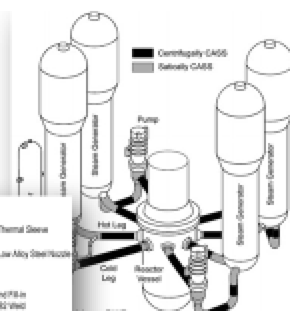
New Energy Applications

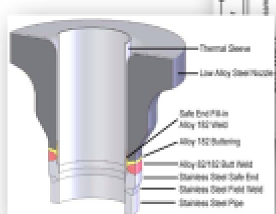
Ashby (2005)

Motivation

- Additive manufacturing has emerged as potential route for manufacturing nuclear power components with dissimilar materials.
- Other applications
  - Control rods
  - Spray nozzles
  - Cooling channels
  - Instrumentation
- What do we need?
  - Process optimization
  - In-situ and Ex-situ Qualification with and without radiation

Reactor Pressure Vessels – Dissimilar Material Joints

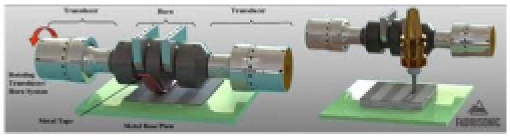


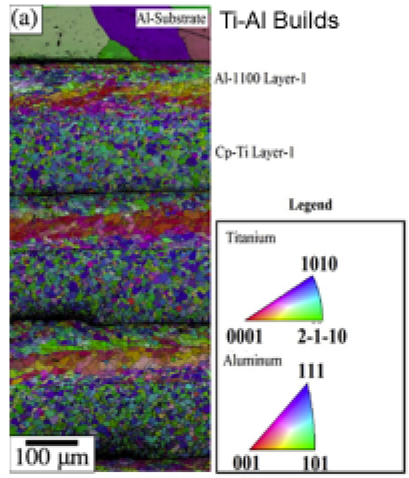


Courtesy: EPRI

Complex Geometry Fuel Assembly Structures

Ultrasonic additive manufacturing is based on solid-state welding.





Ti-Al Builds

- How can we do In-situ process qualification?

Sridharan et al (2016)

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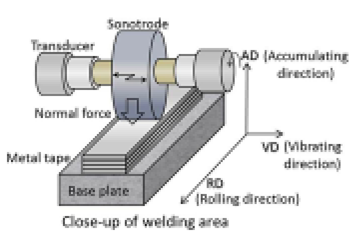
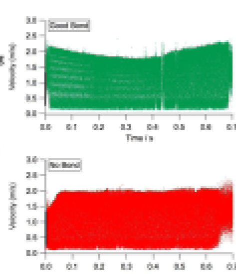
High-frequency (20 kHz) displacement data processes can be used for in-situ process qualification.

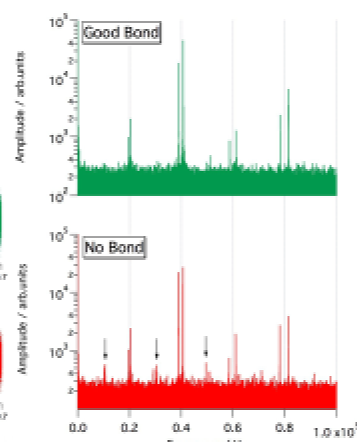
In situ velocity measurements of very high power ultrasonic additive manufacturing using a photonic Doppler velocimeter

D. R. Foster, G. A. Taber, S. S. Babu and G. S. Daehn



Shimuzu et al (2014)





- Let us consider an application case study:

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Ultrasonic additive manufacturing was successfully used to for prototype with embedded neutron absorbers.

Hehr et al (2017)

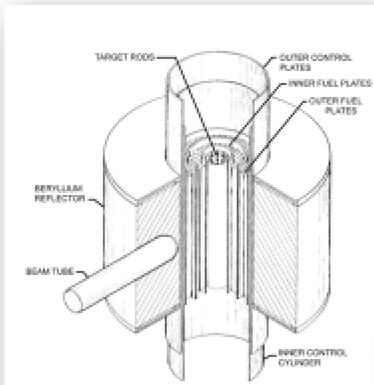
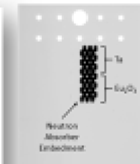
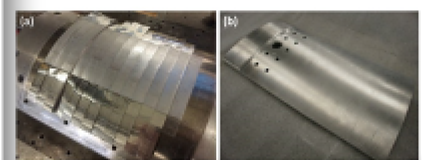


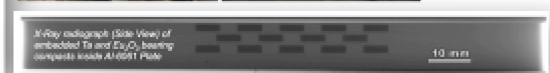
Fig. 1. Simple schematic of HFIR core.



Placement was designed based on neutron-material interaction calculations



UAM Process



- Current work: Ex-situ Qualification after irradiation

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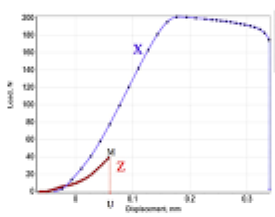
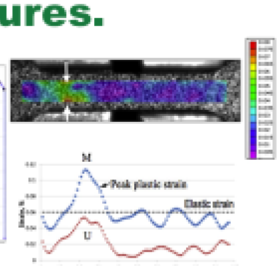
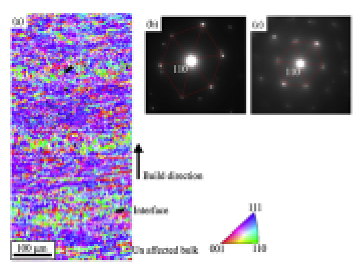
Anisotropic properties in Al-Al and Al-Fe builds are correlated to interface microstructures.

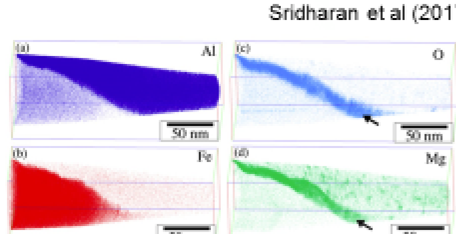






Sridharan et al (2017)

- ORNL's multi-scale ex-situ characterization tools were used to attain these process-structure-property correlations.
- How about after neutron radiation exposure?



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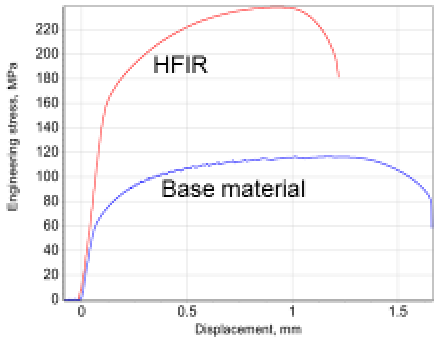
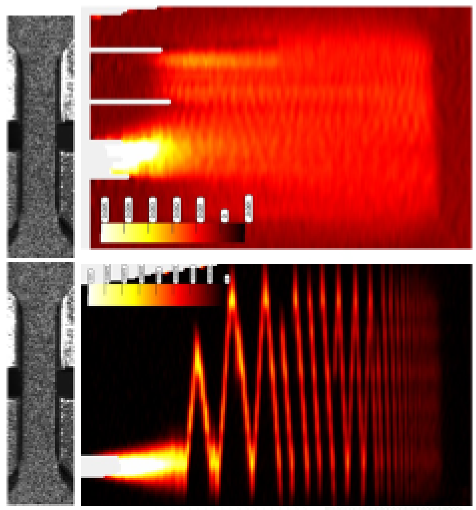
Preliminary results: After irradiation campaign (0.913 dpa), base material UAM joints were tested.



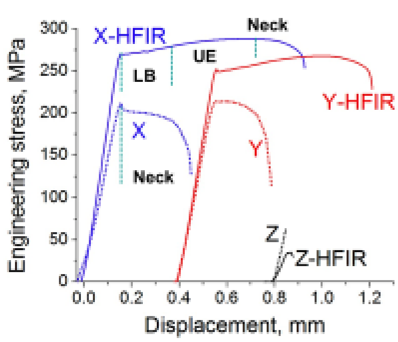
- Base material shows neutron hardening.
- How about the UAM builds?



Time, strain->

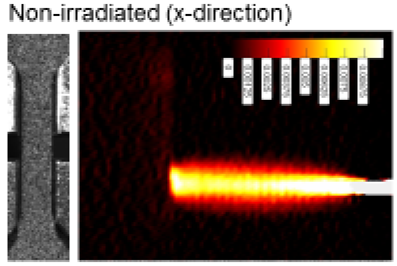
Anisotropic properties still persist, however, neutron irradiation effects can be observed.

Load-displacement Curves

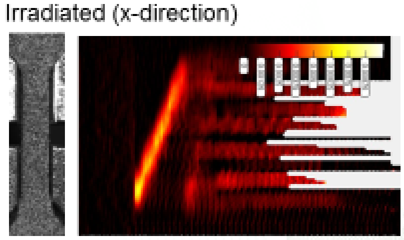


- What is the role of post-process heat treatment (180°C/8h)?

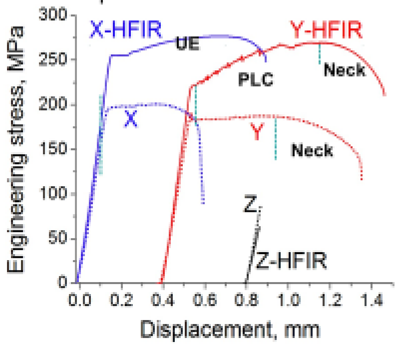
Non-irradiated (x-direction)

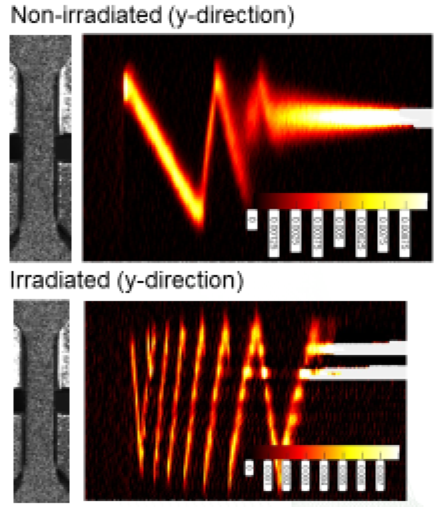


Irradiated (x-direction)



Complex strain transients (Luders band) were observed during tensile testing of aged samples.





- Interpretation: Crystallographic texture may play a role.
- Data will be used for qualifications of the hybrid parts.

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Laser Direct Energy Deposition (DED) process is widely used in gas turbine industries for repair.

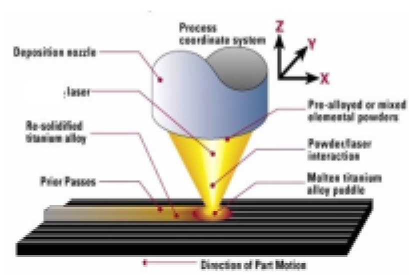
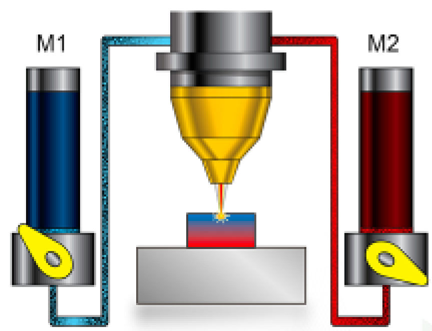


Image courtesy of Kelly, S. (2004). Thermal and Microstructure Modeling of Metal Deposition Processes with Application to Ti-6Al-4V.



Courtesy: Sridharan and Jordon (ORNL)

- Process has ability to transition from one alloy to another easily (up to four). Can we extend this process for designing and fabrication of dissimilar metal transition joints within reactor pressure vessels?

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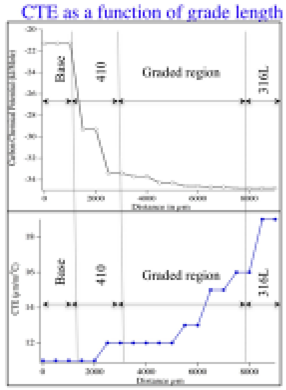
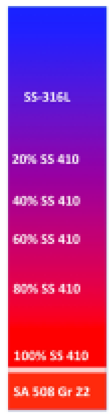
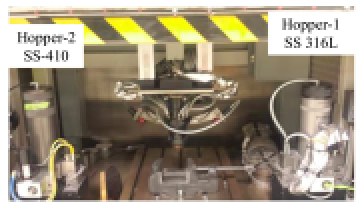
Using computational thermodynamic and kinetic ICME tools, Cr-Mo to 316L transition joint was designed.

Change in Carbon Chemical potential and CTE as a function of grade length





Sirdharan et al (2017)



- Transition joint was fabricated using the following parameters
  - Travel speed: 600mm/min
  - Step over 0.5mm
  - Power 400W
  - Powder feed rate: 5g/min
- Preheat maintained at 300°C using a hot plate

- Did we achieve the transition?

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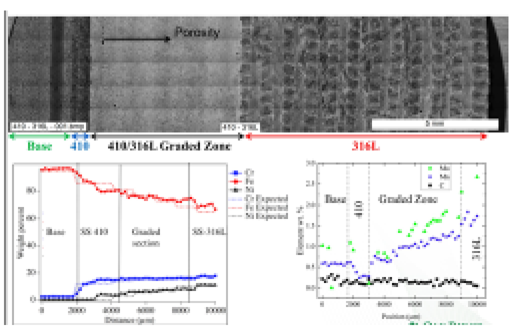
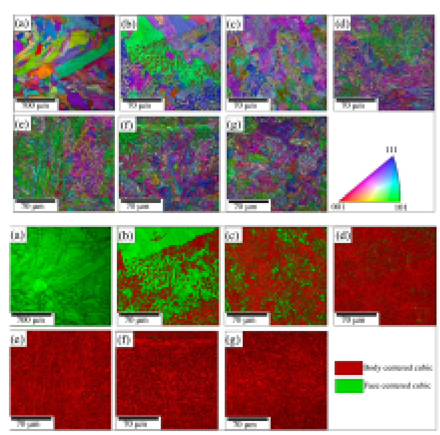
DED process allowed us to fabricate transition joints with controlled compositions and phase variations.





- Gradual transition from BCC to FCC structure was achieved.
- How does this complex microstructure behave under loading conditions?

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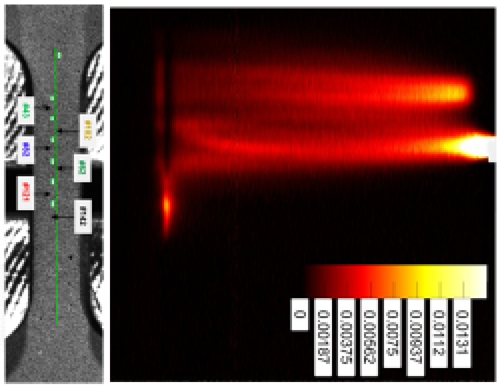
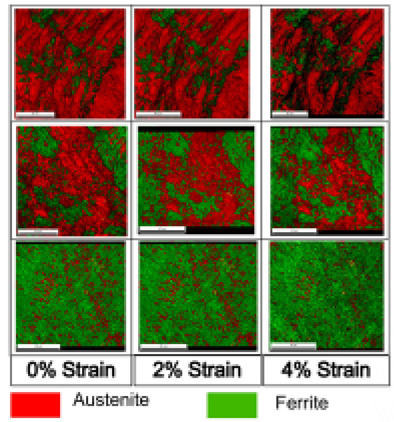
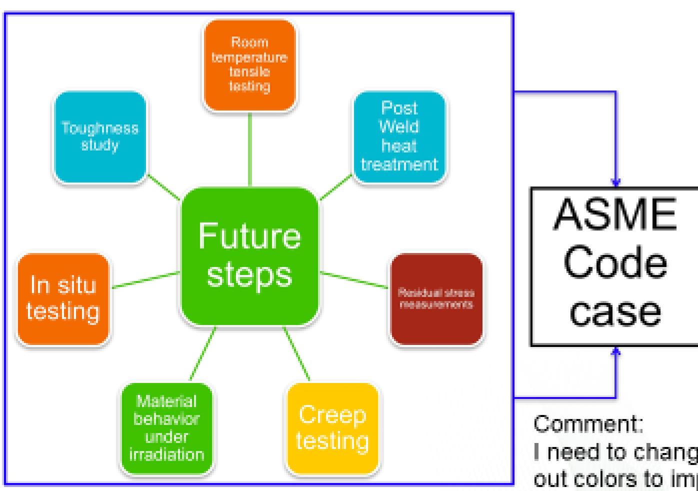
Transition joint shows typical strain partitioning due to transformation of austenite (FCC) to martensite (BCC/BCT).





- We are using this data to design and test new generation of transition joints.

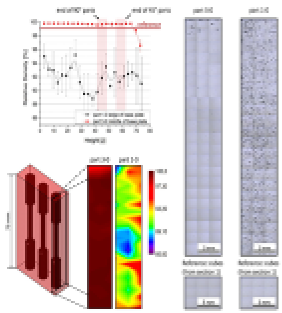
Future Directions (1): Develop datasets for traditional qualifications.



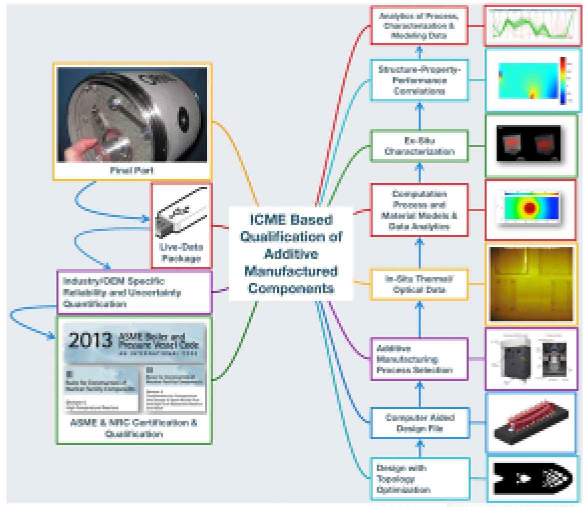
Comment:
I need to change this to with out colors to improve readability

- How about component level qualifications?

Future Directions (2): Develop in-situ monitoring, modeling and process based qualifications



Research by Popp (2015) proved that cubes are not satisfactory qualification artifacts!



Requires integration of tools for modeling, making and measuring.

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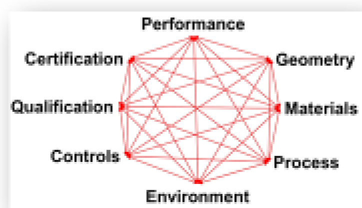
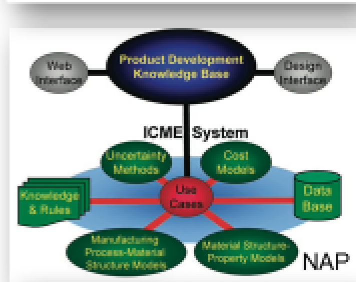
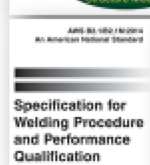
Summary and Conclusions

- Information Infrastructure for AM of complex components: interaction between geometry, materials, processes, controls, qualification, certification and performance under service
- It is possible to ICME models, extend in-situ and ex-situ characterization to develop rapid qualification methodologies for both fusion and solid-state AM processes.
- Case studies were presented in support of the same notion.







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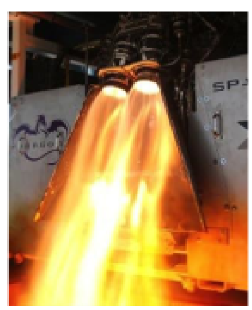
4.25 **Standardization in Additive Manufacturing: Challenges in Structural Integrity Assurance (Doug Wells, NASA-MSFC)**

Structural Integrity in Additive Manufacturing

- NASA is integrating critical AM parts into human-rated flight systems: Space Launch System : : Orion Spacecraft : : Commercial Crew

Aerojet Rocketdyne RS-25



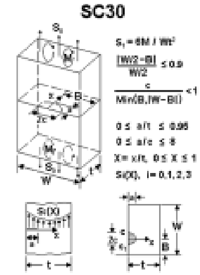
SpaceX SuperDraco

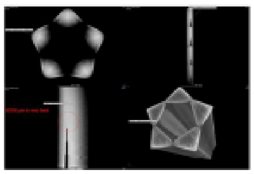
Ensuring structural integrity is the highest challenge - Quality Assurance and standardization are fundamental to this endeavor.

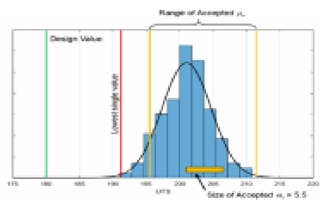
2

Summary of Topics

1. Additive Manufacturing Standards Landscape
2. Integration of structural integrity rationale in AM
3. Process qualifications – standardization
4. Material property transferability
5. NDE standardization status in AM
6. Impending, near-term reliance on computed tomography
7. Coming reliance on in-situ monitoring







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Standardization in Additive Manufacturing

America Makes/ANSI Additive Manufacturing Standardization Collaborative

AMSC

Focused on identifying gaps in AM standardization

America Makes ANSI

ASTM International	International Organization For Standardization	American Society of Mechanical Engineers
SAE International	American Welding Society	Institute of Electrical and Electronics Engineers
MITA Medical Imaging & Technology Alliance	Association for the Advancement of Medical Instrumentation	IPC - Association Connecting Electronics Industries
	Metal Powder Industries Federation	

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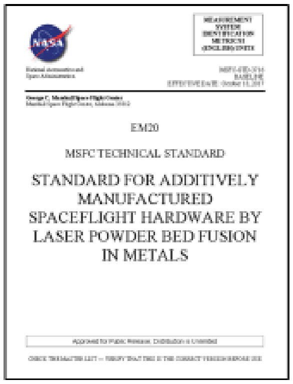
Standardization in Additive Manufacturing

NASA-MSFC Technical Standards for L-PBF
- MSFC-STD-3716
- MSFC-SPEC-3717


NASA

EM20

MSFC TECHNICAL STANDARD

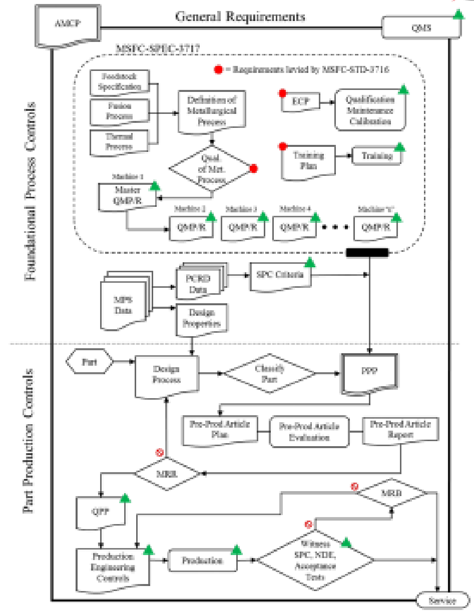
STANDARD FOR ADDITIVELY MANUFACTURED SPACEFLIGHT HARDWARE BY LASER POWDER BED FUSION IN METALS


NASA

EM20

MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES



Integration of Structural Integrity

- **AM components often require a more integrated approach to substantiate the rationale for structural integrity**
  - Not a new concept--basics of fracture control--AM atypically complex
  - Developing a structural integrity rationale from multiple mitigations to guard against multiple risks is new to many.
  - Fracture control challenges are more frequent

MSFC-STD-3716: *Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals*
- AM ***Part Production Plan*** required to illuminate risks
- Includes the ***Integrated Structural Integrity Rationale*** – a concise summary of how structural integrity is assured commensurate with the part's risk classification

Integrated Structural Integrity Rationale

Mitigations

- Process Controls
- *Process Qualifications* (In-Situ Process Monitoring)
- Process Witness Testing
- *NDE: CT, RT, PT, ET, UT*
- Part Acceptance Tests (dimensional, proof, leak)
- PPA assessment

Risks

- Process Escapes
- Physical defects (cracks, voids)
- Material capability debits
- High structural demand
- Complex geometry
- Surface quality
- Uninspectable volume and surface

7

Process Qualification

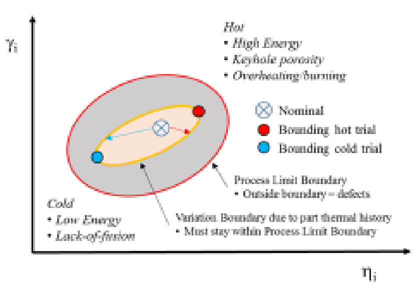
Standardization Need: Definition of a Qualified AM Process

MSFC-SPEC-3717: ***Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes***

- Defines a Qualified Metallurgical Process (**QMP**) (represents a first attempt)
- Consensus Standards are beginning to establish definitions and requirements

A Qualified AM Process is *critical* to knowing

- Consistency of process over time and across platforms,
  - Individual machine capability
- What material condition is characterized/represented in design data
- What material condition is expected in parts
- Transferability and equivalence in material structural performance



IN718 Microstructural Evolution

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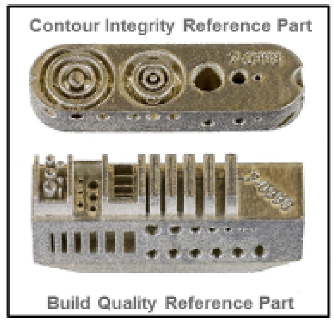
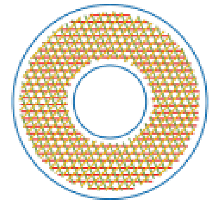
Defining a Qualified AM Process

Need consensus definitions of AM process quality for consistency

- Powder controls
- Process parameters
- Chamber environment
- Material integrity / acceptable defect state
- Microstructure evolution
- Mechanical properties
- Surface quality and detail resolution
- Variability across build volume
- Variability with part/bed thermal history





The first question to ask relative to any data, parts, or products from AM:

How was the AM process qualified?

Coming hurdle: Accommodating adaptive AM processes
- Move from qualifying process to qualifying algorithm
- Increased reliance on pre-production article evaluations

9

Material Property Transferability

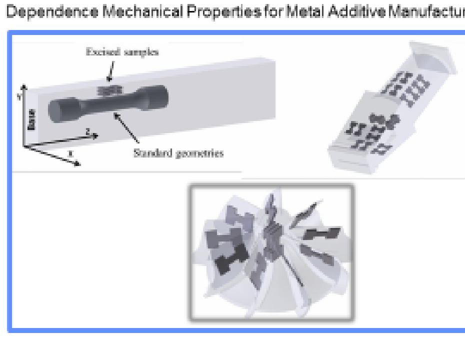
Standardization Need: Establishing Material Property Transferability

- Evaluation of standard specimens for mechanical properties in tensile, fatigue, and fracture mechanics developed by AM processes
  - **Standard specimens will be used to establish engineering design values**
- How do properties vary within AM parts?
- Essential to association of process qualification to part qualification
- Critical to know properties within part are represented by characterization

Critical aspects in structural integrity:

- **Witness specimen correlation**
- **"Influence factors" in AM materials**
  - **Thermal history in build**
  - **Surface texture**
  - **Thin section capability**
- Capability and reliability of thermal post-processing to homogenize and control microstructural evolution to lessen transferability risk.

ASTM F42.01 Work Item WK49229: Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing



10

NDE Standardization in AM

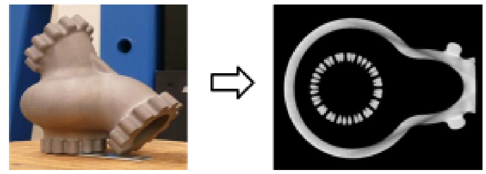
Standardization Need: Non-destructive Evaluation for AM

E07.10 Work Item – WK47031: *Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build*

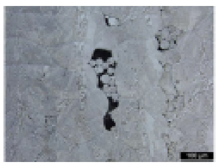
F42.01 Work Item – WK56649: *Standard Practice/Guide for Intentionally Seeding Replica into Additively Manufactured (AM) Structures*

High Priority: *Defect Catalog for AM*

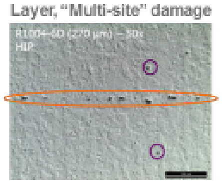
- Analogous to references used to identify defects in casting or welding
- Correlation of defect type to AM process, NDE method, and reliability of detection
- Correlation of defect risk to structural integrity



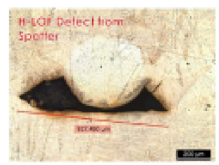
Vertical Lack-of-Fusion



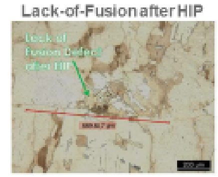
Layer, "Multi-site" damage



Horizontal Lack-of-Fusion



Zero-volume Lack-of-Fusion after HIP



Near-term Reliance on CT

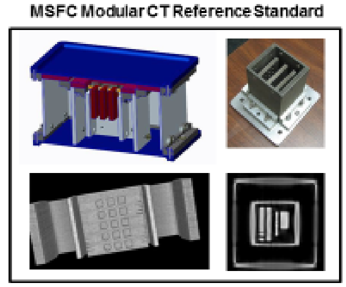
Standardization Need: Computed Tomography (CT) with Quantified Reliability

For aerospace, CT is not an industry standard technique with quantified reliability for detection of defects – Probability of Detection (POD)

Current state of the art: reliance on Representative Quality Indicators (RQIs)

- See ASTM E1817 *Standard Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)*

MSFC Modular CT Reference Standard



AM Complications for CT:

- Penetration vs resolution
- Complex AM geometry
- Low-volume defects
- Physics: beam hardening, edge artifacts, etc.
- Makes generalization difficult

Planned work in E07.01 Radiography

- Build on 2D CT and DR standards
- Application to structural integrity requirements such as POD methods may require broader cooperative efforts

Numerical CT simulations may help with defining detection capability and uncertainty quantification.

Coming Reliance on In-Situ Monitoring

How to approach in-situ monitoring of AM processes?

- Harnessing the technology is only half the battle
  - Detectors, data stream, data storage, computations
- Second half of the battle is quantifying in-situ process monitoring **reliability**

Community must realize passive in-situ monitoring is an NDE technique

1. Understand physical basis for measured phenomena
2. Proven causal correlation from measured phenomena to a well-defined defect state
3. Proven level of reliability for detection of the defective process state
   - False negatives and false positives → understanding and balance is needed

Closed loop in-situ monitoring adds significantly to the reliability challenge

- No longer a NDE technique – *may not be non-destructive*
- Establishing the reliability of the algorithm used to interact and intervene in the AM process adds considerable complexity over passive systems

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Final Summary

1. Additive Manufacturing Standards Landscape
   - Diverse and developing rapidly, still limited in detail for structural integrity challenges
2. Integration of structural integrity rationale in AM
   - Essential to understanding risks on a part-by-part basis
3. Process qualifications – standardization
   - AM process qualification needs standard definition
4. Material property transferability
   - Applicability of design values depends upon methods to understand property transferability from coupon to part
5. NDE standardization status in AM
   - Primary, quantifiable reference for structural integrity. Active work items in E07
6. Near-term reliance on computed tomography
   - Needs methodologies to quantify reliability, particularly for low-volume defects
7. Coming reliance on in-situ monitoring
   - Potential great enabler for structural integrity, but caution required.

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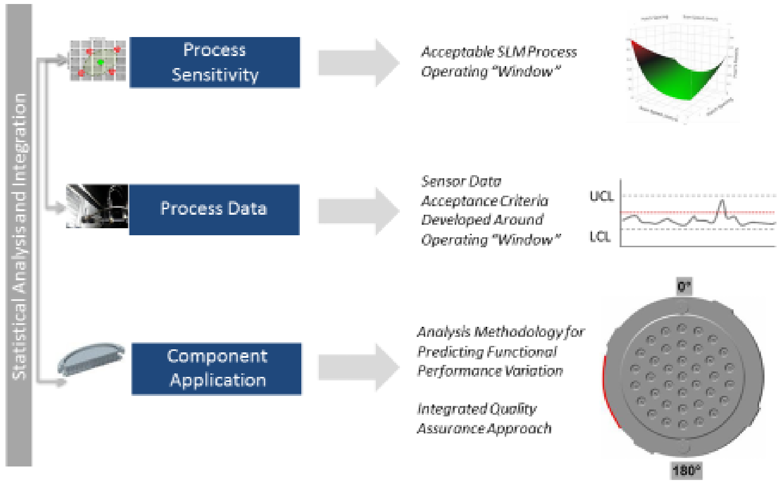
Example of development: In-Situ Monitoring

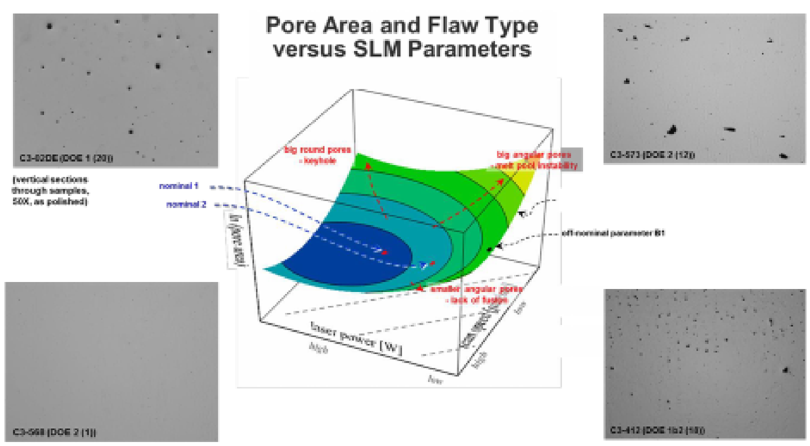
Additive Manufacturing Qualification Process



Used with Permission: Nick Mulé
Distribution Statement A: Approved for Public Release

15

Example of development: In-Situ Monitoring



Flaw types clearly defined and correlated with pore area gradient.

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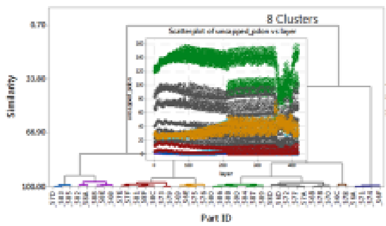
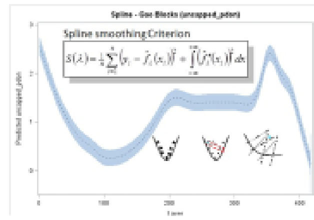
Example of development: In-Situ Monitoring

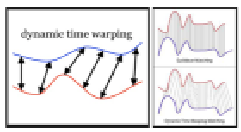
Unique Off-Nominal Signatures



Process Limit Approach Developed



Cluster Analysis Methodology



- Unique part signatures are generated for DOE processing condition and identified as discernably different than the nominal response
- Methodology to establish control limits around the nominal part signature

Unique Signatures Generated and Discernable For Each DOE Processing Condition

AEROJET ROCKETDYNE Used with Permission: Nick Mulé
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Thank You

Additive Manufacturing at MSFC

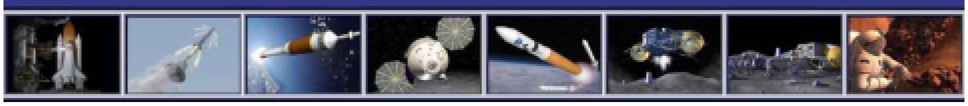
4.26 **NDE & Inspection Challenges for Additively Manufactured Components (Jess Waller, NASA-WSTF)**

NDE and Inspection Challenges for Additively Manufactured Components

Jess M. Waller • NASA-JSC WSTF

NRC Additive Manufacturing Public Meeting
Session 4

Tuesday, Nov. 28, 2017
1330 Eastern Time
UTC-05:00



BACKGROUND

- On paper, the merits of additive manufacturing are compelling. For example, because of real (and perceived) gains:
  - reduced waste
  - simpler (fewer welds) yet highly optimized designs (topology optimization)
  - reduced production lead time
  - lighter weight

  AM parts are being actively considered at NASA and its commercial space partners for flight critical rocket engine and structural applications.
- However, numerous technology gaps prevent full, reliable, and safe use of this technology. Important technology gaps are:
  - integrated process control (in-situ monitoring during build)
  - material property controls (input materials, qualified material processes)
  - mature process-structure property correlations (design allowables data)
  - mature effect-of-defect (includes fracture mechanics)
  - mature quality control measures (includes NDE tailored to AM)

2

Metallic Aerospace AM Parts – Example 1

NASA's rocket injectors manufactured with traditional processes would take more than a year to make, but with new 3D printing processes, the parts can be made in less than four months, with a 70 percent **reduction in cost**.

Using traditional manufacturing methods, 163 individual parts would be made and then assembled. But with 3D printing technology, **fewer parts** (2) were required, saving time and money and allowing engineers to build parts with **enhanced performance** and are **less prone to failure**.

28-element Inconel® 625 fuel injector built using an laser powder bed fusion (L-PBF) process

Metallic Aerospace AM Parts – Example 2

GE Aviation will install 19 fuel nozzles into each Leading Edge Aviation Propulsion (LEAP) jet engine manufactured by CFM International, which is a joint venture between GE and France's Snecma. CFM has orders for 6000 LEAPs.

Lighter – the weight of these nozzles will be 25% lighter than its predecessor part.

Simpler design – reduced the number of brazes and welds from 25 to 5.

New design features – more intricate cooling pathways and support ligaments will result in 5X higher durability vs. conventional manufacturing.

"*Today, post-build inspection procedures account for as much as 25 percent of the time required to produce an additively manufactured engine component,*" said Greg Morris, GE Aviation's business development leader for AM. "*By conducting those inspection procedures while the component is being built, (we) will **expedite production rates** for GE's additive manufactured engine components like the LEAP fuel nozzle.*"

GE Leap Engine fuel nozzle. CoCr material fabricated by direct metal laser melting (DMLM), GE's acronym for DMLS, SLM, etc.

BACKGROUND

- America Makes, ANSI, ASTM, NASA and others are providing key leadership in an effort linking government and industry resources to speed adoption of aerospace AM parts.
- Participants include government agencies (NASA, USAF, NIST, FAA), industry (commercial aerospace, NDE manufacturers, AM equipment manufacturers), standards organizations and academia.
- NDE is identified as a universal need for all aspects of additive manufacturing.

5

Key Documents to Improve Reliability and Safety of Metal AM Parts

split into 2 documents

6

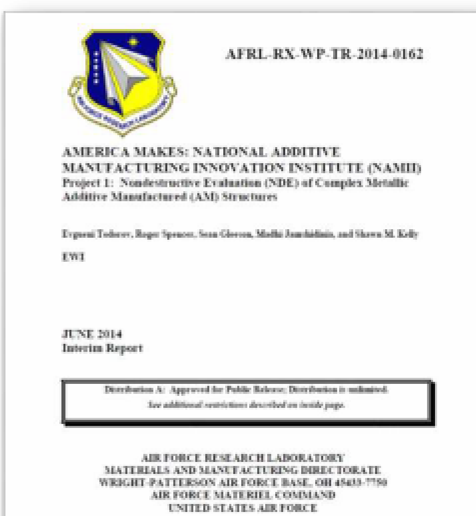
Key NASA AM Qualification & Certification Documents (cont.)

July 2015

released
October 18, 2017

7

USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures



Contact: *Evgueni Todorov (EWI)*

- Early results on NDE application to AM are documented.
- Report has a ranking system based on **geometric complexity of AM parts to direct NDE efforts**.
- Approach laid out for future work based on CT and PCRT and other NDE techniques.

8

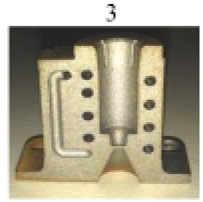
Effect of AM Part Complexity on NDE

Most NDE techniques can be used for Complexity Groups[§] 1 (Simple Tools and Components) and 2 (Optimized Standard Parts), some for Group 3 (Embedded Features); only Process Compensated Resonance Testing and Computed Tomography can be used for Groups 4 (Design-to-Constraint Parts) and 5 (Free-Form Lattice Structures):

1

2

3



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5

[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures

NDE options for design-to-constraint parts and lattice structures: LT, PCRT and CT/µCT

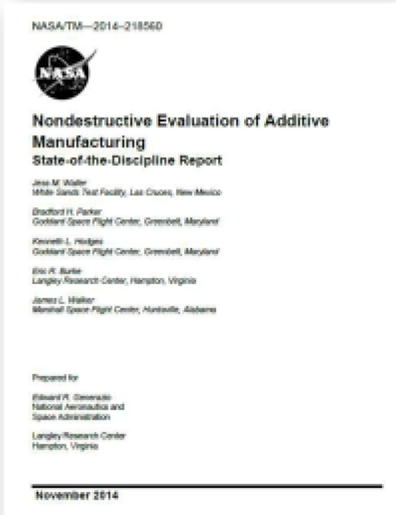
NDE Technique	Geometry Complexity Group					Comments
	1	2	3	4	5	
VT	Y	Y	P[a]	NA	NA	
LT	NA	NA	Y	Y	NA	Screening
PT	Y	Y	P[a]	NA	NA	
PCRT	Y	Y	Y	Y	Y	Screening; size restrictions (e.g., compressor blades)
EIT	Y	Y	NA	NA	NA	Screening; size restrictions
ACPD	Y	Y	P[c]	NA	NA	Isolated microstructure and/or stresses
ET	Y	Y	P[c]	NA	NA	
AEC	Y	Y	P[c]	NA	NA	
PAUT	Y	Y	P[b]	NA	NA	
UT	Y	Y	P[b]	NA	NA	
RT	Y	Y	P[d]	NA	NA	
X-Ray CT	Y	Y	Y	Y	NA	
X-ray Micro CT	Y	Y	Y	Y	Y	

Key:
Y = Yes, technique applicable
P = Possible to apply technique given correct conditions
NA = Technique Not applicable

Notes:
(a) Only surfaces providing good access for application and cleaning
(b) Areas where shadowing of acoustic beam is not an issue
(c) External surfaces and internal surfaces where access through conduits or guides can be provided
(d) Areas where large number of exposures/shots are not required

[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

NASA/TM-2014-218560 / NDE of AM State-of-the-Discipline Report


NASA/TM—2014–218560

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

Jesse M. Waller
White Sands Test Facility, Las Cruces, New Mexico

Bradford H. Parker
Goddard Space Flight Center, Greenbelt, Maryland

Kenneth L. Hodges
Goddard Space Flight Center, Greenbelt, Maryland

Eric R. Burke
Langley Research Center, Hampton, Virginia

James L. Walker
Marshall Space Flight Center, Huntsville, Alabama

Prepared for
Edward R. Generazio
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

November 2014

Contacts: *Jess Waller (WSTF); James Walker (MSFC); Eric Burke (LaRC); Ken Hodges (MAF); Brad Parker (GSFC)*

- Industry, government and academia were asked to share their NDE experience on AM parts.
- NDE state-of-the-art was documented.
- **NASA Agency efforts catalogued** through 2014.
- NIST and USAF additive manufacturing roadmaps were surveyed and a **technology gap analysis performed**.

11

NASA Agency & Prime Contractor Activity, ca. 2014


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


EBF3 wire-fed system during parabolic flight testing


28-element Inconel 625 fuel injector

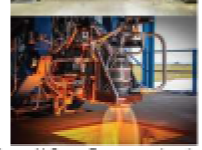

Prototype titanium to niobium gradient rocket nozzle


Made in Space AMF on ISS


ISRU regolith structures


Aerojet Rocketdyne RL-10 engine thrust chamber assembly and injector

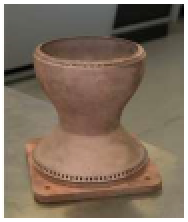

Dynetics/Aerojet Rocketdyne F-1B gas generator injector


SpaceX SuperDraco combustion chamber for Dragon V2

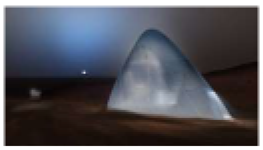
12

NASA Agency & Prime Contractor Activity, Recent

JPL Mars Science Laboratory Cold Encoder Shaft fabricated by gradient additive processes

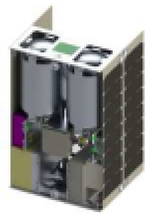


MSFC copper combustion chamber liner for extreme temperature and pressure applications

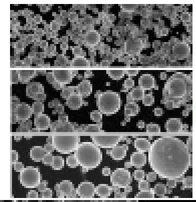


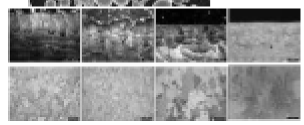
NASA-sponsored 3-D Printed Habitat Challenge Design Competition

MSFC rocket engine fuel turbopump



NASA Space Technology Mission Directorate-sponsored Cube Quest challenge for a flight-qualified cubesat (shown: cubesat with an Inconel 718 additively manufactured diffuser section, reaction chamber, and nozzle)





Additive Manufacturing Structural Integrity Initiative (AMSII) Alloy 718 powder feedstock variability

MSFC Space Launch System NASA's RS-25 core stage engine certification testing

13

NASA/TM-2014-218560 NDE of AM Technology Gap Analysis

NDE-related Technology Gaps:

first
- Develop a defects catalogue
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use 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

somewhere in the middle

last
- Develop NDE-based qualification and certification protocols for flight hardware (screen out critical defects)

14

NDE Challenges for AM parts

AM challenges for NDE specialist:

- Complex geometry (see AFRL-RX-WP-TR-2014-0162)
- Deeply embedded flaws and internal features
- Rough as-built surface (interferes with PT, ET)
- Variable grain structure or metastable microstructure
- Lack of physical reference standards with same material and processing history as AM parts (demonstrate NDE capability)
- Lack of effect-of-defect studies (use sacrificial defect samples)
- Methods to seed flaws are still being developed
- High part anisotropy with 2D planar defects perpendicular to Z-direction
- Critical flaw types, sizes and distributions not established
- Defect terminology harmonization still occurring
- Little (any?) probability of detection (POD) data
- Lack of written NDE procedures for AM parts (area of focus today)
- Lack of mature in-process monitoring techniques
- Process-specific defects can be produced, some unique to AM

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Develop a defect catalogue

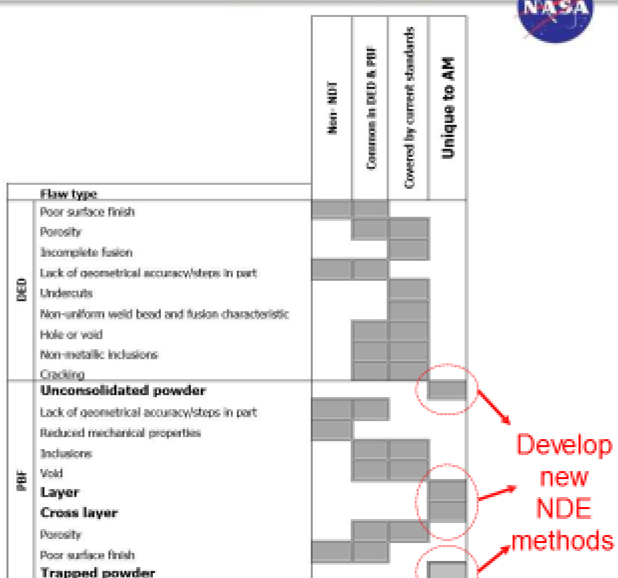
NASA/TM-2014-218560 NDE of AM Technology Gap Analysis

- Develop a defects catalogue
- 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)

17

Defects – Effect of Process[§]

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.



[§] 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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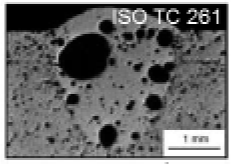
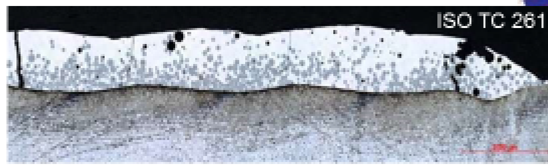
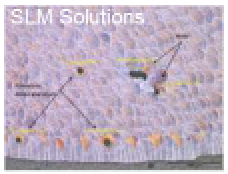
Typical PBF and DED Defects



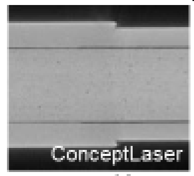
PBF Porosity



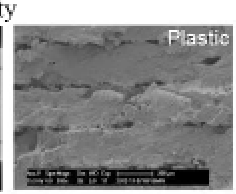
DED Porosity



Porosity and Voids



Voids



Also interested in (gas) porosity and voids due to structural implications

Note: proposed new definitions in ISO/ASTM 52900 Terminology:

lack of fusion (LOF) *n*—flaws caused by incomplete melting and cohesion between the deposited metal and previously deposited metal.

gas porosity, n—flaws formed during processing or subsequent post-processing that remain in the metal after it has cooled. Gas porosity occurs because most metals have dissolved gas in the melt which comes out of solution upon cooling to form empty pockets in the solidified material. Gas porosity on the surface can interfere with or preclude certain NDE methods, while porosity inside the part reduces strength in its vicinity. Like voids, gas porosity causes a part to be less than fully dense.

void, n—flaws created during the build process that are empty or filled with partially or wholly un-sintered or un-fused powder or wire creating pockets. Voids are distinct from gas porosity, and are the result of lack of fusion and skipped layers parallel or perpendicular to the build direction. Voids occurring at a sufficient quantity, size and distribution inside a part can reduce its strength in their vicinity. Voids are also distinct from intentionally added open cells that reduce weight. Like gas porosity, voids cause a part to be less than fully dense.

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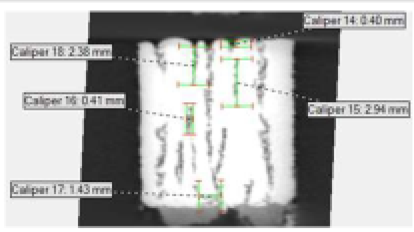
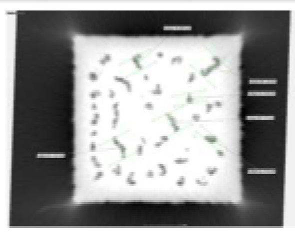
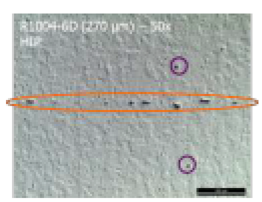
Typical PBF Defects of Interest





Cross layer

Lack of Fusion (LOF)



Layer

Trapped Powder

Also have unconsolidated powder, lack of geometrical accuracy/steps in the part, reduced mechanical properties, inclusions, gas porosity, voids, and poor or rough surface finish

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Use of NDE to Detect Defects of Interest

TABLE 4.3 Application of NDT to Detect Additive Manufacturing Defect Classes [A]

	Covered in this Guide							Not covered in this Guide				
Defect Class	**CT/RT/ CR/DR**	**ECT**	**MET[B]**	**PCRT**	**PT**	**TT**	**UT**	**AE**	**LT**	**ND**	**MT**	**VT**
Surface	X[C]	X[D]	X	...	X[D]	...	...	...	...	...	...	X
Porosity	X	X[D]	...	X	X[D]	...	X	...	...	...	...	X[F]
Cracking	X	X[D]	...	X	X[D]	X	X	X	X[F]	...	X	X
Lack of Fusion	X	X[D]	...	X	X[D]	X	X	X	...	...	X	...
Part Dimensions	X	...	X	...	...	...	...	...	...	...	...	...
Density[G]	X[H]	...	...	...	...	...	...	...	...	...	...	...
Inclusions	X[I]	X[D]	...	...	...	X	X	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	X[D,J]	...	...	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X[F]	...	...	...

[A] Abbreviations used: ... = not applicable, Acoustic Emission, CR = Computed Radiology, CT, = Computed Tomography, Dr = Digital Radiology, ECT = Eddy Current Testing, Leak Testing = LT, MET = Metrology, MT = Magnetic Particle Testing, ND = Neutron Diffraction, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing, VT = Visual Testing.
[B] Includes Digital Imaging.
[C] Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal feature not accessible to MET, PT or VT (including borescopy).
[D] Applicable if on surface.
[E] Macroscopic cracks only.
[F] If large enough to cause a leak or pressure drop across the part.
[G] Pycnometry (Archimedes principle).
[H] Density variations will only show up imaged regions having equivalent thickness.
[I] If inclusions are large enough and sufficient scattering contrast exists.
[J] Residual stress can be assessed if resulting from surface post-processing (for example, peening).

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Defect Causes

- **Bulk Defects**
  - **Lack of Fusion**
    - **Horizontal Lack of Fusion Defect**
      - Insufficient Power
      - Laser Attenuation
      - Spatter
    - **Vertical Lack of Fusion Defect**
      - Large Hatch Spacing o
    - Sh rt Feed
  - **Spherical Poros ity**
    - Keyhole
  - **Welding Defects**
    - Cracking
- **Surface Defects**
  - **Worm Track**
    - High Energy Core Parameters
    - Re-coater Blade interactions
  - **Core Bleed Through**
    - Small Core Offset
    - Overhanging Surface
  - **Rough Surface**
    - Laser Attenuation
    - Overhanging Surfaces
  - **Skin Separation**
    - Sub-Surface Defects
    - Detached Skin

- The list to the left is color coded to show the know causes of the defects
- Although some defects are tolerable, many result in the degradation of mechanical properties or cause the part to be out of tolerance
- Most defects can be mitigated by parameter optimization and process controls

- **Parameters**
- **In-Process Anomaly**
- **Material Property**

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Defect Consequences

- **Bulk Defects**
  - **Lack of Fusion**
    - **Horizontal Lack of Fusion Defect**
      - Insufficient Power
      - Laser Attenuation
      - Splatter
    - **Vertical Lack of Fusion Defect**
      - Large Hatch Spacing
    - Short Feed
  - **Spherical Porosity**
    - Keyhole
  - **Welding Defects**
    - Cracking
- **Surface Defects**
  - **Worm Track**
    - High Energy Core Parameters
    - Re-coater Blade interactions
  - **Core Bleed Through**
    - Small Core Offset
    - Overhanging Surface
  - **Rough Surface**
    - Laser Attenuation
    - Overhanging Surfaces
  - **Contour Separation**
    - Sub-Surface Defects
    - Detached Skin

- Defects are color coded to show the effect-of-defect on part performance.
- Trade-offs were noted, for example, reducing the offset to eliminate the contour separation defects results in the hatch from the core bleeding through the contour. As a result the part will not look as smooth but will perform better.

- **Degradation of Mechanical Properties**
- **Minor or No Observed effect on performance**
- **Out of Tolerance**
- **Unknown**

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NDE of AM
Voluntary Consensus Standards

NASA/TM-2014-218560 NDE of AM Technology Gap Analysis

- Develop a defects catalogue
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use 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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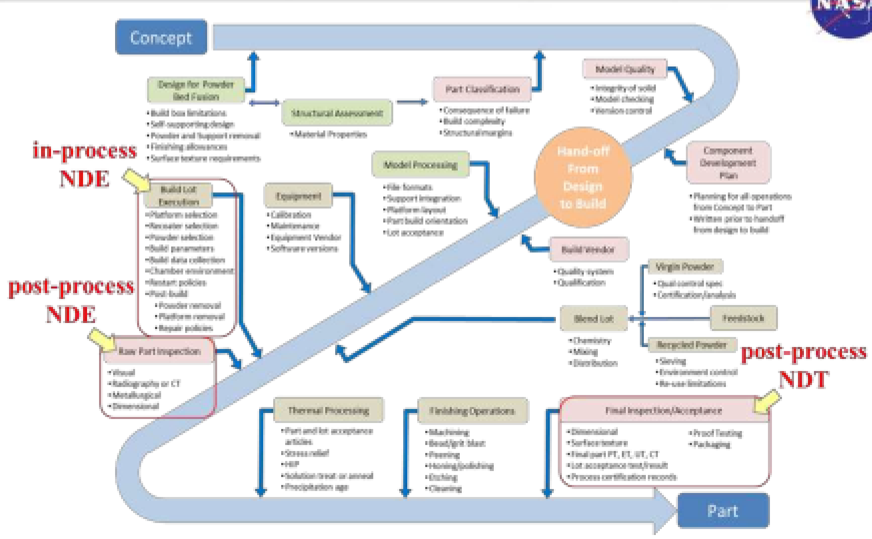
NDE of AM Parts relative to Life Cycle



- In-process monitoring/optimization
- Post-manufacturing inspection
- Receiving inspection

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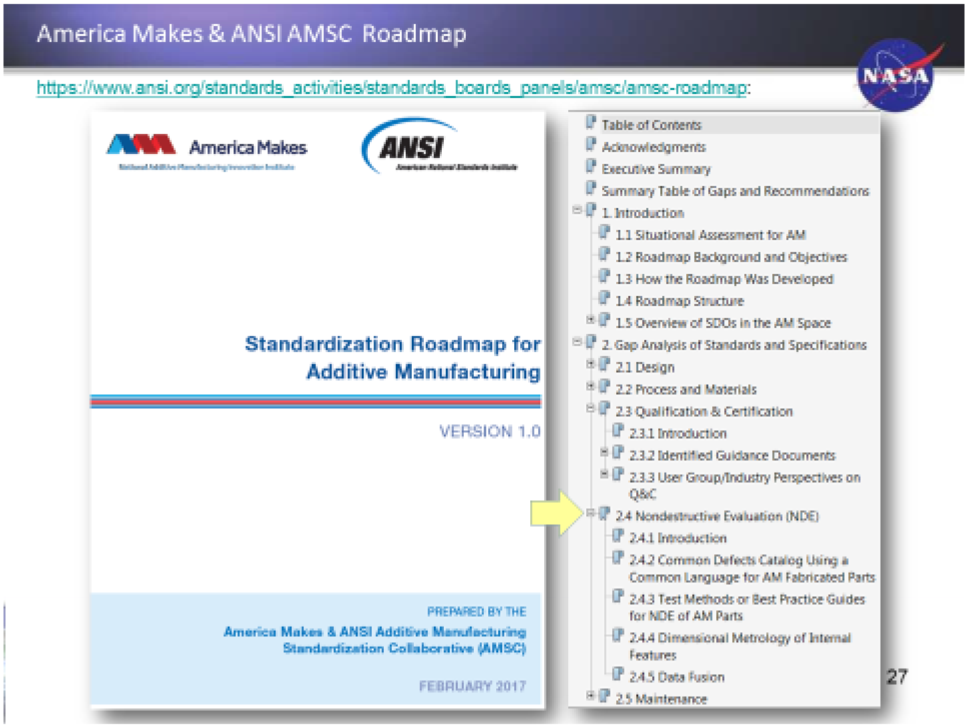
America Makes & ANSI AMSC Roadmap
https://www.ansi.org/standards_activities/standards_boards_panels/amsc/amsc-roadmap:
America Makes
ANSI
Standardization Roadmap for Additive Manufacturing
VERSION 1.0
PREPARED BY THE
America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)
FEBRUARY 2017
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1.1 Situational Assessment for AM
1.2 Roadmap Background and Objectives
1.3 How the Roadmap Was Developed
1.4 Roadmap Structure
1.5 Overview of SDOs in the AM Space
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2.1 Design
2.2 Process and Materials
2.3 Qualification & Certification
2.3.1 Introduction
2.3.2 Identified Guidance Documents
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2.4 Nondestructive Evaluation (NDE)
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2.4.2 Common Defects Catalog Using a Common Language for AM Fabricated Parts
2.4.3 Test Methods or Best Practice Guides for NDE of AM Parts
2.4.4 Dimensional Metrology of Internal Features
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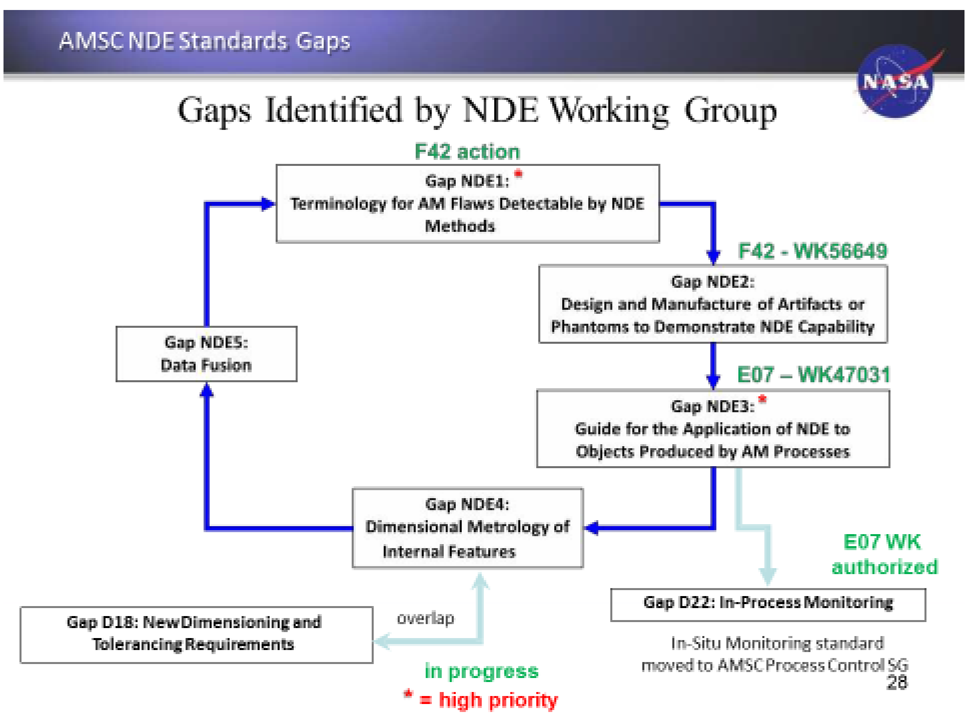
AMSC NDE Standards Gaps
Gaps Identified by NDE Working Group
F42 action
Gap NDE1: *
Terminology for AM Flaws Detectable by NDE Methods
F42 - WK56649
Gap NDE2:
Design and Manufacture of Artifacts or Phantoms to Demonstrate NDE Capability
E07 – WK47031
Gap NDE3: *
Guide for the Application of NDE to Objects Produced by AM Processes
Gap NDE4:
Dimensional Metrology of Internal Features
Gap NDE5:
Data Fusion
E07 WK authorized
Gap D22: In-Process Monitoring
In-Situ Monitoring standard moved to AMSC Process Control SG
Gap D18: New Dimensioning and Tolerancing Requirements
overlap
in progress
* = high priority
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Gap NDE3: ASTM E07.10 WK47031 balloting status

CT, ET, MET, PCRT, PT, RT, TT, and UT sections

- ANSI/America Makes AMSC Gap NDE3
- ECT section added
- Re-balloted 7/14/27, closing date 8/14/17
- 1 negative/7 comments being resolved/incorporated

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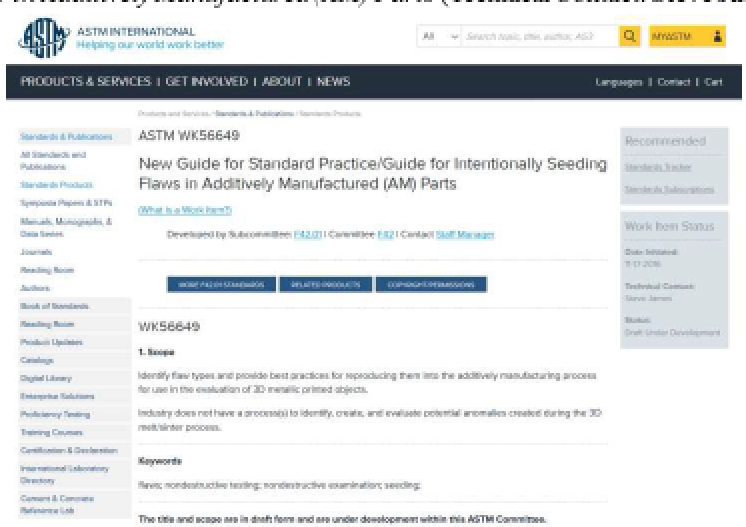
Gap NDE2: ASTM F42 Work Item WK56649

- ASTM F42 Work Item WK56649*: Standard Guide for Intentionally Seeding Flaws in Additively Manufactured (AM) Parts* (Technical Contact: **Steve James**)



https://www.astm.org/WorkItems/WK56649.htm

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Gap NDE2: ASTM F42 Work Item WK56649

- ASTM F42 Work Item WK56649*: Standard Guide for Intentionally Seeding Flaws in Additively Manufactured (AM) Parts* (Technical Contact: **Steve James**)

- In CA member review
- discussed at the ASTM F42/ISO TC 261 meeting in September
- Plans are in work to initiate balloting in F42 this year

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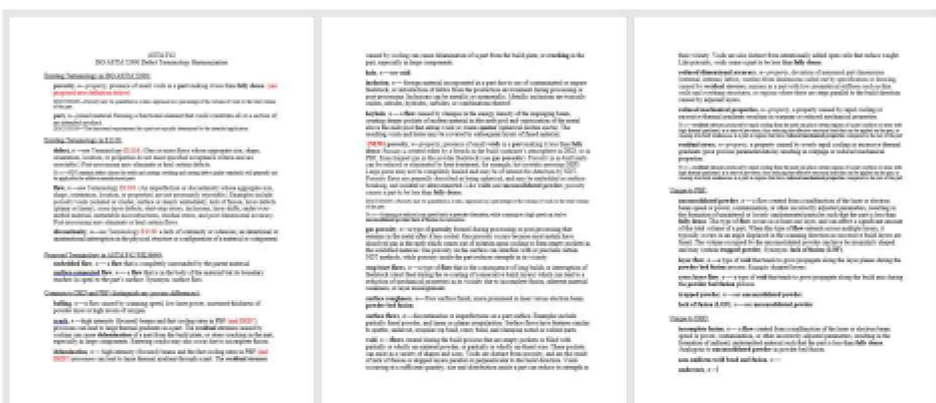
Gap NDE1: ASTM F42 Terminology for AM Flaws Detectable by NDE

Proposed Terminology:



- Request made for an editorial comparison of defect terms already in ASTM.
- Goal is to use terminology that already exists to save time and effort needed versus developingnew definitions.
- F42 and ISO TC 261 are considering balloting of the above terms in the ASTM/SIO 52900 terminology standard, and to put these terms high on the list for consideration.

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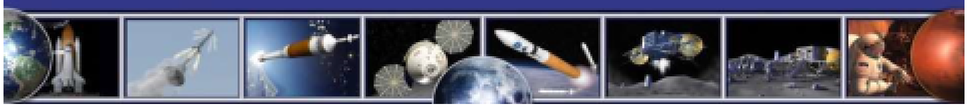
Round Robin Testing

1) Physical Reference Standards
2) Effect-of-Defect



NASA/TM-2014-218560 NDE of AM Technology Gap Analysis

- Develop a defects catalogue
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use parts
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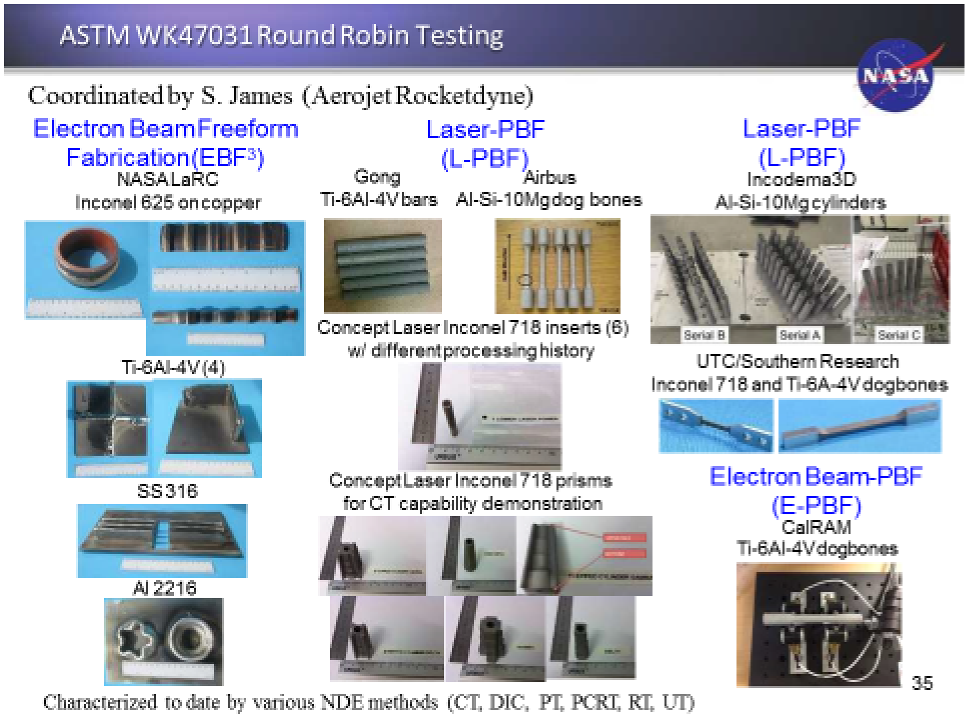
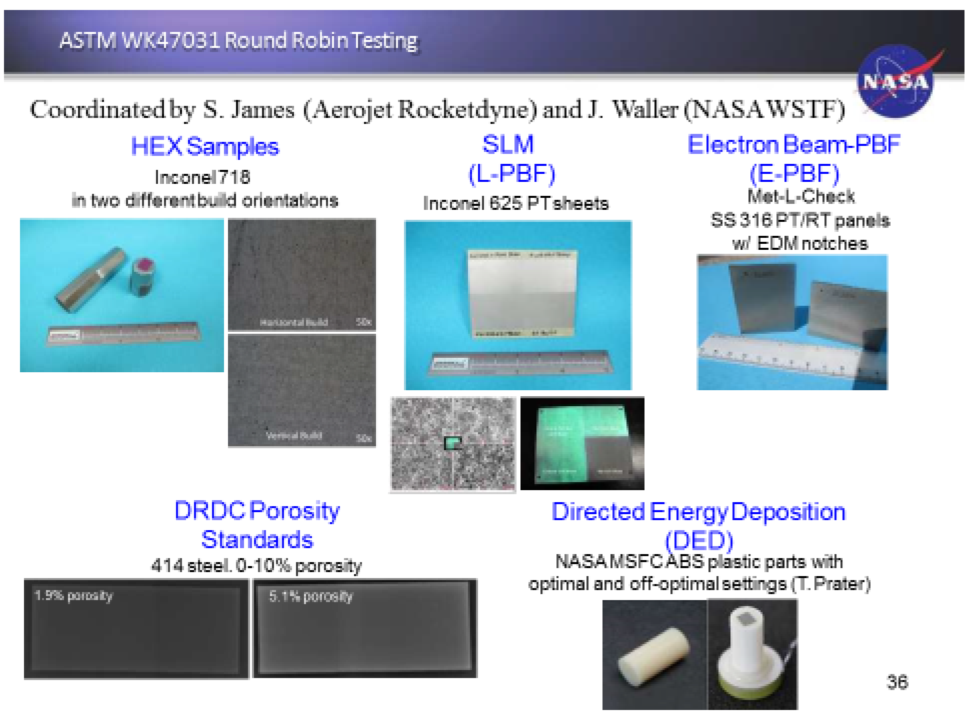
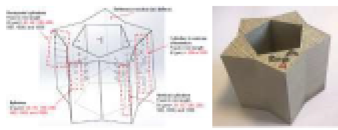

ASTM WK47031 Round Robin Testing
Coordinated by S. James (Aerojet Rocketdyne)
Electron Beam Freeform Fabrication (EBF3)
NASA LaRC
Inconel 625 on copper
Ti-6Al-4V (4)
SS316
Al 2216
Laser-PBF (L-PBF)
Gong
Ti-6Al-4V bars
Airbus
Al-Si-10Mg dog bones
Concept Laser Inconel 718 inserts (6) w/ different processing history
Concept Laser Inconel 718 prisms for CT capability demonstration
Laser-PBF (L-PBF)
Incodema3D
Al-Si-10Mg cylinders
Serial B
Serial A
Serial C
UTC/Southern Research
Inconel 718 and Ti-6A-4V dogbones
Electron Beam-PBF (E-PBF)
CalRAM
Ti-6Al-4V dogbones
Characterized to date by various NDE methods (CT, DIC, PT, PCRT, RT, UT)
35


ASTM WK47031 Round Robin Testing
Coordinated by S. James (Aerojet Rocketdyne) and J. Waller (NASA WSTF)
HEX Samples
Inconel 718
in two different build orientations
Horizontal Build
Vertical Build
SLM (L-PBF)
Inconel 625 PT sheets
Electron Beam-PBF (E-PBF)
Met-L-Check
SS 316 PT/RT panels
w/ EDM notches
DRDC Porosity Standards
414 steel. 0-10% porosity
1.9% porosity
5.1% porosity
Directed Energy Deposition (DED)
NASA MSFC ABS plastic parts with optimal and off-optimal settings (T. Prater)
36

ASTM WK47031 Round Robin Testing

Coordinated by B. Dutton (MTC)

Star artefacts
(L-PBF)
Inconel, Ti-6Al-4V



Air foil
(L-PBF)
Inconel

Star artefact
(E-PBF)
Ti-6Al-4V

Aluminum planned

ASTM Round Robin Report being compiled by S. James
(post review copy on WK47031 CA in December)

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ASTM WK47031 Effort: CT of Concept Laser Samples in North America

CT Round Robin Testing (Previously Evaluated)

Europe; The Fraunhofer Development Center X-ray Technology, Yxlon, GE
Japan; JAXA

Planned Evaluation (12)
N America; NASA MSFC, LMCO, Pratt & Whitnet/UTC, NASA GSFC, Boeing (two locations), GE Aviation, JHUAPL, Yxlon, UTAS, EWI, Vibrant EWI

Preplanning – Participation Rules

- Samples will be shipped as one set
- Two Week loan period
- Present findings at WK47031 Link Call
- Provide presentation to WK47031
- Ship to next participant on list

Proposed Schedule

Affiliation	Date
JHUAPL	7/31 – 8/11
NASA	8/16 – 8/30
UTAS	9/4 – 9/15
PW	9/20 – 10/4
EWI	10/9 – 10/20
Boeing	10/25 – 11/8
NASA	11/13 – 12/1
AF	12/6 – 12/20
NSI	1/3 – 1/17

List with addresses will accompany the samples

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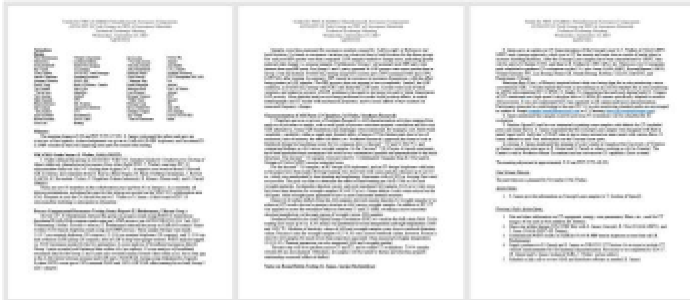
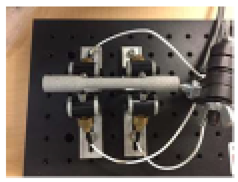
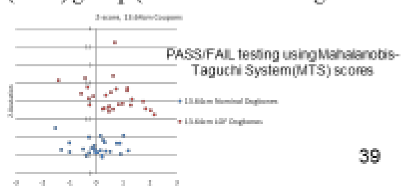


September Webmeeting Round Robin Sample Activity

Vibrant statused the group on PCRT evaluation of three groups of CalRAM Ti6-4 tensile dogbones made using an E-PBF process: 1) 10.7-cm nominal dogbones, 2) 13.6-cm nominal dogbones, and 3) 13.6-cm lack of fusion (LOF) group (area of LOF in dog bone gauge section).





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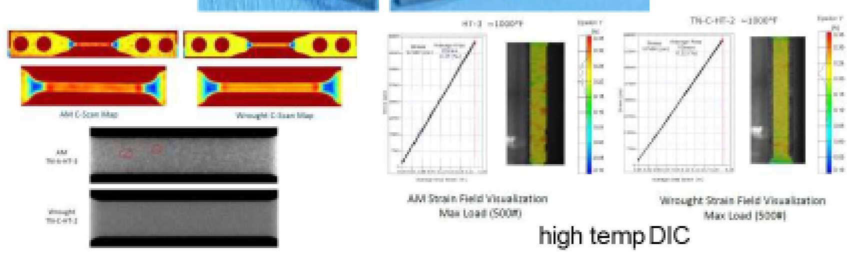
ASTM WK47031 Round Robin Activities / Sept. 27, 2017 telecon

September Webmeeting Round Robin Sample Activity (cont.)

- Southern Research reported on process-structure-property correlation and low-cost NDE alternatives on nominal and off-nominal AM sacrificial tensile specimens made with two common alloys (Inconel® 718 and Ti-6Al-4V, plus wrought controls). So far, Inconel® (Cluster A) specimens have been machined from rectangular bar stock in two orientations (parallel and perpendicular to the build direction) and characterized by RT, UT, and high temperature Digital Image Correlation (DIC).



- The next telecon will be November 15, 2017 at 11:00 a.m. EST

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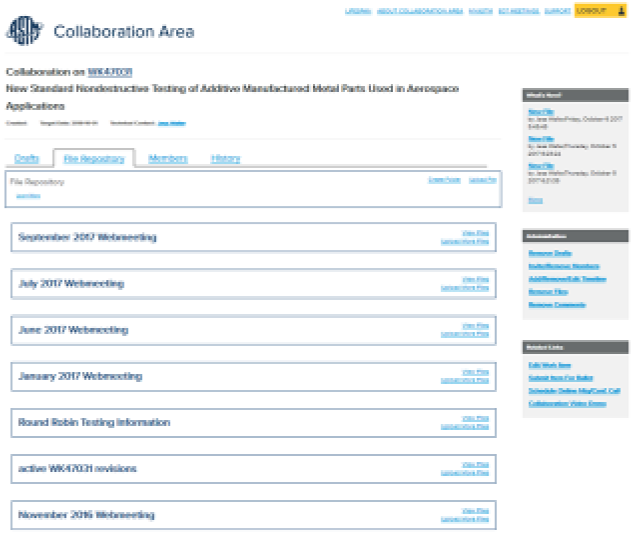
ASTM E07.10 WK47031 Round Robin Testing Online Collaboration Area

Working drafts of the Standard Guide, meeting minutes, and round-robin testing activity presentations are posted on-line:



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Qualification & Certification

Qualification & Certification/NASA MSFC Guidance

Contact: *Doug Wells (MSFC)*

- Provides a consistent framework for the development, production, and evaluation of AM spaceflight parts.
- 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 and effect-of-defect are still emerging

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

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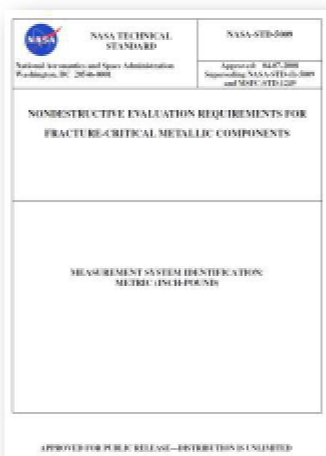
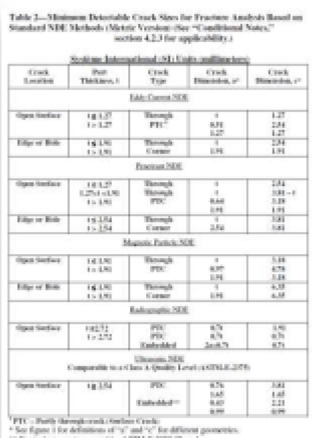
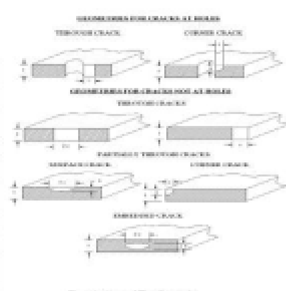
Fracture Critical Metal AM Part Requirements

Fracture critical damage tolerant metal AM hardware must meet NDE requirements given in NASA-STD-5009§; however, the 5009 90/95 POD flaw types and sizes are generally inappropriate for AM.







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

Qualification & Certification/NASA MSFC Guidance

MSFC-STD-3716

Lists process and part production control **requirements**:

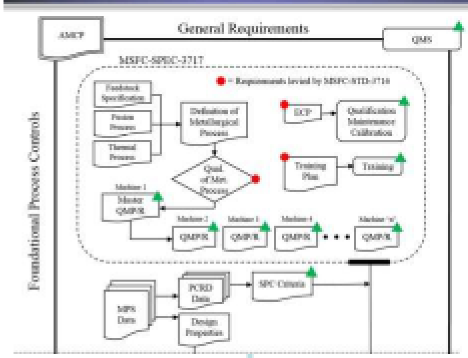
- Qualified Metallurgical Process
- Equipment Control
- Personnel Training
- Material Property Design Values
- Part Design and Production Control Requirements

MSFC-SPEC-3717

Contains **procedures** for implementing the requirements in 3616:

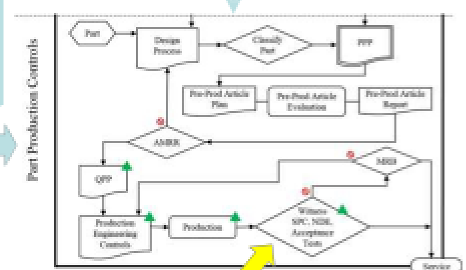
- Qualified Metallurgical Process
- Equipment Control
- Personnel Training

Overview of MSFC-STD-3716 Standard



Process Controls provide the basis for reliable part design and production

Part Production Controls are typical of aerospace operations and include design, part classification, pre-production and production controls



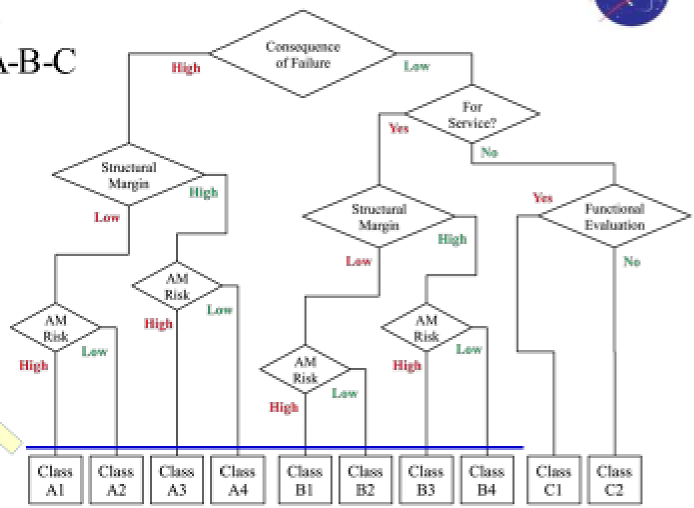
NDE decisional point

- ▲ Identifies key points of QMS involvement.
- ● Identifies PBF requirements levied by MSFC-STD-3716 with procedures in MSFC-SPEC-3717
- ⊗ Negative outcome of decisional action

Qualification & Certification/NASA MSFC Guidance

NASA AM Part Classification A-B-C

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.

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Acknowledgments

CT/MET, MSFC/J. Walker
*metal SLM parts, MSFC/K. Morgan, B. West, Brown, A.
*ABS plastic parts, MSFC/N. Werkheiser, T. Prater
CT, GSFC/J. Jones
*EBF³ metal parts, LaRC/K. Taminger
— NASA

POD/NDE of AM, ESA/G. Sinnema, M. Born, L. Pambaguian — ESA
CT, JAXA/S. Hori, T. Nakagawa, M. Mitsui, H. Kawashima — JAXA

AE, MRI/E. Ginzel
CT/acoustic microscopy, Honeywell/S. Singh
UT/PT, Aerospace Rocketdyne/S. James
CT/RT, USAF/J. Brausch, K. LaCivita
CT, Fraunhofer/C. Kretzer
CT, GE Sensing GmbH/T. Mayer
PCRT, Vibrant Corporation/E. Biedermann
PT, Met-L-Check/M. White
RT, UT, DIC, Southern Research/J. Chambers, M. Parks
NRUS, LANL/M. Remillieux
— Commercial/Gov NDE

*Concept Laser/M. Ebert
*DRDC/S. Farrell
†*Airbus/A. Glover
*Incodema3D/A. Krishnan, S. Volk
†*CalRAM/S. Collins
†*UTC/J. Middendorf, G. Loughnane
— Commercial/Gov AM Round Robin Sample Suppliers

* delivered or committed to deliver samples
† E8 compliant or tensile sacrificial dogbone samples

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4.27 Measurement Science for Metals-Based Additive Manufacturing (Kevin Jurrens, NIST)

National Institute of Standards and Technology (NIST)

- National Metrology Institute for the United States
- Mission:

  Topromote U.S. innovation and industrial competitiveness by advancing **measurement science, standards**, and **technology** in ways that enhance economic security and improve our quality of life

MSAM 2

Role of NIST Research Laboratories

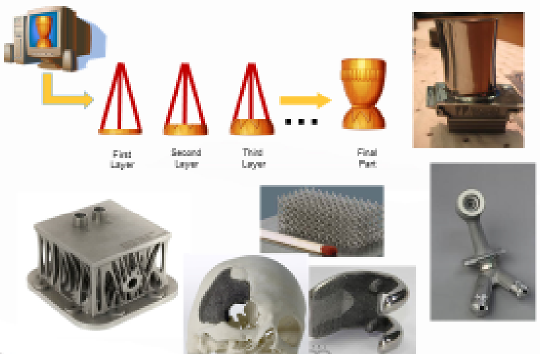
- Emphasis on infrastructural metrology and non-proprietary, standardized metrology methods that address a broad class of measurement challenges
- Emphasis on rigorous and generic procedures to characterize measurement uncertainty that comply with international standards
- Long-term commitment, expertise, and neutrality essential for harmonized and unbiased national and international standards
- Leverage NIST core competences in measurement science, rigorous traceability, and development and use of standards -- as well as specific expertise in measurements and standards for manufacturing systems, processes, and equipment

➢ **Measurements and Standards**

MSAM 3

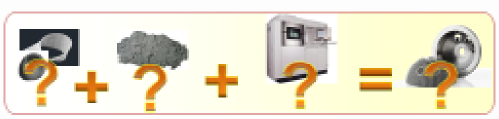
Why Focus on Additive Manufacturing?

<u>Definition:</u> The process of joining materials, usually layer upon layer, to make objects from 3D model data.

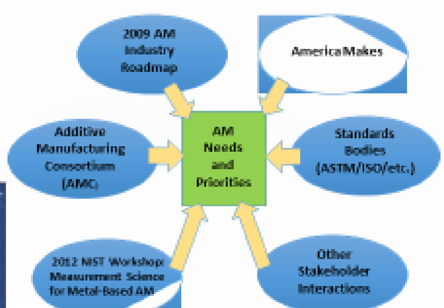


- AM provides rapid art-to-part capability of fabricating **complex, high-value, highly-customized parts** – significant revolutionary potential for U.S. manufacturing
- Worldwide AM products and services - $ 5.1 B (Wohler's report)
  - **5 fold growth in the past 6 years!**
- U.S. market for AM is currently about $ 2 B
- Metal-based AM is still in its infancy for applications in aerospace, biomedical, dental, and automotive industries
- Much momentum and rapid changes – the AM industry is poised for growth, innovations, and new products

Measurement Science Needs for AM



Uncertainties in <u>feedstock material</u> characteristics coupled with uncertainties in the <u>AM process</u> lead to uncertainties in the <u>final product</u>

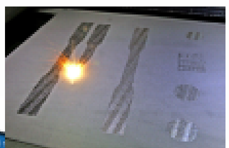


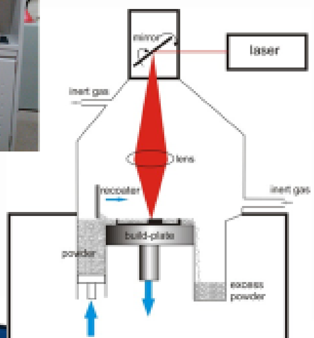
Major barriers to broad adoption of AM include:

- Limited material types and **unknown / non-uniform properties**
- Lack of **process repeatability** and inconsistent system performance
- Consensus protocols and test data for **qualification and certification** do not exist
- Insufficient **part accuracy** without significant post-processing
- Insufficient **surface finish**
- Lack of **AM standards**
- **Insufficient data** to develop robust material specifications
- Need for improved **non-destructive evaluation methods** for complex defects and part geometry
- Requirements for secondary post-processing
- Lack of AM-specific **design tools / design guidelines** to take advantage of new AM capabilities

NIST Measurement Science for Additive Manufacturing (MSAM) Program

- Measurement science advancements in four program thrust areas
- Focus on metals-based AM processes and systems
- Goal: Enable rapid design-to-product transformation



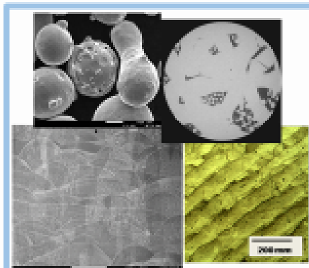


Laser Powder Bed Fusion Process

Program thrusts:

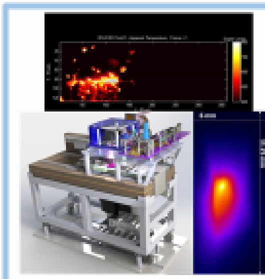
- Characterization of AM Materials
- Qualification of AM Materials, Processes, and Parts
- Real-Time Monitoring and Control of AM Processes
- Systems Integration for AM

MSAM Projects



Characterization of Additive Manufacturing Materials

Deliver new standardized feedstock and AM-built material **characterization methods, exemplar data, and databases** to accelerate the design and use of additive manufacturing parts in high-performance applications (e.g., critical parts in high-stress applications such as turbine blades or engine components).

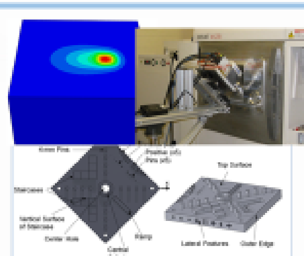


Real-Time Monitoring and Control of Additive Manufacturing Processes

Develop **process metrology, in-process sensing methods, and real-time process control approaches** to maximize part quality and production throughput in Additive Manufacturing (AM).

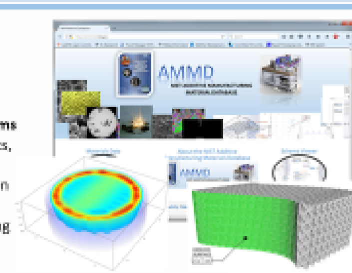
Qualification for Additive Manufacturing Materials, Processes, and Parts

Develop **test methods and protocols, provide reference data, and establish requirements** to reduce the cost and time to qualify AM materials, processes, and parts.



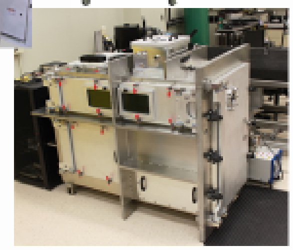
Systems Integration for Additive Manufacturing

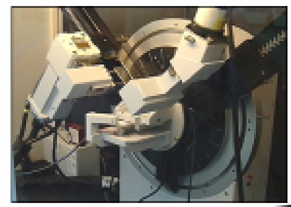
Deliver an **information systems architecture,** including metrics, information models, and **validation methods** to shorten the design-to-product cycle time in additive manufacturing (AM).



Research Testbeds and Facilities

- Additive Manufacturing Research Center (AMRC)
- Commercial AM platforms
  - EOS M270, EOS M290
  - Optomec LENS MR7, ExOne
- AM Metrology Testbed (AMMT)
- Powder Characterization Laboratory
  - Dynamic imaging for particle size distribution
  - Laser flash for thermal properties
  - Rheometer and powder spreading test platform
- Post-processing and testing facilities
  - High temperature heat treatment furnace, electrical discharge machining
  - X-ray computed tomography, white light interferometry, mechanical testing, electron microscopes





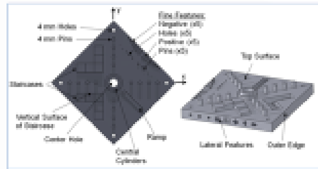
Interactions and Collaborations

- **NIST internal collaborations**
  - **Materials Measurements Laboratory** – AM material property measurements, material testing and modeling
  - **Center for Neutron Research** – neutron imaging, residual stress measurements
  - **Physical Measurements Laboratory** – thermal emissivity measurements for AM processes, laser power measurements
  - **Information Technology Laboratory** – statistical analysis of AM Round Robin studies, AM Materials Database development
  - **Manufacturing Extension Partnership** – industry outreach
  - **Office of Advanced Manufacturing Programs** – Measurement science for advanced manufacturing awards
- **Consortia**: America Makes, Additive Manufacturing Consortium, GO Additive, AM-Bench
- **Roadmapping Activities**: America Makes, ANSI/AMSC, DoD/SOCOM, AMTech
- **Federal collaborators**: LLNL, ORNL, CIA, BIS, GAO, DARPA, AFRL, ARL, NRL, NSF, NASA, DOE, FAA
- **Industry**: GE Aviation and GE Global Research, Honeywell Aerospace, Pratt & Whitney, Carpenter Powder, NCMS, APL, ExOne, Northstar, Nikon, Xometry, TA Instruments, 3DSIM, SigmaLabs, Granta, EWI, and others
- **Academia**: CMU, Virginia Tech, NC State, Penn State, Rutgers, UT Austin, U of Arkansas, U of Alabama, NIU, U of Michigan, U of Louisville, U of Nebraska, U Mass, UNCC, UDC, U of Maryland, Purdue, and others
- **Local outreach**: National Maker Faire, Capitol Hill Maker Faire, US Science and Engineering Festival

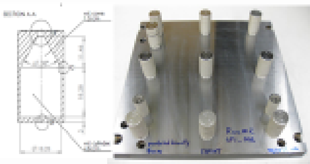
Sample Research Results

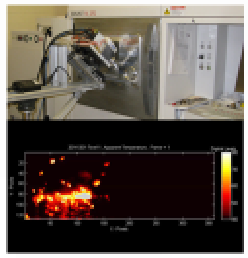
- New methods and tools
- Round robin studies / trusted data
- Technical basis and content for AM standards
- Publications

AM Test Artifact

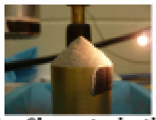


Traceable powder bed density measurements



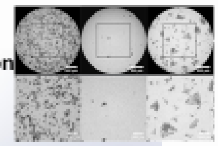


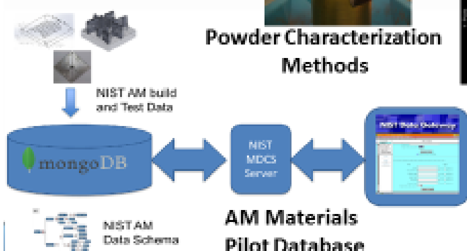
Reference data to validate physics-based models



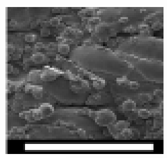
Powder Characterization Methods

Defect Characterization Methods

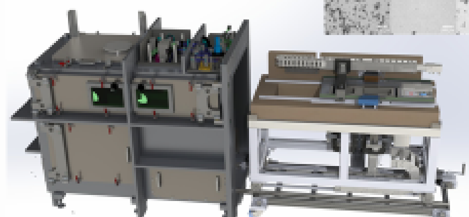




AM Materials Pilot Database



Surface Characterization Methods



Additive Manufacturing Metrology Testbed

Publications (2014-2017)

- 17 journal papers in
  - Additive Manufacturing
  - ASTM Journal of Testing and Evaluation
  - Rapid Prototyping Journal
  - Journal of Manufacturing Science and Engineering
  - Journal of Materials Engineering and Performance
  - Journal of Materials Research
  - Journal of Measurement Science and Technology
  - Journal of Mechanical Design
  - Journal for Smart and Sustainable Manufacturing Systems
  - NIST Journal of Research
- 41 conference proceedings
  - Solid Freeform Fabrication Symposium
  - ASPE
  - MS&T
  - TMS
  - ASME/IDETC CIE; ASME MSEC; ASME IMECE, ASME AM3D
- 9 NIST publications and reports
- 3 Book Chapters

https://www.nist.gov/topics/additive-manufacturing/am-publications

Role of Additive Manufacturing Standards

- Standards can be used for (among others):
  - specifying requirements
  - communicating guidance
  - documenting best practices
  - defining test methods and protocols
  - documenting technical data
  - accelerating the adoption of new technologies
- Certifying bodies typically reference publicly available standards in their procedures
- Standards development in the U.S. is conducted through voluntary participation and consensus

Multiple Standards Bodies Relevant to Additive Manufacturing

- ASTM Committee F42 on Additive Manufacturing Technologies
- ISO Technical Committee 261 on Additive Manufacturing
- ASME Y14.46 Committee on Geometric Dimensioning & Tolerancing (GD&T) Requirements for Additive Manufacturing
- SAE Aerospace Material Specifications for Additive Manufacturing (AMS-AM) Committee
- AWS D20 Committee on Additive Manufacturing
- ISO TC184 / SC4, STEP-based data representation for AM
- ASME B46 Project Team 53, Surface Finish for AM
- <others – the list is growing>

NIST Contributes to All of These Efforts

<u>Some Challenges:</u> high risk of duplication of efforts and overlapping content; potential for inconsistencies or even contradictions; conflicting standards create ambiguity and confusion; increased requirements for communication and coordination; need for liaisons; limited resources

Additive Manufacturing Standards Collaborative (AMSC)

- ***Purpose:*** coordinate and accelerate development of additive manufacturing standards consistent with stakeholder needs and facilitate growth of the additive manufacturing industry
- AMSC launched in March 2016 following two planning meetings
- Facilitated by American National Standards Institute (ANSI) through cooperative agreement with America Makes
- ***Phase 1 Outcome:*** "Standardization Roadmap for Additive Manufacturing" released in February 2017
  - 88 gaps identified; 18 high priority, 51 medium priority, 19 low priority; 57 require R&D
- Phase 2 AMSC Kick-Off in September 2017 – currently active and new participants welcome

MSAM 14

NIST Perspectives on AM Standards

- NIST has been influential in leading and developing AM standards from the start
  - Contributions to more than 40 AM standards activities across 7 standards bodies
  - Multiple leadership roles in ANSI Additive Manufacturing Standards Collaborative
- NIST will continue to support AM standards development through measurement science research and service on standards committees
- **NIST Motivations:**
  - High quality, technically accurate standards
  - Usable and high impact standards that meet stakeholder needs
  - Integrated and cohesive set of standards: consistent, non-contradictory, non-overlapping
  - No duplication of effort
  - Use of existing standards, modified for AM when necessary
- Coordination, communication, and cooperation are necessary among AM users, standards bodies, and regulatory agencies
  - AMSC established in 2016 to serve this role; NIST contributes to the coordination and communication

MSAM

Conclusion

- MSAM program is addressing high priority **pre-competitive challenges** faced by the metal AM industry
- Program develops **metrology** driven methods and tools for the benefit and use of AM stakeholders
- Results of the research activities are **publicly disseminated** broadly throughout the AM community
- Results of the research activities are used as the basis for new AM **standards**
- Program's world-class **staff and facilities** are widely recognized for their critical contributions to AM field

MSAM 16

Questions and Discussion

Contact:
Kevin Jurrens
kevin.jurrens@nist.gov
Office: 301-975-5486

MSAM 17

What is Measurement Science?

- Development of performance metrics, measurement and testing methods, predictive modeling and simulation tools, knowledge modeling, protocols, technical data, and reference materials and artifacts
- Conduct of inter-comparison studies and calibrations
- Evaluation of technologies, systems, and practices, including uncertainty analysis
- Development of the technical basis for standards, codes, and practices—in many instances via testbeds, consortia, standards development organizations, and/or other partnerships with industry and academia

MSAM

NIST Influence on AM Standards

- Identify standards needs and priorities through workshops and industry meetings
- Develop technical basis for standards through measurement science research
  - Draft content and starting point for development of documentary standards
- Serve on standards committees
  - Leadership roles
  - Technical standards development
  - Strategic planning / big picture view
- Support the coordination, facilitation, and communication among standards groups

MSAM

NIST Contributions to AM Standards

Technical basis, content, and leadership for AM standards

- MSAM program has contributed, by leading or participating, in **over 40 AM standards** either developed or in development across **7 SDOs**
  - Technical leadership in
    - Multiple efforts in ASTM Committee F42 and ISO TC 261
    - ASME Y14.46 on Product Definition and GD&T for AM
  - Participation in :
    - SAE AM-AMS committee, Aerospace Material Specifications for Additive Manufacturing
    - AWS D20 committee on Additive Manufacturing
    - ISO TC184 / SC4, STEP-based data representation for AM
    - ASME B46 Project Team 53, Surface finish for AM
    - ASME V&V 50 Subcommittee on Advanced Manufacturing
- Multiple leadership positions in **ANSI Additive Manufacturing Standards Collaborative** (AMSC)

ASTM Committee F42 on Additive Manufacturing Technologies

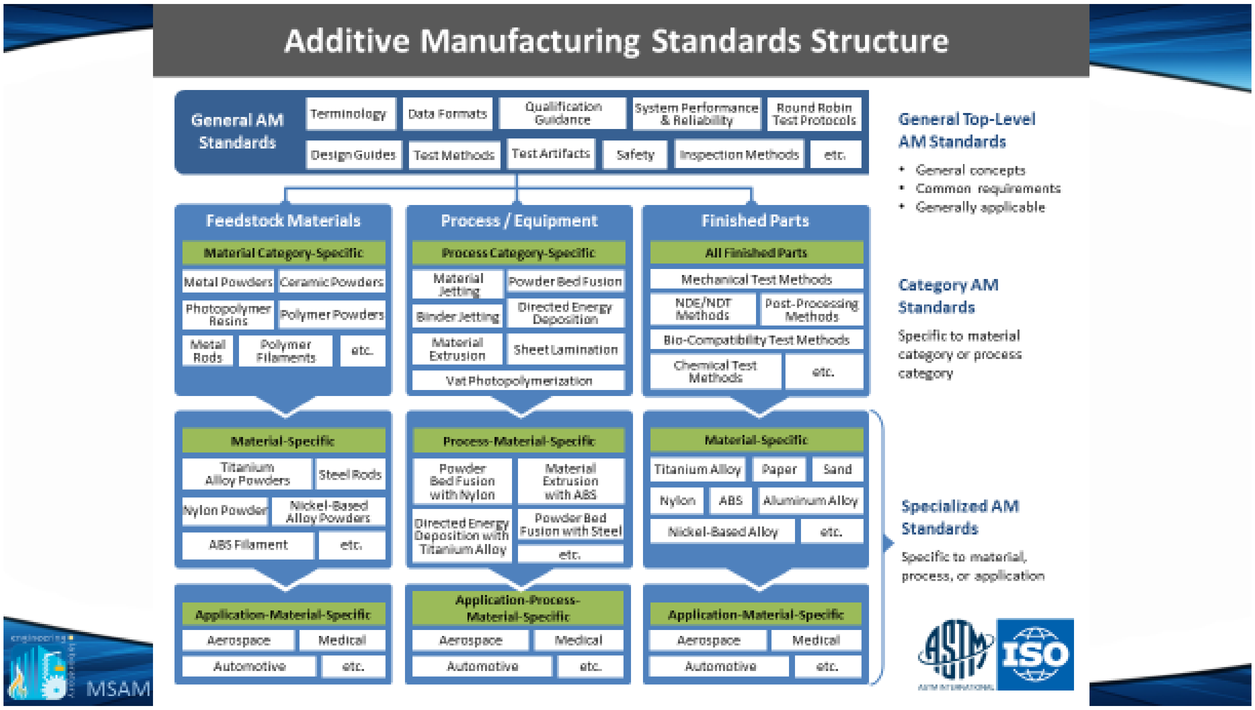
- Established in January 2009 to address high-priority standards needs
- F42 subcommittees:
  - *Terminology*
  - *Test Methods*
  - *Materials and Processes*
  - *Design (including data formats)*
  - *Environment, Health, and Safety*
  - *U.S. Technical Advisory Group (TAG) to ISO TC 261*
- F42 roster: ~400 members; 22 countries represented
- Status: 17 approved standards; 25+ work items in development
- http://www.astm.org/COMMITTEE/F42.htm

ISO Technical Committee 261 on Additive Manufacturing

- TC261 Working Groups established for:
  - WG1 – Terminology
  - WG2 – Methods, Processes, and Materials
  - WG3 – Test Methods
  - WG4 – Data and Design
- 22 Participating (P) countries:
  - USA, UK, France, Germany, Denmark, Russia, Japan, South Korea, Belgium, Netherlands, Ireland, Poland, China, Canada, Finland, Sweden, Norway, Switzerland, Singapore, Spain, Italy, Czech Republic
- 6 Observing (O) countries:
  - Austria, Romania, Iran, New Zealand, South Africa, Israel

Formal Agreement Established between ASTM F42 and ISO Technical Committee 261

- Formal collaboration established between ASTM and ISO (first of its kind!) for joint development of AM standards
- Results in co-branded ISO and ASTM standards (same content, no need for future harmonization)
- Guiding principles and specific procedures for how ASTM and ISO will cooperate and work together are defined in the "Joint Plan for Standards Development"
  - One set of AM standards to be used all over the world; common standards roadmap and organizational structure; use and build upon existing standards, modified for AM when necessary; co-located meetings; emphasis on joint standards development and joint working groups; etc.



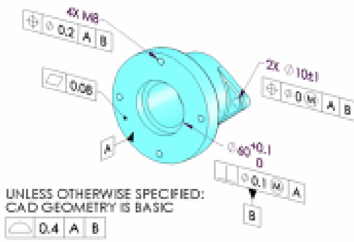
Joint Development of AM Standards by ASTM F42 and ISO TC261

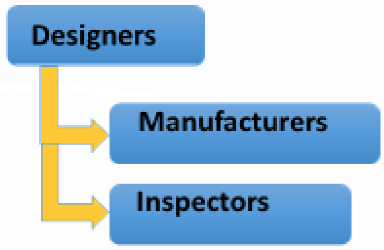
- Terminology
- Standard test artifacts
- Requirements for purchased AM parts
- Design guidelines
- Specification for extrusion-based AM of plastic materials
- Practice for metal powder bed fusion to meet rigid quality requirements
- Specific design guidelines for powder bed fusion
- Qualification, quality assurance, and post processing of powder bed fusion metallic parts
- Nondestructive testing for AM parts
- Intentional seeding of flaws in AM parts
- Anisotropy effects in mechanical properties of AM parts
- Conducting round robin studies
- Additive manufacturing format support for solid modeling
- AM of stainless steel alloy with powder bed fusion
- Specification of metal powders
- Design of functionally-graded AM parts

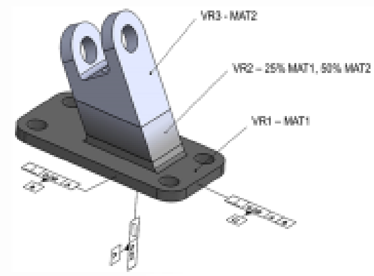
MSAM

ASME Y14.46 Standards Committee

- Geometric Dimensioning & Tolerancing (GD&T) requirements that are *unique to additive manufacturing*
- Builds on long-standing expertise and several GD&T standards developed by ASME Y14 committee
- GD&T: the language for communicating geometric tolerance specification and design intent between:



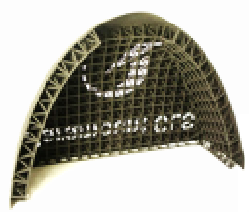


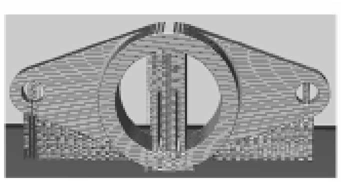


MSAM

GD&T Issues for Additive Manufacturing

- Free-form complex surfaces
- Internal features / lattice structures
- Support structures
- Build direction dependent properties
- Multiple materials / functionally-gradient materials
- As-built assemblies





MSAM

4.28 **<u>America Makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC) (Jim McCabe, ANSI)</u>**

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

Overview

Jim McCabe, Senior Director, Standards Facilitation

American National Standards Institute

America Makes ANSI

The Need for a Standardization Roadmap for Additive Manufacturing

- A number of standards developing organizations (SDOs) are engaged in standards-setting for various aspects of additive manufacturing (AM)
- Coordination is needed to maintain a consistent, harmonized, and non-contradictory set of AM standards and specifications
- Prior to 2016, there was no process for identifying priorities and interdependencies in the development of AM standards and specs

America Makes ANSI

NRC November 29, 2017 – slide 2

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

- Phase One launched March 31, 2016; Phase Two launched September 7, 2017
- America Makes is the nation's leading and collaborative partner in AM and 3D printing technology research, discovery, creation, and innovation
- ANSI is the national coordinating body for voluntary standardization in the United States, with a history of serving as a neutral facilitator to identify standards needs
- National Institute of Standards and Technology (NIST), U.S. Department of Defense (DoD), Federal Aviation Administration (FAA), several SDOs, were instrumental in formation of AMSC

America Makes

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AMSC Purpose

- To coordinate and accelerate the development of industry-wide additive manufacturing standards and specifications, consistent with stakeholder needs, and thereby facilitate the growth of the additive manufacturing industry
- AMSC's charter does not include developing standards or specifications; rather, the hope is to help drive coordinated activity among SDOs

America Makes

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AMSC Objectives

- Coordinate and provide input to AM SDOs
- Encourage liaisons between them
- Clarify the current standards landscape
- Avoid duplication of effort
- Drive coordinated standards activity
- Better inform decision-making on resource allocation for standards participation
- Establish a common framework of AM standards and specs
- Provide subject matter experts to work with SDOs to accelerate the development of AM standards and specs

America Makes

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ANSI

AMSC Participation

- Participation is open to additive manufacturing stakeholders that have operations in the U.S.
  - List of participating organizations posted online
- Membership in America Makes and ANSI is not a prerequisite
- Members include:
  - Original Equipment Manufacturers (OEMs)
  - Feedstock Material Producers
  - User Stakeholders - Industry and Government
  - R&D Community - Academia and Government
  - SDOs
- More than 260 individuals from 150 public- and private-sector organizations involved in phase one
  - Drew heavily from aerospace, defense and medical sectors
- Most work done via online meetings

America Makes

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ANSI

AMSC Leadership

- Chair – Jim Williams (All Points Additive)
- Vice Chair – Lauralyn McDaniel (SME)
- Staff – Jim McCabe, Sarah Bloomquist (ANSI)
- Sponsor – Rob Gorham, John Wilczynski (America Makes)

- Activities overseen by the America Makes Additive Manufacturing Standards, Specs, and Data Schemas Advisory Group

America Makes

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AMSC Deliverables

- AMSC Standardization Roadmap for Additive Manufacturing, Version 1.0 (February 2017)
  - Identifies existing standards and specifications, as well as those in development, assesses gaps, and makes recommendations for priority areas where there is a perceived need for additional standardization

- AMSC Standards Landscape
  - A list of standards that are directly or peripherally related to the issues described in the roadmap

- Both available as free downloads on www.ansi.org/amsc

America Makes

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AMSC Roadmap Organization “life cycle assessment of an AM part”

- Design
- Process and Materials
  - Precursor Materials
  - Process Control
  - Post-processing
  - Finished Material Properties
- Qualification & Certification
- Nondestructive Evaluation
- Maintenance

America Makes

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ANSI

Phase One Promotion & Phase Two Goals

- Promoting the roadmap at industry events
- Meeting with SDOs to discuss actions to implement roadmap recommendations

<u>Phase Two Goals</u>

- Provide an update on gaps already identified
- Identify potentially overlooked gaps
- Discuss needs of other industries (e.g., ground vehicles/heavy equipment, energy, industrial & commercial machinery, electronics)
- Expand discussion of other materials (e.g., polymers)
- Targeting publication of roadmap version 2.0 end of June 2018

America Makes

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ANSI

Roadmap Layout

- Summary Table of Gaps and Recommendations
- Introductory Information / Overview of SDO work programs
- Gap Analysis of Standards and Specifications
- Next Steps
- Glossary

Examples of SDOs Already Involved or Getting Involved in AM Standardization

ASTM International

International Organization For Standardization

American Society of Mechanical Engineers

SAE International

American Welding Society

Institute of Electrical and Electronics Engineers

MITA Medical Imaging & Technology Alliance, a division of NEMA

Association for the Advancement of Medical Instrumentation

IPC - Association Connecting Electronics Industries

Metal Powder Industries Federation

Organization of Topical Areas

- Describe the relevant subtopics and issues
- Identify published or in development standards and specs
- State any standards gap(s)
  - A "gap" means no published standard or specification exists that covers the particular issue in question
- Make a recommendation(s) how to fill the gap(s)
- Determine if additional R&D is needed
- Establish the priority for action (high, medium, or low)
- Identify an organization(s) that potentially can address the gap both for R&D and developing the standard

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ANSI

Sample Gap Statement
(simple example)

- **Gap M1: AM Analyses in RCM and CBM**. Standards for AM analyses in Reliability Centered Maintenance (RCM) and Conditioned Based Maintenance (CBM+) are needed.
- **R&D Needed:** No
- **Recommendation:** Update SAE JA1012 RCM, a guide to provide analytics for AM trade-offs in RCM and CBM+.
- **Priority:** Medium
- **NEW for Phase 2: Status of Progress:** Closed (completed), or using a traffic light analogy, Green (moving forward), Yellow (delayed), Red (at a standstill), Not Started, or Unknown
- **NEW for Phase 2: Update:** Narrative text describing what action, if any, has been taken by an SDO or other organization in relation to the gap since roadmap version 1.0 was published in February 2017
- **Organization:** SAE, ISO, ASTM

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ANSI

AMSC Gaps Breakdown - Version 1.0

Section	High (0-2 years)	Medium (2-5 years)	Low (5+ years)	Total
Design	5	15	6	26
Precursor Materials	1	4	2	7
Process Control	4	8	5	17
Post-processing	0	4	2	6
Finished Material Properties	2	3	0	5
Qualification & Certification	5	6	4	15
Nondestructive Evaluation	2	3	0	5
Maintenance	0	8	0	8
Total	19	51	19	89

- 58 gaps require additional research and development (R&D)

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High Priority Gaps - Version 1.0

- D4: Application-Specific Design Guidelines
- D14: Designing to be Cleaned
- D17: Contents of a TDP
- D18: New Dimensioning and Tolerancing Requirements
- D19: Organization Schema Requirement
- PM5: Feedstock Sampling
- PC2: Machine Calibration and Preventative Maintenance
- PC7: Recycle & Re-use of Materials
- PC9: Environmental Conditions: Effects on Materials
- PC14: Environmental Health and Safety: Protection of Machine Operators

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High Priority Gaps (contd.)

- FMP3: Cleanliness of Medical AM Parts
- FMP4: Design Allowables (Material Properties)
- QC1: Harmonization of AM Q&C Terminology
- QC2: Qualification Standards by Part Categories
- QC4: DoD Source (i.e., Vendor) Approval Process for AM Produced Parts
- QC9: Personnel Training for Image Data Set Processing
- QC10: Verification of 3D Model
- NDE1: Terminology for the Identification of AM Flaws Detectable by NDE Methods
- NDE3: Standard Guide for the Application of NDE to Objects Produced by AM Processes

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ANSI

Design WG

Co-Chairs: John Schmelzle, NAVAIR; Paul Witherell, NIST

- Design Guides
- Design Tools
- Design for Specific Applications
  - Design for Assembly
  - Design for Printed Electronics
  - Design for Medical
- Design Documentation
- Design Verification and Validation

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ANSI

Precursor Materials WG

Co-Chairs: Jim Adams, MPIF; Justin Whiting, NIST

- Storage, Handling and Transportation
- Characterization
  - Chemical composition
  - Flowability
  - Spreadability
  - Density (apparent vs. tapped)
  - Particle Size and Particle Size Distribution
  - Particle Morphology
  - Feedstock Sampling
  - Hollow Particles and Hollow Particles with Entrapped Gas
- AM Process-Specific Metal Powder Specifications

America Makes

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ANSI

Process Control WG

Co-Chairs: Susan Hovanec, NAVSEA: Justin Rettaliata, NAVSEA

- Digital Format and Digital System Control
- Machine Calibration and Preventative Maintenance
- Machine Qualification
- Parameter Control
- Adverse Machine Environmental Conditions: Effect on Component Quality
- Precursor Material Handling: Use, Re-use, Mixing, and Recycling Powder
- Precursor Material Flow Monitoring
- Environmental Health and Safety: Protection of Machine Operators
- Configuration Management: Cybersecurity
- Process Monitoring

America Makes

NRC November 29, 2017 – slide 20

ANSI

Post-processing WG

Co-Chairs: Dave Winchester, MITRE; Jing Zhang, IUPUI

- Heat Treatment (metals)
- Hot Isostatic Pressing (HIP) (metals)
- Surface Finish (Surface Texture) (metals, polymers)
- Machining (metals, polymers)
- Post-curing Methods (polymers)

America Makes

NRC November 29, 2017 – slide 21

ANSI

Finished Material Properties WG

Co-Chairs: Mohsen Seifi, ASTM International; Roger Narayan, UNC/NCSU

- Mechanical Properties
- Component Testing
- Bio-compatibility & Cleanliness of Medical Devices
- Chemistry
- Design Allowables
- Microstructure

America Makes

NRC November 29, 2017 – slide 22

ANSI

Qualification & Certification WG

Co-Chairs: Rachael Andrulonis, Wichita State Univ-NIAR; Jessica Coughlin, Naval Nuclear Laboratory

- Identified Guidance Documents
  - FDA Guidance on Technical Considerations for AM Devices
  - Lockheed Martin AM Supplier Quality Checklist
  - Aerospace Corp Mission Assurance Information Workshop
  - Composite Materials Handbook-17 (CMH-17) & Metallic Materials Properties Development and Standardization (MMPDS) Handbook
  - AWS D20
  - NASA Marshall Space Flight Center Draft Standard for Laser Powder Bed Fusion AM
  - ASME Y14.46
- User-Group/Industry Perspectives on Q&C

America Makes

NRC November 29, 2017 – slide 23

Nondestructive Evaluation (NDE) WG

Co-Chairs: Patrick Howard, GE Aviation; Steve James, Aerojet Rocketdyne

Scope: NDE of Finished Parts (NDE for Process Monitoring under Process Control WG)

- Common Defects Catalog Using a Common Language for AM Fabricated Parts
- Test Methods or Best Practice Guides for NDE of AM Parts
- Dimensional Metrology of Internal Features
- Data Fusion

America Makes

NRC November 29, 2017 – slide 24

Maintenance WG

Co-Chairs: David Coyle, NAVSUP WSS; Carlo Canetta, MITRE

- Standard Repair Procedures
- Standard Technical Inspection Processes
- Model-Based Inspection
- Standards for Tracking Maintenance Operations
- Cybersecurity for Maintenance
- Finishing and Assembly, Welding, Grinding, Coating, Plating

America Makes

NRC November 29, 2017 – slide 25

ANSI

Polymers WG

Co-Chairs: Jim Williams, All Points Additive; Doug Greenwood, NAVAIR

- Consider the need to enhance content on polymers across the AMSC roadmap
- New text or gaps identified by the Polymers WG will be shared with the other applicable WGs

America Makes

NRC November 29, 2017 – slide 26

ANSI

Medical WG

Co-Chairs: Lauralyn McDaniel, SME; and Dan Fritzinger, Johnson and Johnson

- Because of resource considerations, the medical sector determined during phase one to meet as a sector to look at horizontal topics across the WGs
- It will continue to do so in phase two

Questions

- More Information / To Get Involved www.ansi.org/amsc

4.29 **ASME Additive Manufacturing Standards (Kate Hyam, ASME)**

SET I G THE S T A N D A R D

ASME Additive Manufacturing Standards

November , 2017

Kathryn Hyam
Project Engineering Manager
ASME Nuclear and Standardization S&C

Additive Manufacturing For Reactor Materials & Components
Cat 3 Public Meeting
November 28-29 2017

New Activities Related to Manufacturing

- Y14.46 – Product Definition for Additive Manufacturing
- Y14.47 - Model Organization Schema Practices
- Y14.48 - Universal Direction and Load Indicators
- B46 - Classification and Designation of Surface Qualities – for items made by additive manufacturing
- B89.4.23- 201x X-ray Computed Tomography (CT) Performance Evaluation Standard
- V&V 50 – Verification and Validation in Computational Modeling for Advanced Manufacturing
- Model Based Enterprise (MBE)
- Pressure Retaining Equipment – Additive Manufacturing

ASME SETTING THE STANDARD

Y14 Engineering Product Definition and Related Documentation Practices

- Charter: The development and maintenance of national standards for defining and documenting a product throughout its life cycle and related certification activities. This shall be accomplished by:
  1. recognizing the continuing need for existing standards regardless of the source medium (e.g., paper, film, and digital) or method of preparation (e.g., manual or computer generated);
  2. providing standardization where a variety of practices exist within industry and government;
  3. providing standards for new concepts and technologies; and
  4. supporting and coordinating development and harmonizing of standards with responsible standardization bodies, including ANSI, ISO, and government agencies.

ASME SETTING THE STANDARD

Y14.46 – Product Definition for Additive Manufacturing

- Charter: Standardization of dimensioning and tolerancing methods, systems, and indications on engineering product definition digital data sets promotes uniform practices and should facilitate a common interpretation of these requirements
- Subcommittee formed in in October 2014
- 25 members from throughout industry and academia, with collaborating government agencies:
  - NIST
  - US Army
  - NAVAIR
  - Office of Naval Research

Y14.46 – Product Definition for Additive Manufacturing

- Supplements the requirements of Y14.5 and it addresses methods to control the product definition for Additive Manufacturing such as supporting structures, assemblies, embedded components, test coupons and heterogeneous materials. The standard establishes methods to specify AM process specific characteristics (e.g. build orientation and placement) that affect the product definition.
- Document was recently published as a DRAFT STANDARDS FOR TRIAL USE.
- A free Webinar is scheduled for January 10, 2018 on the document

  https://shop.asme.org/Registrations/Conference/Y1446JAN18

Y14.47 - 3D Model Data Organization Schema Practices

- The Standard establishes a schema for organizing information in a model within a digital product definition data set when conveying the product definition in a Model Based Enterprise (MBE). The schema defines a common practice to improve design productivity and to deliver consistent data content and structure to consumers of the data.
- This schema document was developed to provide a set of reference standards and guidelines for the CAD user. The Draft is based on Appendix B of MIL-STD-31000A, Technical Data Packages (TDP).
- The need for this standard was identified in the ANSI/America Makes gap analysis.

ASME
SETTING THE STANDARD

Y14.47 - 3D Model Data Organization Schema Practices

- The Subcommittee was formed in October 2013.
- There are 23 members on the subcommittee.
- The document has been Standards Committee approved but recently received a Public Review comment. Subcommittee met in October 2017 and has prepared a resolution of the comments. Will be balloted again.
- Once ANSI approved, this standard is expected to be published in the first half of 2018.

ASME
SETTING THE STANDARD

Y14.48 - Universal Direction and Load Indicators

- Charter: Standardization of methods to unambiguously define and specify directions, directional requirements, loads, and loading requirements in product definition data sets.
- The standard will add more tools for the designer to address direction on their drawing and model (e.g., direction of the Additive Manufacture build).
- Subcommittee formed in October 2016
- Eight Members on the Subcommittee
- Held their first face-to-face SC meeting in October 2017
- An initial draft was prepared by a volunteer and will be reviewed by the subcommittee.

ASME SETTING THE STANDARD

B46 - Classification and Designation of Surface Qualities

- B46.1 defines surface texture and its constituents: roughness, waviness and lay, and parameters for quantifying surface texture.
- The terms and ratings in this standard relate to surfaces produced by such means as abrading, casting, coating, cutting, etching, plastic deformation, sintering, wear, erosion, etc.
- The current measurement and analysis methods were developed primarily to characterize surfaces created by conventional machining and grinding. The surfaces created by Additive Manufacturing have distinctly different geometric characteristics.

ASME SETTING THE STANDARD

B46 - Project Team 53
Surface Finish for Additive Manufacturing

- Formed in October 2015 in response to an identified need noted in the ANSI/America makes gap analysis.
- A survey was sent to related ASME committees and other requesting input on Surface Finish needs in the Additive Manufacturing field. The Survey results have been compiled and are being analyzed.
- The Project Team usually hold two face-to-face meetings a year and teleconference in between meetings
- Work is currently focused on two documents: White paper and Functional Correlation document

ASME SETTING THE STANDARD

B89 – Dimensional Metrology

- Charter: The calibration, performance evaluation, uncertainty evaluation, and specification of dimensional measuring instruments and gages and the methods of their use for measuring various geometrical characteristics such as lengths, plane surfaces, angles, circles, cylinders, cones, spheres, and tori, as well as profiles.
- Standards, Guidelines and Technical Papers on the following:
  - B89 Division 1 - Length
  - B89 Division 3 - Geometry
  - B89 Division 4 - Coordinate Measuring Technology
  - B89 Division 5 - General Principles and Definitions
  - B89 Division 6 - Environment
  - B89 Division 7 - Measurement Uncertainty

ASME SETTING THE STANDARD

B89.4.23 - X-ray Computed Tomography (CT) Performance Evaluation Standard

- This standard specifies the dimensional measurement accuracy of X-ray computed tomography (CT) systems for point-to-point length measurements of homogeneous materials.
- The Standard is applicable to dimensional measurements made at the surface of the workpiece, i.e. at the workpiece material – air interface, including those of internal cavities. The evaluation of workpieces composed of multiple materials or of "density gradient" measurements, e.g., gradual density variations within the material, is outside the scope of this Standard.
- The document is approximately 85-90% complete and should be balloted after the next face-to-face meeting in April 2018.

ASME SETTING THE STANDARD

Verification & Validation of Computational Modeling

- Charter: Coordinate, promote, and foster the development of standards that provide procedures for assessing and quantifying the accuracy and credibility of computational models and simulations.
- V&V Subcommittees
  1. V&V 10 Verification and Validation in Computational Solid Mechanics
  2. V&V 20 Verification and Validation in Computational Fluid Dynamics and Heat Transfer
  3. V&V 30 Verification and Validation in Computational Simulation of Nuclear System Thermal Fluids Behavior
  4. V&V 40 Verification and Validation in Computational Modeling of Medical Devices
  5. V&V 50 Verification and Validation of Computational Modeling for Advanced Manufacturing
  6. V&V 60 Verification and Validation of Computational Modeling in Energy Systems

ASME SETTING THE STANDARD

V&V 50 – Computational Modeling for Advanced Manufacturing

- Charter: To provide procedures for verification, validation, and uncertainty quantification in modeling and computational simulation for advanced manufacturing.
- Subcommittee was formed in March 2016 and currently about 33 members including members from FDA, FAA, and NASA, as well as major National Labs
- V&V 50 Subgroups – recently formed on:
  1. Terminology, Concepts, Relationships and Taxonomy for VVUQ in Additive Manufacturing
  2. V&V Interactions with the Model Life Cycle
  3. VVUQ Challenges and Methods in Systems of Models
  4. VVUQ Methods in Data-driven and Hybrid models
  5. VVUQ Applications in Process Technologies

Model Based Enterprise (MBE)

- Proposed Charter: Development of standards that provide rules, guidance, and examples for the creation and use of model-based digital datasets, data models, and related topics within a Model-Based Enterprise (MBE).
- Concern use of the model from cradle to grave – from the concept stage, through design, to manufacturing, inspection, to customer feedback and retirement
- The MBE effort supports Additive Manufacturing

Pressure Retaining Equipment – Additive Manufacturing

- The Board on Pressure Technology Codes & Standards (BPTCS) and the Board on Nuclear Codes and Standards (BNCS) have identified the potential need/use of Additive Manufacturing (3D Printing) as a process for the construction of pressure equipment.
- BPTCS/BNCS have formed a Special Committee on Use of Additive Manufacturing for Pressure Equipment

Questions?

4.30 **<u>BPTCS/BNCS Special Committee on use of Additive Manufacturing (Dave Rudland, NRC)</u>**

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

BPTCS/BNCS Special Committee on Use of Additive Manufacturing

Remarks by

David L. Rudland
Senior Level Advisor for Materials
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission

Additive Manufacturing For Reactor Materials & Components
Cat 3 Public Meeting
November 28-29 2017

Who and What

- BPTCS – Board on Pressure Technology Codes and Standards
  - Management of all ASME activities related to codes, standards, guidelines, and accreditation programs directly applicable to nonnuclear pressure containing equipment
- BNCS – Board of Nuclear Codes and Standards
  - Management of all ASME activities related to codes, standards and guides directly applicable to nuclear facilities and technology

2

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Charter

- Special committee appointed June 2017
- To develop a technical baseline to support development of a proposed Boiler and Pressure Vessel standard or guideline addressing the pressure integrity governing the construction of pressure retaining equipment by additive manufacturing processes
  - Construction, as used in this Charter, is limited to materials, design, fabrication, examination, inspection, and testing.

Scope

- Perform gap analysis, evaluate results, and make recommendations for potential incorporation of additive manufacturing (AM) processes in ASME Codes to construct pressure retaining equipment.

Current Activities

- Will recommend a multi-year task plan for developing baseline to support standards development
- The plan will include
  - Development of relevant data and other information required to complete the gap analysis, evaluate results, and make recommendations
  - Current, nationally recognized AM standards will be used to support the deliverable
  - Input will be requested from BPV service committees
    - NDE (BPV V)
    - Welding Brazing and Fusing (BPV IX)
    - Materials (BPV II)

U.S.NRC

5

Current Activities

- Preparation of future ASME requirements for AM pressure equipment will consider information or data from the America Makes* and ANSI standards effort.

- Committee will be meeting on a regular basis and will be looking for subject matter experts for the committee – NRC staff will be represented

- The final approved revisions or additions to the Boiler and Pressure Vessel Code will be applicable to Nuclear and non-nuclear pressure vessels and components

*America Makes is the nation's leading and collaborative partner in additive manufacturing (AM) and 3D printing (3DP) technology research, discovery, creation, and innovation.

U.S.NRC

4.31 **The Status of Global Additive Manufacturing Standardization to Support Q&C (Mohsen Seifi, ASTM)**

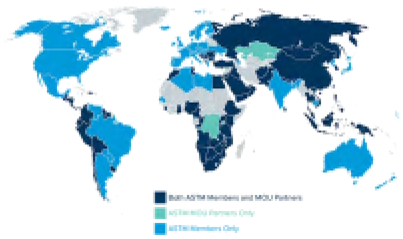
Topics

- About ASTM
- AM Programs
- AM Center of Excellence
- Standardization Activities (ASTM F42/ISO 261)
- Proficiency Testing Program (PTP)
- ASTM WK49229/JG61 at F42/TC261- (Measurement of Orientation/Location Dependent Mechanical Properties for Metal AM)

About ASTM?

A Proven and Practical System

- Established in 1898
- 149 Committees & 12,500+ Standards
- ****Newest F48 Exoskeletons and Exosuits***
- 33,000 members
  - 8,000+ International Members from 135 countries
  - 5,100 ASTM standards used in 75 countries
- Accreditation:
  - American National Standards Institute (ANSI)
  - Standard Council of Canada (SCC)
- Process complies with WTO principles: Annex 4 of WTO/TBT Agreement



- Development and delivery of information made uncomplicated
- A common sense approach: **industry driven**
- Consensus based approach
- Market relevant globally
- No project costs

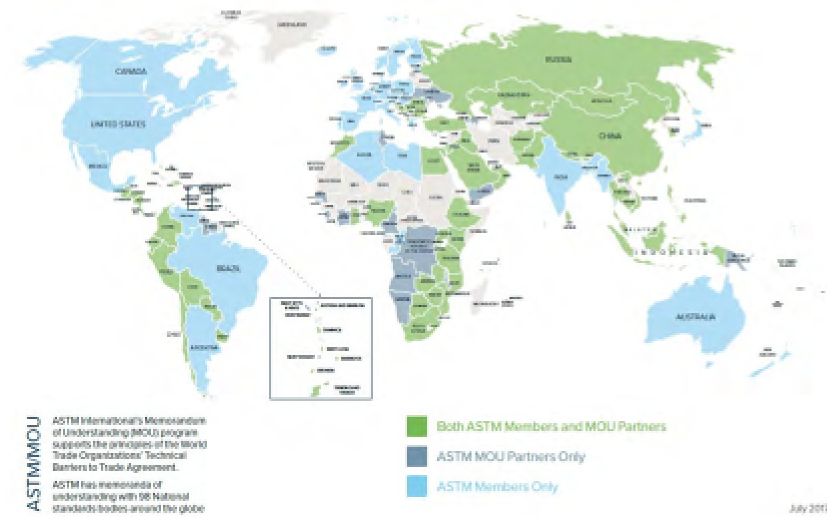
150
main committees plus 2,030+ subcommittees

Over a Century of Openness

How We Work

- **Provide Infrastructure and Tools**
  - Templates, Online balloting, Online collaboration areas, meetings support, managers, administrative support, editors, promotional support
- **Industry comes Together:**
  - Exchange expertise and knowledge
  - Participating in a transparent process – open to anyone, anywhere
- **Development, Delivery, & Implementation**
  - Programs & Services for Integration, Implementation and Access
- Activities are Industry-driven
- Staff does not write standards, remain neutral

ASTM's Membership Globally



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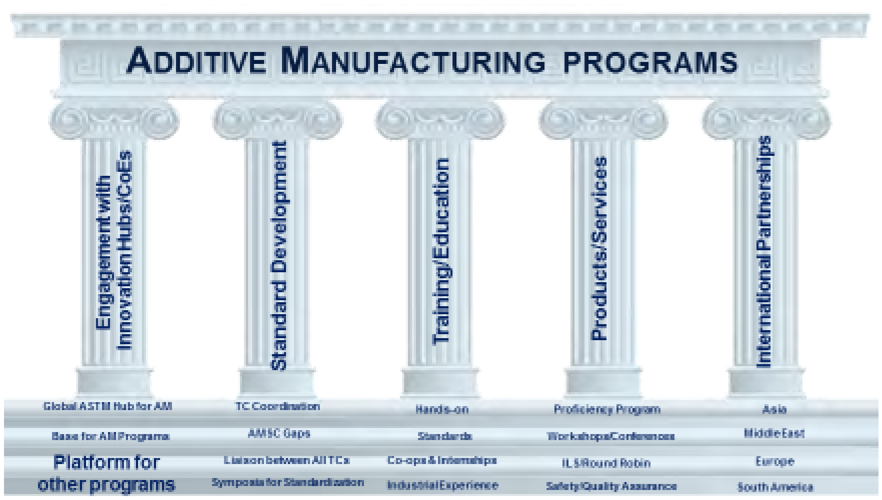
ASTM Additive Manufacturing Initiatives



ASTM Landscape Analysis on Workforce/Education

Process the Nexight Team followed when conducting the Landscape Analysis

1. The focus was mainly on AM workforce activities from 2016-2017.
2. AM research and development (R&D) activities were considered out-of-scope for the analysis.
3. Once we had collected AM workforce education activities using the parameters previously described, these activities were researched in detail and organized into the "AM Workforce Framework for Global 3D Printing Technologies: AM Workforce Development Structure" matrix (☞)

Specific Skills Required in the AM Community		Application				Target Workforce		Type of Education/Training Mechanism being offered by ASTM			
		General	Aerospace	Automotive	Bio/Medical	Future AM workforce (e.g., K-12, college, new graduates)	Incumbent experts	E-learning	In-person training	Webinar	Other delivery methods
General/high-level AM technologies	AM terminology										
	Test methods										
	Inspection methods										
	Design										
	Environment, health, and safety										
Feedstock materials	Material category-specific (e.g., Metal powders/rods, Polymer powders/filaments, and Ceramic powders)										
	Material-specific (e.g., Ti-alloy powders, steel rods, etc.)										
AM process and equipment	Process category-specific (e.g., Powder bed fusion, material extrusion, etc.)										
	Process material-specific (e.g., directed energy deposition with Ti-alloy, Powder bed fusion with steel, etc.)										
Finished AM parts	All finished parts (e.g., NDE/NDT methods, post-processing methods, etc.)										
	Material-specific (e.g., Ti-alloy, Al-alloy, or Ni-based alloy)										
Other AM skills	AM data analysis (e.g., 3D image analysis)										

ASTM INTERNATIONAL

NEXIGHT GROUP

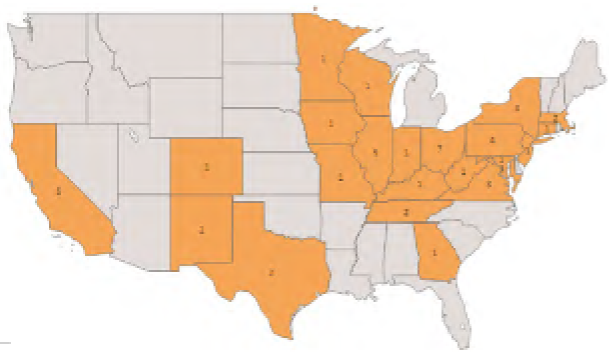
AM Workforce Development Activities from ASTM Landscape Analysis (National)

50

U.S.-based organizations in 23 states

99

key activities or offerings for AM workforce development



Organization Type	U.S. Organizations Included in Analysis																							
State	CA	CO	CT	D.C.	GA	IA	IL	IN	KY	MA	MD	MN	MO	NJ	NM	NY	OH	PA	TN	TX	VA	WI	WV	Total
Industry			1				1				1		1	1		1	1	2			1			10
Academia		1			1	1	2	1	1	1					1	2	2	2	1	2		1		19
Profit /Nonprofit	5						2			1		1				1	4				1		1	18
Government				1															1		1			3
State Total	5	1	1	1	1	1	5	1	1	2	1	1	1	1	1	4	7	4	2	2	3	1	1	50

8

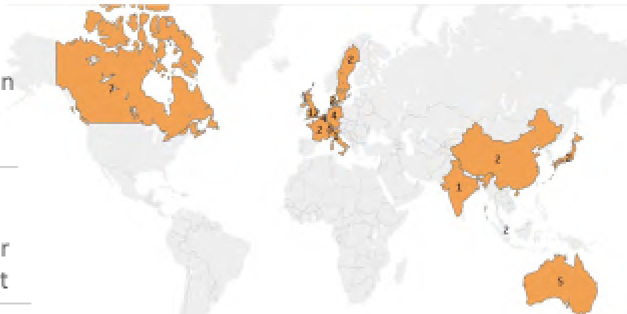
AM Workforce Development Activities from ASTM Landscape Analysis (International)

57

international organizations in 16 countries, including the European Union (EU)

76

key activities or offerings for AM workforce development

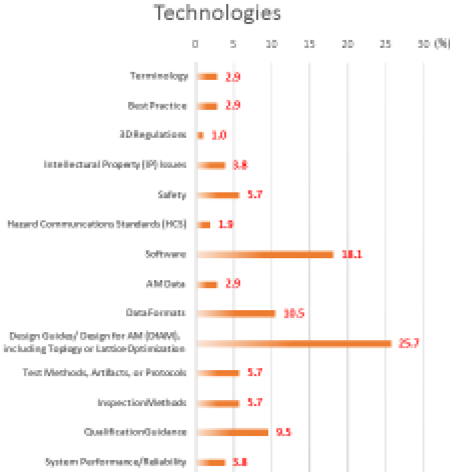


Organization Type	International Organizations Included in Analysis																
Country	Australia	Belgium	Canada	China	Denmark	EU	France	Germany	India	Italy	Japan	Netherland	Singapore	Sweden	Switzerland	UK	Total
Industry		2	2	1	1		2	3			1					4	16
Academia	2	2	3					1		1			2	2	3	4	20
Profit-/Nonprofit	2		2		1				1			3			2	4	15
Government	1			1		3					1						6
Country Total	5	4	7	2	2	3	2	4	1	1	2	3	2	2	5	12	57

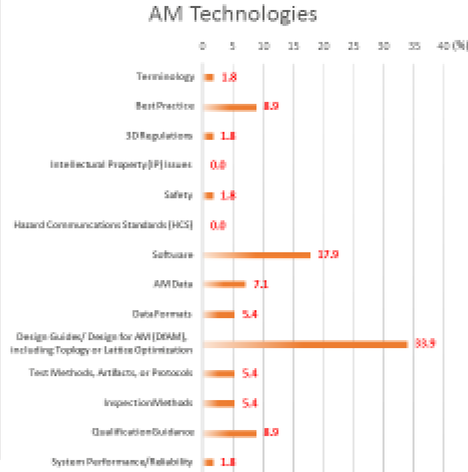
3

AM Workforce Development Activities: Top-Level AM Technologies

U.S. AM Workforce Development Activities: Top-Level AM Technologies



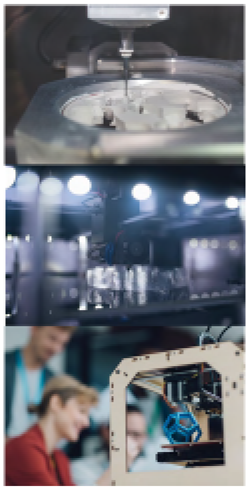
International AM Workforce Development Activities: Top-Level AM Technologies



ASTM INTERNATIONAL

NEXIGHT GROUP

Education/Training webinar series



Additive Manufacturing (AM) Webinar Series

Includes Six Courses:

Course 1: Principles of Additive Manufacturing (David Bourell)
- Session 1: Intro to AM
- Session 2: AM Process
- Session 3: Materials for AM

Course 2: Design for AM (David Rosen)

Course 3: Metal AM Processing (Frank Medina)
- Session 1: Powder Bed Fusion
- Session 2: Directed Energy Deposition

Course 4: Polymer AM Processing (Kalman Migler)

Course 5: Non-destructive Testing of AM Metal Parts (Jess Waller)
- Session 1: Non-destructive Testing of AM Metal Parts (1)
- Session 2: Non-destructive Testing of AM Metal Parts (2)

Course 6: Powder Characterization (Justin Whiting, Ed Garboczi)
- Session 1: Characterization and analysis of powder for AM
- Session 2: Size and Shape Characterization of Metallic Powder for Additive Manufacturing Using Novel Techniques

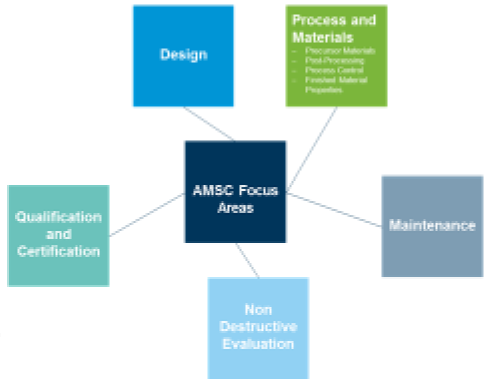
Webinar Dates: October 24, 2017 – February 27, 2018

ASTM Additive Manufacturing Initiatives

ASMC Roadmap Focus Areas

Of that total 89 gaps:

- 19 gaps/recommendations have been identified as **high priority**,
- 51 as **medium priority**,
- 19 as **low priority**.
- ASTM is already positioned to address 82 gaps in conjunction with ISO.



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ANSI

Example Gap Statement- Precursor Materials

Gap PM2: Spreadability. There is no known description of spreadability or standard for how to quantitatively assess powder spreadability.

R&D Needed: Yes. R&D is needed to measure and quantify spreadability, as well as to correlate powder characteristics with spreadability.

Recommendation: A standard should be created that guides the measurement of a powder's spreadability. This standard may be comprised of a series of tests that together describe a powder's spreading performance.

Priority: Medium

Organization: ISO/ASTM, NIST

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Two NIST reports investigated ASTM standards relevance to AM (ASTM E28, E08, B09, D20, ...)

NISTIR 8005

Applicability of Existing Materials Testing Standards for Additive Manufacturing Materials

John Slotwinski
Shawn Moylan

http://dx.doi.org/10.6028/NIST.IR.8005

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

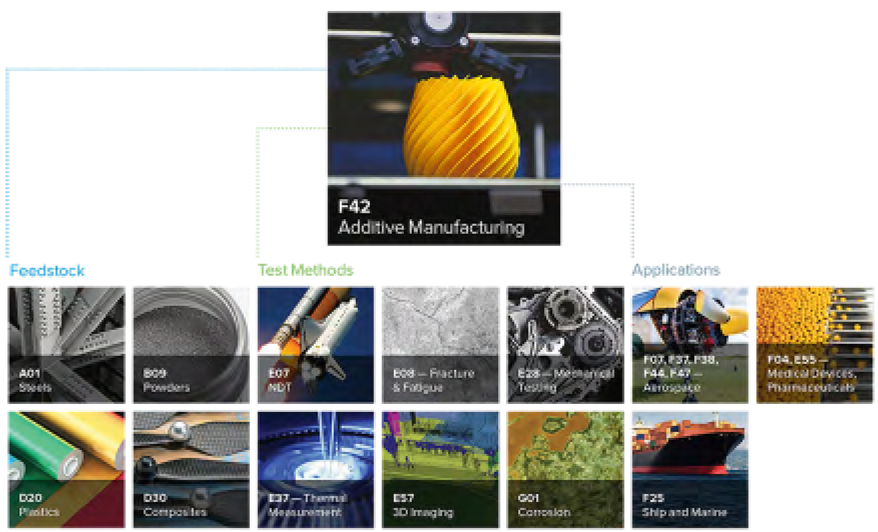
Materials Testing Standards for Additive Manufacturing of Polymer Materials:
State of the Art and Standards Applicability
Aaron M. Forster

Standard Designation	Standard Name	Applicable for AM Testing?	Notes
ASTM E1681	Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials	Yes with Guidance	Appears to be basic method, requires environmental chamber. Requires post-processing to make initial pre-crack since most metal-based AM cannot produce a test specimen with a small enough crack.
ASTM E2472	Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions	Yes with Guidance	For low-constraint conditions (crack-length-to-thickness and un-cracked ligament-to-thickness ratios are greater than or equal to 4) and that are tested under slowly increasing remote applied displacement. Requires post-processing to make initial pre-crack.
ASTM B769	Standard Test Method for Shear Testing of Aluminum Alloys	Yes with Guidance	Double-shear loading using a tension or compression testing machine. Requires post-processing in order to meet surface finish specification.
ASTM B565	Standard Test Method for Shear Testing of Aluminum and Aluminum-Alloy Rivets and Cold-Heading Wire and Rods	No	Metal wire, rivets, and rods are difficult to make via additive manufacturing.

Standard Designation	Standard Name	Applicable for AM Testing	Notes
Flexure Control			
ASTM D6272 – 10	Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four Point Bending	Yes with guidance	Similar to D790 except a four point method that might work better for materials that do not fail within strain limits of D790.
ASTM D7264 / D7264M	Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials	No	Specific to continuous fiber reinforced composites. Not applicable given current AM technologies for composite production.
ASTM D790 – 10	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials	Yes with guidance	Basic method for testing the flexure properties of unreinforced and reinforced plastics using three point bend. Requires material to fail in outer surface with 5% of strain limit for flexural strength. Measured modulus will be impacted by layer stacking.

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Additive Manufacturing Sector:
Technical Committees relevant to AM



ASTM Additive Manufacturing Center of Excellence

November, 2017

Dr. Mohsen Seifi, Director of AM Programs
Christine DeJong, Director of Business Development
Brian Meincke, VP of Business Development
and Pat Picariello, Director of Operational Developments

A Hybrid Industry-University AM CoE

ASTM INTERNATIONAL

AM CoE Vision & Mission

VISION

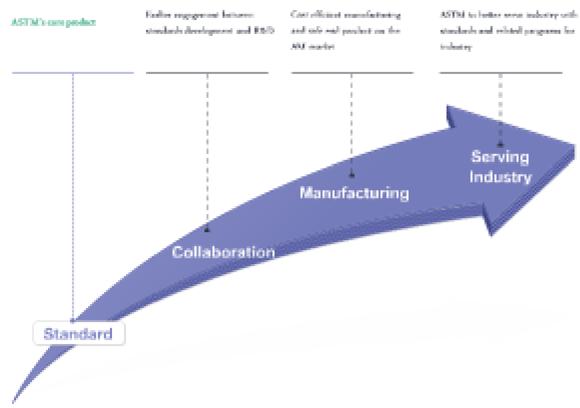
The CoE program **facilitates collaboration and coordination** between government, academia, and industry to advance **AM standardization** and expand ASTM and our partner's capabilities.

MISSION

The CoE is to bridge standards development with R&D to better enable efficient development of standards, education and training, certification and proficiency testing programs.

Why does ASTM want to create a CoE?

- Critical need to develop the globally accepted standards
- Critical need to educate the next generation of manufacturing professionals

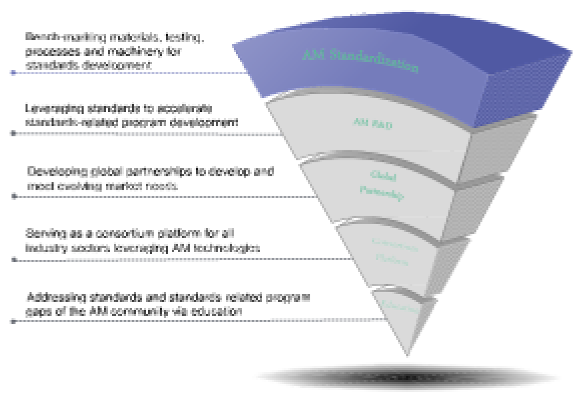


Core/Major Activities of ASTM AM CoE

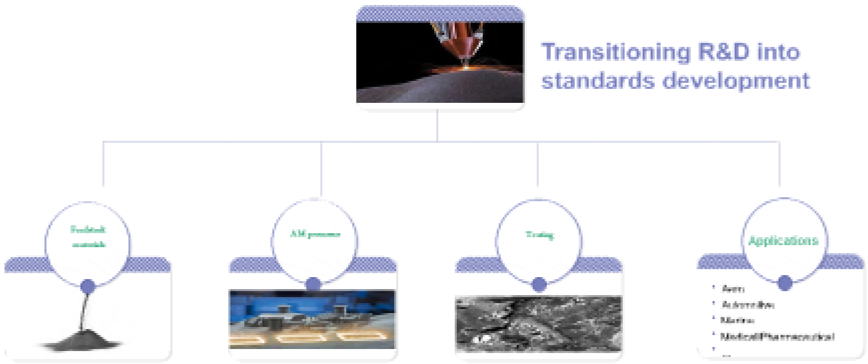
AM CoE

To solve complex AM problems through systemic approaches in a more synergistic and collaborative environment

Industry-University Collaborative Activities include:

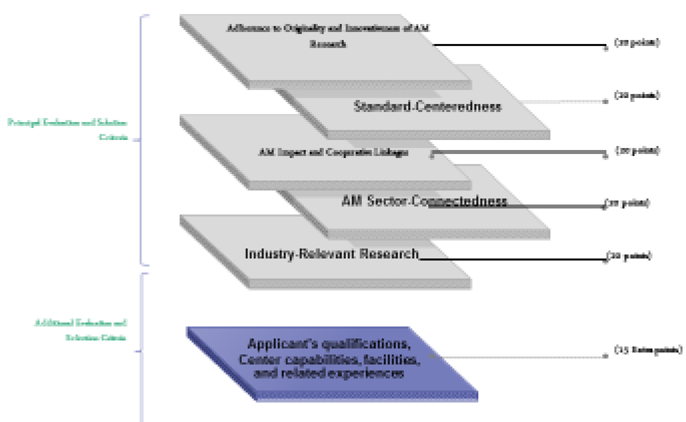


What makes the ASTM CoE different from existing AM centers?

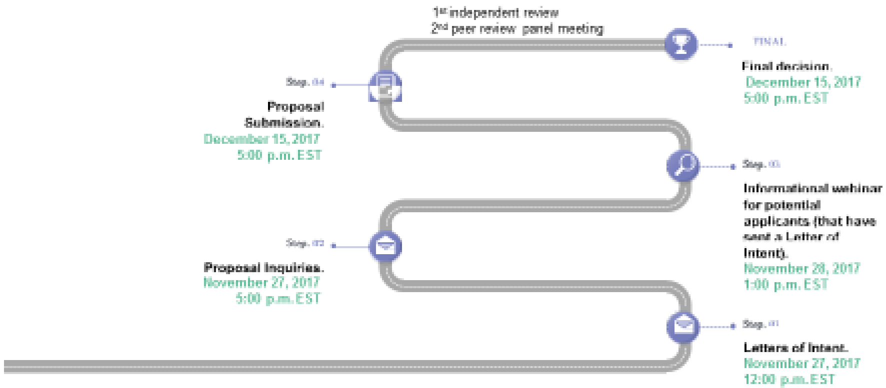


Focusing on AM Standard gaps

Evaluation and Selection Criteria



AM CoE Review and Selection Processes



- **Over 80 inquiries**
- **40 letter of intents: 23 universities, 17 companies/labs**
- **8 countries: USA, Canada, Germany, UK, Australia, China, Singapore, Mexico**

Award Information

Anticipated Funding Amount

Up to $250K annually for five years, provided from in-kind contributions combined with funds, with the possibility of exceeding $250K from provided in-kind contributions

---

Award Period

Annually by calendar year, up to five years with annual reviews, with a three-year base period and a two-year option period

ASTM F42 Fact Sheet 2017

Quick facts

Formed: 2009
Current Membership: 550+ members (Fastest growing TC across ASTM)
Standards: 17 approved, 35 in development
Meet twice a year, next meeting: JHU/APL, April 3rd-6th, 2018

Subcommittees and Focus Areas

Global Representation:
(26 Countries Represented!)

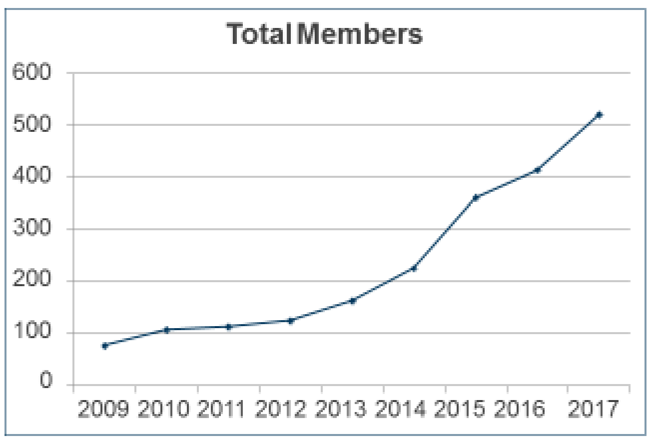
Belgium
Canada
China
France
Germany
India
Italy
Japan
Singapore
Mexico
Netherlands
Norway
Pakistan
Singapore
Slovakia
South Africa
Spain
Sweden
Switzerland
Taiwan
United Kingdom
United States

PARTNERSHIPS:

- *MOU with SME*
- *Partnership in Standards Development (PSDO) & US TAG:* ISO TC 261
- *America Makes Membership + MOU* - Integration of R&D to standards
- *Partnership with 3MF* – File format standardization

F42 Membership: True Exponential Growth! Similar trend on ISO TC261

Year	Total Members
2017	520
2016	413
2015	360
2014	225
2013	162
2012	124
2011	112
2010	106
2009	76



Standardization Framework: ASTM / ISO TC261 Develops AM Standards

Great collaborative coordination to avoid duplication and contradiction:

ASTM INTERNATIONAL
Helping our world work better

International Organization for Standardization

James Thomas, ASTM President, and Rob Steele, ISO Secretary-General

Stakeholder Representation (examples)

Government

Air Force Research Lab (US), FAA (US), FBI (US), FDA (US), NASA (US), NAVAIR (US), NIST (US)

Academia

China Jiliang University (China), Cornell University (US), DeMontfort University (UK), Georgia Institute of Technology (US), Milwaukee School of Engineering (US), North Carolina University (US), Norwegian University of Science and Technology (Norway), Rochester Institute of Technology (US), Texas University at El Paso (US), University of Louisville (US), University of Maryland (US), University of Nottingham (UK), University of Texas (US), Universidad de Zaragoza (Spain), University of Ulster (UK),

Industry

Arconic (US), Arcam (Sweden), Arkema (France), Autodesk (US), BAE Systems (UK), Boeing (US), China Nuclear Power Engineering Company (CNPEC - China), EOS (Germany), Evonik Degussa (Germany), GE (US), GKN Aerospace (US), Gulfstream Aerospace (US), Honeywell (US), Lockheed (US), Materialise (Belgium), Met-L-Flo, Inc. (US), Northrop Grumman (US), Objet Geometries (Israel), Pratt & Whitney (US), Rolls Royce (US), Schlumberger (US), Siemens (Germany), Stratasys (US)

Trade Associations

CECIMO (EU), National Center for Manufacturing Sciences (US), Rapid Product Development Association of South Africa (RSA), Society of Manufacturing Engineers (US)

PARTNERSHIPS

Partnership in Standards Development (PSDO) & US TAG: **ISO TC 261**
America Makes **- US Innovation Institute, Integration of R&D to standards**
Partnership with 3MF **– Data formatting standardization**

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Aerospace/Defense Stakeholders at F42

NIST
AFRL
Federal Aviation Administration
NASA
Lockheed Martin
NAVAIR
Boeing
Rolls-Royce
Airbus
GE Aviation
United Technologies
TIMET
Northrop Grumman
dstl
Honeywell
Parker
Gulfstream
MITRE
Arconic
LAI International
Aerospace
Barnes Aerospace
IHI
Pratt & Whitney
ATI
GKN Aerospace
Woodward
Incodema3D
Aerojet Rocketdyne
CTC
Johns Hopkins Applied Physics Laboratory
Moog
CalRAM
PennState Applied Research Laboratory

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Additive Manufacturing OEM Stakeholders at F42

eos e-Manufacturing Solutions
Arcam EBM A GE Additive Company
SLM Solutions
Concept Laser a GE Additive company
3D Systems
Renishaw apply innovation™
TRUMPF
ExOne Digital Part Materialization
Fraunhofer ILT

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Polymer focused stakeholders at F42

Medical focused stakeholders at F42

Automotive/machinery/tooling stakeholders at F42

BOSCH

Ford

BMW

KOMATSU

KENNAMETAL

F42.91 Terminology

Approved (1)

ISO/ASTM 52900 General principles -- Terminology

7 AM Categories:

3.2 *Process Categories*

binder jetting, *n*—**additive manufacturing** process in which a liquid bonding agent is selectively deposited to join powder materials.

directed energy deposition, *n*—**additive manufacturing** process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

DISCUSSION—"Focused thermal energy" means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

material extrusion, *n*—**additive manufacturing** process in which material is selectively dispensed through a nozzle or orifice.

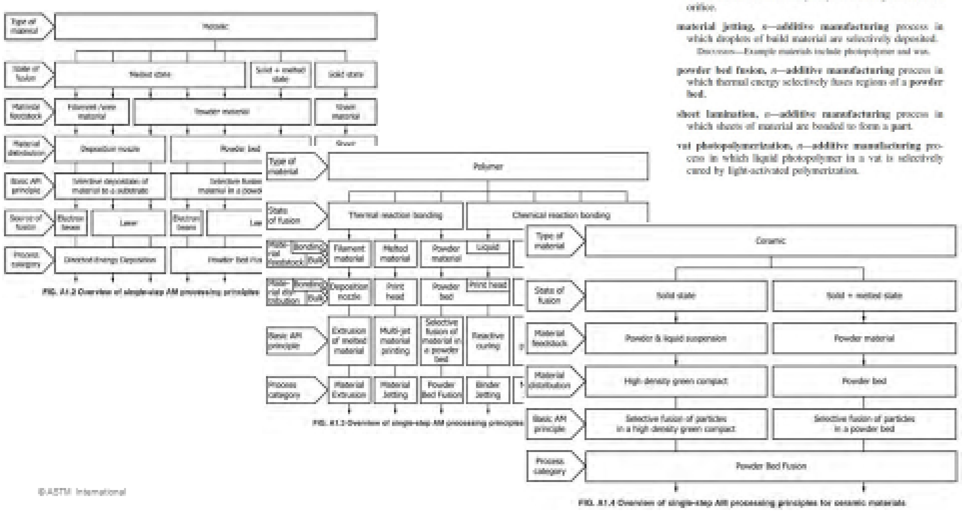
material jetting, *n*—**additive manufacturing** process in which droplets of build material are selectively deposited.

DISCUSSION—Example materials include photopolymer and wax.

powder bed fusion, *n*—**additive manufacturing** process in which thermal energy selectively fuses regions of a **powder bed.**

sheet lamination, *n*—**additive manufacturing** process in which sheets of material are bonded to form a part.

vat photopolymerization, *n*—**additive manufacturing** process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.



F42.01 Test Methods

Approved (3)

F2971 Practice for Reporting Data for Test Specimens Prepared by AM
F3122 Guide for Evaluating Mechanical Properties of Metal Materials Made via AM Processes

ISO/ASTM 52900 General principles -- Terminology
ISO/ASTM 52921 Terminology for AM-Coordinate Systems and Test Methodologies

Under Development (4)

WK56649 / JG 60 - Practice for Intentionally Seeding Flaws in (AM) Parts
WK49229 / JG 61 - Orientation and Location Dependence Mechanical Testing for Metal AM
WK55297 / JG 52 - General Principles -- Standard Test Artefacts for AM
WK55610 / JG 63 - Characterization of Powder Flow Properties

Joint Groups (7)

JG59: NDT of additive manufactured products
JG62: Guide for Conducting Round Robin Studies
JG66: Technical specifications on metal powders

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Stakeholders

F42.04 Design

Approved (4)

ISO/ASTM52915 Specification for AM File Format (AMF) Version 1.2
ISO/ASTM 52910 Guide for Design for Additive Manufacturing
JG57 Design Guideline for Laser-based PBF of Polymers
JG57 Design Guideline for Laser-based PBF of Metals

Under Development (4)

WK48549 Specification for AMF Support for Solid Modeling
WK54856 Principles of Design Rules

Joint Groups (4)

JG54: Design Rules
JG67: Design of Functionally Graded Materials

195
Stakeholders

F42.05 Materials and Processes:
Covers Metals and Polymers

314
Stakeholders

Approved (9)
Specs:
F2924 Specification for AM **Ti-6Al-4V** w/Powder Bed Fusion
F3001 Specification for AM **Ti-6Al-4V ELI** w/Powder Bed Fusion
F3184 Specification for AM **316 Steel Alloy** w/Powder Bed Fusion
F3055 Specifications for AM **IN718** w/Powder Bed Fusion
F3056 Specifications for AM **IN625** w/Powder Bed Fusion
F3091/F3091M Specification for Powder Bed Fusion of **Plastic Materials**
Guides:
F3049 Guide for **Characterizing Properties of Metal Powders** Used for AM Processes
F3187 Guide for **Directed Energy Deposition** of Metals
ISO/ASTM 52910 Guide for AM, General Principles, **Requirements for Purchased AM Parts**

Under Development (6)
WK51329 **Cobalt-28 Chromium-6 Molybdenum** Alloy with Powder Bed Fusion
WK53878 **Material Extrusion** Based AM of Plastic Materials - Part 1, 2, 3: Feedstock materials, Equipment, Final parts
WK53423 **AlSi10Mg** with Powder Bed Fusion
WK60552 Finished Part Properties - Standard Specification for **Titanium Alloys** via PBF
WK58225 **Facility Requirements** for Metal Powder Bed Fusion
WK58240 Grippers of **Control Rod Drive Mechanism** (CRDM) of Nuclear Power Plants

Joint Groups (4)
JG56: Standard Practice for Metal PBF Process to **Meet Critical Applications**
JG58: **Qualification, Quality Assurance and Post Processing** of PBF Metallic Parts
JG66: Technical Specification on **Metal Powders**
JG--: Post Processing Methods- Standard specification for **thermal post-processing** of metal parts via PBF

Standard Guide for
Additive Manufacturing – General Principles – Requirements for Purchased AM Parts[1]

This standard is issued under the fixed designation ISO/ASTM 52901; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision.

1. Scope

1.1 This document defines and specifies requirements for purchased parts made by additive manufacturing.

1.2 It gives guidelines for the elements to be exchanged between the customer and the part provider at the time of the order, including the customer order information, part definition data, feedstock requirements, final part characteristics and properties, inspection requirements, and part acceptance methods.

1.3 It is applicable for use as a basis to obtain parts made by additive manufacturing that meet minimum acceptance requirements. More stringent part requirements can be specified through the addition of one or more supplementary requirements at the time of the order.

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2.3 *ISO/ASTM Standard:*[2,3]
ISO/ASTM 52921 Standard terminology for additive manufacturing – Coordinate systems and test methodologies

2.4 *ISO Standard:*[3]
ISO 17296-3 Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods

3. Terms and definitions

3.1 *Definitions:* For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 and the following apply.[4]

3.1.1 *pre-shipment inspection*—inspection carried out by the part producer on the parts to be supplied according to the part definition or on the test units in order to verify that these parts are in compliance with the order requirements.

3.1.2 *qualification part*—part fabricated prior to commencing production which is used to qualify specific aspects of the manufacturing process or part characteristics in order to use as a basis to initiate production.

3.1.3 *first production part*—part with the same geometry

ISO/ASTM 52901 Presentation of general principles – Requirements for purchased parts made by additive manufacturing

A1. Typical content of a purchase order

A1.1 Part ordering information

Information	Relevant subclause of ISO/ASTM 52901	Content
Reference identification of this document, i.e. ISO/ASTM 52901	4.2(a)	
Customer organization and contact information	4.2(e)	
Customer part order identification (requisition number, requisition date, etc.)	4.2(f)	
Designation or description of the part(s) desired (part number/identification, revision index, etc.)	4.2(g)	
Quantity of parts desired	4.2(h)	
Required delivery date (if single order)	4.2(i)	
Required delivery quantity, frequency, and time duration of the order (if ongoing or multiple orders)	4.2(j)	
Required marking or tagging of the parts	4.2(k)	
Part packaging requirements for delivery to the customer	4.2(l)	
Customer shipping address	4.2(m)	

A1.2 Definition of the part to be manufactured

Information	Relevant subclause of ISO/ASTM 52901	Content
Engineering drawing reference (number, index and version)	4.3.2(a)	
Digital file reference (name, format, version)	4.3.2(b)	
Geometric description (either paper drawing or digital file)	4.3.2(c)	
Tolerances	4.3.3	
Surface texture	4.3.4	
Build orientation of the part	4.3.5	
Feedstock for the part to be manufactured: — feedstock characteristics — storage, handling and processing requirements — method for transmitting information on the feedstock recycling (including frequency and percentage)	4.3.6	
Repair methods	4.3.7	
Acceptable imperfection(s) or non-conformance	4.3.8	
Process control information	4.3.9	

A1.3 Part characteristics, functionality and performance

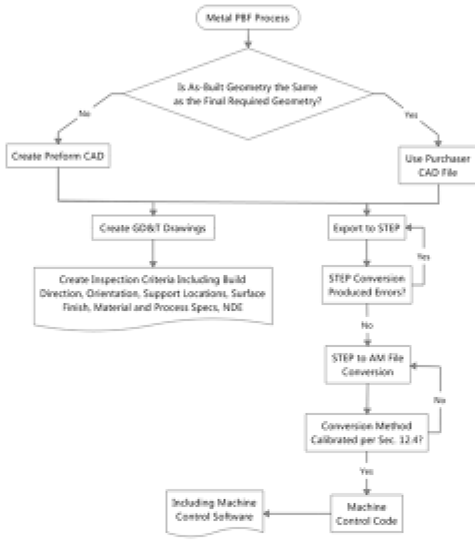
Characteristic	Relevant subclause of ISO/ASTM 52901	Content: Reference to standards to be used, frequency and number of tests – requirements to be fulfilled
Dimensional accuracy	4.4.1 and 4.4.2	
Defects	4.4.1 and 4.4.2	
Mechanical properties	4.4.1 and 4.4.2	
Residual stress	4.4.1 and 4.4.2	
Chemical composition	4.4.1 and 4.4.2	
Functionality	4.4.3	
Inspection	4.4.4	
Post-Processing	4.4.5	
Other Requirements	4.4.6	

ISO/TC 261/ ASTM F42 / JG 56:

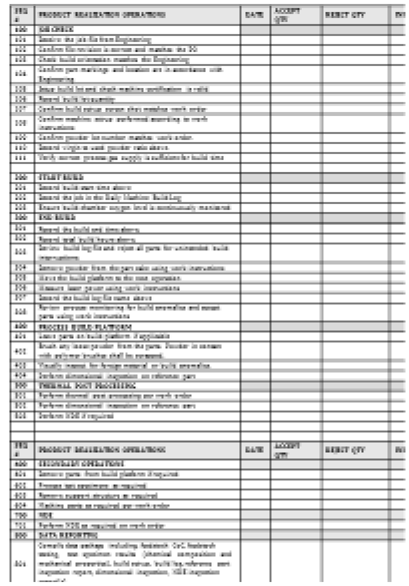
Process Characteristics and Performance: Standard Practice for Metal PBF Process to Meet Critical Applications

Contents

ISO/TC 261/ ASTM F42 / JG 56:
Process Characteristics and Performance: Standard Practice for Metal PBF Process to Meet Critical Applications



Example of a manufacturing plan



F42.05 Materials and Processes Sub-groups: Approved last week in Stockholm

F42.05
Materials and Process
Chair Person
Secretary

Chair: Shane Collins, Additive Industries
Vice-Chair: Matt Donovan, Oerlikon
Secretary: Ryan Spotts, Emerson

- Automotive/Heavy Machinery
- Nuclear?

F42.05.01	F42.05.02	F42.05.03	F42.05.04
Metals	Polymers	Medical Devices	Aerospace
Shane Collins (Additive Industries)	Ralph Buoniconti (SABIC)	Rod McMillan (Johnson & Johnson)	Hector Sandoval (Lockheed Martin)

ASTM Polymer AM Standards (published, drafts)

1. F3091: Standard Specification for Powder Bed Fusion of Plastic Materials (Very general)

2. ISO/ASTM DIS 52903-1: Standard specification for material extrusion based additive manufacturing of plastic materials -- Part 1: **Feedstock materials**
3. ISO/ASTM CD 52903-2: Standard specification for material extrusion based additive manufacturing of plastic materials -- Part 2: Process – **Equipment**
4. ISO/ASTM CD 52903-3: Standard Specification for Material Extrusion Based Additive Manufacturing of Plastic Materials -- Part 3: Part 3: **Final parts**

5. WK59167: Technical Design Guideline for Powder Bed Fusion, Part 2: Laser-based Powder Bed Fusion of Polymers **(Under ballot)**

6. WK: Standard Specification for Polyketones Processed (PEEK, PAEK, PEKK) with Powder Bed Fusion **(Under development)**

Designation: XXXXX-XX

Work Item Number: WKXXXXX

Date: 5/12/17

Include Ballot Rationale Here (Required for all Ballots)

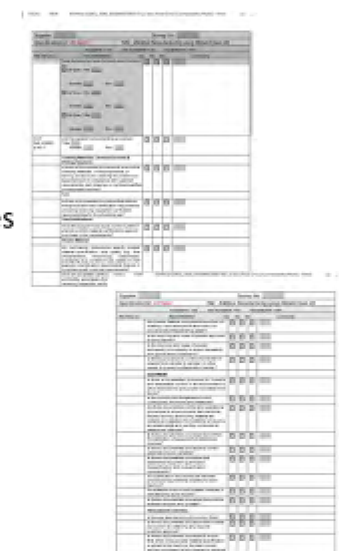
Standard Specification for Polyketones Processed with Powder Bed Fusion

This standard is issued under the fixed designation XXXXX; 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.

NadCap AM Checklists

LOCKHEED MARTIN

- Supplier Quality
  - Survey and Capability
- AM Metals Powder bed and FDM Processes
- Part category focused
- Focused on accepting the finished part
  - ***Not*** Design /Program / Build Qualification



Supporting NADCAP Accreditation Check list

F42.05 Material and Processes

National Aerospace and Defense Contractors Accreditation Program

Specifications and Practices

— WK58233 Specification for **Post Thermal Processing** of Metal Powder Bed Fusion Parts
— WK58222 Practice for **Metal Powder Reuse** in the Powder Bed Fusion Process
— WK58227 Practice for **Digital Data Workflow Control** for the Metal Powder Bed Fusion Process
— WK58234 Practice / Guide for **Storage of Build Cycle** Technical Data

Guides for Metal Powder Bed Fusion

- WK58219 Creating Feedstock Specifications
- WK58220 Specifying Gases and Nitrogen Generators
- WK58221 Receiving and Storing of Metal Powders
- WK58223 Machine Cleaning
- WK58224 Powder Disposal
- WK58226 IQ, OQ and PQ
- WK58228 Manufacturing Plan for Production Parts
- WK58229 Metallographic Porosity Evaluation of Test Specimens and Parts
- WK58230 Personnel Training Program
- WK58231 Maintenance Schedules and Maintaining Machines
- WK58232 Calibrating Machines and Subsystems

15
Drafts Under Development

More info: http://www.astmnewsroom.org/default.aspx?pageid=4264

F42.06 Environmental, Health and Safety

Subcommittee Chair: Taylor Valone (GE Additive)
Subcommittee Secretary: Ebrahim Asadi

One Approved Work Item – WK59813, Guide for Hazard Risk Ranking and Safety Defense

Scope
This guide will help users understand the risks associated with different types of AM technologies as well as understand the recommended PPE and safety defenses utilized to ensure the operations are completed in a safe manner. Additionally, the guide will also help producers of the equipment understand industry standards and leverage the hierarchy of controls to improve the safety of the machine operation.

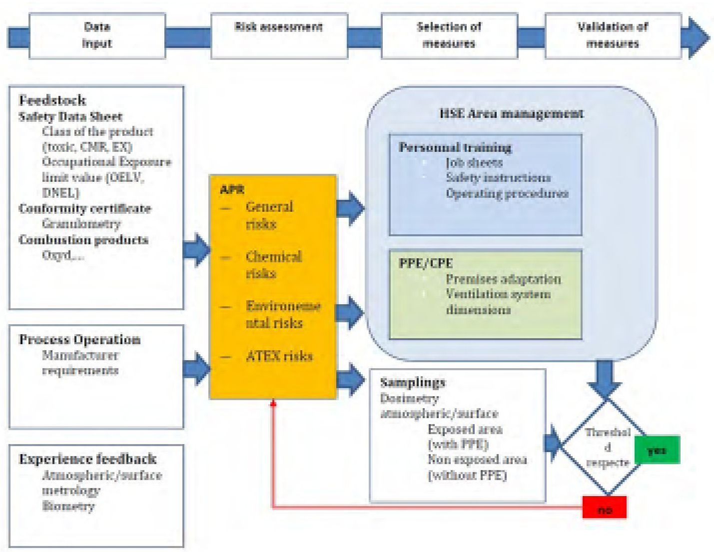
ASTM/ISO/WD 529:201(E)

Additive manufacturing — Guideline for safety, hygiene and environment — Requirements for metallic materials

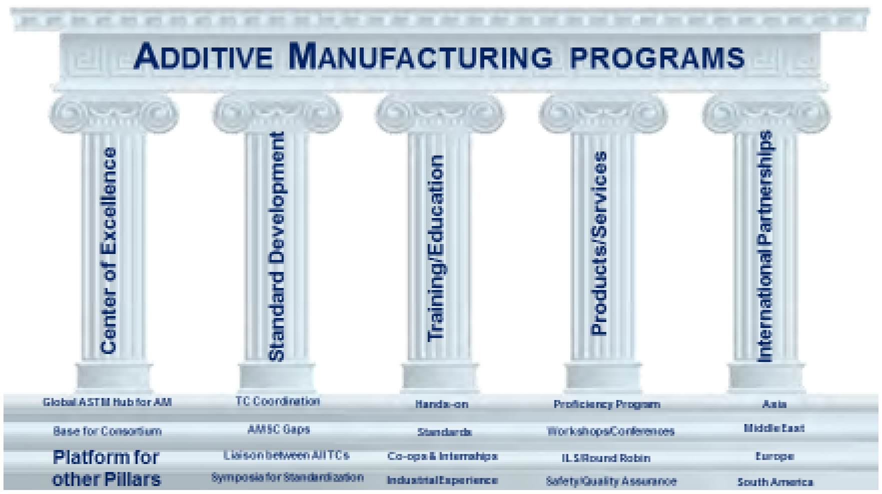
Contents Page

ASTM/ISO/WD 529:201(E)

Additive manufacturing — Guideline for safety, hygiene and environment — Requirements for metallic materials



ASTM Additive Manufacturing Initiatives



What is the ASTM Proficiency Testing Program

—A program designed as a statistical quality control tool enabling participating laboratories to assess their performance in conducting ASTM or other committee approved test methods, such as ISO, IP, EN, UOP, AATCC, etc.

—ASTM provide management and the administrative support:

- Program registration, contract negotiations for sample preparation and distribution, data collection and generation of statistical summary reports

—Coordinate the preparation and distribution of test samples

- Test samples are prepared by outside contractors

—Our program provides reporting instructions, lab test worksheets and electronic data report forms for submitting lab data, all accessible on the ASTM PTP website portal

PTP's
exercising proficiency in over 330 different test methods

ASTM Proficiency Testing Program

New Proposed ASTM Proficiency Testing Program for Metal Powders

Powder Characterization/Test Method

- B215 Practices for Sampling Metal Powders
- B212 Test Method for Apparent Density of Free-Flowing Metal Powders Using the Hall Flowmeter Funnel
- B213 Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
- B214 Test Method for Sieve Analysis of Metal Powders
- B329 Test Method for Apparent Density of Metal Powders and Compounds Using the Scott Volumeter
- B417 Test Method for Apparent Density of Non-Free- Flowing Metal Powders Using the Carney Funnel
- B527 Test Method for Determination of Tap Density of Metallic Powders and Compounds
- B703 Test Method for Apparent Density of Metal Powders and Related Compounds Using the Arnold Meter
- B822 Test Method for Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering
- B855 Test Method for Volumetric Flow Rate of Metal Powders Using the Arnold Meter and Hall Flowmeter Funnel
- B923 Test Method for Metal Powder Skeletal Density by Helium or Nitrogen Pycnometry
- B964 Test Methods for Flow Rate of Metal Powders Using the Carney Funnel

Short summary of a survey to launch this PTP by the numbers:

- 265 companies responded
- 46 companies responded with Yes to this type of PTP, 76 responded with Probably
- 18 – 49 labs would provide results, depending on the test method
- 81 companies would prefer a frequency of 2X/year

Technical Reviewers:

- Selected F42 and B09 executive members

ASTM INTERNATIONAL
Helping our world work better

ASTM WK49229/JG61 at F42:

Guide for Measurement of Orientation and Location Dependent Mechanical Properties for Metal Additive Manufacturing

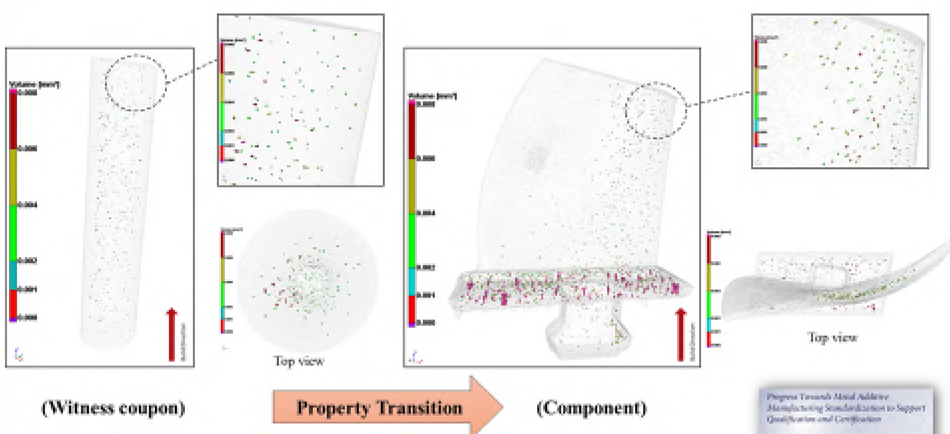
Required R&D and support!

Symposium on Fatigue and Fracture of Additively Manufactured Materials and Components (E08, F42, NIST Sponsored)- November 15th - 16th, 2017

Topics to be addressed include:

- Applicability of existing fatigue and fracture test methods to AM materials
- Development of new fatigue and fracture test methods for AM materials
- Fatigue and fracture behavior of components fabricated using AM
- Residual stress effects
- Effects of process and design parameters on fatigue and fracture behavior
- Process optimization to improve fatigue performance of AM materials
- Nondestructive evaluation of components fabricated using AM
- High-speed, low-cost nondestructive evaluation techniques for AM

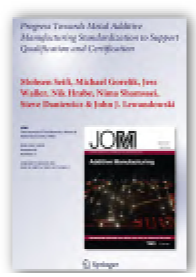
Challenging transition from coupon to real component? (Not exclusive to AM)



- XCT results conducted on a witness coupon and a component made at the same time demonstrating challenging property/characteristics transfer from witness coupon to the actual component.

Seifi et. al, JOM,69(3):439–455, March 2017

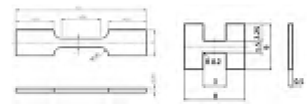
Collaborative joint effort that includes contribution of colleagues at FAA, NASA and NIST



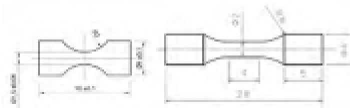
Small samples : Micro-tensile/fatigue Tests (MTT, MFT)

ASTM WK49229, "Guide for Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing," ASTM International, 2015.

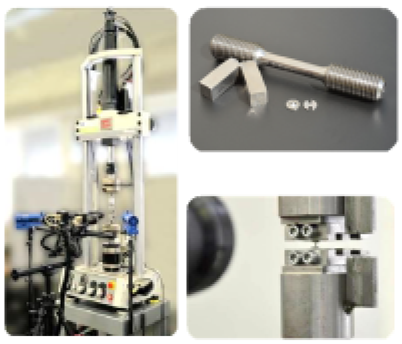
- **Sample dimensions comparable to SPT disc**
- **Deformation measurements using ARAMIS system (Digital Image Correlation)**
- **Tensile diagrams identical with standard tests**

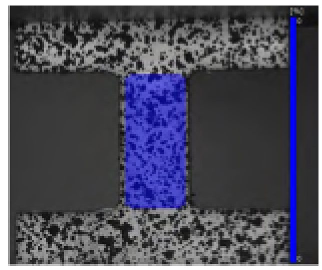


Static: a) proportional specimens, b) short specimen

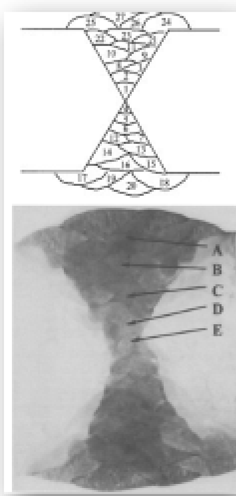


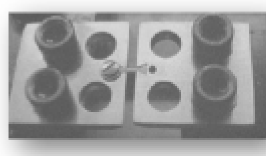
Fatigue: a) force controlled, b) strain controlled





Location-specific properties of welds

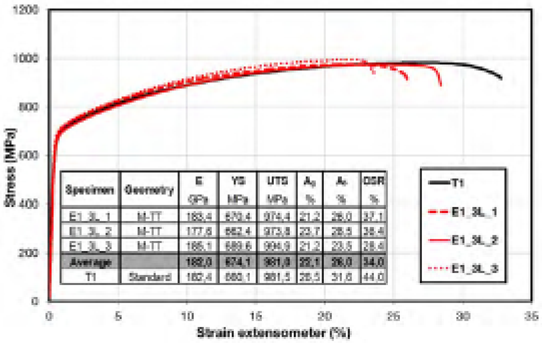




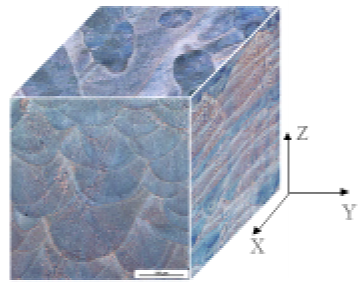
Location	0.2 Percent Yield (MPa)
Macro	486 ± 12.4
23 mm from center	426 ± 59
17 mm from center	443 ± 50
10 mm from center	466 ± 60
4 mm from center	550 ± 67
Center	675 ± 29
Macro	664 ± 38
22 mm from center	621 ± 41
17 mm from center	621 ± 47
11 mm from center	607 ± 38
6 mm from center	690 ± 25
Center	756 ± 29

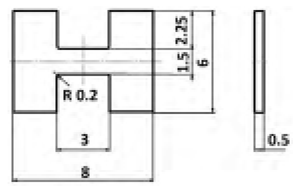
LaVan and Sharpe, *Experimental Mechanics*, *39* (1999) 210–216

Comparison of standard and miniature specimens for AM-produced Inconel 718

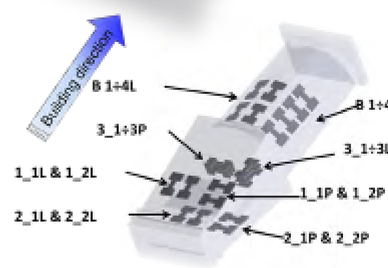


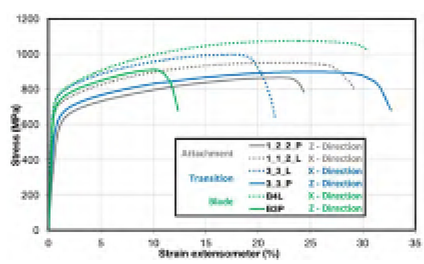
Specimen	Geometry	E GPa	YS MPa	UTS MPa	A_g %	A_5 %	DSR %
E1_3L_1	M-TT	183,4	670,4	974,4	21,2	26,0	37,1
E1_3L_2	M-TT	177,6	662,4	973,8	23,7	28,5	38,4
E1_3L_3	M-TT	185,1	689,6	994,9	21,2	23,5	28,4
Average		182,0	674,1	981,0	22,1	26,0	34,0
T1	Standard	182,4	680,1	981,5	26,5	31,6	44,0





Orientation and Location Specific

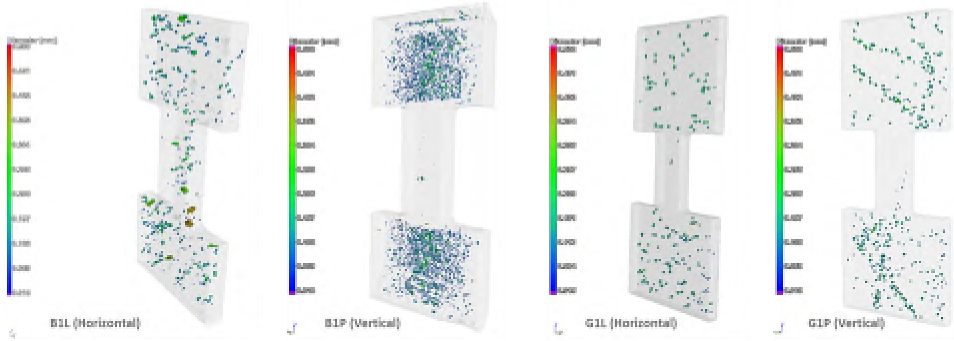




J. Dzugan, M. Seifi, and J. J. Lewandowski et. Al "Miniaturized Mechanical Testing of Components Processed by Metal Additive Manufacturing" Fatigue Fract. Eng Mater. Struct., In submission, 2017.

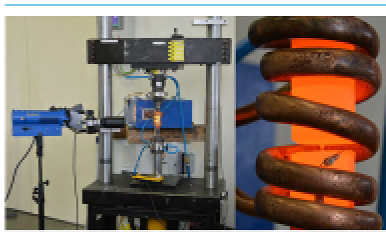
Local characterization of defects, microstructure linkage: SLM IN718

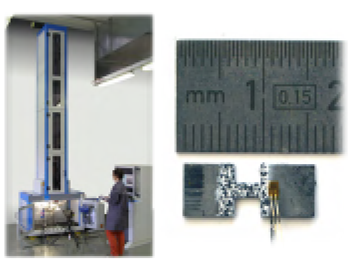
ASTM WK49229, "Guide for Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing," ASTM International, 2015.



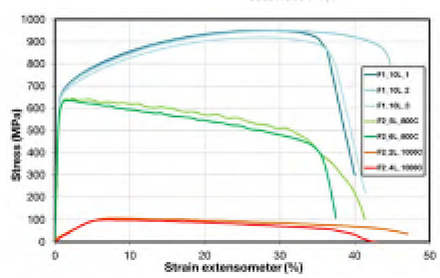
J. Drugan, M. Seifi, and J. J. Lewandowski et. Al "High Temperature, High Rate Fracture Behavior of SLM Processed IN 718 Using Miniaturized Specimens," Adv. Eng. Mater., In submission, 2017.

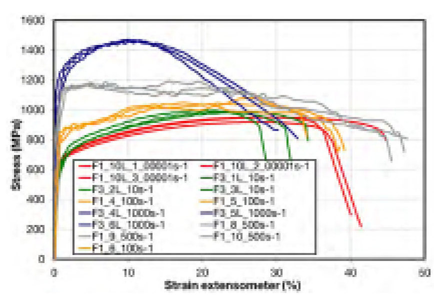
Ongoing Testing Plans -High temperature/rate tests

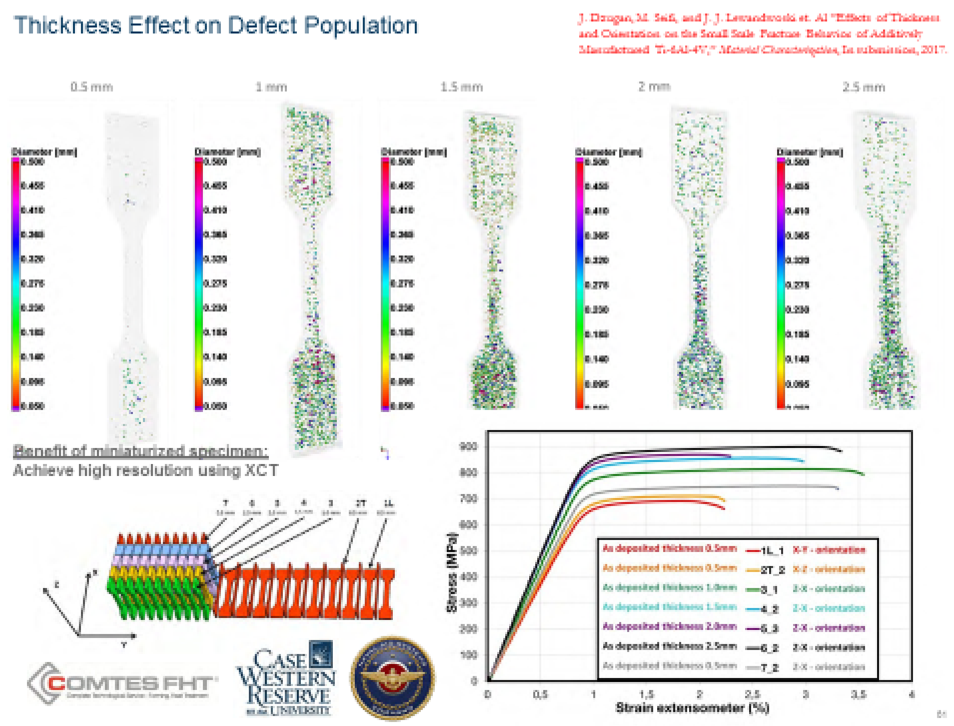




J. Drugan, M. Seifi, and J. J. Lewandowski et. Al "High Temperature, High Rate Fracture Behavior of SLM Processed IN 718 Using Miniaturized Specimens," Adv. Eng. Mater., In submission, 2017.






Thickness Effect on Defect Population
J. Dzugan, M. Seifi, and J. J. Lewandowski et. Al "Effects of Thickness and Orientation on the Small Scale Fracture Behavior of Additively Manufactured Ti-6Al-4V," Material Characterization, In submission, 2017.
0.5 mm
1 mm
1.5 mm
2 mm
2.5 mm
Diameter [mm]
Benefit of miniaturized specimen:
Achieve high resolution using XCT
COMTES FHT
CASE WESTERN RESERVE UNIVERSITY
Stress (MPa)
Strain extensometer (%)
As deposited thickness 0.5mm 1L_1 X-Y - orientation
As deposited thickness 0.5mm 2T_2 X-Z - orientation
As deposited thickness 1.0mm 3_1 Z-X - orientation
As deposited thickness 1.5mm 4_2 Z-X - orientation
As deposited thickness 2.0mm 5_3 Z-X - orientation
As deposited thickness 2.5mm 6_2 Z-X - orientation
As deposited thickness 0.5mm 7_2 Z-X - orientation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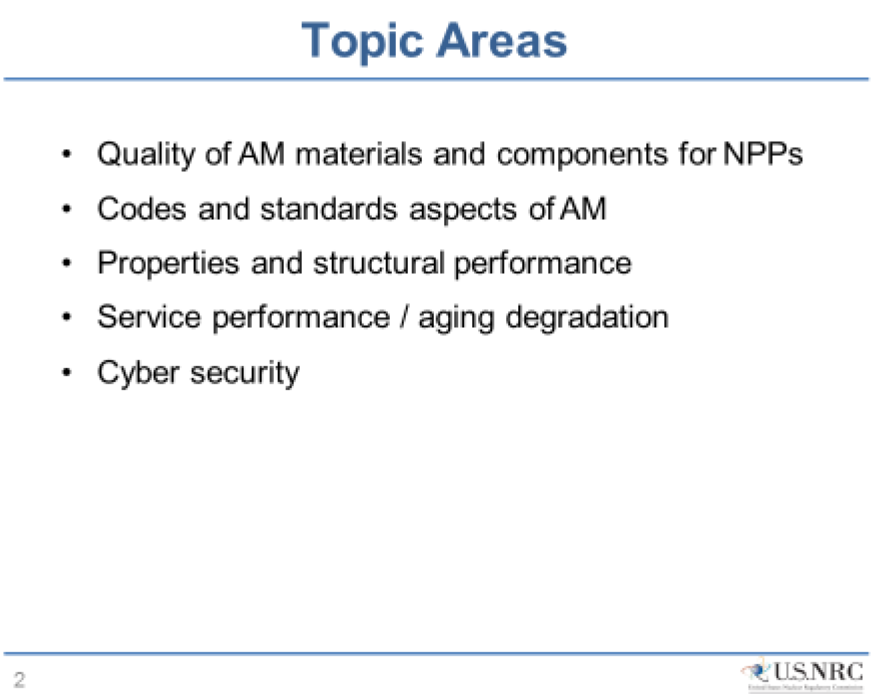
4.32 **<u>Topics of Interest for AM of Reactor Materials and Components (Allen Hiser, NRC)</u>**



But First – For NRC Planning Purposes

- Schedule for industry implementation of AM
  - Topical report process
  - License amendment process
  - 10 CFR 50.59 process
  - Timing of plant-specific implementation vis-à-vis codes/standards action and/or topical report approval will significantly affect review complexity
- Volume of licensing actions
  - Could lead to prioritization of reviews
- Scope of actions that are of interest to NRC – similar to License Renewal
  - safety-related systems, structures, and components (SSCs)
  - all nonsafety-related SSCs whose failure could adversely impact functionality of safety-related SSCs
  - SSCs relied on in certain safety analyses or plant evaluations for specific NRC regulations.

Quality of AM Parts for NPPs

- AM Build Process
  - Critical parameters
  - Directionality
  - Uniformity
  - Residual stresses
  - Surface roughness
  - Density
  - Powder reuse
- Post-Build Processing
  - Densification (e.g., Hot Isostatic Pressing)
  - Annealing
  - Surface processing

Codes and Standards Aspects of AM

- American Society of Mechanical Engineers (ASME)
- ASTM International
  - formerly American Society for Testing and Materials
- American National Standards Institute (ANSI)
- American Society for Nondestructive Testing (ASNT)
- NACE International
  - formerly National Association of Corrosion Engineers

Properties and Structural Performance

- Properties
  - As-built
  - After post-build processing
  - Coupons vs. component
  - Fatigue performance
  - Comparison to conventional manufacturing methods
- Defect Characteristics/Populations
  - Type
  - Size
  - Density
  - Impact on structural integrity

Properties and Structural Performance

- Inspectability
  - In-process examinations
  - Methods capable of finding structurally relevant defects
  - Pre-service inspections
  - Inservice inspections

Service Performance / Aging Degradation

- In various service environments
  - Aqueous
    - Corrosion
    - Stress corrosion cracking (SCC)
    - Environmental fatigue life
    - Environmental fatigue crack growth
  - Neutron effects
    - Loss of fracture toughness
    - Swelling
    - IASCC
  - Thermal effects
    - Loss of fracture toughness
    - Thermal expansion

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Summary

- Additive Manufacturing has been identified as an area of potential future utilization by the nuclear industry – "when" and "how many" are the questions
- NRC interest areas
  - The quality of AM parts
  - The properties of AM parts
  - The structural performance of AM parts, including their inspectability
  - The service performance and aging degradation of AM parts
- Codes and standards aspects of AM is a key to successful implementation
- Comparison of performance of parts from AM and conventional manufacturing process

5 SUMMARY

This conference was a large success due to the participation of those members of the industry and NRC that presented. Valuable information was gathered and many important questions were raised, answered, and collected. Section 4 of this document provided the presentations given during the conference. Once again, the views, opinions, and recommendations presented in this document do not constitute any NRC approval or agreement and do not provide regulatory guidance for Additive Manufacturing. Thank you to those that participated in this conference and provided the valuable data necessary for the NRC to understand Additive Manufacturing and its role in nuclear power plants.

NRC staff are in the early stages of developing an agency action plan. This action plan will (1) address preparation of NRC readiness for review of AM parts; (2) provide for interoffice coordination; and (3) guide agency involvement in codes and standards organizations.

Next steps include further engagement with industry to understand potential implementation and with other organizations to understand expertise and resources. Discussions are underway about possibly conducting a modified PIRT-type process of the vast amount of information captured from this meetings and others similar to it. Tables would be constructed similar to that shown below.

Example of Significant Knowledge Gaps concerning Advanced Methods of Manufacturing (modified from NUREG/CR-6944, Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTS), Vol 4: High-Temperature Materials PIRTS, 40 pp., November 2007)

ID No.	Phenomena	Phenomena Importance (H, M, L or NR=Not Ranked)	Rationale for Rankings of Phenomenon Importance	Knowledge Level (H, M, L or NR=Not Ranked)	Rationale for Rankings of Knowledge	Suggested Additional Research	Reference (paper)
1	Radiation Degradation	H	Use of components in pressure boundaries and ASME Class 1 systems makes radiation degradation testing a requirement	L	Insufficient data exists to support the use of AM components in pressure boundary and ASME Class 1 systems.	Perform radiation degradation testing in a qualified laboratory to determine the effect of radiation over time on AM components.	4,2, 4.18
2	Crack Initiation & subcritical crack growth	H	Change in porosity can increase SCC and CGR.	L	Hard to appraise incomplete recrystallization affects SCC.	Further testing.	4.3
3	Welding	H	Transition joint produced by non-equilibrium weld, solid-state phase transformations occur.	L	AM data has much commonality with weld data.	Further testing.	4.24

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NRC FORM 335 (12-2010) NRCMD 3.7 — U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG/CP-0310
2. TITLE AND SUBTITLE Proceedings of the Public Meeting on Additive Manufacturing for Reactor Materials and Components	3. DATE REPORT PUBLISHED MONTH: July — YEAR: 2019 4. FIN OR GRANT NUMBER
5. AUTHOR(S) Amy Hull, Carol Moyer, Brian Harris, and Jason Christensen	6. TYPE OF REPORT Technical 7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Division of Engineering
Office of Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Construction Inspection and Operational Programs
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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The U.S. Nuclear Regulatory Commission's (NRC's) Offices of Nuclear Regulatory Research (RES), Nuclear Reactor Regulation (NRR) and New Reactors (NRO) organized this Workshop on Additive Manufacturing for Reactor Materials & Components (AM-RMC). The workshop was held November 28-29, 2017, at NRC Headquarters, 11545 Rockville Pike, Rockville, Maryland.

The NRC had been earlier informed in mid-2017 that reactor components made by additive manufacturing (AM), and especially by powder bed fusion/direct metal laser melting (DMLM)/sintering, were being considered for applications in the operating fleet as early as calendar year 2018. Given the anticipated level of activity, the objectives for this public meeting were to:
(1) Engage with industry and Government counterparts to obtain information needed for anticipated licensing actions related to AM.
(2) Address fabrication, qualification, and regulation topics in the field.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	13. AVAILABILITY STATEMENT
Additive Manufacturing Advanced Manufacturing Powder Bed Fusion Direct Metal Laser Melting	unlimited
	14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified
	15. NUMBER OF PAGES
	16. PRICE

Printed on recycled paper

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

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Proceedings of the Public Meeting on Additive Manufacturing for Reactor Materials and Components

July 2019