U.S.NRC
United States Nuclear Regulatory Commission
*Protecting People and the Environment*

RIL 2021-03

# NRC WORKSHOP ON ADVANCED MANUFACTURING TECHNOLOGIES FOR NUCLEAR APPLICATIONS

## Part II – Workshop Slides

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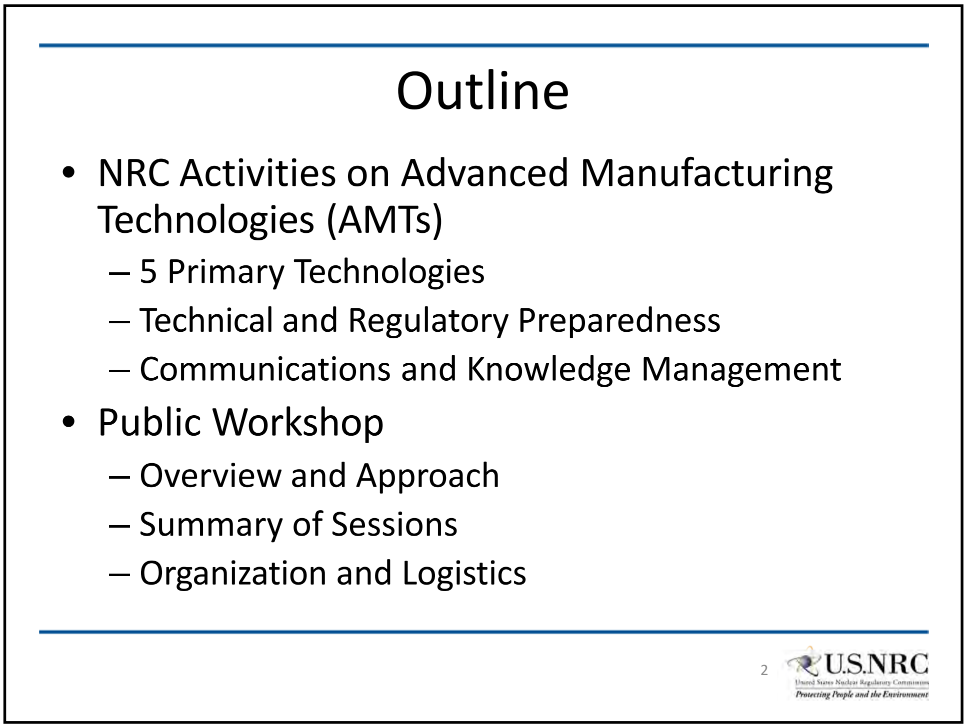
**Research Information Letter**
**Office of Nuclear Regulatory Research**

# Disclaimer

# NRC Public Workshop on Advanced Manufacturing Technologies for Nuclear Applications

Matthew Hiser and Mark Yoo
Office of Nuclear Regulatory Research
December 7, 2020



## Outline

- NRC Activities on Advanced Manufacturing Technologies (AMTs)
  - 5 Primary Technologies
  - Technical and Regulatory Preparedness
  - Communications and Knowledge Management
- Public Workshop
  - Overview and Approach
  - Summary of Sessions
  - Organization and Logistics

# Advanced Manufacturing Technologies

- Techniques and material processing methods that have **not** been:
  - Traditionally used in the U.S. nuclear industry
  - Formally standardized/codified by the nuclear industry
- Key AMTs based on industry interest:
  - Laser Powder Bed Fusion (LPBF)
  - Direct Energy Deposition (DED)
  - Electron Beam Welding
  - Powder Metallurgy - Hot Isostatic Pressing (PM-HIP)
  - Cold Spray

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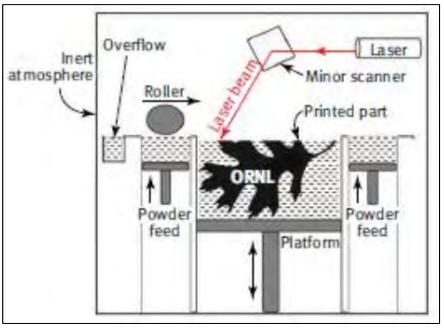
# Laser Powder Bed Fusion

- Process:
  - Uses laser to melt or fuse powder particles together within a bed of powder
  - Generally most advantageous for more complex geometries
- Potential Applications
  - Smaller Class 1, 2 and 3 components, fuel hardware, small internals

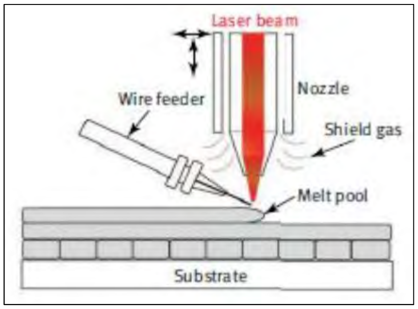


Schematic of LPBF process*

* https://www.osti.gov/pages/servlets/purl/1437906

# Directed Energy Deposition

- Process:
  - Wire or powder fed through nozzle into laser or electron beam
  - Fundamentally welding using robotics/ computer controls



Schematic of DED process*

- Potential Applications
  - Similar to LPBF, although larger components due to faster production and greater build chamber volumes

* https://www.osti.gov/pages/servlets/purl/1437906

# Powder Metallurgy – Hot Isostatic Pressing (PM-HIP)

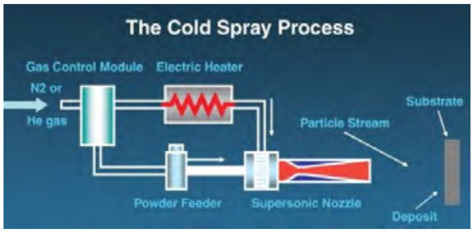
- Process:
  - Metal powder is encapsulated in a form mirroring the desired part
  - The encapsulated powder is exposed to high temperature and pressure, densifying the powder and producing a uniform microstructure
  - After densification, the capsule is removed, yielding a near-net shape component where final machining and inspection can be performed
- Potential Applications
  - All sizes of Class 1, 2 and 3 components and reactor internals
  - EPRI / DOE focused on use with electron-beam welding to fabricate NuScale reactor vessel

# Electron Beam Welding

- Process:
  - Fusion welding process that uses a beam of high-velocity electrons to join materials
  - Single pass welding without filler metal
  - Welding process can be completed much more quickly due to deep penetration
- Potential Applications
  - For welding medium and large components, such as NuScale upper head

# Cold Spray

- Process:
  - Powder is sprayed at supersonic velocities onto a metal surface and forms a bond with the part
  - This can be used to repair existing parts or as a mitigation process



Schematic of cold spray process*

- Potential Applications
  - Mitigation or repair of potential chloride-induced stress corrosion cracking (CISCC) in spent fuel canisters
  - Mitigation or repair of stress corrosion cracking (SCC) in reactor applications

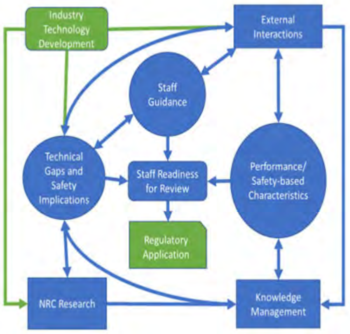
*https://www.army.mil/article/148465/army_researchers_develop_cold_spray_system_transition_to_industry

# NRC Action Plan

- NRC activities related to AMTs have been organized and planned through the AMT action plan (Rev. 1 in June 2020 - ML19333B980) with the following objectives:
  - Assess the safety significant differences between AMTs and traditional manufacturing processes, from a performance-based perspective.
  - Prepare the NRC staff to address industry implementation of AMT-fabricated components through the 10 CFR 50.59 process.
  - Identify and address AMT characteristics pertinent to safety, from a risk-informed and performance-based perspective, that are not managed or addressed by codes, standards, regulations, etc.
  - Provide guidance and tools for review consistency, communication, and knowledge management for the efforts associated with AMT reviews.
  - Provide transparency to stakeholders on the process for AMT approvals.

# Action Plan – Rev. 1 Tasks

- Task 1 - Technical Preparedness
  - Technical information, knowledge and tools to prepare NRC staff to review AMT applications
- Task 2 - Regulatory Preparedness
  - Regulatory guidance and tools to prepare staff for efficient and effective review of AMT-fabricated components submitted to the NRC for review and approval
- Task 3 - Communications and Knowledge Management
  - Integration of information from external organizations into the NRC staff knowledge base for informed regulatory decision-making
  - External interactions and knowledge sharing, i.e. AMT Workshop



# Technical Preparedness Activities

- Subtask 1A: AMT Processes under Consideration
  - Perform a technical assessment of multiple selected AMTs (Laser Powder Bed Fusion, Directed Energy Deposition, PM-HIP, EB-welding, and Cold Spray)
  - Gap assessment for each selected AMTs vs traditional manufacturing techniques
- Subtask 1B: NDE Gap Assessment
  - Assess the state of technologies in the testing and examination of AMTs
  - Will inform staff decisions related to use of NDE on AMT-fabricated components
- Subtask 1C: Microstructural and Modeling
  - Evaluate modeling and simulation tools used to predict the initial microstructure, material properties and component integrity of AMT components
  - Identify existing gaps and challenges that are unique to AMT compared to conventional manufacturing processes

# Regulatory Preparedness Activities

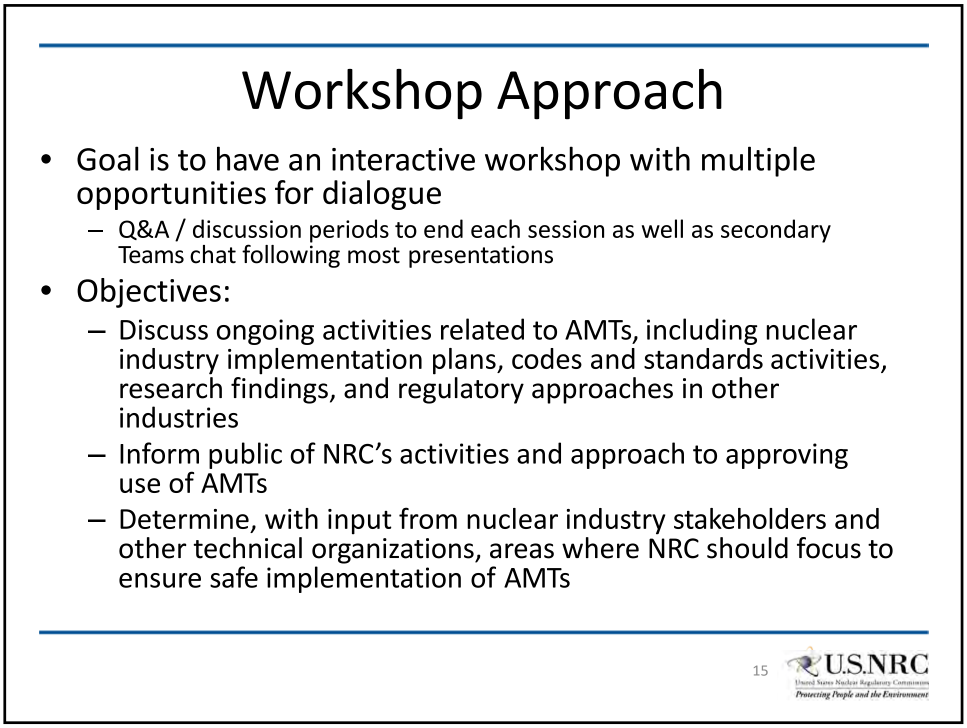
- Subtask 2A: Implementation using the 10 CFR 50.59 Process
  - Provide guidance and support to regional inspectors regarding AMTs implemented under 50.59
- Subtask 2B: Assessment of Regulatory Guidance
  - Assess whether any regulatory guidance needs to be updated or created to clarify the process for reviewing submittals with AMT components
  - Complete: ML20233A693
- Subtask 2C: AMT Guidance Document
  - Develop a report which describes the generic technical information to be addressed in AMT submissions
  - Public meeting discussing initial framework was held July 30, 2020: https://www.nrc.gov/pmns/mtg?do=details&Code=20200816
  - Meeting summary can be found here: ML20240A077

# Communications and KM Activities

- Subtask 3A: Internal Interactions
  - Internal coordination with NRC staff in other areas (e.g., advanced reactors, dry storage, fuels)
- Subtask 3B: External Interactions
  - Engagement with codes and standards, industry, research, international
- Subtask 3C: Knowledge Management
  - Seminars, public meetings, training, knowledge capture tools
- Subtask 3D: Public Workshop
- Subtask 3E: AMT Materials Information Course
  - Internal NRC staff training

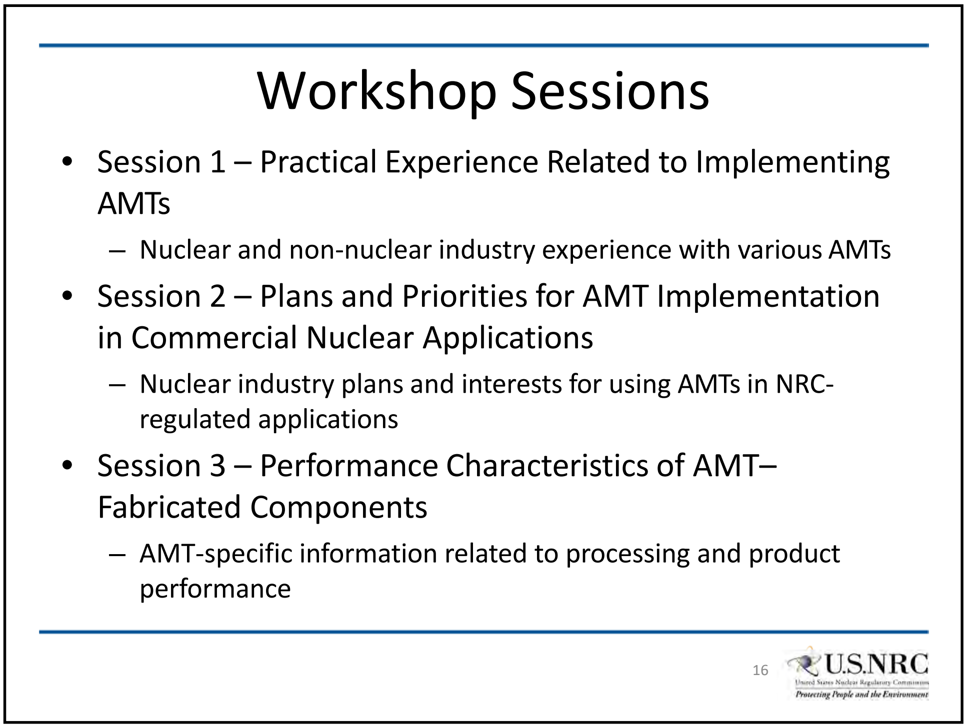
# Workshop Overview

- Location/Dates: Virtual, December 7-10, 2020
- Website: https://www.nrc.gov/public-involve/conference-symposia/amt-workshop.html
- Motivation:
  - Increasing industry interest and plans to implement AMTs for nuclear applications
    - Replacement components in operating nuclear power plants and in initial construction of small modular and advanced reactors.
  - NRC must be prepared to efficiently and effectively regulate and respond to industry submittals that apply AMTs for both operating and future plants.
- Participants
  - Vendors, utilities, EPRI, NEI, DOD, DOE (incl. labs), NIST, NASA, regulators (other U.S. government, international)



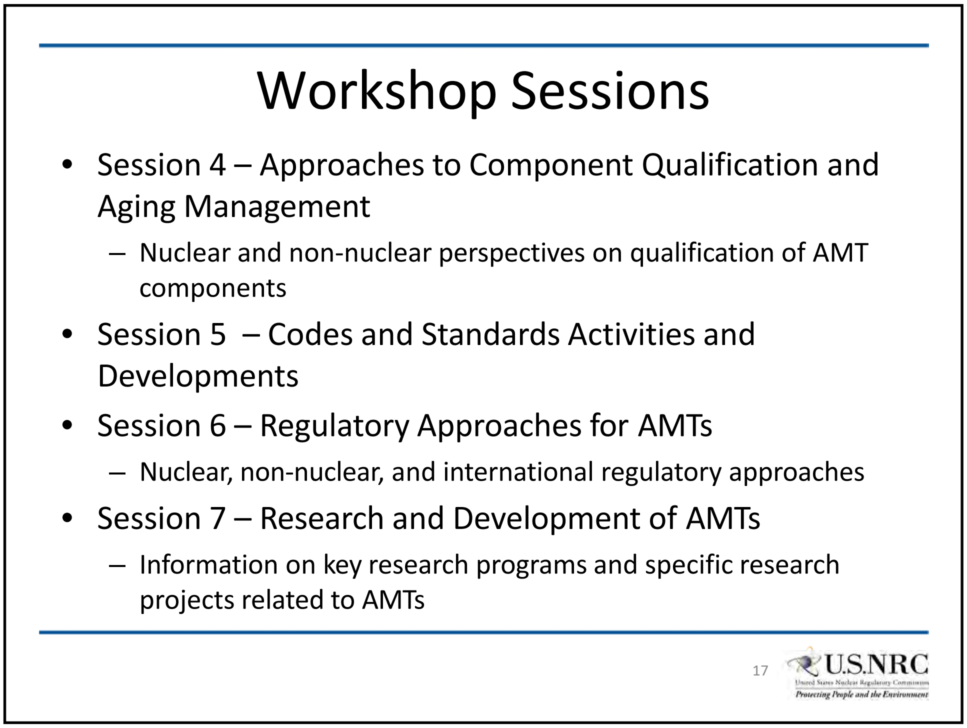
# Workshop Approach

- Goal is to have an interactive workshop with multiple opportunities for dialogue
  - Q&A / discussion periods to end each session as well as secondary Teams chat following most presentations
- Objectives:
  - Discuss ongoing activities related to AMTs, including nuclear industry implementation plans, codes and standards activities, research findings, and regulatory approaches in other industries
  - Inform public of NRC’s activities and approach to approving use of AMTs
  - Determine, with input from nuclear industry stakeholders and other technical organizations, areas where NRC should focus to ensure safe implementation of AMTs



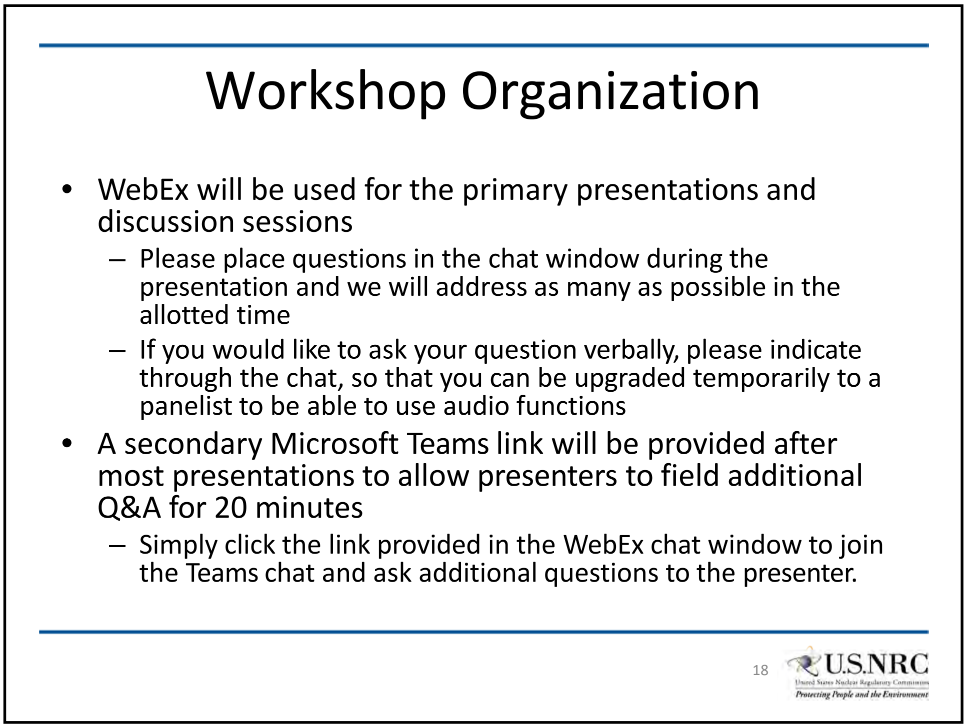
# Workshop Sessions

- Session 1 – Practical Experience Related to Implementing AMTs
  - Nuclear and non-nuclear industry experience with various AMTs
- Session 2 – Plans and Priorities for AMT Implementation in Commercial Nuclear Applications
  - Nuclear industry plans and interests for using AMTs in NRC-regulated applications
- Session 3 – Performance Characteristics of AMT–Fabricated Components
  - AMT-specific information related to processing and product performance



# Workshop Sessions

- Session 4 – Approaches to Component Qualification and Aging Management
    - Nuclear and non-nuclear perspectives on qualification of AMT components
- Session 5 – Codes and Standards Activities and Developments
- Session 6 – Regulatory Approaches for AMTs
    - Nuclear, non-nuclear, and international regulatory approaches
- Session 7 – Research and Development of AMTs
    - Information on key research programs and specific research projects related to AMTs



# Workshop Organization

- WebEx will be used for the primary presentations and discussion sessions
    - Please place questions in the chat window during the presentation and we will address as many as possible in the allotted time
    - If you would like to ask your question verbally, please indicate through the chat, so that you can be upgraded temporarily to a panelist to be able to use audio functions
- A secondary Microsoft Teams link will be provided after most presentations to allow presenters to field additional Q&A for 20 minutes
    - Simply click the link provided in the WebEx chat window to join the Teams chat and ask additional questions to the presenter.

# Siemens Gas and Power
# Overview of additive manufacturing, benefits and challenges industrial approach for AM

**Pajazit Avdovic PhD, Senor Key Expert AM**

NRC Workshop on Advanced Manufacturing

2020-12-07

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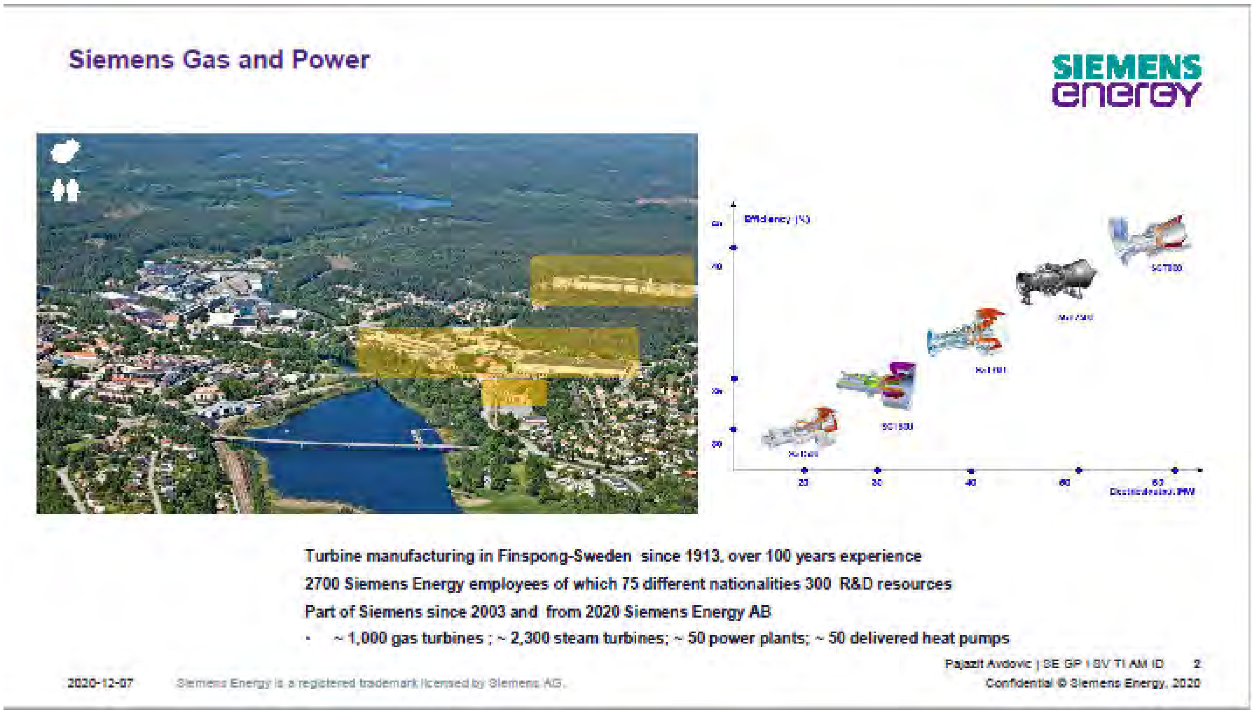


## Siemens Gas and Power

Turbine manufacturing in Finspong-Sweden since 1913, over 100 years experience

2700 Siemens Energy employees of which 75 different nationalities 300 R&D resources

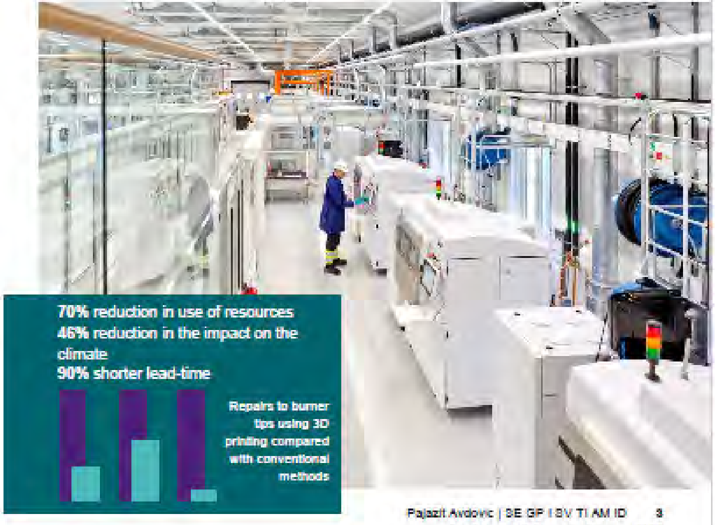
Part of Siemens since 2003 and from 2020 Siemens Energy AB

- ~ 1,000 gas turbines ; ~ 2,300 steam turbines; ~ 50 power plants; ~ 50 delivered heat pumps

## Pioneering Additive Manufacturing

Dedicated workshops in Finspång for development, serial manufacturing and repairs of turbine parts in metal using 3D printing (Additive Manufacturing)

- Pioneers in 3D printing
- Previously "impossible" designs are now possible
- Minimal environmental impact
- Development of components for $CO_2$-free fuels such as hydrogen
- Enables the use of biogas in our own gas turbine testing facility in order to become fossil-free in 2030



**70% reduction in use of resources**
**46% reduction in the impact on the climate**
**90% shorter lead-time**

**Repairs to burner tips using 3D printing compared with conventional methods**

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## Siemens Gas and Power
## Key factors and technologies in the development of future gas turbines

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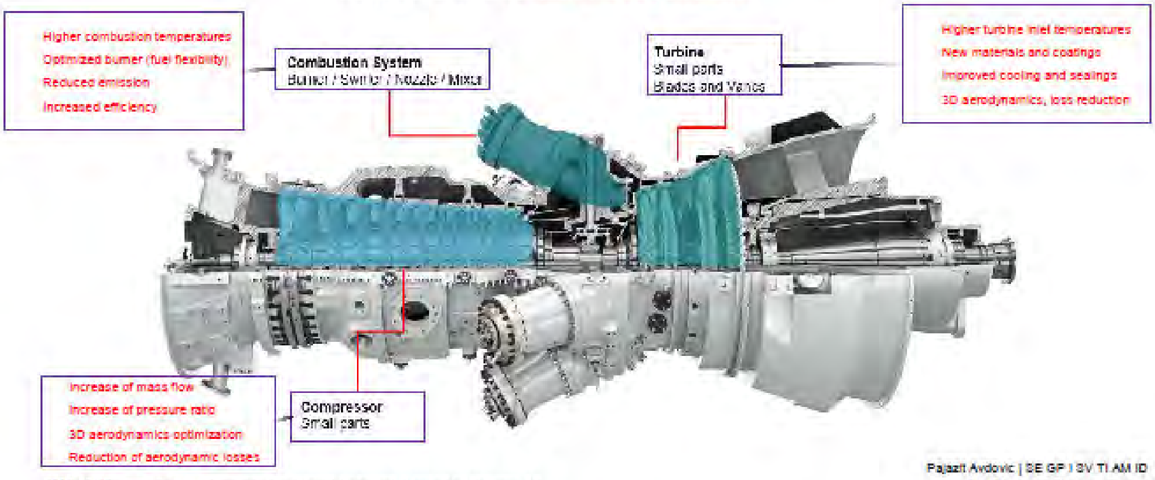
*Gas turbines with it's complex parts in expensive material*
*and*
*relatively small volumes makes AM very attractive!*



Higher combustion temperatures
Optimized burner (fuel flexibility)
Reduced emission
Increased efficiency

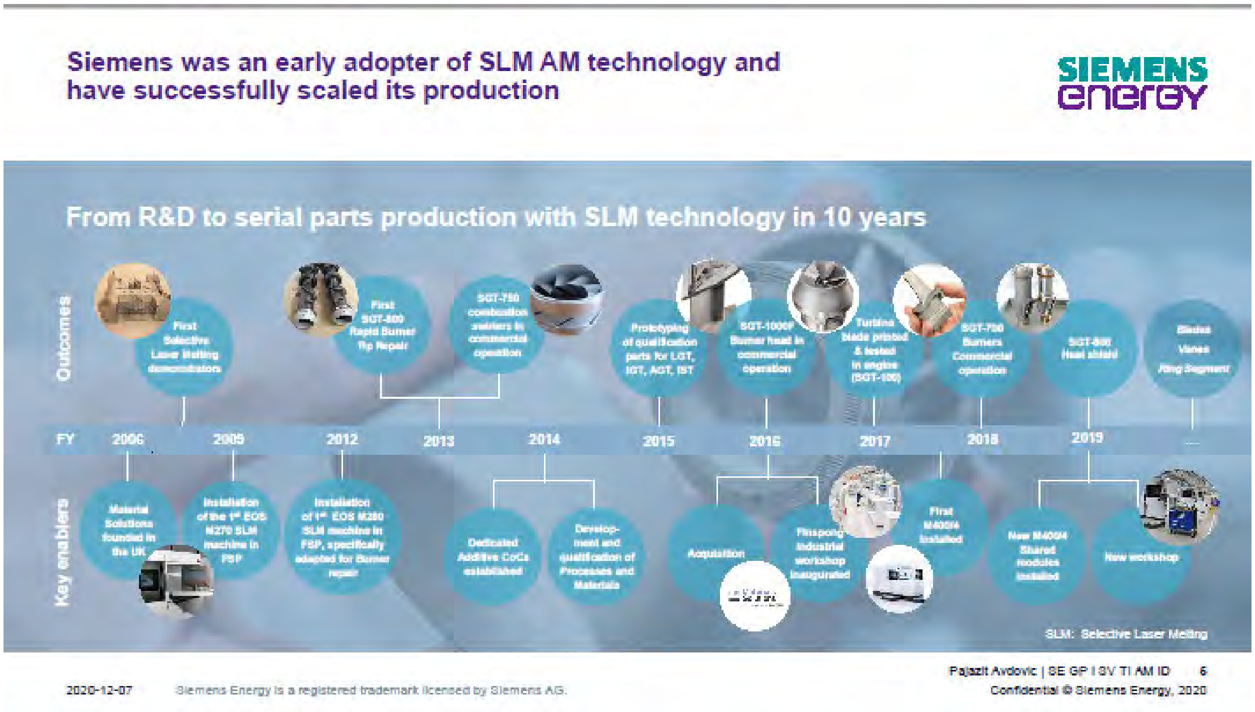
**Combustion System**
Burner / Swirler / Nozzle / Mixer

**Turbine**
Small parts
Blades and Vanes

Higher turbine inlet temperatures
New materials and coatings
Improved cooling and sealings
3D aerodynamics, loss reduction

Increase of mass flow
Increase of pressure ratio
3D aerodynamics optimization
Reduction of aerodynamic losses

Compressor
Small parts



## Siemens was an early adopter of SLM AM technology and have successfully scaled its production

SIEMENS energy

### From R&D to serial parts production with SLM technology in 10 years

**Outcomes**

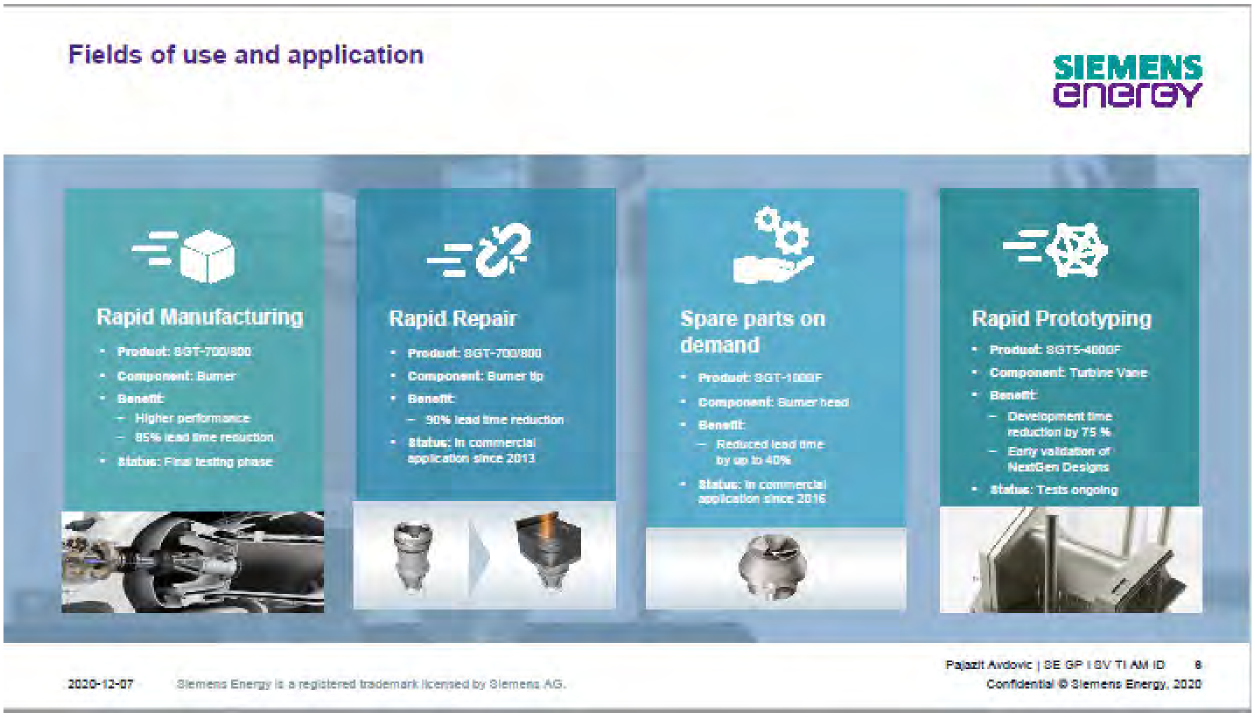
- 2009: First Selective Laser Melting demonstrators
- 2013: First SGT-800 Rapid Burner Tip Repair
- 2013: SGT-750 combustion swirlers in commercial operation
- 2015: Prototyping of qualification parts for LGT, IGT, AGT, IST
- 2016: SGT-1000F Burner head in commercial operation
- 2017: Turbine blade printed & tested in engine (SGT-400)
- 2018: SGT-700 Burners Commercial operation
- 2019: SGT-800 Heat shield
- …: Blades, Vanes, Ring Segment

**FY** 2006 | 2009 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | …

**Key enablers**

- 2006: Material Solutions founded in the UK
- 2009: Installation of the 1st EOS M270 SLM machine in FSP
- 2012: Installation of 1st EOS M280 SLM machine in FSP, specifically adapted for Burner repair
- 2014: Dedicated Additive CoCs established
- 2014: Development and qualification of Processes and Materials
- 2016: Acquisition
- 2016: Finspong industrial workshop inaugurated
- 2017: First M400/4 installed
- 2019: New M400/4 Shared modules installed
- 2019: New workshop

SLM: Selective Laser Melting



## Fields of use and application

SIEMENS energy

### Rapid Manufacturing

- **Product:** SGT-700/800
- **Component:** Burner
- **Benefit:**
  - Higher performance
  - 85% lead time reduction
- **Status:** Final testing phase

### Rapid Repair

- **Product:** SGT-700/800
- **Component:** Burner tip
- **Benefit:**
  - 90% lead time reduction
- **Status:** In commercial application since 2013

### Spare parts on demand

- **Product:** SGT-1000F
- **Component:** Burner head
- **Benefit:**
  - Reduced lead time by up to 40%
- **Status:** In commercial application since 2016

### Rapid Prototyping

- **Product:** SGT5-4000F
- **Component:** Turbine Vane
- **Benefit:**
  - Development time reduction by 75 %
  - Early validation of NextGen Designs
- **Status:** Tests ongoing

## Siemens Gas and Power is one of the world leaders in designing and producing commercial AM components for serial production

SIEMENS energy

**Siemens Gas and Power's experience covers today more than…**

**40+**
3D printing machines operational worldwide

Over **10 years**
experience of SLM

**20+**
components already commercially implemented

Energy
3rd party business
Aerospace
Automotive
Tooling & processing

**>1 500 000**
operating hours on Siemens turbines

**150+**
specialized engineers

**200**
components identified for AM until 2025

## AM challenges and opportunities

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*Challenges*
- *Material knowledge*
- *Design culture*
- *Stand-alone software*
- *Training*
- *Machine performance*
- *Quality issues*
- *Health and Safety concerns*

***Disappointment:***
***"It is not just 3D-Printing!***
***It is much more complex.."***

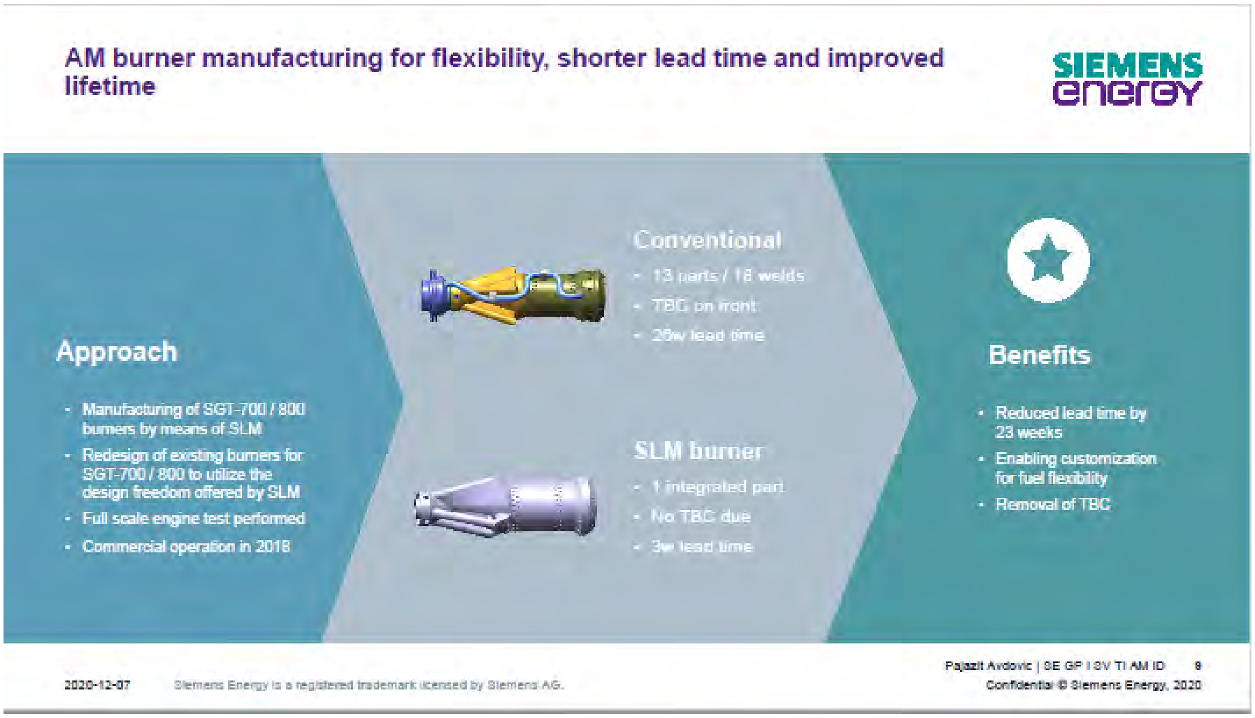
**Autonomous AM 2025 +**
IoT for AM

**Intelligent AM**
"Intelligent" through **Robots**, **VR/AR**, **AI**

**Learning AM**
"Learning" through **Big Data Analytics**, **AM Monitor**, **Virtual Storage** and **Machine Learning**

**Connected AM**
Connected" through **MES**, **AM Network**, **Digital Twin** and Use **Build Job Simulation**

**Traditional AM**



## AM burner manufacturing for flexibility, shorter lead time and improved lifetime

SIEMENS energy

### Approach

- Manufacturing of SGT-700 / 800 burners by means of SLM
- Redesign of existing burners for SGT-700 / 800 to utilize the design freedom offered by SLM
- Full scale engine test performed
- Commercial operation in 2018

### Conventional

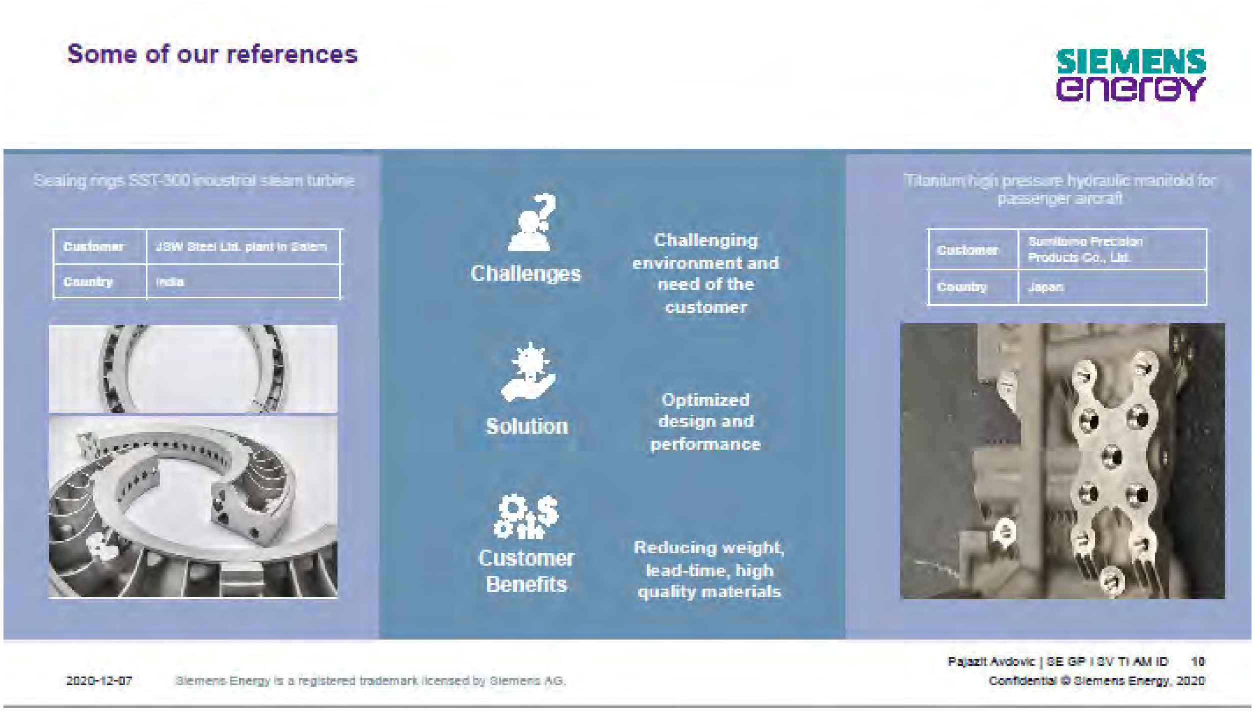
- 13 parts / 18 welds
- TBC on front
- 26w lead time

### SLM burner

- 1 integrated part
- No TBC due
- 3w lead time

### Benefits

- Reduced lead time by 23 weeks
- Enabling customization for fuel flexibility
- Removal of TBC



## Some of our references

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Sealing rings SST-300 industrial steam turbine

| | |
|---|---|
| Customer | JSW Steel Ltd. plant in Salem |
| Country | India |

**Challenges** Challenging environment and need of the customer

**Solution** Optimized design and performance

**Customer Benefits** Reducing weight, lead-time, high quality materials

Titanium high pressure hydraulic manifold for passenger aircraft

| | |
|---|---|
| Customer | Sumitomo Precision Products Co., Ltd. |
| Country | Japan |

## Our Unique Propositions

One of the largest Metal AM Printer fleets in the world

Printers
EOS (M280;M290;M400-4)

**Post processing**
- Ultrasonic Cleaning
- 5 Axis Machining
- Blasting
- EDM Cutting/Bandsaw
- 3D GOM Scanning
- CMM
- Flow testing
- Coating
- Heat treatment
- Heat treatment
- Brazing

Unique capability

**Qualified print process**
- Nickel Superalloys
- Ferrous alloys
- Cobalt alloys
- Titanium alloys

Fully qualified with design data

Aim at highest quality

One of the industry leading within Quality Assurance

Validation and Qualification

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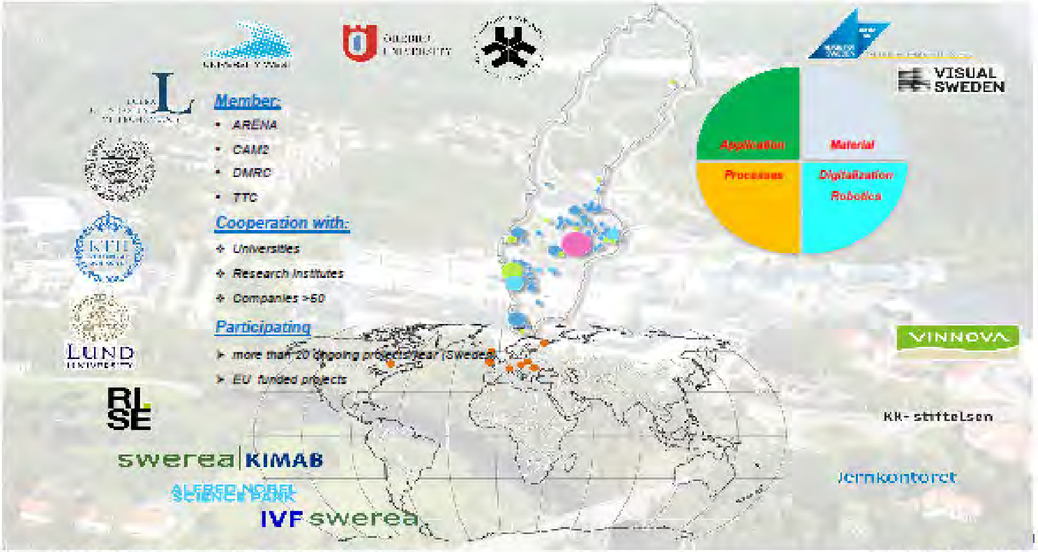
## Siemens Energy and University cooperation in AM area



*Member:*
- *ARENA*
- *CAM2*
- *DMRC*
- *TTC*

*Cooperation with:*
- *Universities*
- *Research Institutes*
- *Companies >60*

*Participating*
- *more than 20 ongoing projects/year (Sweden)*
- *EU funded projects*

# The projects as a result of cooperation with universities and research institutes

Several aspects related to AM automation

- Analyze and create directives and guidelines for what and in which situations AM production should be automated.
- Adapt the automation based on the need, not the need based on the automation of AM
- Automation level of AM, what is the company's policy ?

Collaborative robots for cleaning of machines chamber

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# Selection of the Criteria for Parts

- Dimensions & Weight
- Material
- Design features & complexity
- Function
- Loading
- Inspection requirement
- Accessibility
- Risk of failure
- Consequence of failure

# The document states requirements

- The material produced by additive manufacturing is evaluated against the internal Siemens Energy quality document.
- Scope and procedures for metallurgical examinations (Material identification (powder alloy / material chemistry to certify the composition of the actual material)

Process Validation:

The components prints together with Test Specimens on the same building Plate

Scope and procedures for testing as per Siemens Energy standard material and quality requirements)

- Destructive testing
  - Tensile testing
  - Charpy testing
  - Hardness testing
  - Metallography (porosity, lack of fusion, contamination, hot cracking)
- Non-destructive testing
  - Radiographic testing (RT)
  - Ultrasonic testing (UT)
  - Penetrant testing (PT)
  - Inspection

- Counting of components after important operations (cutting separation from building plate, heat treatment, machining....)
- Requirements for traceability (powder, component, process)

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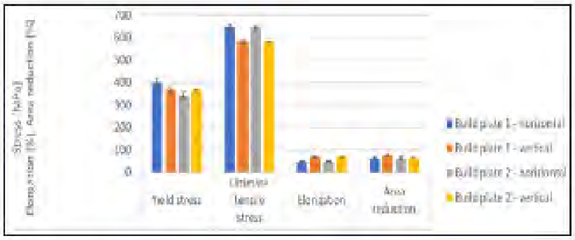
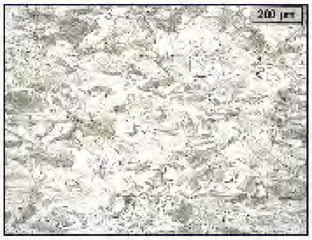
# The document states requirements for:



*Results from tensile testing of witness coupons in the two build jobs for the current project (average values).*



*Microstructure example (witness coupon)*

**From the performed investigations (witness coupon) it can be concluded that:**

- The material is within chemistry specifications
- The material fulfils quality control material properties
- The microstructure is normal for the process/material
- The Mechanical properties from two build jobs are in the same range

## 3D printed parts are in use at Nuclear Power Plant Krško, Slovenia

SIEMENS

Siemens sets industry milestone with first 3D printed part operating in nuclear power plant

Advantages of 3D printing with Additive Manufacturing

- Lead time reduction for parts replacement
- Obsolete parts can be produced
- Saving of material
- Eliminated tools
- On demand

SIEMENS

REFERENCE CONFIRMATION

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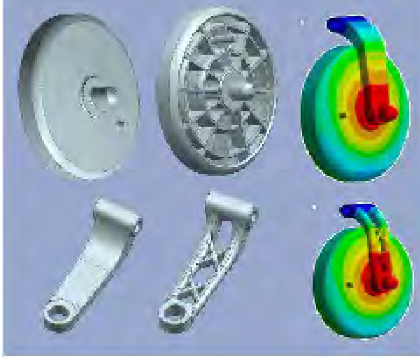
## 3D printed Clapper and Clapper holder

| | |
|---|---|
| Customer | Nuclear Power Plant |
| Country | Spain |



| | | |
|---|---|---|
| Challenges | Obsolete part | Obsolete part, since the original supplier no longer existed |
| Solution | Reverse engineering and qualification of high requirements | - Experts at Siemens Energy reverse engineered the Clapper and Clapper holder to produce a "digital twin" that served as the basis for the 3D printing technique<br>- Assured qualification of part with high safety and reliability requirements |
| Customer Benefits | Significant lead time reduction | - Possibility to re-produce an obsolete part<br>- Lead time reduction for parts replacement<br>- Saving of material<br>- Eliminated tools<br>- On demand |

## Siemens Energy – AM Strategy

SIEMENS energy

- Producing of Components for:
    - Own products – Gas Turbine (prototyping, new components, repair)
    - Nuclear Area, Hydraulic .....

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Pajazit Avdovic | SE GP I SV TI AM ID 19
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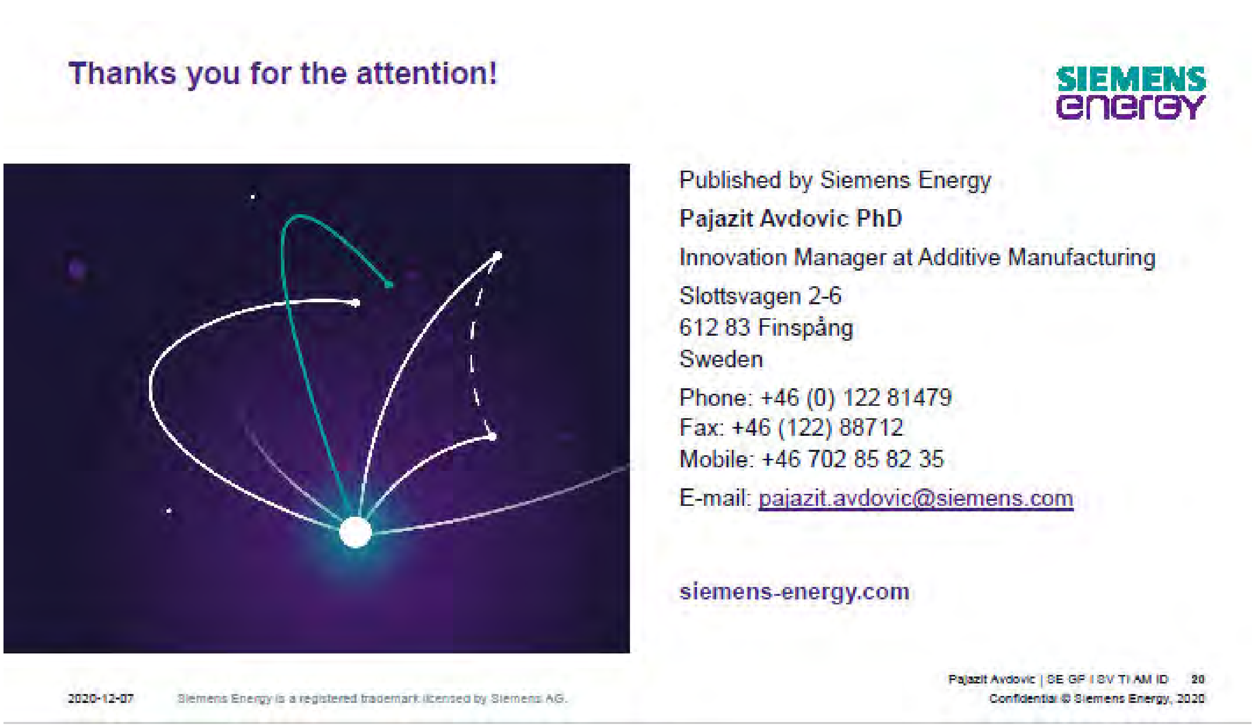

## Thanks you for the attention!

SIEMENS energy

Published by Siemens Energy
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ENGIE Electrabel
ENGIE Laborelec

# ENGIE Experience with Additive Manufacturing and Related Nuclear Applications

US NRC Workshop on Advanced Manufacturing
Technologies for Nuclear Applications
7 December 2020

Arne CLAES
Steve NARDONE

## ENGIE Experience with Additive Manufacturing and Related Nuclear Applications

- Additive Manufacturing @ ENGIE
- ENGIE Qualification Approach for Laser Powder Bed Fusion Process
- Implementation of qualification approach to tackle ENGIE obsolescence challenges

# Additive Manufacturing @ ENGIE

ENGIE Laborelec

ENGIE Electrabel

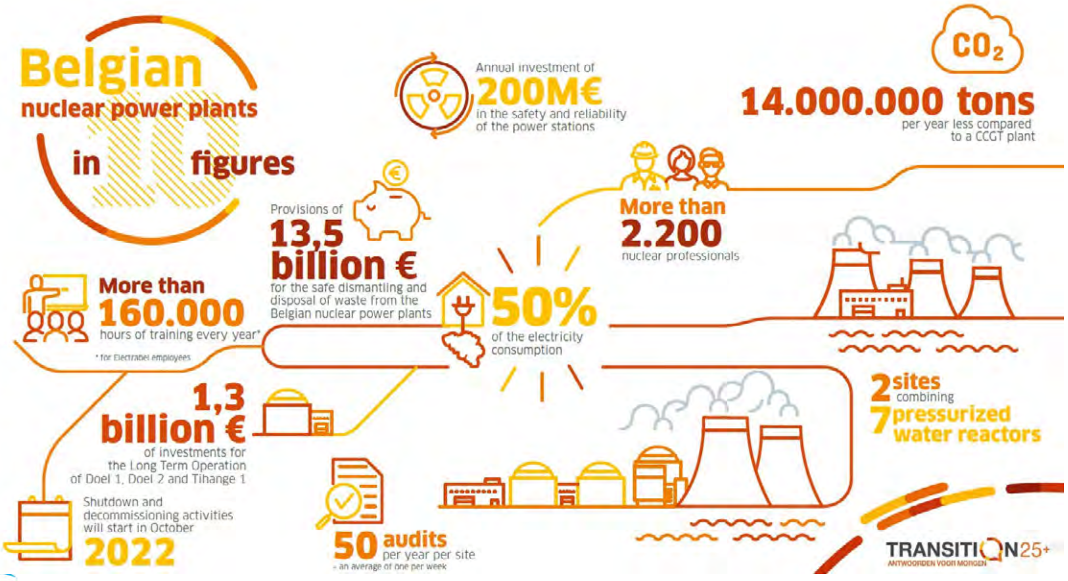
## ENGIE Laborelec

### In a nutshell

- ENGIE Laborelec is a leading **expertise** and **research** center in **electrical power technology**.
- Founded in 1962, the company has **over 55 years** experience in the power sector.
- ENGIE Laborelec is a **cooperative company** with ENGIE and independent grid operators as shareholders.
- Our competencies cover the **entire electricity value chain**: generation, transmission & distribution, RES, storage, usage of the energy for the industry and other end-users.
- We put a strong focus on the **energy transition** and the 3D's : **decentralization**, **decarbonization** and **digitalization**.
- We offer **specialized services**, R&D and **global solutions** in each of these domains, to companies in **all parts of the world**.

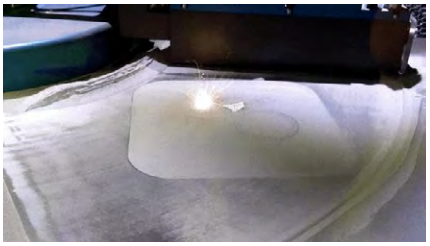
ENGIE Laborelec

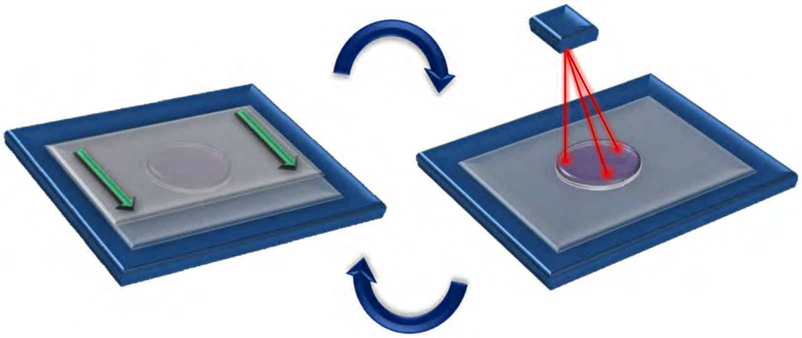
## ENGIE Electrabel in a nutshell



## This webinar deals exclusively with the Laser Powder Bed Fusion process

Local fusion of successive metal powder layers using a high energy laser.

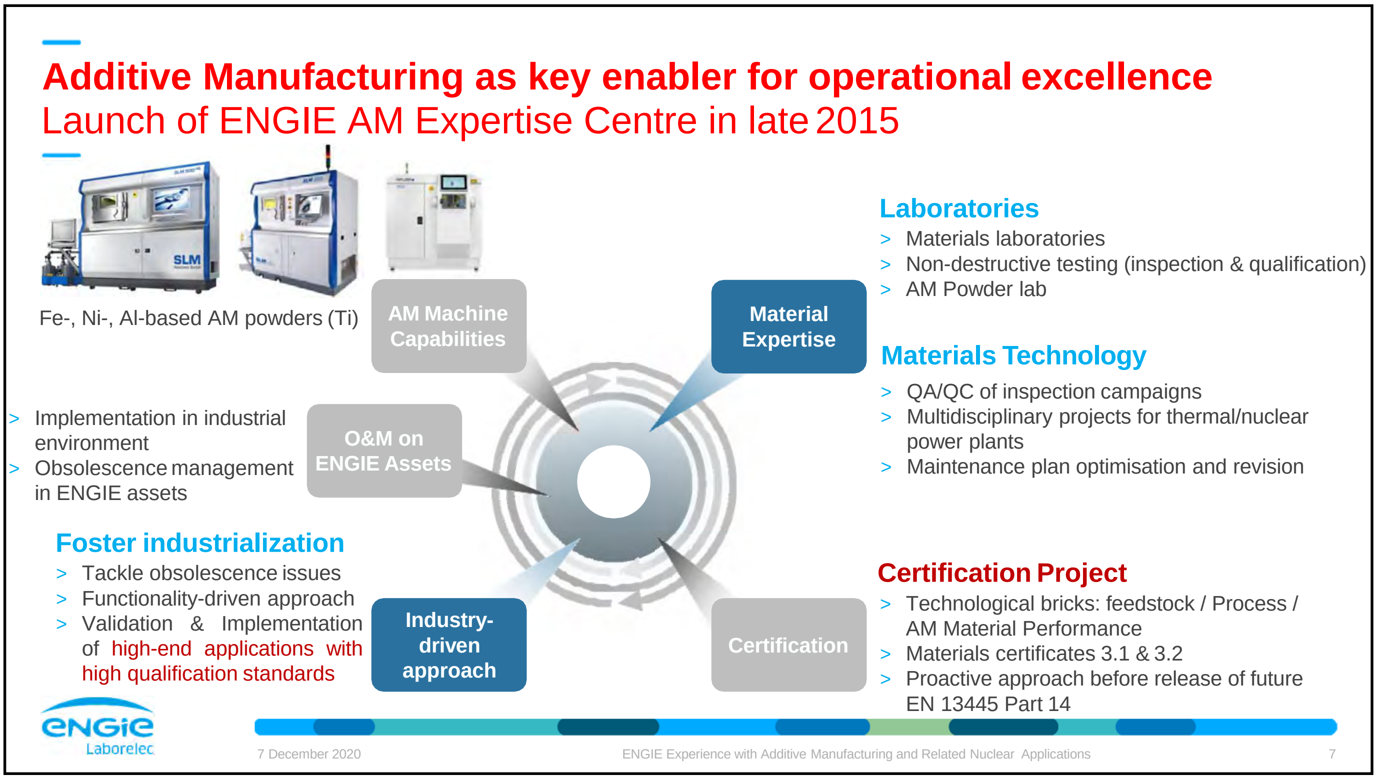




### Simple facts

Production of 10mm-cube using 50µm-layer thickness requires:

- *200 meters of scanned lines !*
- *200 layers !*
- *Fast and local welding process with high heating/cooling cycles*



# Additive Manufacturing as key enabler for operational excellence

## Launch of ENGIE AM Expertise Centre in late 2015

Fe-, Ni-, Al-based AM powders (Ti)

**AM Machine Capabilities**

**Material Expertise**

**O&M on ENGIE Assets**

**Industry-driven approach**

**Certification**

### Laboratories

- Materials laboratories
- Non-destructive testing (inspection & qualification)
- AM Powder lab

### Materials Technology

- QA/QC of inspection campaigns
- Multidisciplinary projects for thermal/nuclear power plants
- Maintenance plan optimisation and revision

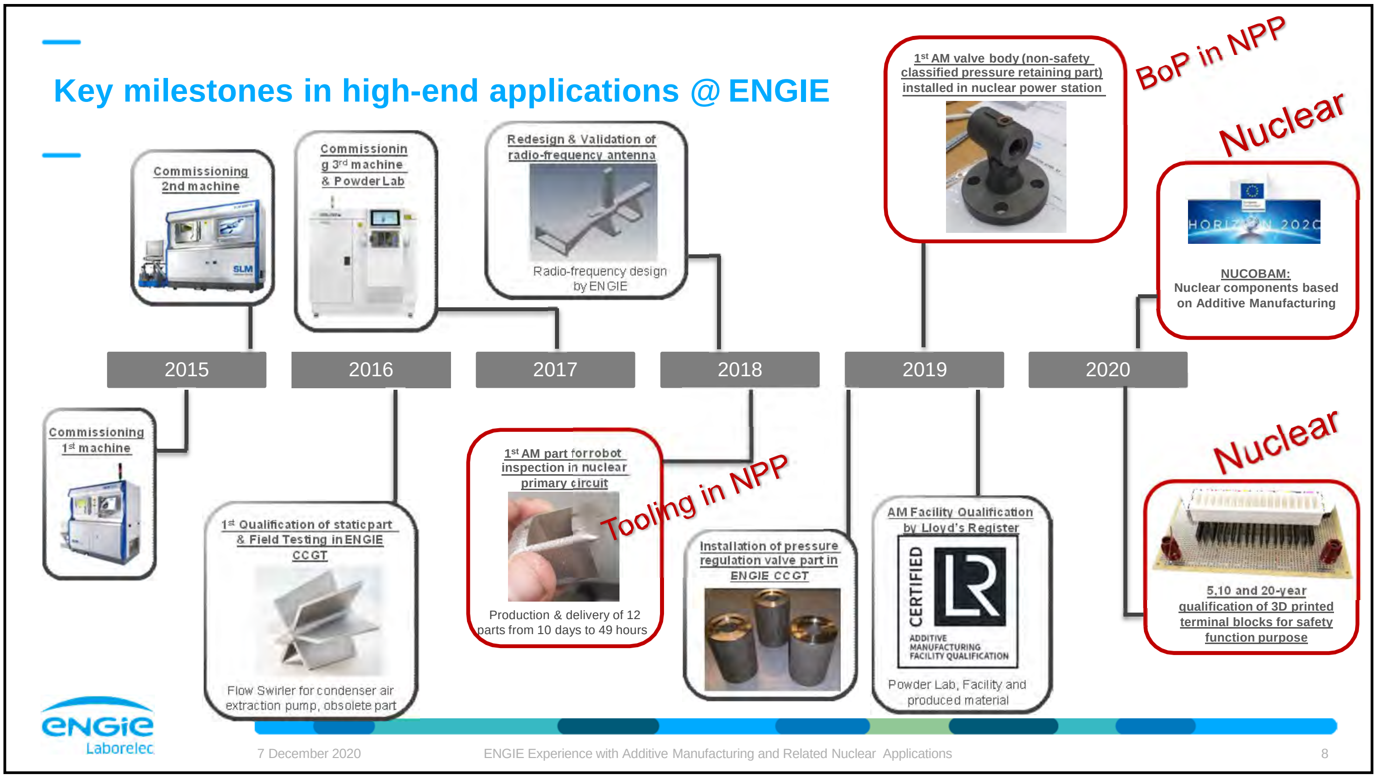
- Implementation in industrial environment
- Obsolescence management in ENGIE assets

### Foster industrialization

- Tackle obsolescence issues
- Functionality-driven approach
- Validation & Implementation of high-end applications with high qualification standards

### Certification Project

- Technological bricks: feedstock / Process / AM Material Performance
- Materials certificates 3.1 & 3.2
- Proactive approach before release of future EN 13445 Part 14



# Key milestones in high-end applications @ ENGIE

2015

**Commissioning 1st machine**

**Commissioning 2nd machine**

2016

**Commissioning 3rd machine & Powder Lab**

**1st Qualification of static part & Field Testing in ENGIE CCGT**

Flow Swirler for condenser air extraction pump, obsolete part

2017

**Redesign & Validation of radio-frequency antenna**

Radio-frequency design by ENGIE

**1st AM part for robot inspection in nuclear primary circuit**

Production & delivery of 12 parts from 10 days to 49 hours

Tooling in NPP

2018

**Installation of pressure regulation valve part in ENGIE CCGT**

2019

**1st AM valve body (non-safety classified pressure retaining part) installed in nuclear power station**

BoP in NPP

**AM Facility Qualification by Lloyd's Register**

Powder Lab, Facility and produced material

2020

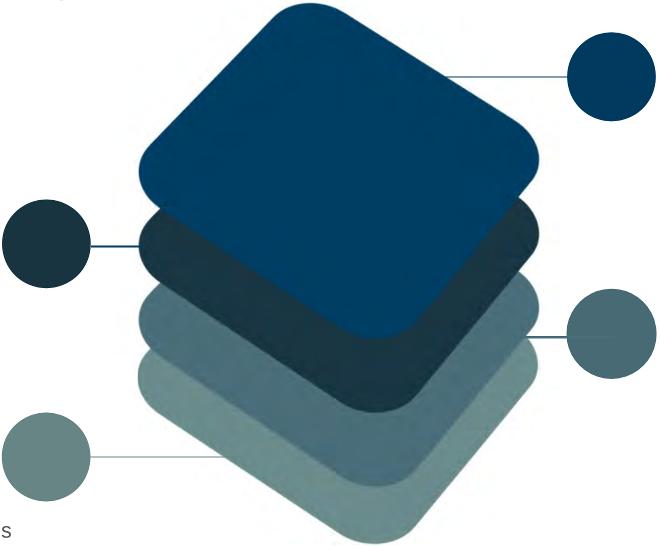
Nuclear

**NUCOBAM:**
**Nuclear components based on Additive Manufacturing**

Nuclear

**5,10 and 20-year qualification of 3D printed terminal blocks for safety function purpose**

# Additive Manufacturing Product Quality
## High-Level Overview



### Process Reproducibility
- From machine to machine (same SLM brand)
- From machine to machine (different SLM brand)

### Process Repeatability
- Consistent product quality from build job to build job
- Powder management, storage and reuse

### Process Stability
- Consistent product quality throughout the build height
- Consistent product quality on the entire build plate

### Process Qualification
- Process parameters optimization
- Sensitivity analysis
- Transferability from coupons to industrial part

ENGIE Laborelec

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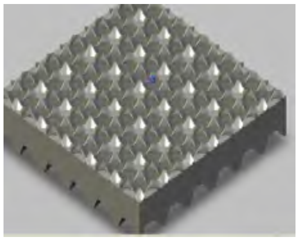
# NUCOBAM: **NU**clear **CO**mponents **B**ased on **A**dditive **M**anufacturing
## Horizon 2020 Nuclear Fission and Radiation Protection Research

Nuclear

HORIZON 2020

- **Context:** State-of-the-art **nuclear design codes** and assessment procedures do not take into consideration the Additive Manufacturing Technologies
- **Objectives:**
  - Establish a qualification methodology for AM nuclear components to be proposed for standardization and to be communicated to nuclear design code committees
  - Develop a manufacturing plan that ensures and demonstrates process stability, repeatability and reproducibility that meet nuclear quality standards
  - Demonstrate that laser powder bed fused material performance meets qualification requirements
  - Demonstrate that in-core AM use case meets its safety-related function and operational requirements
  - Assess the operational performance of ex-core AM components regarding safety-related function and operational requirements
  - Disseminate and prepare the exploitation of results with nuclear industries and regulatory bodies in support to codification and industrialization of AM
- **Key information:**
  - Project Duration: 48 months (Oct. 2020 – Sept. 2024)
  - Total Budget: 3,9M€
  - AM machines: Laborelec (SLM500), CEA (SLM280), VTT (SLM125) and AMRC (AM250)

**Gate Valve DN25 (ex-core pressure retaining application)**



**Debris Filtering component from fuel assembly (in-core part)**

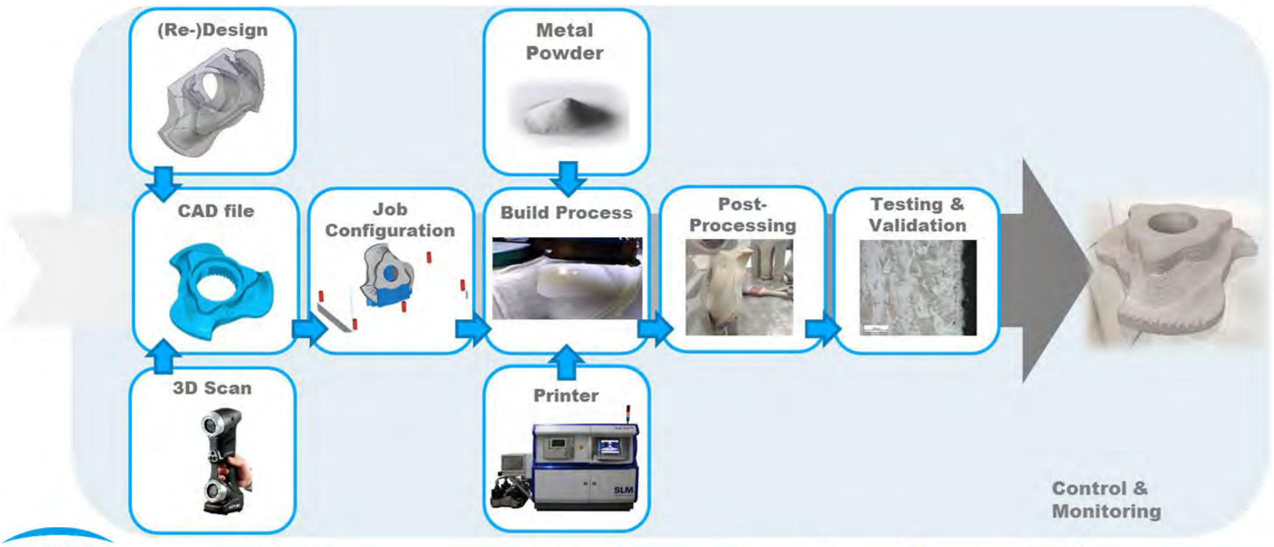
eDF, cea, SCK•CEN, IRSN, framatome, NAVAL GROUP, TRACTEBEL ENGIE, Ramén Valves We know the flow, VTT, Ciemat, ENGIE Laborelec, NUCLEAR AMRC, NATIONAL NUCLEAR LABORATORY

ENGIE Laborelec

# ENGIE Qualification Approach for Laser Powder Bed Fusion Process

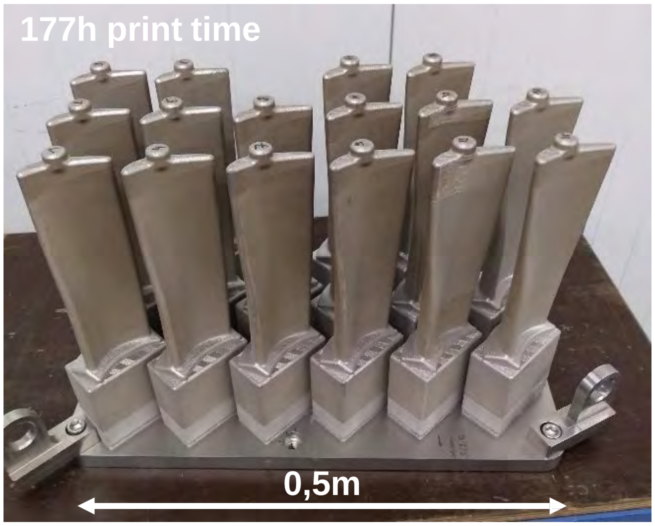
ENGIE Laborelec ENGIE Electrabel

## What can go wrong along the whole value chain ?



ENGIE Laborelec

## Challenges for production of high-end components and large productions runs



Ensuring process stability, quality & reproducibility over the long term for large production runs:

- **Large components**
- **Heavily-loaded build platform**

**FATAM Project** https://www.sim-flanders.be/project/fatam-icon

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## What can go wrong along the whole value chain ?

**Ensuring process stability, quality & reproducibility over the long term for large production runs :**

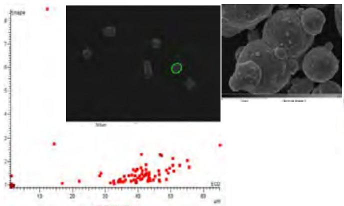
- Influence of powder batch
- Powder storage & recycling
- Influence of build location
- Influence of build height
- Transferability from coupons to industrial part
- From build job to build job

## Material Feedstock for Laser Powder Bed Fusion
### Standardization & acceptance criteria


Sample Thief

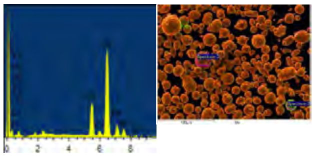

Sample Divider


Particle Size Distribution by Laser Diffraction


Particle Morphology by Scanning Electron Microscopy

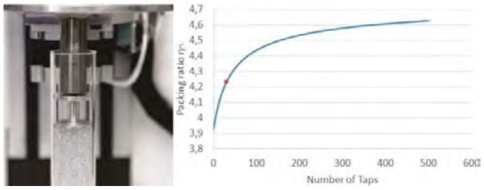

Hall flow, Carney flow and apparent density


Mechanical Sieving

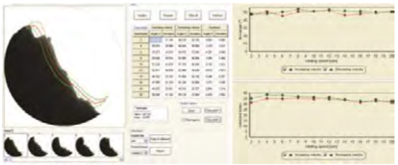

Semi-quantitative chemical analysis by Scanning Electron Microscopy


Archimedes density testing

**Metal Powder Characterization based on ASTM F3049-14**



Semi-automatized tapped density method producing compaction curve as a function of number of taps for a SLM metal powder


Automated measurements of dynamic angle of repose, providing cohesive index and flowing angles for different shearing stresses

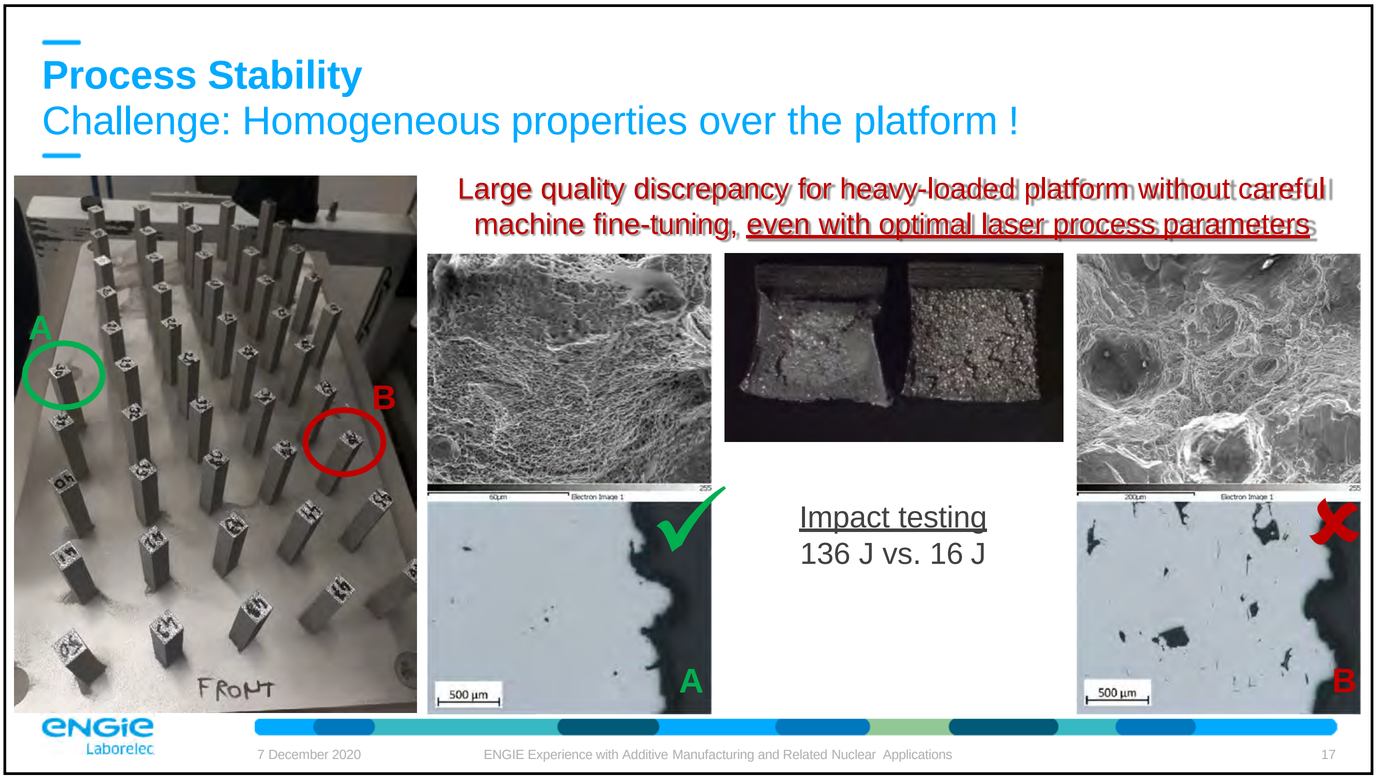
Rheometer, shear cell, wall friction

**New Metal Powder Characterization Methods**

## What can go wrong along the whole value chain ?

### Influence of build location & build height

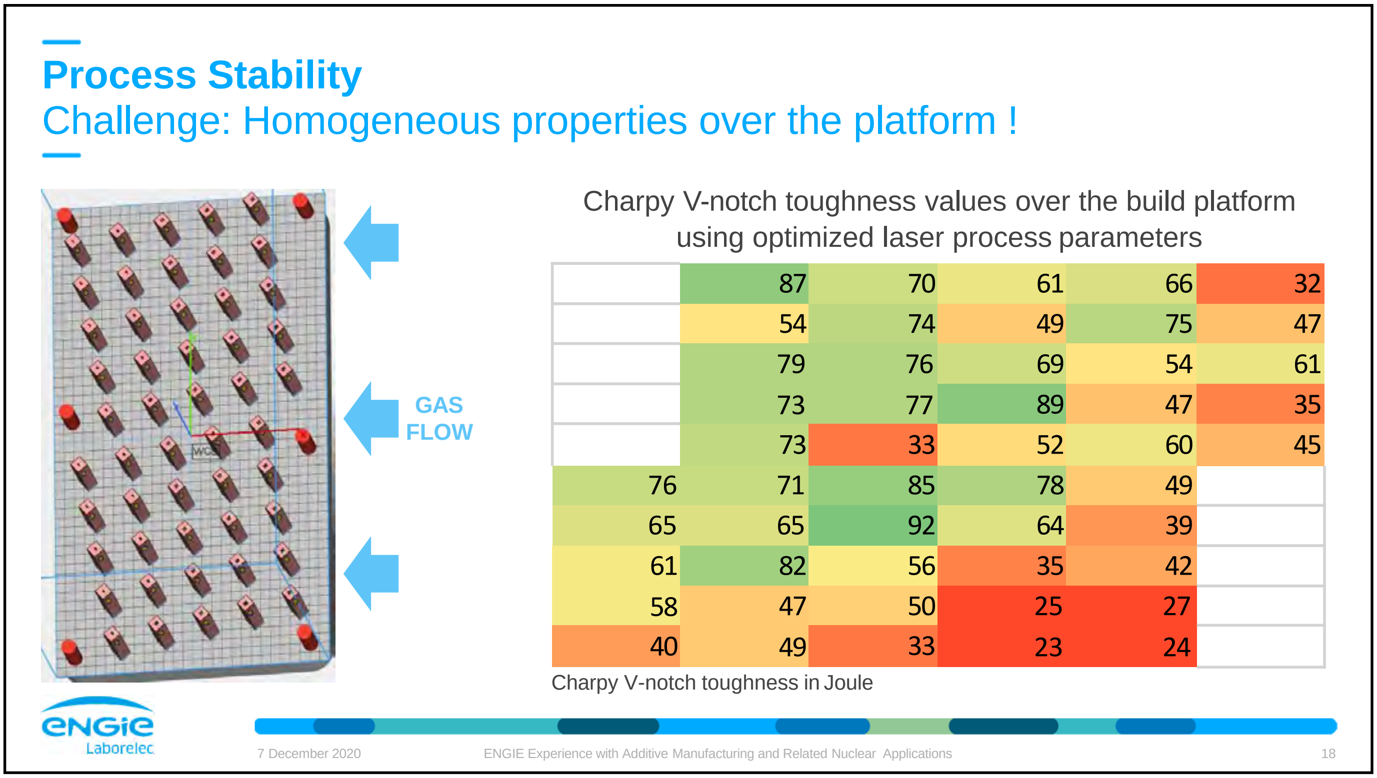
Large quality discrepancy for heavy-loaded platform without careful machine fine-tuning, even with optimal laser process parameters



## Process Stability
### Challenge: Homogeneous properties over the platform !

Large quality discrepancy for heavy-loaded platform without careful machine fine-tuning, even with optimal laser process parameters

Impact testing
136 J vs. 16 J



## Process Stability
### Challenge: Homogeneous properties over the platform !

Charpy V-notch toughness values over the build platform using optimized laser process parameters

| | | | | | |
|---|---|---|---|---|---|
| | 87 | 70 | 61 | 66 | 32 |
| | 54 | 74 | 49 | 75 | 47 |
| | 79 | 76 | 69 | 54 | 61 |
| | 73 | 77 | 89 | 47 | 35 |
| | 73 | 33 | 52 | 60 | 45 |
| 76 | 71 | 85 | 78 | 49 | |
| 65 | 65 | 92 | 64 | 39 | |
| 61 | 82 | 56 | 35 | 42 | |
| 58 | 47 | 50 | 25 | 27 | |
| 40 | 49 | 33 | 23 | 24 | |

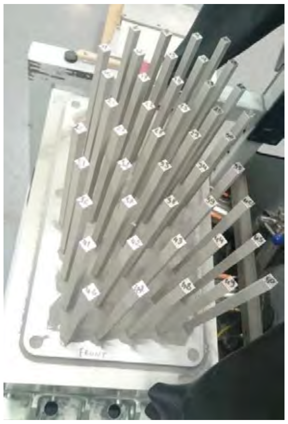
Charpy V-notch toughness in Joule

## Process Stability over build height & Process Transferability

**Full height samples**

Process Stability
- Consistent product quality throughout the build height

| | | | | | |
|---|---|---|---|---|---|
| | 107 | 108 | 104 | 109 | 108 |
| | 110 | 109 | 103 | 115 | 128 |
| | 104 | 111 | 104 | 135 | 140 |
| | 100 | 102 | 114 | 133 | 76 |
| | 113 | 106 | 87 | 121 | 55 |
| 112 | 111 | 109 | 112 | 118 | |
| 107 | 106 | 97 | 118 | 99 | |
| 111 | 118 | 112 | 142 | 85 | |
| 106 | 108 | 111 | 114 | 132 | |
| 104 | 102 | 110 | 116 | 130 | |



**Big blocks**

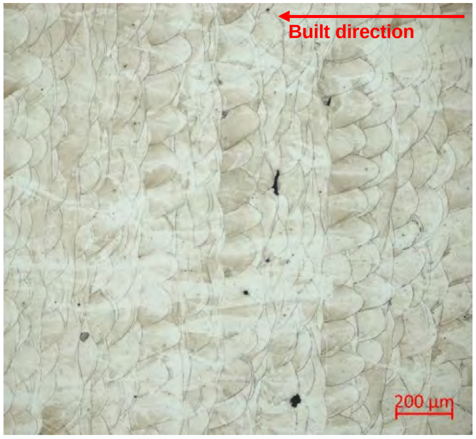
Process Qualification
- Transferability from coupons to industrial part

| | yield strength (MPa) | tensile strength (MPa) | elongation (%) | reduction of area (%) |
|---|---|---|---|---|
| average | 434 | 571 | 45.8 | 59.9 |
| stdev | 18 | 26 | 6.5 | 11.1 |

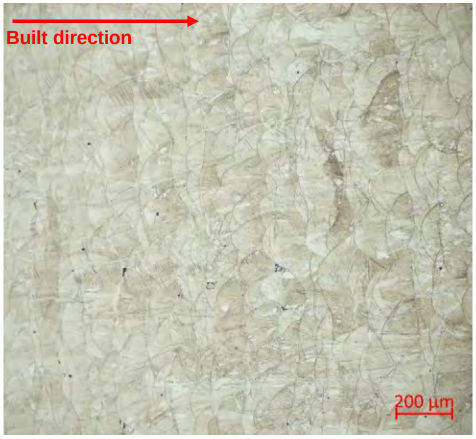
## Process Stability over build height & Process Transferability

### Microstructure

Before gas flow upgrade



After gas flow upgrade

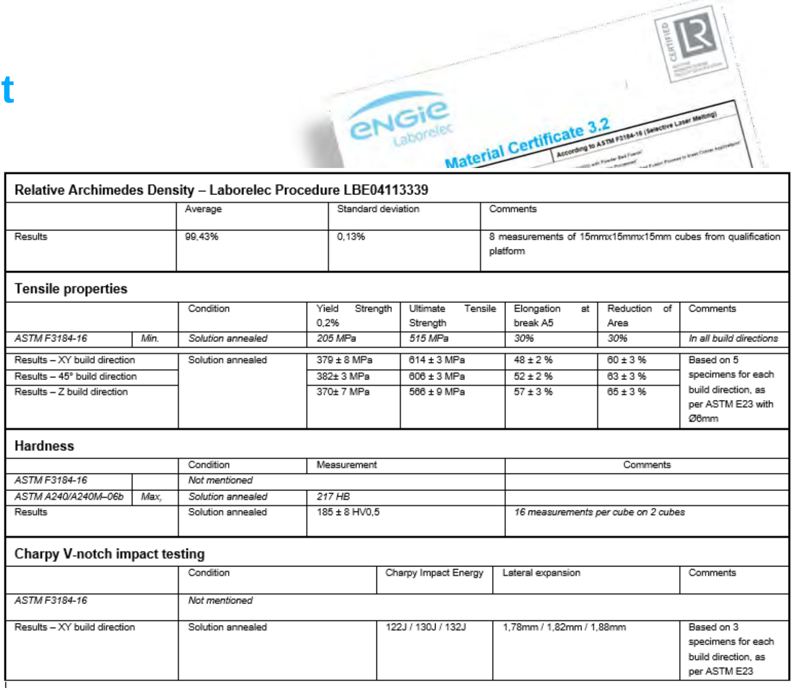


After gas flow upgrade and corresponding parameter optimisation, the visible melt pools after etching seem to be less pronounced and more homogeneous in size

# ENGIE Certification Project

## Successful ENGIE Facility and Powder Lab Certification by Lloyd's Register on 10.09.2019

- ❖ Technological bricks:
  - ▪ Feedstock
  - ▪ Process
  - ▪ AM Material Performance
- ❖ Material certificates 3.1 & 3.2
- ❖ Proactive approach before release of future EN 13445-14


ENGIE Laborelec

Material Certificate 3.2

According to ASTM F3184-16 (Selective Laser Melting)

**Relative Archimedes Density – Laborelec Procedure LBE04113339**

| | Average | Standard deviation | Comments |
|---|---|---|---|
| Results | 99,43% | 0,13% | 8 measurements of 15mmx15mmx15mm cubes from qualification platform |

**Tensile properties**

| | | Condition | Yield Strength 0,2% | Ultimate Tensile Strength | Elongation at break A5 | Reduction of Area | Comments |
|---|---|---|---|---|---|---|---|
| *ASTM F3184-16* | *Min.* | *Solution annealed* | *205 MPa* | *515 MPa* | *30%* | *30%* | *In all build directions* |
| Results – XY build direction | | Solution annealed | 379 ± 8 MPa | 614 ± 3 MPa | 48 ± 2 % | 60 ± 3 % | Based on 5 specimens for each build direction, as per ASTM E23 with Ø6mm |
| Results – 45° build direction | | | 382± 3 MPa | 606 ± 3 MPa | 52 ± 2 % | 63 ± 3 % | |
| Results – Z build direction | | | 370± 7 MPa | 586 ± 9 MPa | 57 ± 3 % | 65 ± 3 % | |

**Hardness**

| | | Condition | Measurement | Comments |
|---|---|---|---|---|
| *ASTM F3184-16* | | *Not mentioned* | | |
| *ASTM A240/A240M–06b* | *Max,* | *Solution annealed* | *217 HB* | |
| Results | | Solution annealed | 185 ± 8 HV0,5 | *16 measurements per cube on 2 cubes* |

**Charpy V-notch impact testing**

| | Condition | Charpy Impact Energy | Lateral expansion | Comments |
|---|---|---|---|---|
| *ASTM F3184-16* | *Not mentioned* | | | |
| Results – XY build direction | Solution annealed | 122J / 130J / 132J | 1,78mm / 1,82mm / 1,88mm | Based on 3 specimens for each build direction, as per ASTM E23 |

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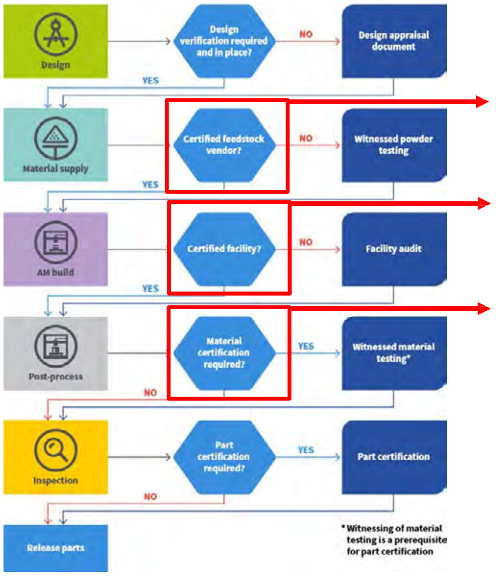
# ENGIE Certification Project

- **Our Main Goal**
  - — Achieving ENGIE AM Facility Qualification & Material Certification
  - — Material Certificate linking Powder Batch, Machine/Process & Formed Material
- Delivery of material certificate 3.1 or 3.2 for 316L material under Lloyd's Register label



* Witnessing of material testing is a prerequisite for part certification

Certification of stainless steel 316L powder feedstock & our Laborelec Powder Lab

Validation of SLM500 equipment at ENGIE Fabricom Zwijndrecht

Certification of produced stainless steel (mechanical performance)

Lloyd's Register

## Additive Manufacturing Product Quality and Control

Off-line / non-destructive

- Material properties determine inspectability for UT and EC
  - New manufacturing technology leads to unique challenges and material properties
  - Codes and regulations require inspection of critical components
  - BenchmarkAM material against industry-standard materials (forging and casting)

Industry-standard material

AM material

Fabrication of standardized blocks with reference defects

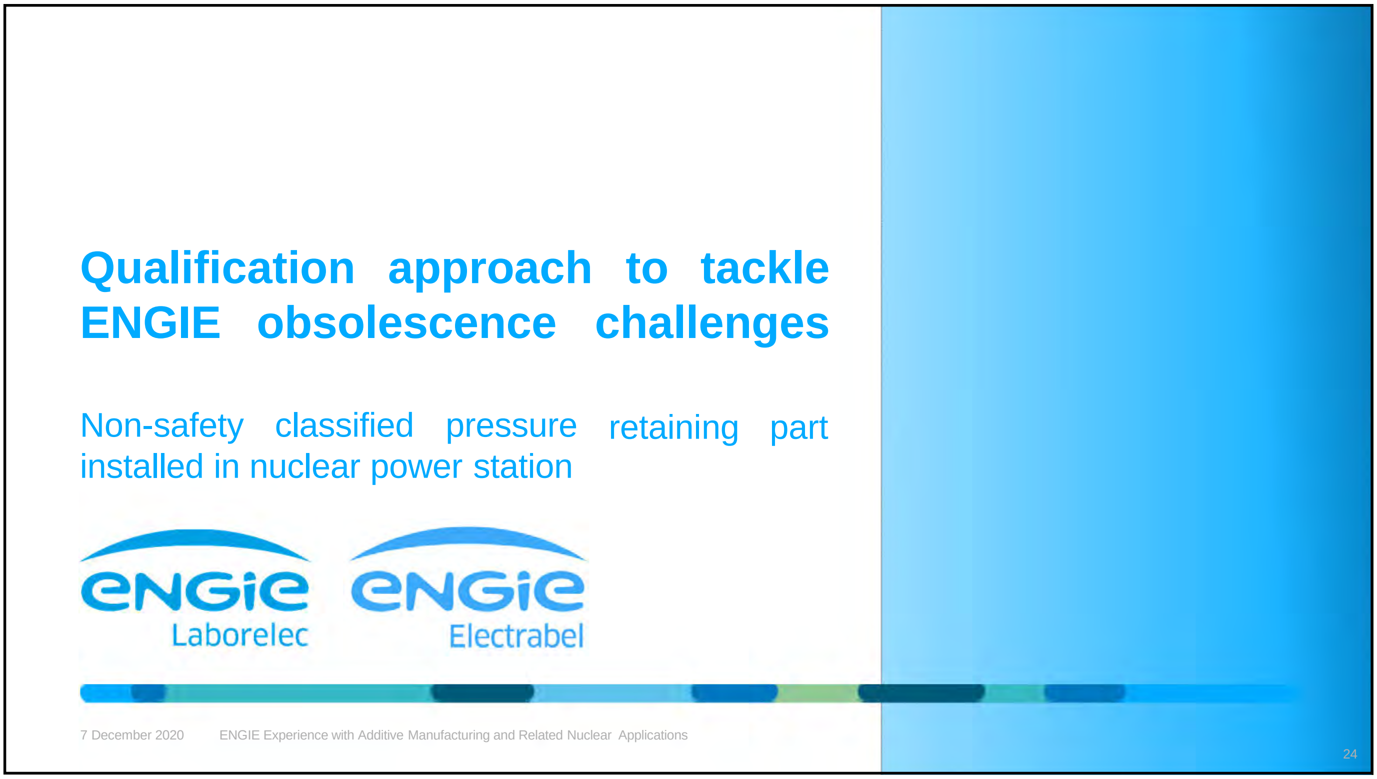
Ultrasound testing

Eddy current testing

Calculate material properties

Benchmark against industry standard

Young modulus
Signal to noise
Absorption
Sound velocity
Anisotropy
Electrical conductivity

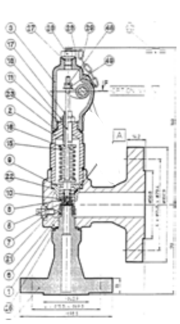


## Qualification approach to tackle ENGIE obsolescence challenges

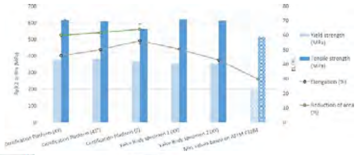
Non-safety classified pressure retaining part installed in nuclear power station

## Problem Statement
## Tackling obsolescence in NPP - CW-VV0592 in KCD3

- Outage Unit 3 at Doel NPP
- Voluntary test of non-safety pressure relief valves in secondary circuit
- Disassembly of the valve showed corrosion and damage
- Obsolescence status: unknown
  - Non-safety related
  - Body was never on stock
  - Low install base (1 location)
- Considered solutions
  - Order original body ► Valve appeared obsolete
  - Equivalent stock replacement ► No equivalent model on stock
  - Order new equivalent model ► Lead time 24 weeks (> outage deadline)
- Reverse Engineering & Metal Additive Manufacturing



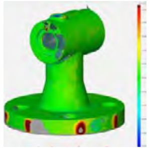
## Reverse Engineering incorporating Metal Additive Manufacturing




Reverse engineering


HEAT TREATMENT CERTIFICATE

| | |
|---|---|
| Customer | Element Materials Technology |
| Project | JOB500 320C |
| Ordernumber | 27005-01 |
| Ordernumber SH | 19-44117 |
| Material | |
| Certificate nr. | 19-030 |



Day 1

**Redaction of Test Specs & Obsolescence Dossier**

**Generation of 3D Model**

**Manufacturing Plan & Printing**

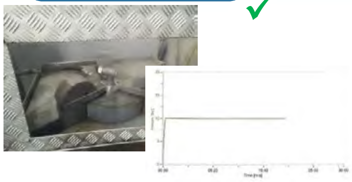
**Post-processing**

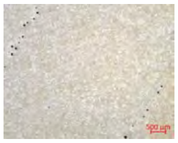
Day 12

**Functional Testing on Industrial Valve** ✓

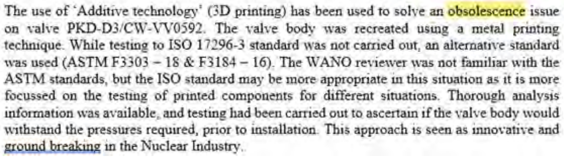
**Destructive Testing on Sacrificial Valve** ✓

CERTIFIED
ADDITIVE MANUFACTURING FACILITY QUALIFICATION



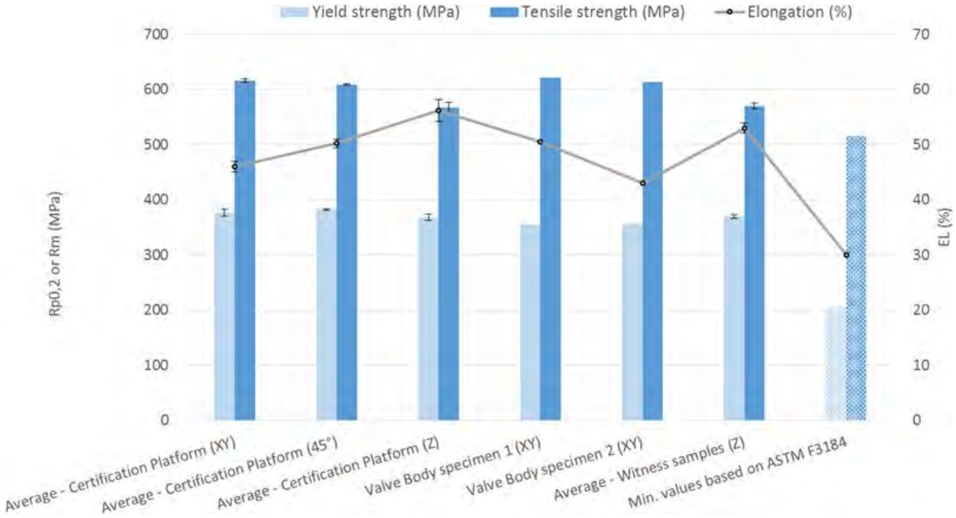


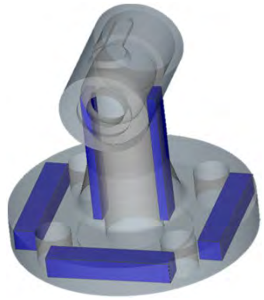
# Reverse Engineering incorporating Metal Additive Manufacturing



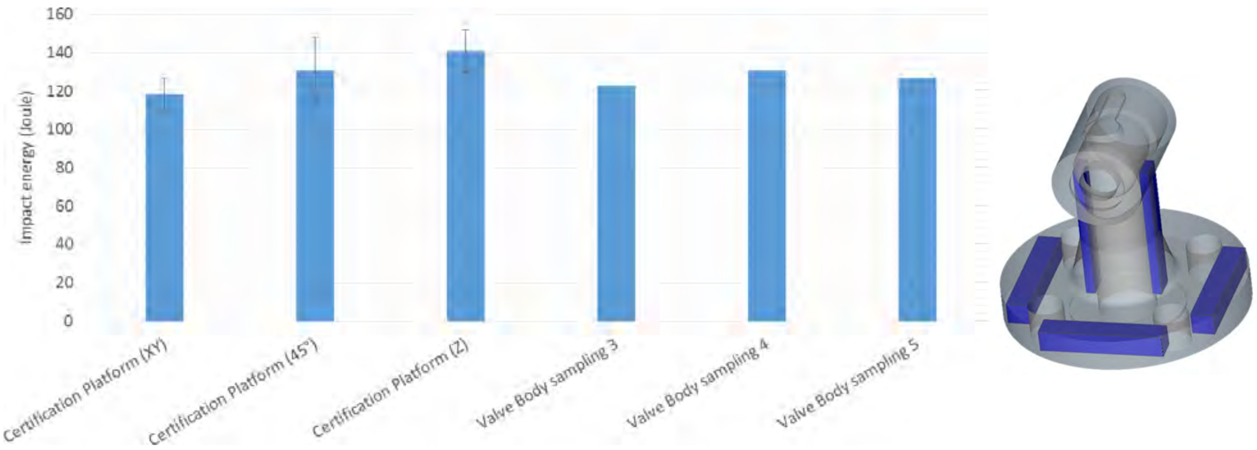
The use of 'Additive technology' (3D printing) has been used to solve an obsolescence issue on valve PKD-D3/CW-VV0592. The valve body was recreated using a metal printing technique. While testing to ISO 17296-3 standard was not carried out, an alternative standard was used (ASTM F3303 – 18 & F3184 – 16). The WANO reviewer was not familiar with the ASTM standards, but the ISO standard may be more appropriate in this situation as it is more focussed on the testing of printed components for different situations. Thorough analysis information was available, and testing had been carried out to ascertain if the valve body would withstand the pressures required, prior to installation. This approach is seen as innovative and ground breaking in the Nuclear Industry.

# Reverse Engineering incorporating Metal Additive Manufacturing Process stability, reproducibility





## Reverse Engineering incorporating Metal Additive Manufacturing Process stability, reproducibility



## Reverse Engineering incorporating Metal Additive Manufacturing

# Qualification approach to tackle ENGIE obsolescence challenges

Safety classified terminal blocks for Belgian nuclear power station

ENGIE Laborelec ENGIE Electrabel

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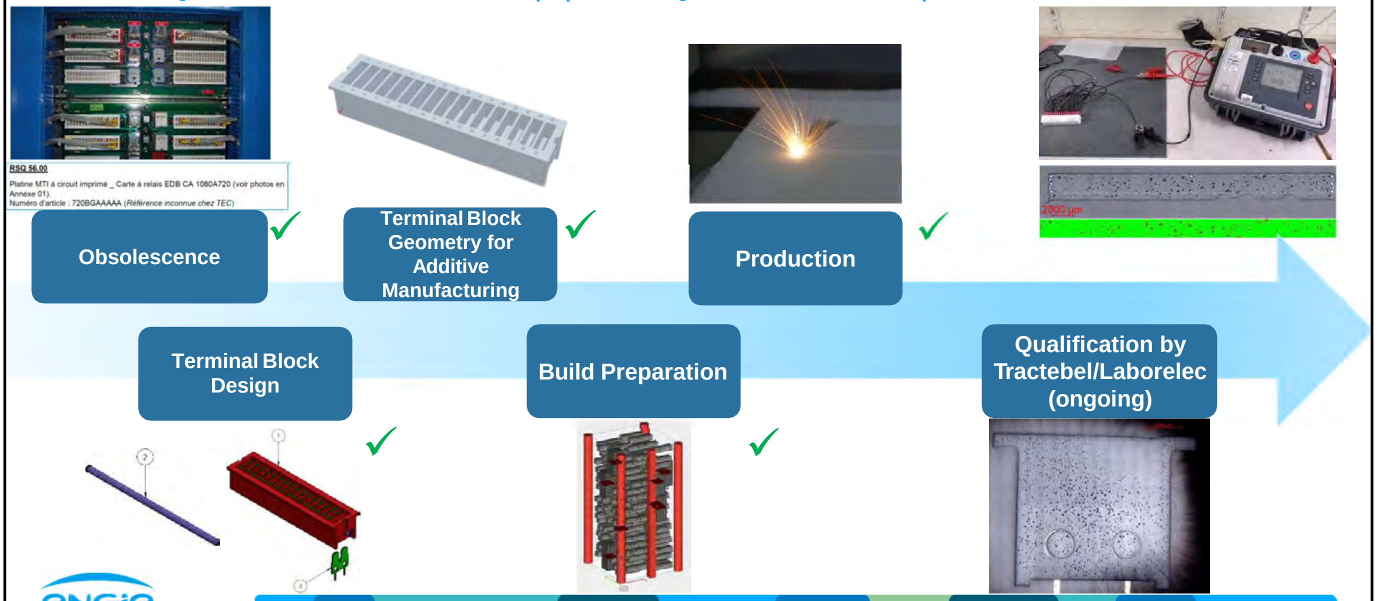
## CNT Qualification & Obsolescence

Nuclear Qualification of Electrical Equipment: Qualification of 3D printed terminal blocks



**RSQ 56.00**

Platine MTI à circuit imprimé _ Carte à relais EDB CA 1080A720 (voir photos en Annexe 01).
Numéro d'article : 720BGAAAAA (*Référence inconnue chez TEC*)

- Obsolescence ✓
- Terminal Block Design ✓
- Terminal Block Geometry for Additive Manufacturing ✓
- Build Preparation ✓
- Production ✓
- Qualification by Tractebel/Laborelec (ongoing)

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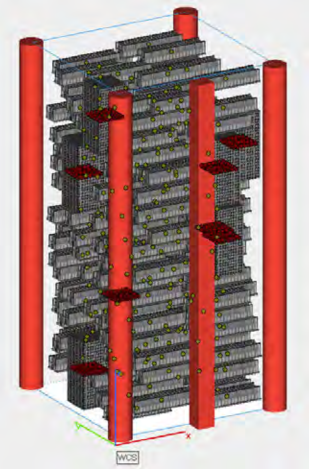
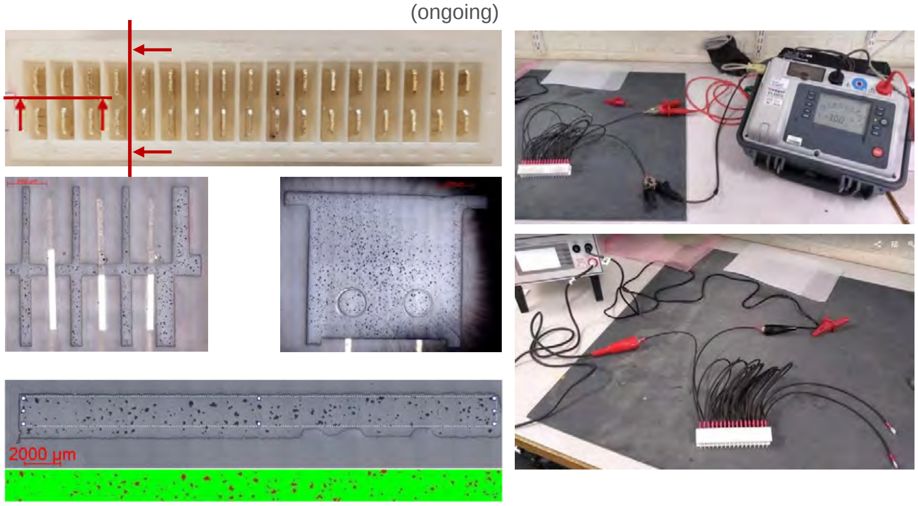
## CNT Qualification & Obsolescence

### Nuclear Qualification of Electrical Equipment: Qualification of 3D printed terminal blocks

Build Preparation



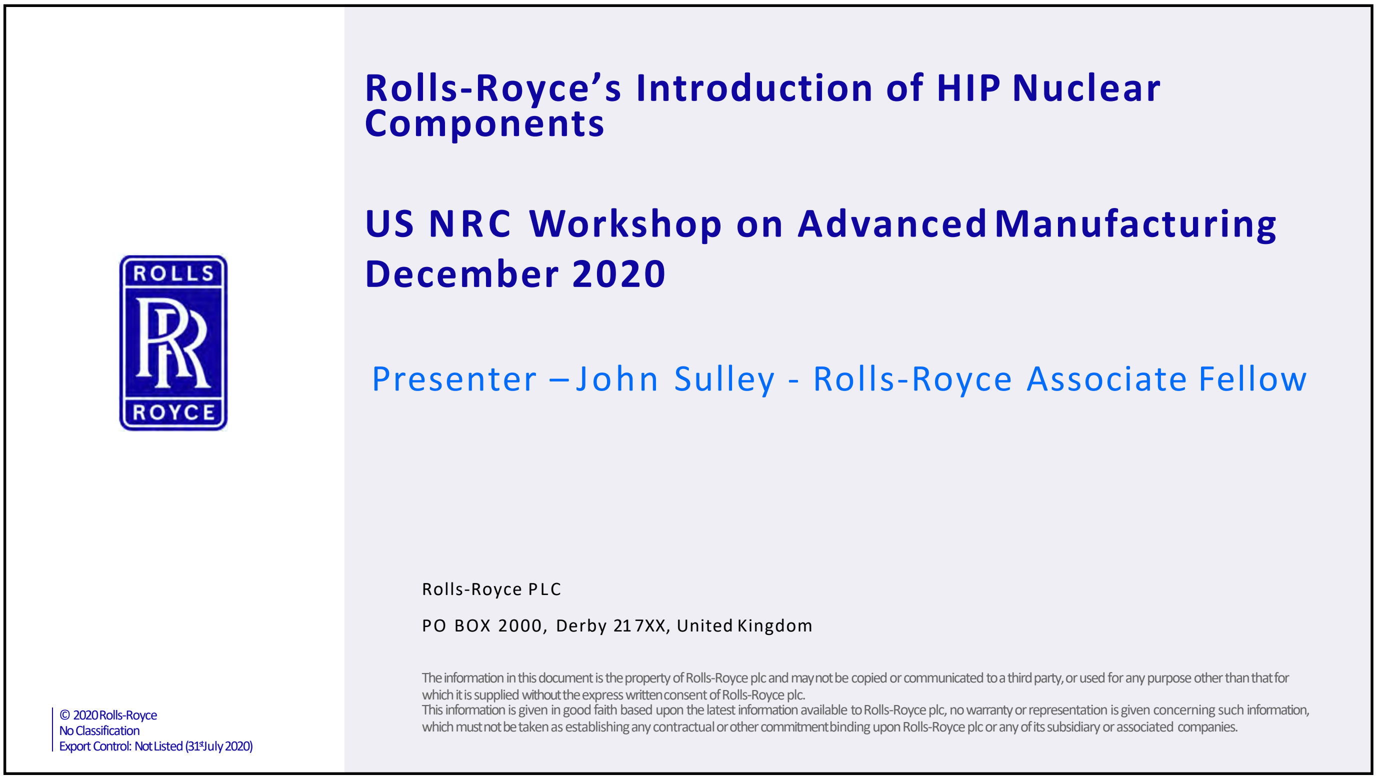
Qualification by Tractebel/Laborelec (ongoing)



ENGIE Laborelec

## Any Questions ?

ENGIE Laborelec ENGIE Electrabel

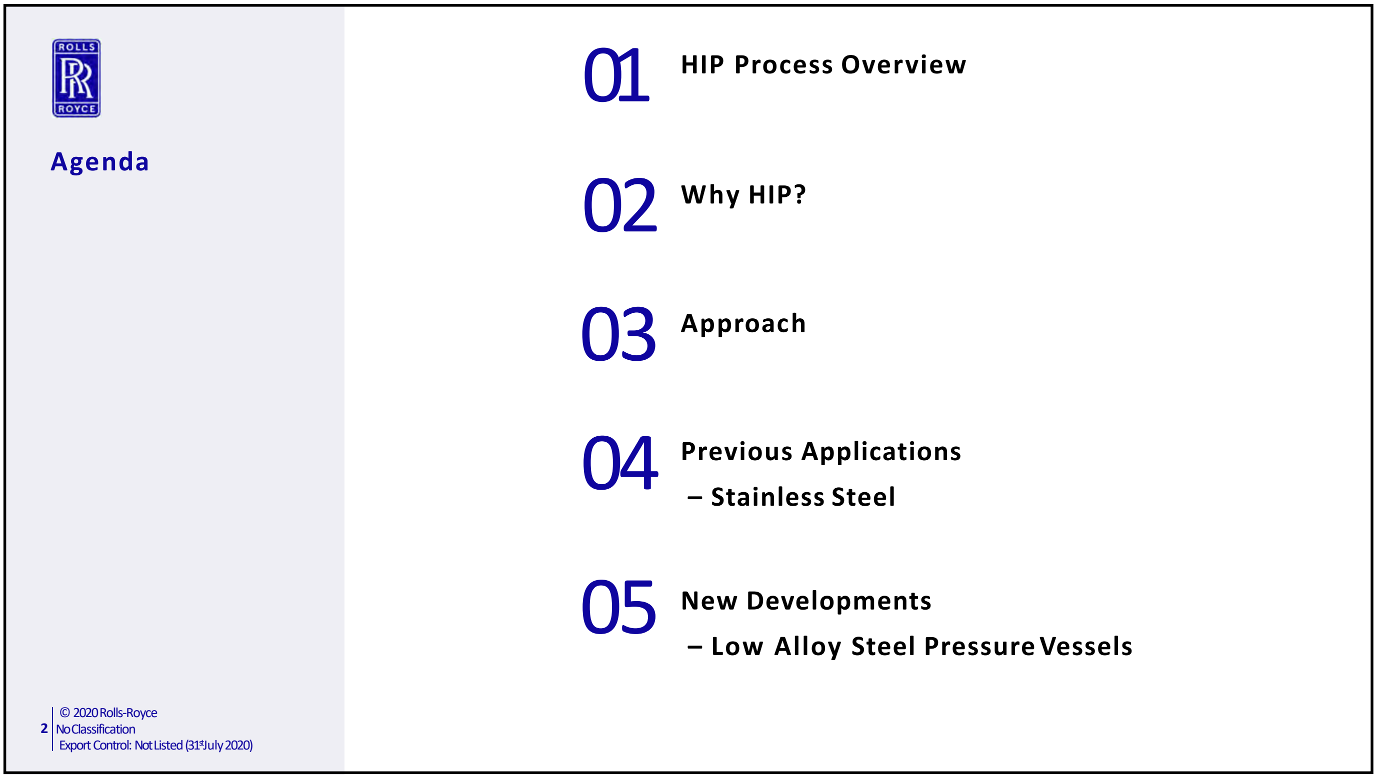


# Rolls-Royce's Introduction of HIP Nuclear Components

## US NRC Workshop on Advanced Manufacturing
## December 2020

Presenter – John Sulley - Rolls-Royce Associate Fellow

Rolls-Royce PLC
PO BOX 2000, Derby 21 7XX, United Kingdom



## Agenda

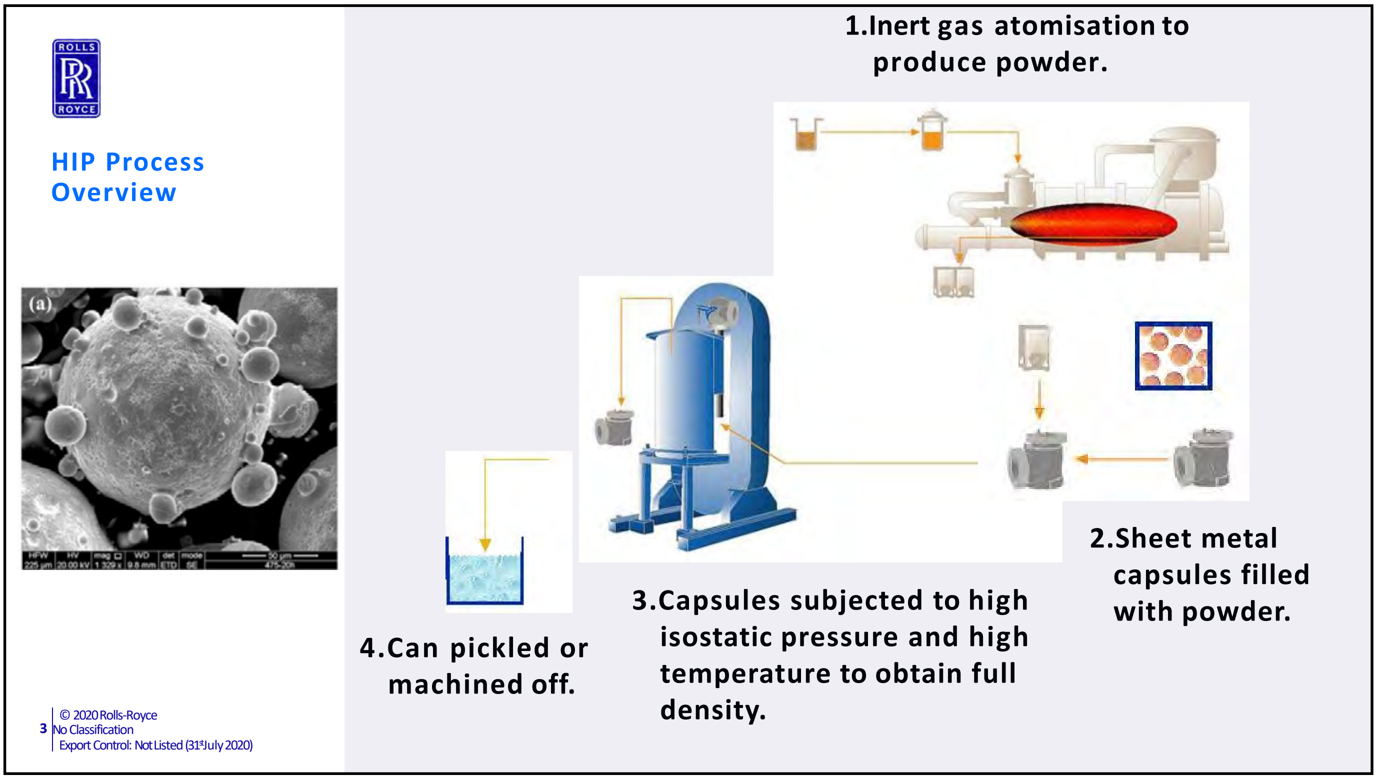
01 **HIP Process Overview**

02 **Why HIP?**

03 **Approach**

04 **Previous Applications**
**– Stainless Steel**

05 **New Developments**
**– Low Alloy Steel Pressure Vessels**



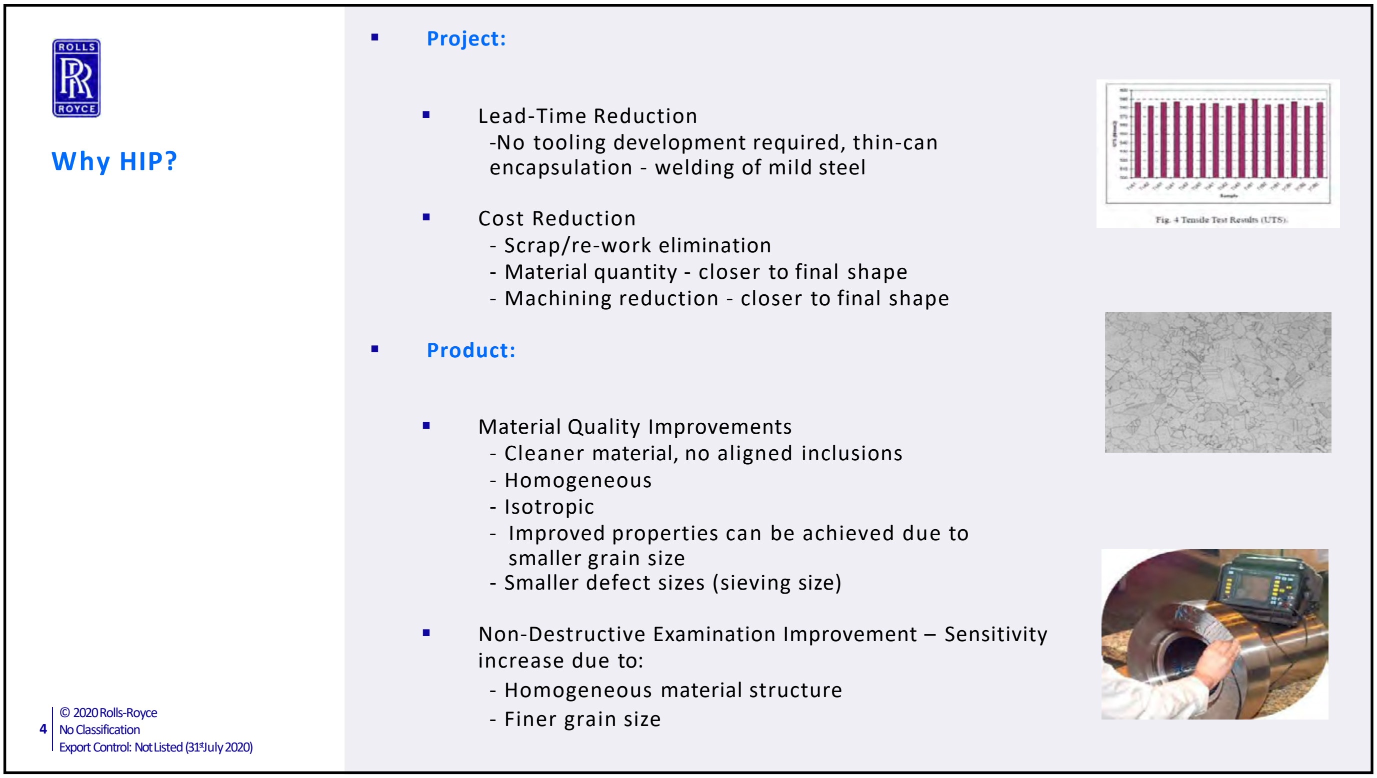
## HIP Process Overview

1.Inert gas atomisation to produce powder.

2.Sheet metal capsules filled with powder.

3.Capsules subjected to high isostatic pressure and high temperature to obtain full density.

4.Can pickled or machined off.



## Why HIP?

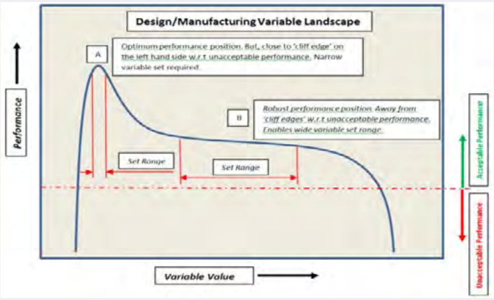
- **Project:**
  - Lead-Time Reduction
    -No tooling development required, thin-can encapsulation - welding of mild steel
  - Cost Reduction
    - Scrap/re-work elimination
    - Material quantity - closer to final shape
    - Machining reduction - closer to final shape
- **Product:**
  - Material Quality Improvements
    - Cleaner material, no aligned inclusions
    - Homogeneous
    - Isotropic
    - Improved properties can be achieved due to smaller grain size
    - Smaller defect sizes (sieving size)
  - Non-Destructive Examination Improvement – Sensitivity increase due to:
    - Homogeneous material structure
    - Finer grain size

Fig. 4 Tensile Test Results (UTS).

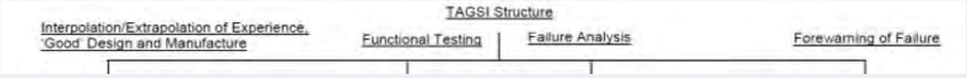
## Approach

### Enable a Project to adopt the technology by:

- Establishing a **robust** Method of Manufacture (MoM) – understanding of variability. Ensuring risks are appropriately mitigated.



- To provide data in order to produce a generic/base level justification – UK TAGSI four-legged structure. Additional, specific application data may still be required.



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## Approach

- Demonstrator units produced for each application.
- Dimensionally inspected to show geometry can be achieved.
- NDE examination and destructive examination. Units cut up for material microstructural assessment and property testing.
- Near Nett Shape? Some benefits, but design for inspectability was key consideration.

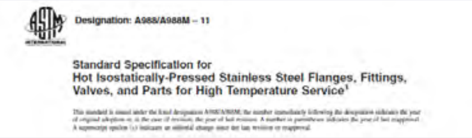
## Approach

- Independent industry survey
- Incremental approach
    - Non-Pressure Boundary
    - Pressure Boundary – Leak Limited
    - Pressure Boundary – Isolable
    - Pressure Boundary - Unisolable
- Material equivalence striven for.

| | | Material Specification | HIP 304LE Cylinder | HIP 304LE Body | Wrought Casts |
|---|---|---|---|---|---|
| 0.2% Proof Stress | | 207 MPa | 274 MPa | 300 MPa | 267 MPa |
| Ultimate Tensile Strength | | 517 MPa | 625 MPa | 628 MPa | 589 MPa |
| Elongation % | Longitudinal | 40 | 73 | 68 | 65 |
| | Transverse | 30 | | | |

CASE
N-834

- ASME code case –N-834



Designation: A988/A988M – 11

Standard Specification for
Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service[1]

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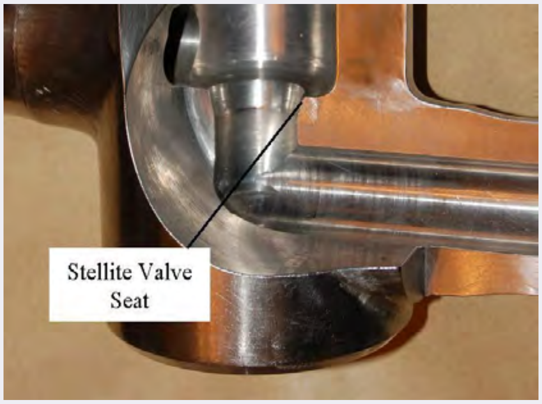
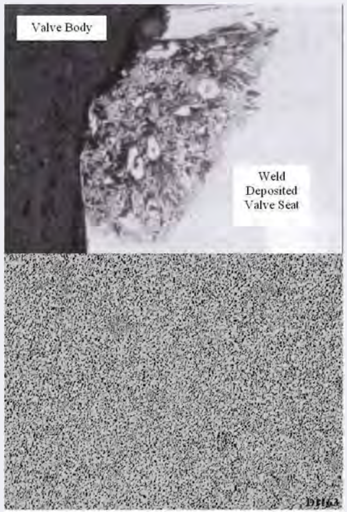
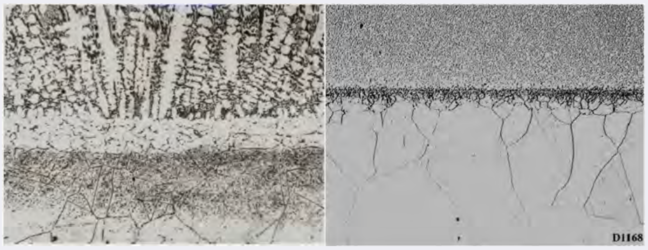
## Applications -
## Valve Hard-Faced Seats







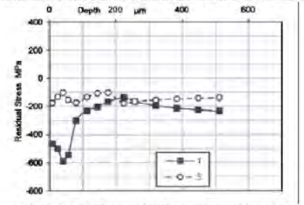


Fig. 9. Residual stress distribution for positions 1 and 5 – Radial/Axial Stresses v Depth.

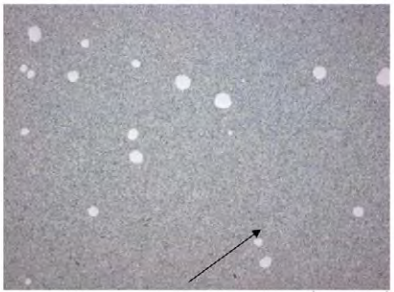
**References:**

ICAPP 08-8110, 2008 [1]

ICONE24-61106, 2016 [2]

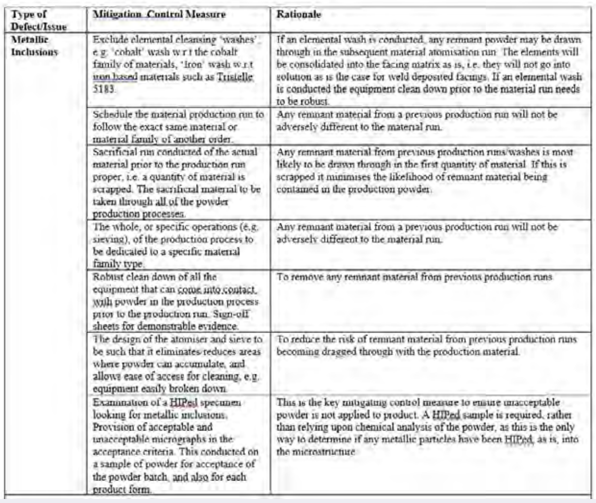
## Applications -

## Valve Hard-Faced Seats



Cobalt Particle Contamination

Contaminated Microstructure



| Type of Defect/Issue | Mitigation Control Measure | Rationale |
|---|---|---|
| **Metallic Inclusions** | Exclude elemental cleansing 'washes', e.g. 'cobalt' wash w.r.t the cobalt family of materials, 'Iron' wash w.r.t iron based materials such as Tristelle 5183. | If an elemental wash is conducted, any remnant powder may be drawn through in the subsequent material atomisation run. The elements will be consolidated into the facing matrix as is, i.e. they will not go into solution as is the case for weld deposited facings. If an elemental wash is conducted the equipment clean down prior to the material run needs to be robust. |
| | Schedule the material production run to follow the exact same material or material family of another order. | Any remnant material from a previous production run will not be adversely different to the material run. |
| | Sacrificial run conducted of the actual material prior to the production run proper, i.e. a quantity of material is scrapped. The sacrificial material to be taken through all of the powder production processes. | Any remnant material from previous production runs/washes is most likely to be drawn through in the first quantity of material. If this is scrapped it minimises the likelihood of remnant material being contained in the production powder. |
| | The whole, or specific operations (e.g. sieving), of the production process to be dedicated to a specific material family type. | Any remnant material from a previous production run will not be adversely different to the material run. |
| | Robust clean down of all the equipment that can come into contact with powder in the production process prior to the production run. Sign-off sheets for demonstrable evidence. | To remove any remnant material from previous production runs |
| | The design of the atomiser and sieve to be such that it eliminates/reduces areas where powder can accumulate, and allows ease of access for cleaning, e.g. equipment easily broken down. | To reduce the risk of remnant material from previous production runs becoming dragged through with the production material. |
| | Examination of a HIPed specimen looking for metallic inclusions. Provision of acceptable and unacceptable micrographs in the acceptance criteria. This conducted on a sample of powder for acceptance of the powder batch, and also for each product form. | This is the key mitigating control measure to ensure unacceptable powder is not applied to product. A HIPed sample is required, rather than relying upon chemical analysis of the powder, as this is the only way to determine if any metallic particles have been HIPed, as is, into the microstructure. |

**Reference:**

**ICONE24-61106, 2016** [2]

No Classification
Export Control: Not Listed (31st July 2020)

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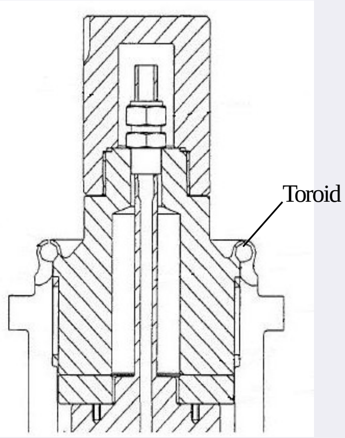
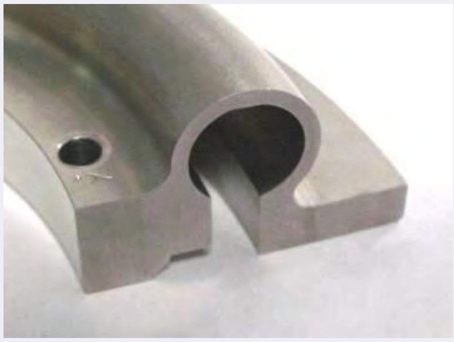
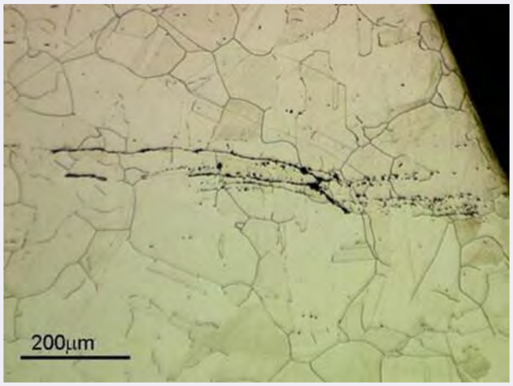
## Applications -

## Thin-Walled Toroidal Seals







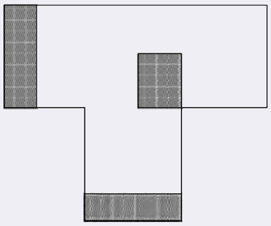
**Reference:**

**ICAPP 08-8110, 2008** [1]

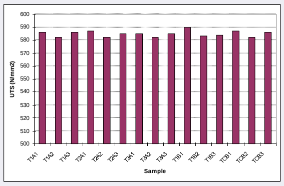
No Classification
Export Control: Not Listed (31st July 2020)

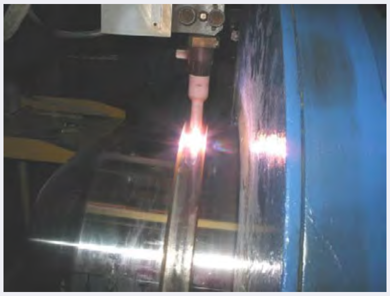
## Applications -

## Thick-Walled Pressure Vessel Section



▨ Locations of material used for testing





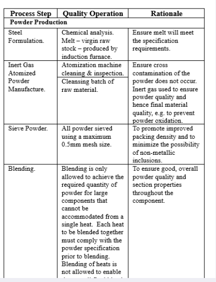
**Reference:**

**ICAPP 09-9389, 2009** [3]

No Classification
Export Control: Not Listed (31st July 2020)

## Applications -

## Large Bore Valves



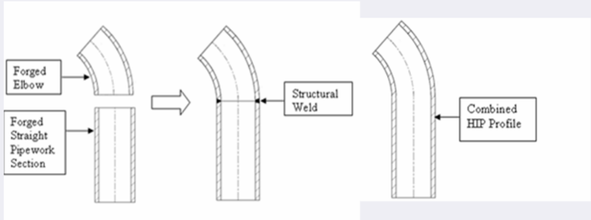
| Process Step | Quality Operation | Rationale |
|---|---|---|
| **Powder Production** | | |
| Steel Formulation. | Chemical analysis. Melt – virgin raw stock – produced by induction furnace. | Ensure melt will meet the specification requirements. |
| Inert Gas Atomized Powder Manufacture. | Atomization machine cleaning & inspection.<br>Cleansing batch of raw material. | Ensure cross contamination of the powder does not occur. Inert gas used to ensure powder quality and hence final material quality, e.g. to prevent powder oxidation. |
| Sieve Powder. | All powder sieved using a maximum 0.5mm mesh size. | To promote improved packing density and to minimize the possibility of non-metallic inclusions. |
| Blending. | Blending is only allowed to achieve the required quantity of powder for large components that cannot be accommodated from a single heat. Each heat to be blended together must comply with the powder specification prior to blending. Blending of heats is not allowed to enable | To ensure good, overall powder quality and section properties throughout the component. |

**Reference:**

**PVP2012-78115, 2012** [4]

No Classification
Export Control: Not Listed (31st July 2020)

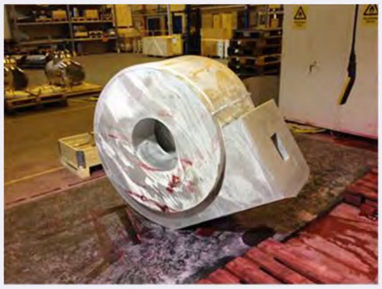
## Applications - Pipework

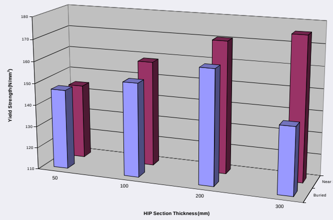


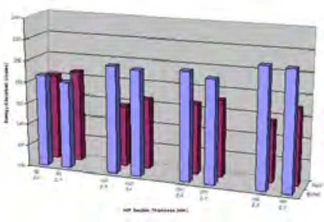
**Reference:**

**AMEE2012, Jan18-19, 2012** [5]

## Applications - Pump Bowls

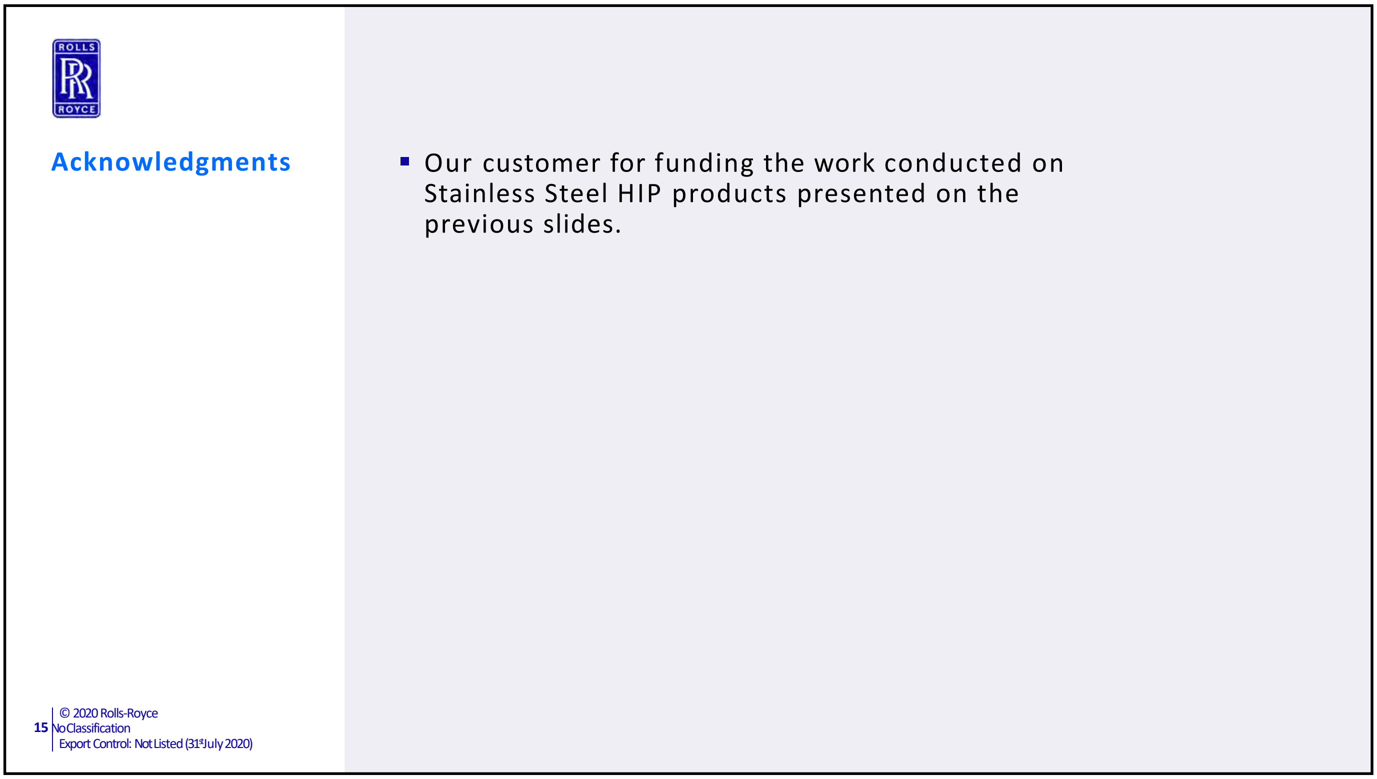






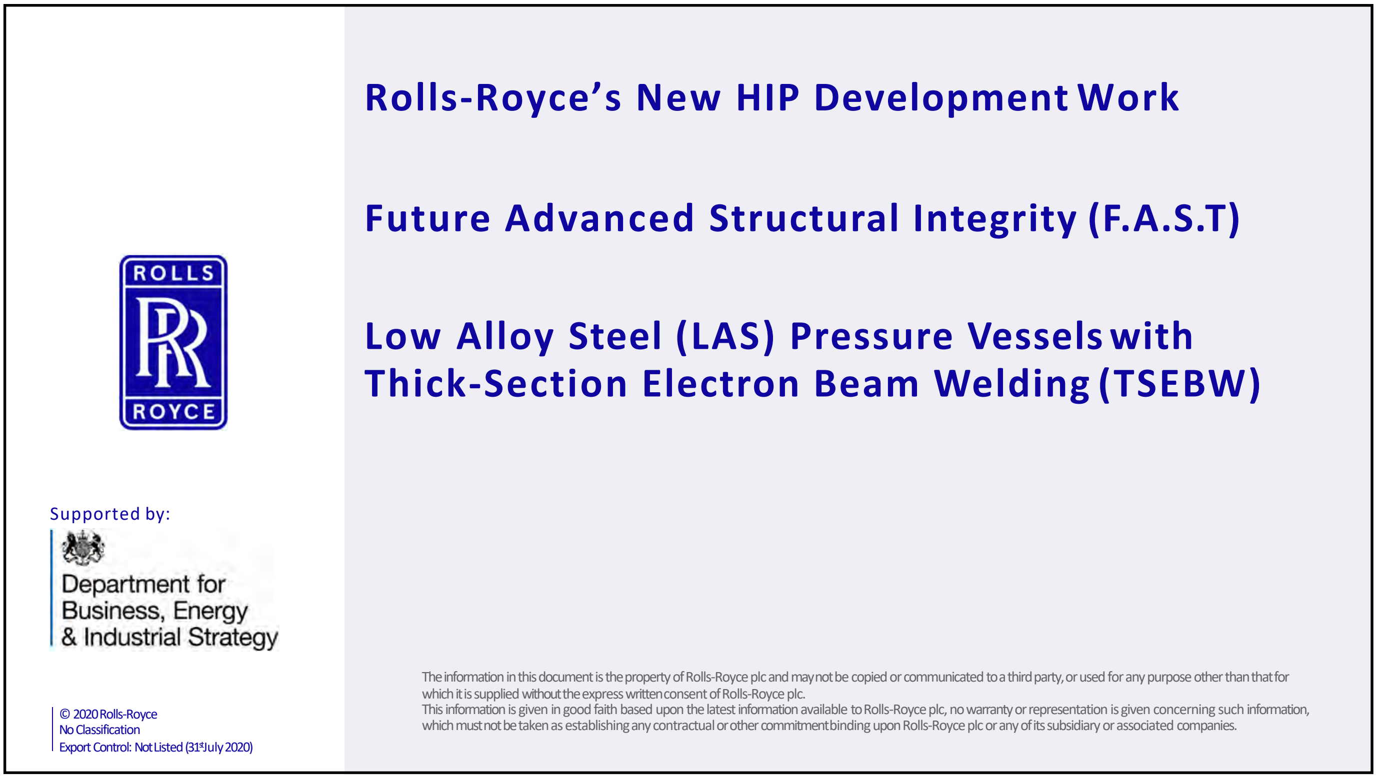
**Reference:**

**PVP2012-78115, 2012** [6]



## Acknowledgments

- Our customer for funding the work conducted on Stainless Steel HIP products presented on the previous slides.



## Rolls-Royce's New HIP Development Work

## Future Advanced Structural Integrity (F.A.S.T)

## Low Alloy Steel (LAS) Pressure Vessels with Thick-Section Electron Beam Welding (TSEBW)

Supported by:

Department for
Business, Energy
& Industrial Strategy

## Rolls-Royce's New Development – LAS Vessels

## Project FAST

## Applying HIP and TSEBW

ROLLS-ROYCE

mtc Manufacturing Technology Centre

**Net Shape Manufacturing Research Group**

National Centre for Netshape (HIP) powder analysis, modelling, canning and filling facilities

**Research and Technology**

Nuclear plant design, manufacture, safety justification, programme management expertise

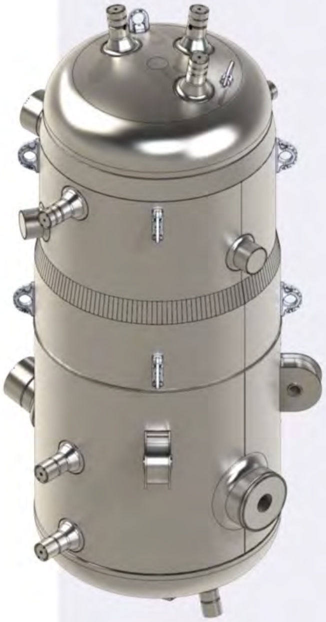
TWI

**Electron Beam Processes Joining Technologies Group**

Thick section electron beam welding expertise

No Classification
Export Control: Not Listed (31st July 2020)

## Project Objectives

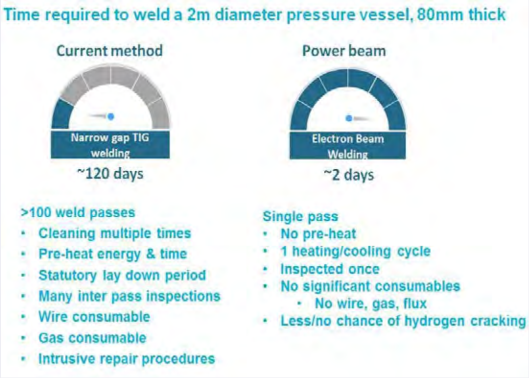


- Move to additive rather than subtractive processes for nuclear quality vessel manufacture.
- Reduce vessel manufacturing cost & lead-time
- Alternative supply chain to mitigate fragility
- Improve material quality
- Possibility to reduce in-service inspections

No Classification
Export Control: Not Listed (31st July 2020)

# TSEBW

# Process Overview & Structural Advantages



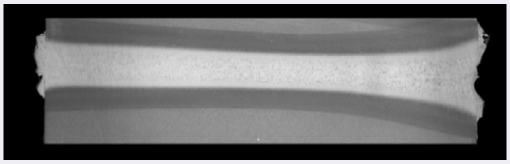
Time required to weld a 2m diameter pressure vessel, 80mm thick

| Current method | Power beam |
|---|---|
| Narrow gap TIG welding | Electron Beam Welding |
| ~120 days | ~2 days |

>100 weld passes
- Cleaning multiple times
- Pre-heat energy & time
- Statutory lay down period
- Many inter pass inspections
- Wire consumable
- Gas consumable
- Intrusive repair procedures

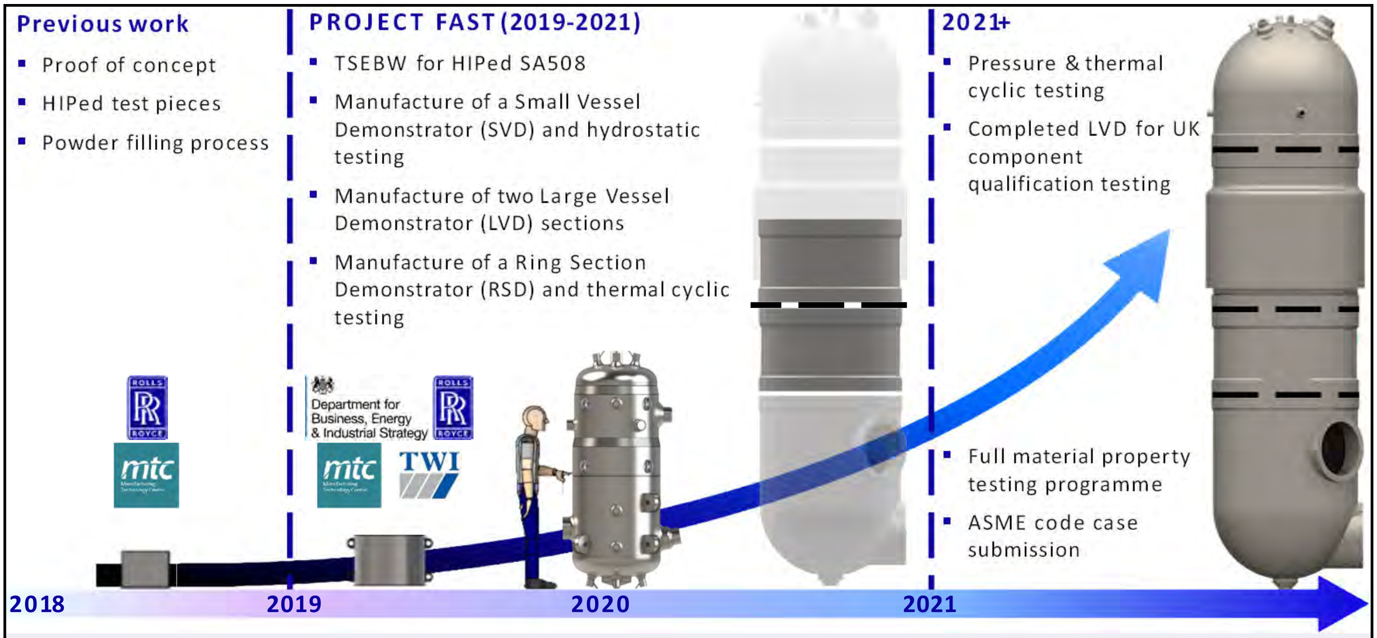
Single pass
- No pre-heat
- 1 heating/cooling cycle
- Inspected once
- No significant consumables
  - No wire, gas, flux
- Less/no chance of hydrogen cracking

ICONE28-POWER2020-16035



**Reference:**

**ICONE28-POWER2020-16035, 2020** [7]



**Previous work**
- Proof of concept
- HIPed test pieces
- Powder filling process

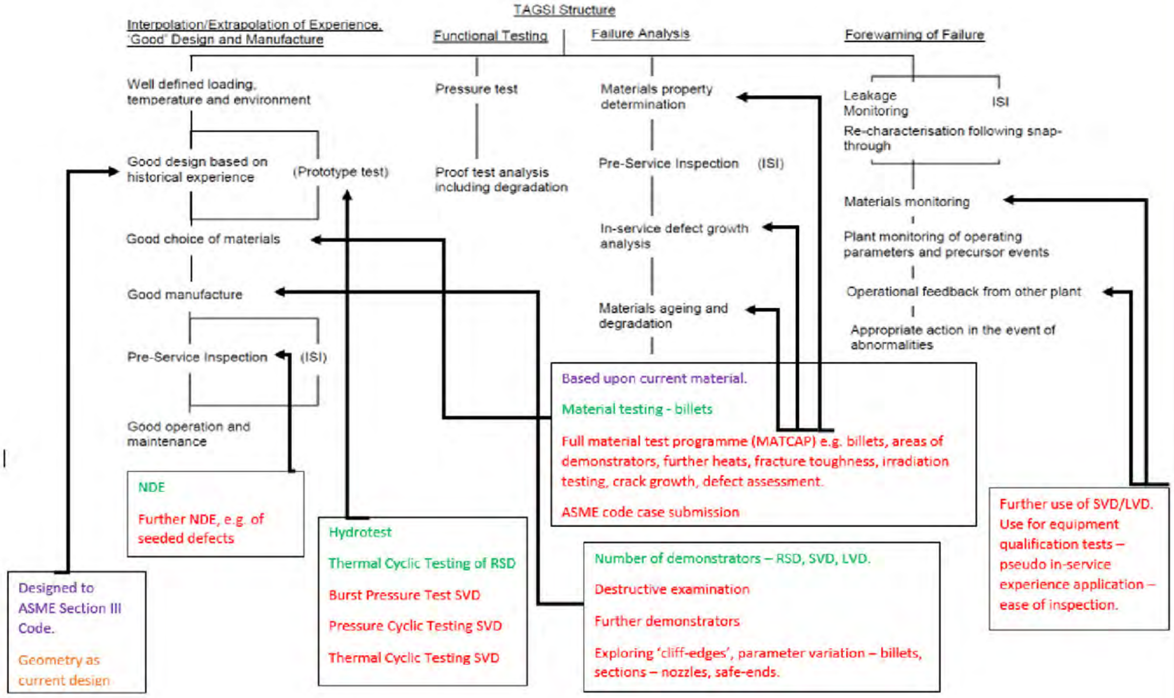
**PROJECT FAST (2019-2021)**
- TSEBW for HIPed SA508
- Manufacture of a Small Vessel Demonstrator (SVD) and hydrostatic testing
- Manufacture of two Large Vessel Demonstrator (LVD) sections
- Manufacture of a Ring Section Demonstrator (RSD) and thermal cyclic testing

**2021+**
- Pressure & thermal cyclic testing
- Completed LVD for UK component qualification testing
- Full material property testing programme
- ASME code case submission

**Reference:**

**ICONE28-POWER2020-16035, 2020** [7]

## Justification Approach



Designed to ASME Section III Code.

Geometry as current design

NDE

Further NDE, e.g. of seeded defects

Hydrotest

Thermal Cyclic Testing of RSD

Burst Pressure Test SVD

Pressure Cyclic Testing SVD

Thermal Cyclic Testing SVD

Based upon current material.

Material testing - billets

Full material test programme (MATCAP) e.g. billets, areas of demonstrators, further heats, fracture toughness, irradiation testing, crack growth, defect assessment.

ASME code case submission

Number of demonstrators – RSD, SVD, LVD.

Destructive examination

Further demonstrators

Exploring 'cliff-edges', parameter variation – billets, sections – nozzles, safe-ends.

Further use of SVD/LVD. Use for equipment qualification tests – pseudo in-service experience application – ease of inspection.

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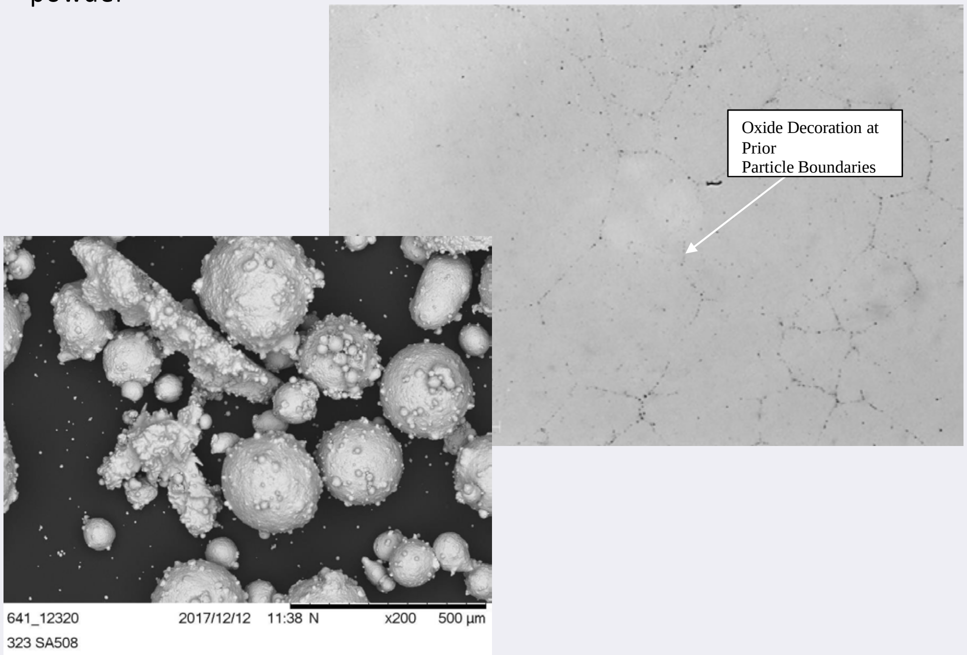
## Key Technical Risks

Reference:

ICONE28-POWER2020-16035, 2020 [7]

- Poor toughness, oxidisation of powder, poor quality powder



## Key Technical Risks

- Can failure during HIP cycle

Can

Unconsolidated Powder

Can

Powder Particle

Ligament between powder particles

**Reference:**

**ICONE28-POWER2020-16035, 2020** [7]

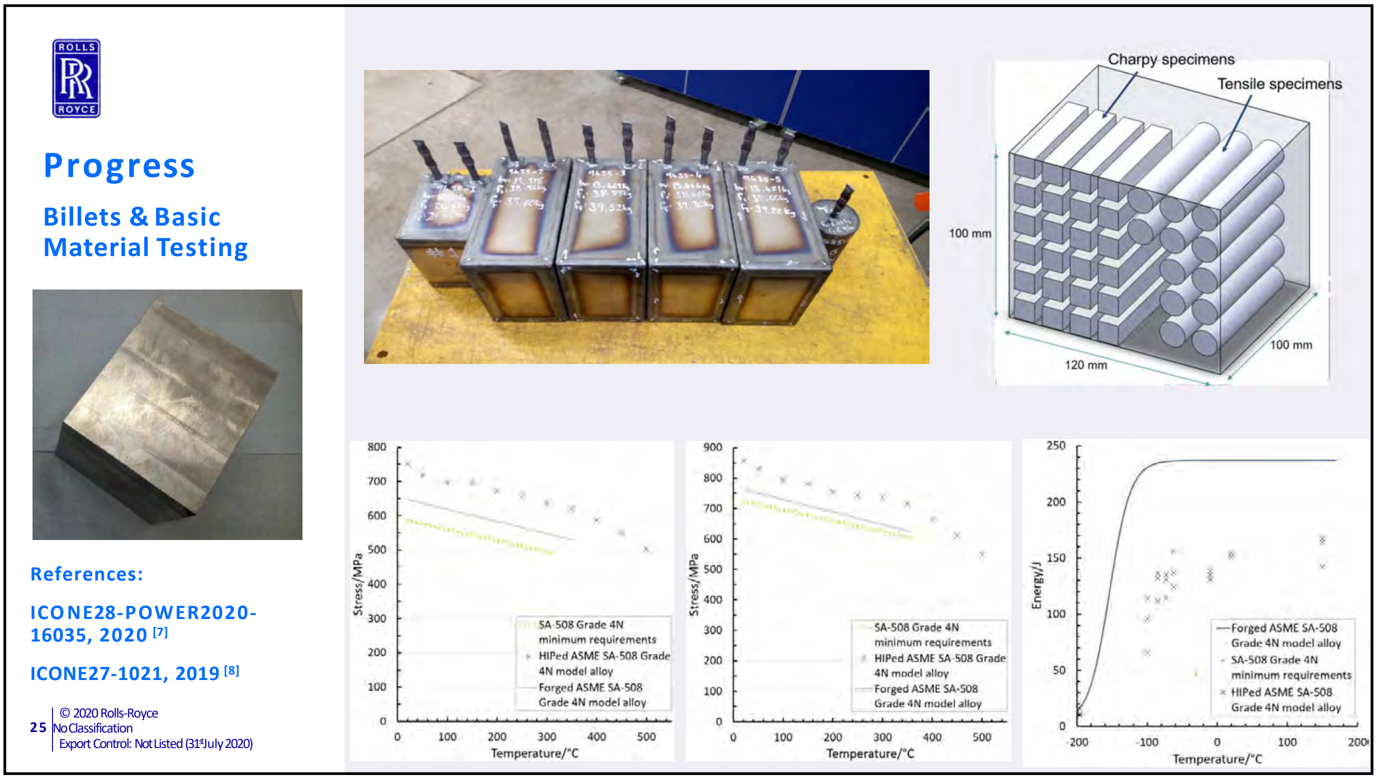
## Key Technical Risks

- Cracking during quench –hydrogen/poor toughness

- Achieving geometry – reducing amount of machining

**Reference:**

**ICONE28-POWER2020-16035, 2020** [7]



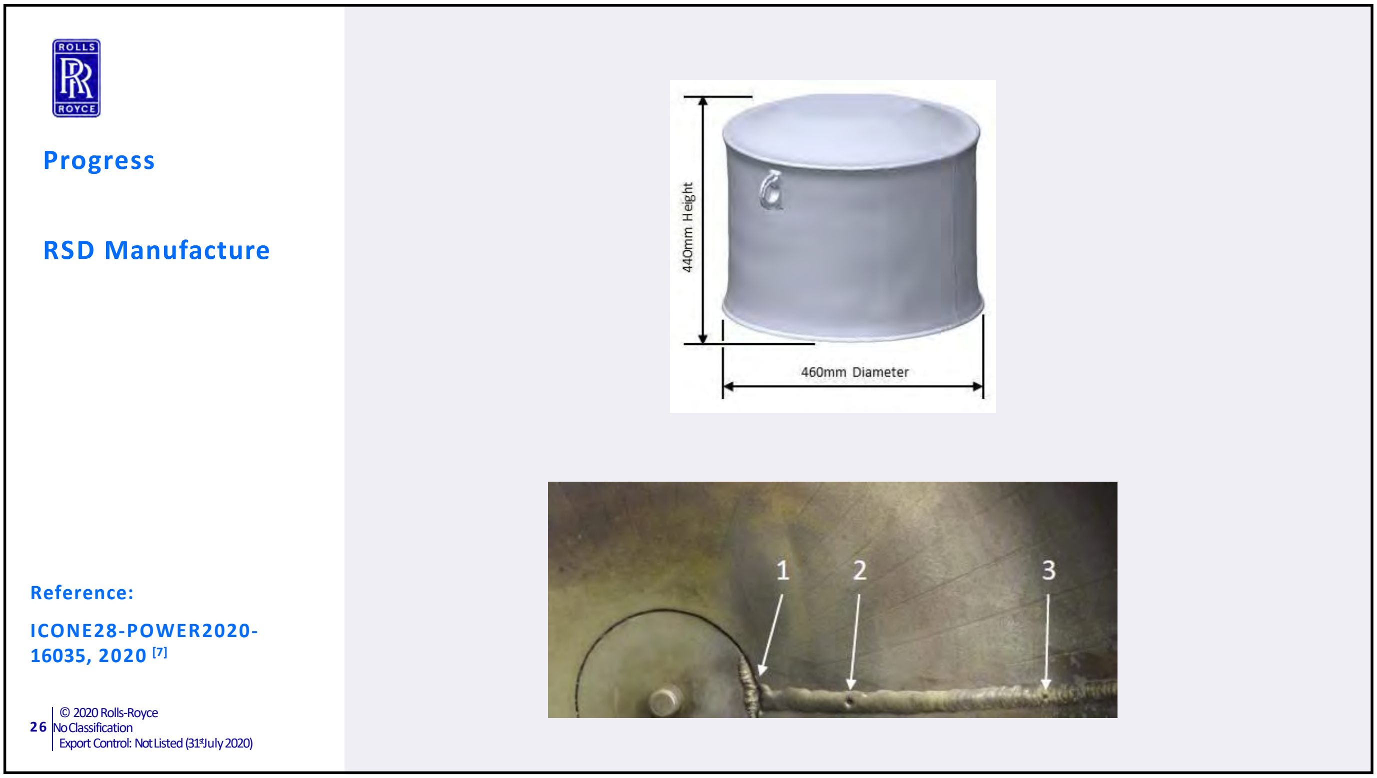
# Progress

## Billets & Basic Material Testing

**References:**

**ICONE28-POWER2020-16035, 2020** [7]

**ICONE27-1021, 2019** [8]



# Progress

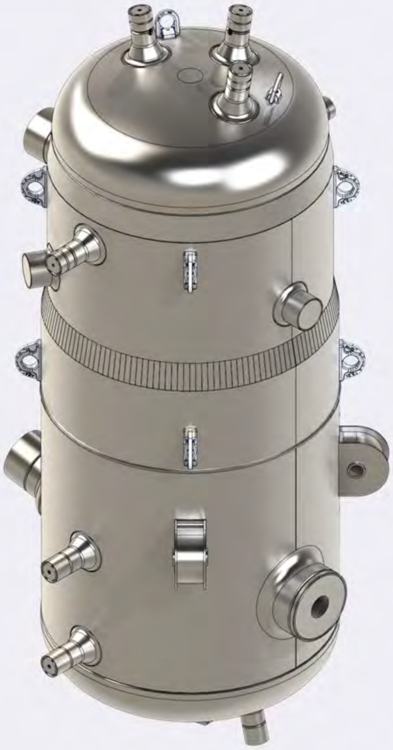
## RSD Manufacture

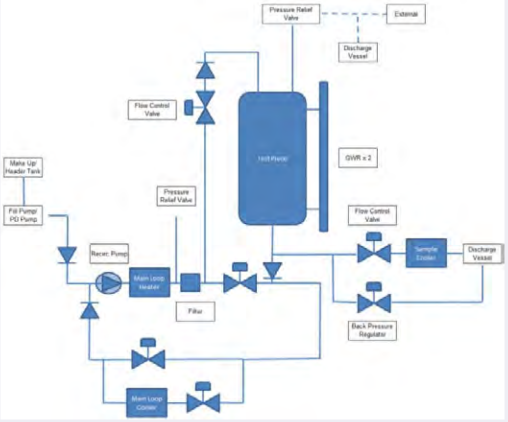
**Reference:**

**ICONE28-POWER2020-16035, 2020** [7]

## Progress

## SVD Design & Manufacture





**Reference:**

**ICONE28-POWER2020-16035, 2020** [7]

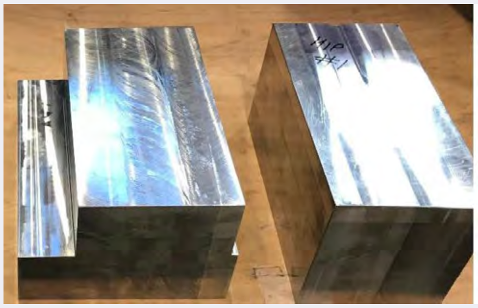
## Progress

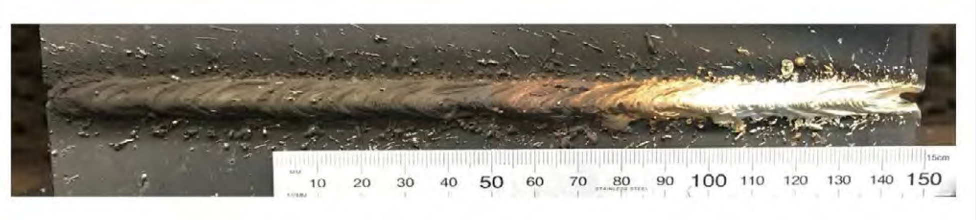
## SVD Manufacture

## Upper and Lower Sections After HIPing Awaiting EBW

## Progress

### EBW





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## Capability Requirements for Deployment

- Large-scale HIP vessel – max dia in Europe = 1.6m
- Large-scale EB chamber
- Improving toughness level –ideally equivalent to forged, oxygen control
- High quality can manufacture – prevention of can failure
- Good quality powder manufacture, low oxygen level, morphology, but at a competitive price, and with reliable, short delivery time – need to ensure competitiveness to forging.
- ASME Code Case – Completion of future full material test programme

**Reference:**

**ICONE28-POWER2020-16035** [7]

## Acknowledgments

- *Project FAST is part funded by the UK Department for Business, Energy & Industrial Strategy as part of the UK £505m Energy Innovation Programme.*

Department for Business, Energy & Industrial Strategy

## References

[1] J L Sulley and I D Hookham, "Justification and Manufacturing Quality Assurance for the Use of Hot Isostatically Pressed, Reactor Coolant System Components in PWR Plant," Proceedings of ICAPP' 08, Anaheim, 2008, CA USA, Paper 8110, p18-20, June 8-12, 2008.

[2] J L Sulley and D Stewart, 'HIPed Hard Facings for Nuclear Applications – Materials, Key Potential Defects and Mitigating Quality Control Measures', Proceedings of the 2016 24th International Conference on Nuclear Engineering ICONE24, June 26 – 30, 2016, Charlotte, North Carolina, ICONE24-61106.

[3] I Hookham, B Burdett, K Bridger, J L Sulley, 'Hot Isostatically Pressed (HIPed) Thick Walled Component for a Pressurised Water Reactor (PWR) Application, Proceedings of ICAPP' 09, Tokyo, Japan, May 10-14, 2009, Paper 9389, p7.

[4] J L Sulley, M Bohan, 'Hot Isostatically Pressed (HIPed) Large Bore Valves for a Pressurised Water Reactor (PWR) Application', Proceedings of PVP-2012: ASME Pressure Vessels and Piping Division, ASME, Toronto, 2012, PVP 2012-78115.

[5] J L Sulley, B Bull, A Wood, 'Hot Isostatic Pressing of Large Bore, Stainless Steel Pipework for a Safety Critical Application,' Proceedings of the International Conference on Applied Materials and Electronics Engineering, AMEE 2012, Jan 18-19, 2012, Hong Kong.

[6] J Sulley, P Mitchell, D Mills, 'Hot Isostatic Pressing of a Varying Thickness, Thick-walled Vessel (Reactor Circulating Pump Bowl) for a Pressurised Water Reactor (PWR) Application', Proceedings of PVP-2014, ASME Pressure Vessels and Piping Division, 20th- 24th July 2014, Anaheim, California, PVP 2014-28013.

[7] J Sulley, P Wallace, T Warner, G Jones, 'Nuclear Pressure Vessel Manufacture Using the Hot Isostatic Pressing (HIP) Process', Proceedings of the 28th International Conference on Nuclear Engineering Joint with the ASME 2020 Power Conference, Anaheim, USA, August 2 – 6, 2020, ICONE 28-POWER2020-16035.

[8] A Morrison, J Sulley, C Carpenter, B Borradaile, G Jones, T Warner, 'HIPed Low Alloy Steel for Nuclear Pressure Vessel Applications – Material Property and Microstructural Assessment', Proceedings of the 27th International Conference on Nuclear Engineering, ICONE 27, Ibaraki, Japan, May 19 – 24, 2019, ICONE 27-1021.

Thank you

## Any Questions?

# U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

## Cold Spray Technology and Experience in Army Applications

Matt Siopis

CCDC-Army Research Labs

07 DEC 2020

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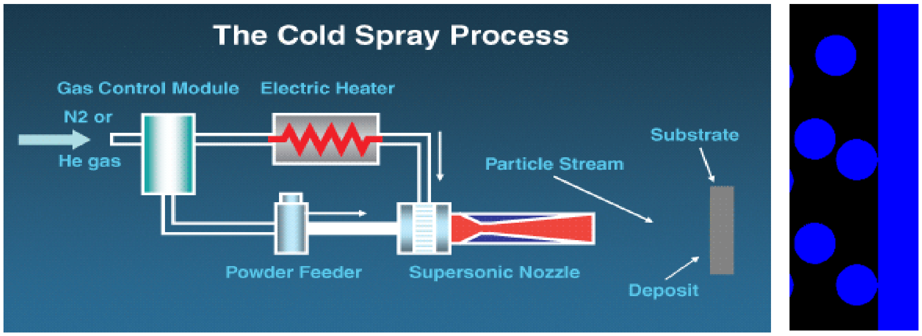
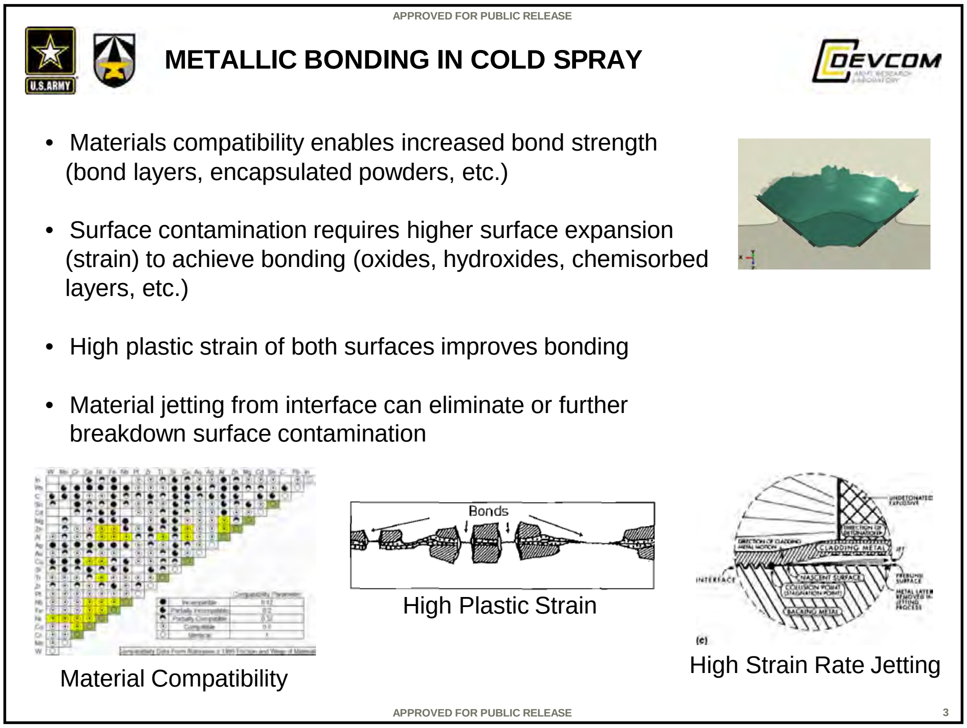
## COLD SPRAY OVERVIEW

**Cold spray is an AM process that incorporates a heated high-pressure gas such as He or N2 together micron sized particles of a metal, ceramic and/or polymer into a gun fitted with a De Laval rocket nozzle designed such that the particles exit at supersonic velocities and consolidate upon impacting a suitable surface to form a coating or a near-net shaped part.**



- Main Gas Stagnation Pressure 100-1,000 psi
- Main Gas Flow Rate 30-100 CFM
- Particle Velocity 300-1500 m/s
- Gas Temperature 0-1000ºC
- High Powder Feed Rates >10 lbs/hr
- Particle Size 10-75 μm diameter



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## METALLIC BONDING IN COLD SPRAY

- Materials compatibility enables increased bond strength (bond layers, encapsulated powders, etc.)
- Surface contamination requires higher surface expansion (strain) to achieve bonding (oxides, hydroxides, chemisorbed layers, etc.)
- High plastic strain of both surfaces improves bonding
- Material jetting from interface can eliminate or further breakdown surface contamination

Material Compatibility

High Plastic Strain

High Strain Rate Jetting

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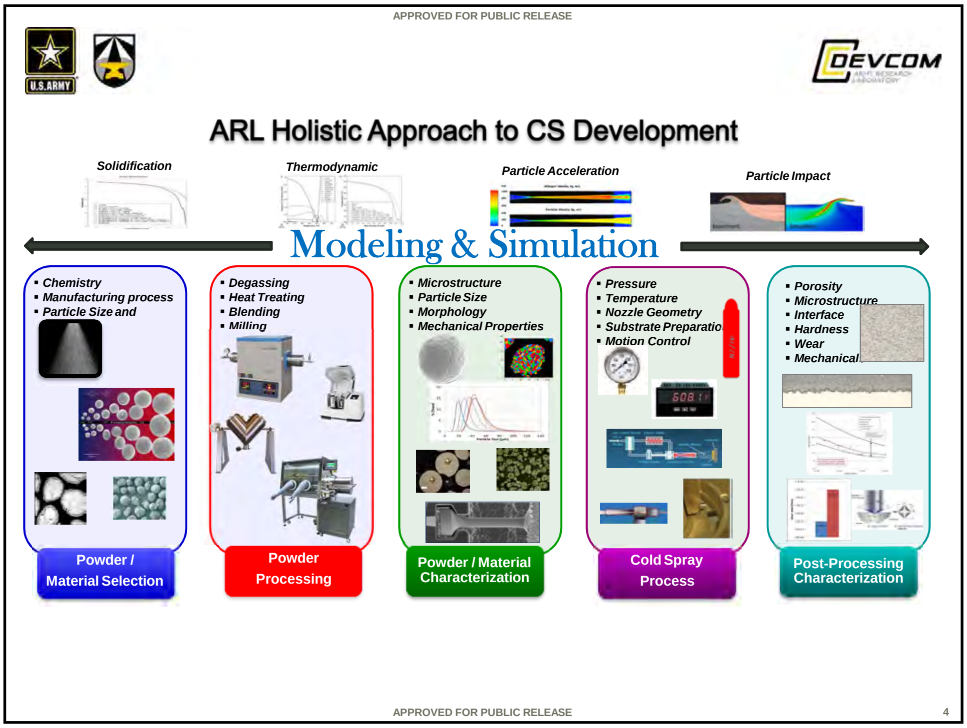

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## ARL Holistic Approach to CS Development

**Powder / Material Selection**
- Chemistry
- Manufacturing process
- Particle Size and

**Powder Processing**
- Degassing
- Heat Treating
- Blending
- Milling

**Powder / Material Characterization**
- Microstructure
- Particle Size
- Morphology
- Mechanical Properties

**Cold Spray Process**
- Pressure
- Temperature
- Nozzle Geometry
- Substrate Preparatio
- Motion Control

**Post-Processing Characterization**
- Porosity
- Microstructure
- Interface
- Hardness
- Wear
- Mechanical

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# POWDER PROCESSING

## *Key Considerations*

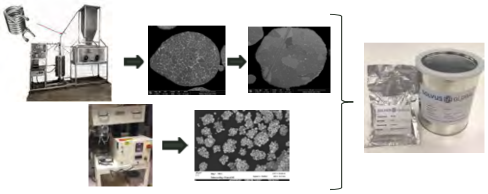
- Mechanical properties (hardness, flow stress, etc.)
- Grain structure
- Phase distribution
- Surface cleanliness (oxide/hydroxide)
- Powder size distribution
- Morphology (clad, layered, etc.)

## *Modeling and Testing*

- Thermodynamic phase modeling
- FEA Modeling
- Single particle impact testing
- Surface characterization
- Conductivity testing
- Microtrac and other PSD evaluation and separation
- Thermal processing

## *ARL Team Developments*

- Development of thermal treatments to degas, homogenize, solution treat, over-age, or anneal powders
- Processes to cost effectively clad powders to develop Cold Sprayable cermets, control chemistry, and improve DE of certain material blends
- Development of fluidized bed processes and equipment on the laboratory and small production scale to perform
  - Thermal processing
  - Degassing
  - Particle sizing
- Worked with Supplier to commercialize powder processing techniques developed



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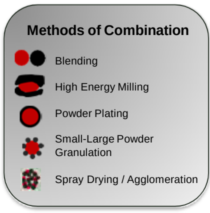
# Cold Spray Powder Development – WIP Coatings

## What makes a high quality Cold Spray coating

- The Cold Spray process achieves particle bonding through a process of high velocity impact and plastic deformation
- Powders used in Cold Spray must contain a "soft" plastic phase in order to properly consolidate when the powder undergoes plastic deformation
- To create hard coatings, a significant quantity of hard phase is required in the coating
- For high toughness coatings less hard phase is required while inter-particle bonding is critical

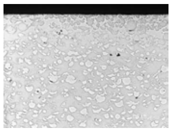
**Materials Selection**

| Hard Phases ● | Soft Phases ● |
|---|---|
| Tungsten Carbide<br>Chrome Carbide<br>Iron Based Hard powders | Nickel<br>Stainless Steel<br>Cobalt<br>Chrome<br>Tantalum<br>Niobium<br>Bronze<br>Copper-Nickel |



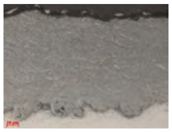
**Methods of Combination**

- Powder Blends have achieved approximately 375-450 HV hardness deposits with moderate to high wear resistance and the best impact properties



Mechanical Blend

- Spray Dried or agglomerated and sintered powders have achieved the highest hardness ranging from 800 – 1300 HV depending on composition



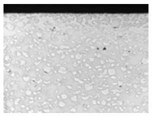
Spray Dried and Sintered

- Design optimized clad agglomerate powders show the best overall properties including higher DE, good toughness, and excellent wear performance

Combined Processing
Spray Dried + Coated

## Current State of Development with WIP Coatings

- WIP-C1 and WIP-C2
  - These deposits are being rolled out into several applications and have by far the most robust set of data and spray conditions of all WIP materials
  - Vendors have been set up to produce this material commercially for easier procurement
  - Deposits have been demonstrated with both helium and nitrogen with good quality
  - Deposits can be machined by milling, turning, or grinding



- WIP-F1
  - This material is very similar to WIP-C1 and C2 but is completely iron based for applications where EH&S concerns about nickel based deposits may be present
  - More work needs to be done to characterize the properties, especially wear performance, of this material
  - Once further data is developed scale-up of this material to production quantities will follow the process for WIP-C1 and C2

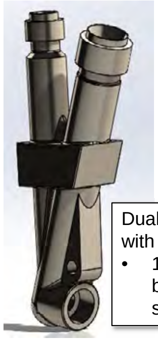
- WIP-W1
  - This material has the greatest potential for direct chrome replacement in most applications
  - The data generated has shown excellent wear and
  - Deposits must be ground, but can be ground with SiC or diamond
  - All powders have been produced using production robust processes

**All coatings can be applied in line of site applications as well as in features as small as 1.8 - 2 inches**

## ID NOZZLE DEVELOPMENT

Single injection design for use with carbide nozzle
- 1.8 in minimum bore, 0.5" standoff

Dual injection design with integral Co-Cr nozzle
- 1.5 in minimum bore, 0.5" standoff



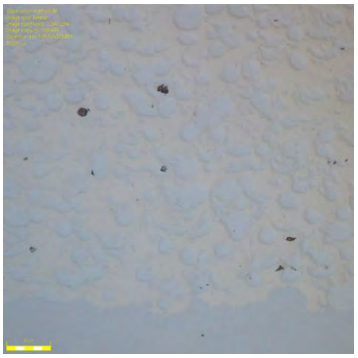
Dual injection design with carbide insert
- 1.5 in minimum bore, 0.5" standoff

Single injection large bore design
- 4 in minimum bore, 0.5" standoff

Single injection design for spraying aluminum
- 1.8 in minimum bore, 0.5" standoff

## WIP-C1 TECHNICAL DATA

- Sprayable with $N_2$ or He
  - 1.5%-3% porosity with $N_2$
  - <1% porosity with He
- Suitable for many substrates
  - HRC 30-55 steels
  - Stainless
  - Monel
  - Copper-Nickel
- Similar or better wear performance than Cr plating
- Suitable for high impact conditions

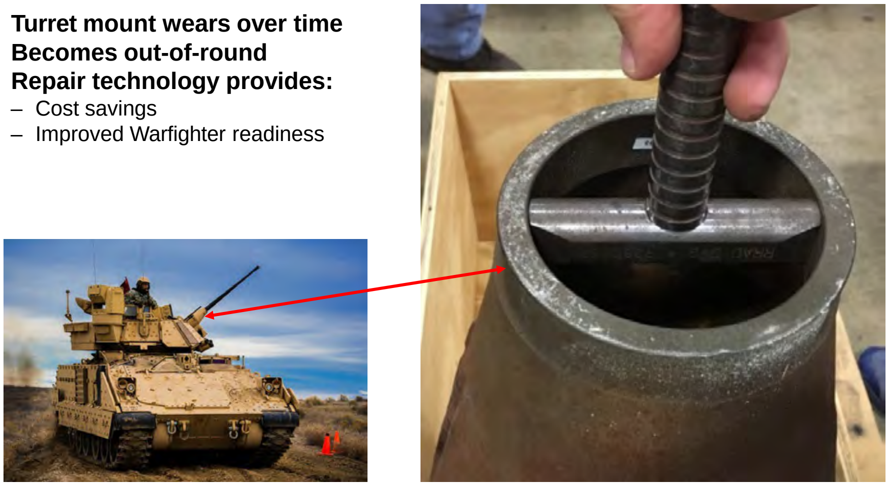


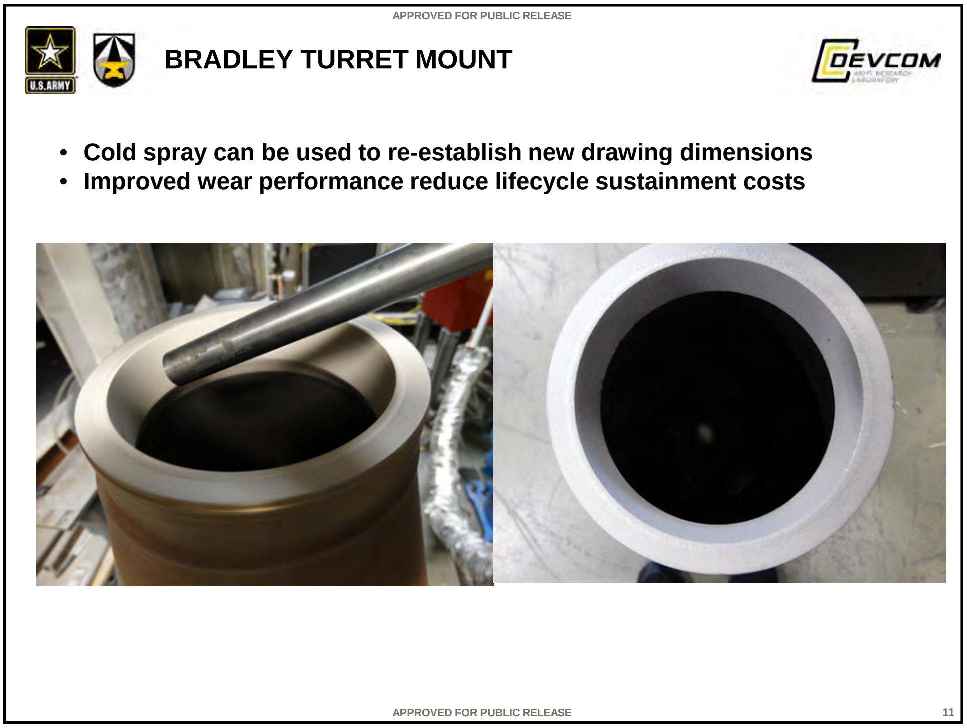
Measured Porosity: <0.5%

| Substrate | Lug Shear Strength (ksi) |
|---|---|
| 17-4PH | ~20 |
| High Hardness Steel | ~20-25 |
| 4340 | 40.6 (He), 28 (N2) |
| 4330V | 38.3 |

## BRADLEY TURRET MOUNT

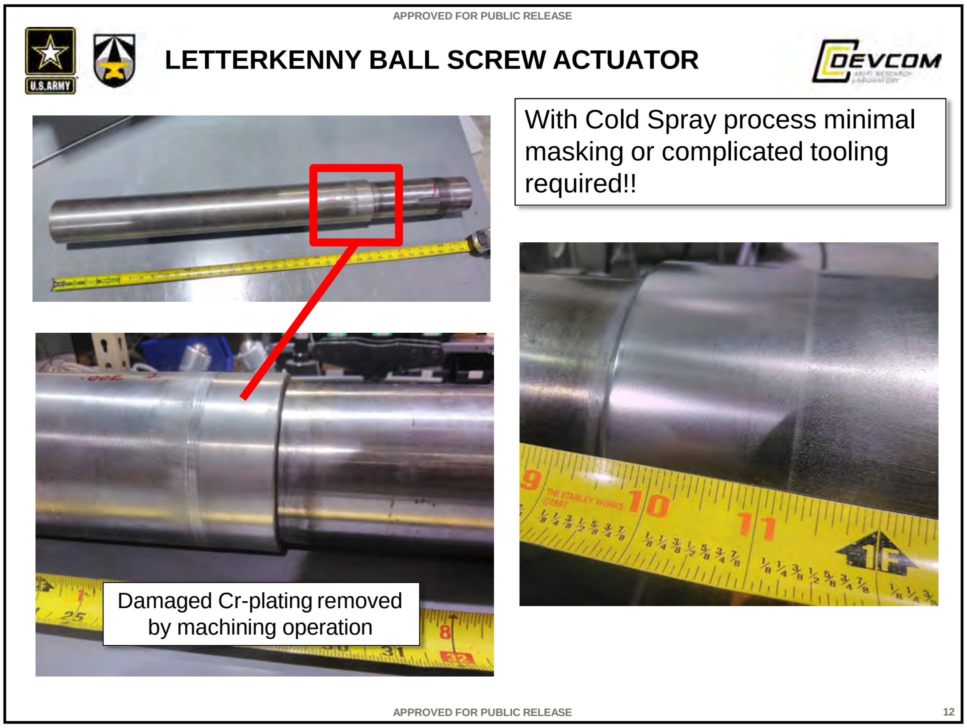
- **Turret mount wears over time**
- **Becomes out-of-round**
- **Repair technology provides:**
  - Cost savings
  - Improved Warfighter readiness





## BRADLEY TURRET MOUNT

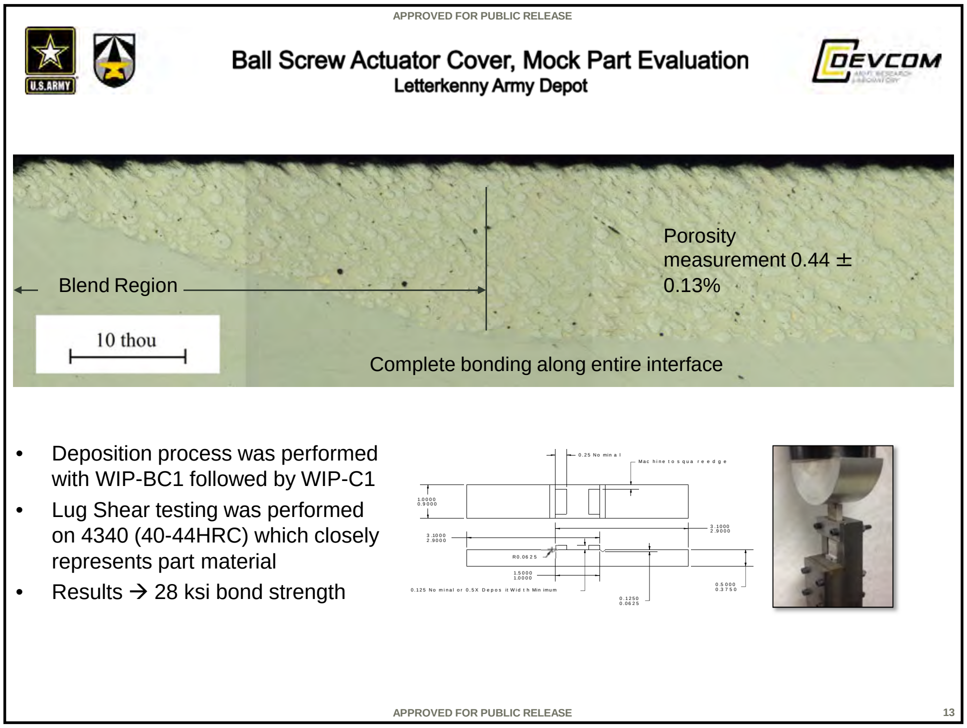
- Cold spray can be used to re-establish new drawing dimensions
- Improved wear performance reduce lifecycle sustainment costs



## LETTERKENNY BALL SCREW ACTUATOR

With Cold Spray process minimal masking or complicated tooling required!!

Damaged Cr-plating removed by machining operation



## Ball Screw Actuator Cover, Mock Part Evaluation

Letterkenny Army Depot

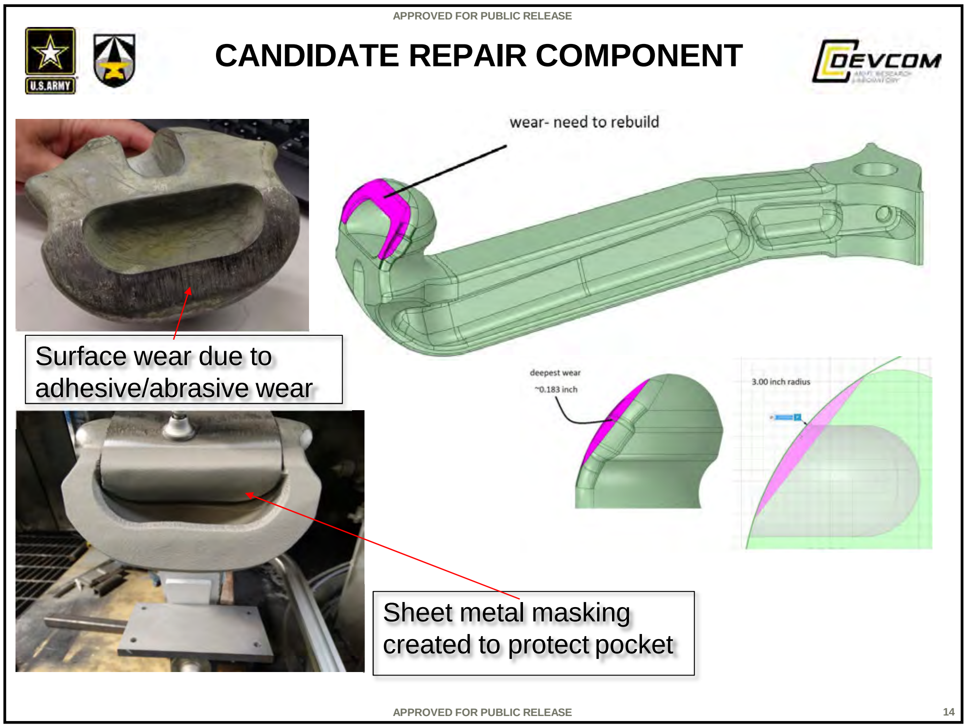
Porosity measurement 0.44 ± 0.13%

Blend Region

10 thou

Complete bonding along entire interface

- Deposition process was performed with WIP-BC1 followed by WIP-C1
- Lug Shear testing was performed on 4340 (40-44HRC) which closely represents part material
- Results → 28 ksi bond strength



## CANDIDATE REPAIR COMPONENT

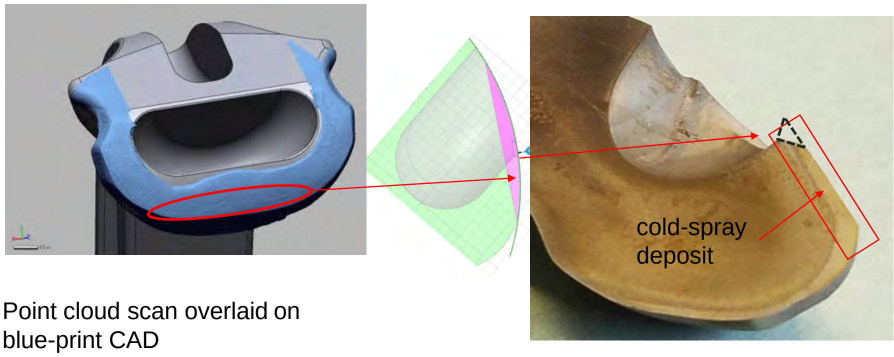
wear- need to rebuild

Surface wear due to adhesive/abrasive wear

Sheet metal masking created to protect pocket

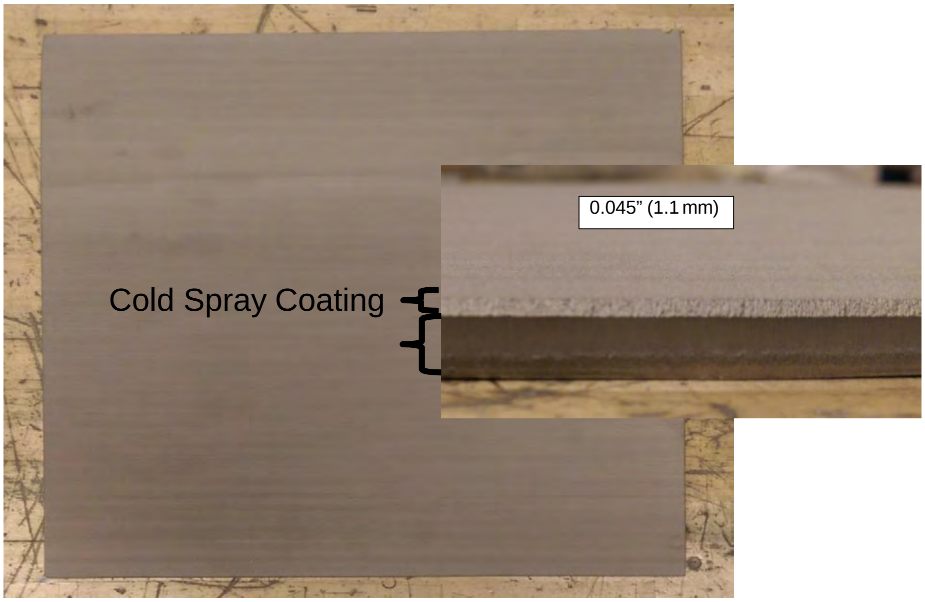
## ARL Cold Spray Process Development

Repair material applied (blue texture) beyond blue-print dimensions
Edge of hole receded due to wear.



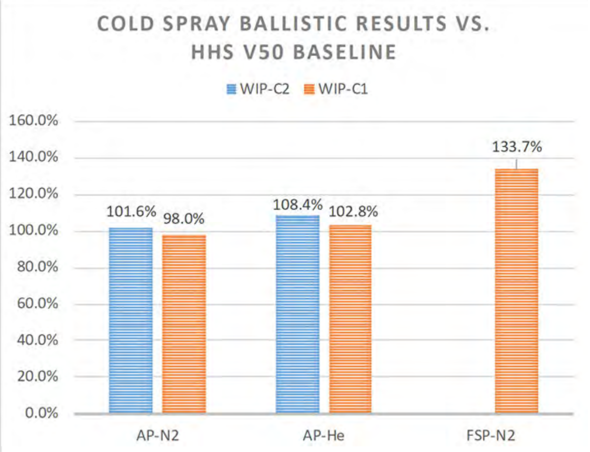
Point cloud scan overlaid on blue-print CAD

## BALLISTIC ARMOR REPAIR

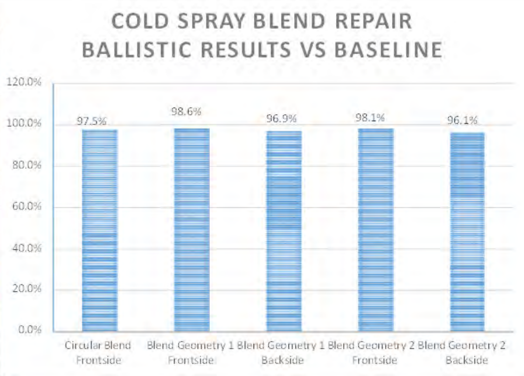


## COLD SPRAY BALLISTIC PERFORMANCE

- Bar chart shows the percentage of ballistic performance restoration indexed to 100% of base metal.
- Repair depth 1mm onto thinned 6.3 mm thick HH steel for a 12” x 12” panel with full coverage.
- Using armor piercing (AP) rounds and fragment stimulating projectile (FSP) rounds.

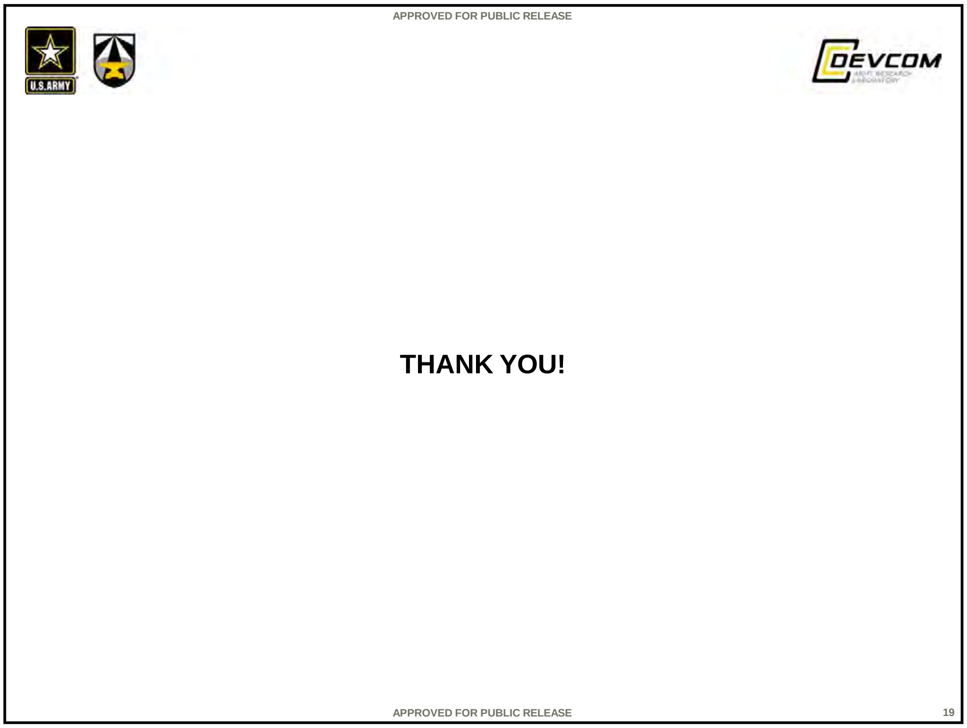


## BLEND AND FILL ARMOR REPAIR



- Repairing pockets yielded similar performance
- Confined delamination area
- Improved Cost Reduction

Near repair CP and PP hit did not induce delamination.



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**THANK YOU!**

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# NAVSEA Additive Manufacturing Program Overview

## NRC Public Workshop on Advanced Manufacturing

Dr. Justin Rettaliata

NAVSEA 05T, AM Technical Warrant Holder

7 Dec 2020

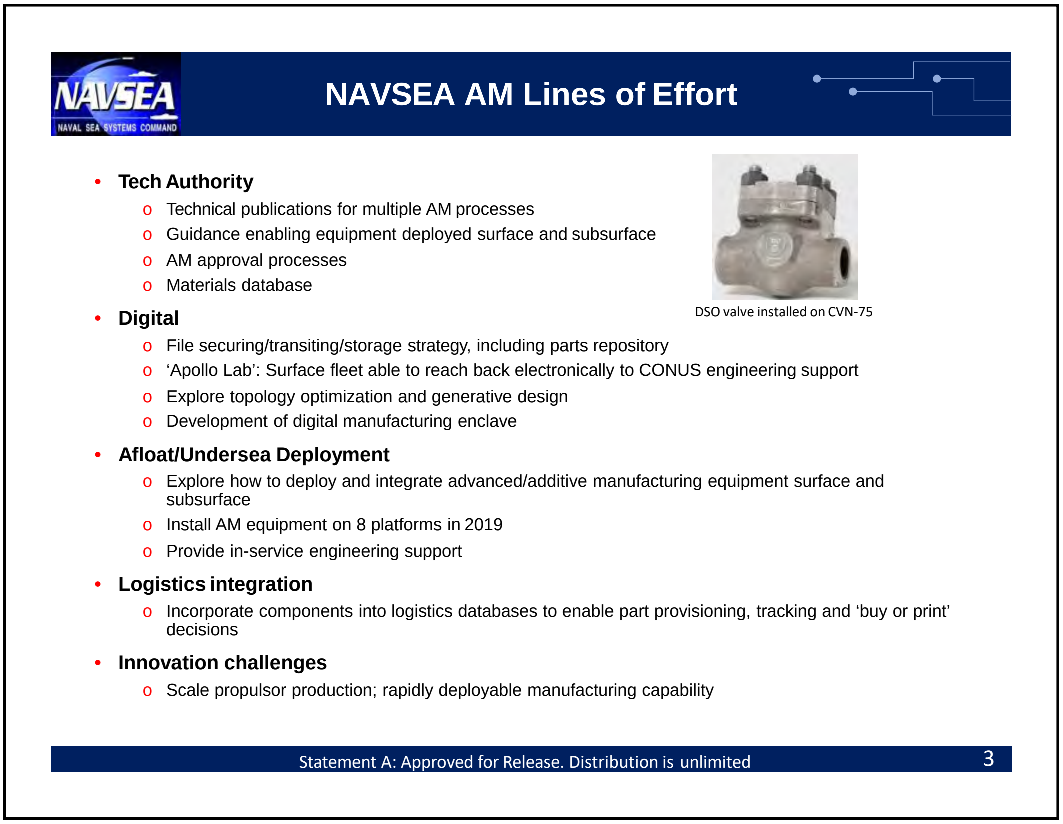
## Additive Manufacturing

Why AM?

- **Increase readiness** through production of obsolete or long-lead items
- **Enhance capabilities** through mission-tailorable solutions and employment of designs not otherwise possible
- **Maintain operational availability** through “good enough” production at the point-of need

Key Initiatives

- Develop specifications and standards necessary to incorporate AM components for surface and subsurface applications
- Engage fleet and leverage logistics databases to ID priority components
- Prototype the digital infrastructure to securely store and share files
- Published policy for installing equipment onboard submarines
- Working closely with industry on identification and approval of components for AM.



# NAVSEA AM Lines of Effort

- **Tech Authority**
  - Technical publications for multiple AM processes
  - Guidance enabling equipment deployed surface and subsurface
  - AM approval processes
  - Materials database
- **Digital**
  - File securing/transiting/storage strategy, including parts repository
  - 'Apollo Lab': Surface fleet able to reach back electronically to CONUS engineering support
  - Explore topology optimization and generative design
  - Development of digital manufacturing enclave
- **Afloat/Undersea Deployment**
  - Explore how to deploy and integrate advanced/additive manufacturing equipment surface and subsurface
  - Install AM equipment on 8 platforms in 2019
  - Provide in-service engineering support
- **Logistics integration**
  - Incorporate components into logistics databases to enable part provisioning, tracking and 'buy or print' decisions
- **Innovation challenges**
  - Scale propulsor production; rapidly deployable manufacturing capability

DSO valve installed on CVN-75

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# Tech Authority Products

- NAVSEA AM Guidance released August 2018
  - Guidelines for use of polymeric materials aboard ship (fire, smoke, and toxicity requirements)
- Powder Bed Fusion Technical Publication published – 21 Jan 2020
- Directed Energy Deposition Technical Publication – Q2 FY21
- Establishing framework for qualifying critical polymer machines and components
- Develop Technical Data Package for AM components
- Performing machine assessment for new metal AM systems going to NSYs and NSWCs
- Engage Standard Development Organizations with industry for AM processes
- Establishing methodology to qualify vendors for metal AM production

Part Risk Assessment 'Boxes'

Yellow: Part received by NAVSEA, in process of risk assessment

Green: Low criticality, can be approved waterfront or shipboard and installed

Blue: Part requires NAVSEA HQ review and approval

Red: Part cannot or should not be produced via additive manufacturing; will inform S&T strategy

Powder Bed Fusion Process | Directed Energy Deposition Process | Material Extrusion | Additive Friction Stir

Ensuring repeatable, reliable production of AM components organically and from industry

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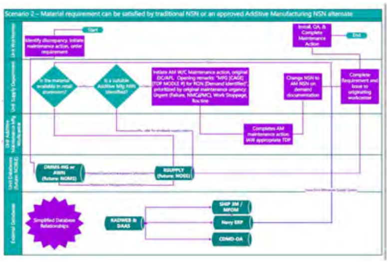
## Logistics Integration



•Motivation: Growing application space for AM across the Naval Enterprise requires supply chain Integration

•Goal: Data-driven AM part identification using automated logistics, supply and maintenance data

- Approach: Leverage existing databases and policies to integrate AM into the supply chain to promote improved agility, lower response times minimize brittleness
- Current Roadmap:
    - Establish cataloging and provisioning guidelines for AM parts
    - Logistics database and search for evaluating AM mission impact and readiness
    - Establish procedures for traceability of shipboard AM components at all levels; risk assessment and management

## Logistics Integration

- Provisioning for AM Components
    - Temporary AM Part Allowance Parts List (APL) set up for AM TDPs as NSNs get assigned
    - 4 AM parts routed for provisioning review
- NSN Assignment of AM Components
    - Federal Cataloging Committee (FCC) Interim plan for identifying AM part at the reference level of NSN
    - Interim policy requires DLA to provide a list of AM NSNs to the services at a minimum monthly cadence
- Mission Impact Analysis
    - Integrating NAVSUP N25 Price Fighter's AM cost/part tool into the TDP development process to provide a more accurate projected AM part cost

Integrating AM components into the Navy supply system

## NAMPIE Events

- Naval Additive Manufacturing Part Identification Exercises (NAMPIE)
    - Organized and supported by greater NAVSEA community
- **Objective:** Identify candidate AM parts onboard ships and influence creation of associated technical data packages (TDPs) for fleet utilization
    - Increase exposure to AM
    - Build database of AM parts
- Began as small data gathering sprint/AM showcase
- Grew into large scale multifaceted event

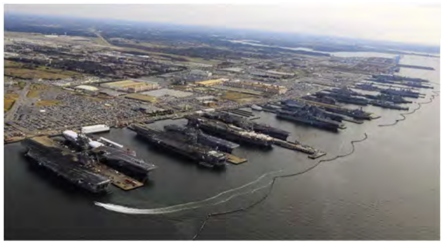
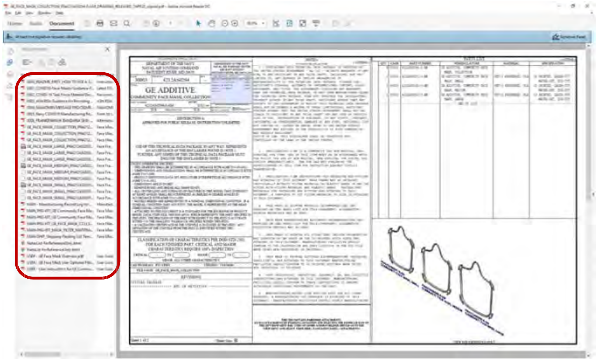


Photo Courtesy: navy.mil

Integrating AM components into the Navy supply system

## Technical Data Packages/Approval



DON COVID-19 non-surgical facemask AM TDP

- Engage fleet and leverage logistics databases to ID priority components
- Interim process established for digitally sharing files
- NAVSEA AM TDP format established
    - DON COVID-19 facemask AM TDP (top left)
    - Supporting attachments within TDP promote repeatable AM parts
- Risk categorization box approach for AM TDPs
    - Yellow = Triage
    - Green = Low risk
    - Blue = Moderate-high risk
    - Red = Not AM capable at this time

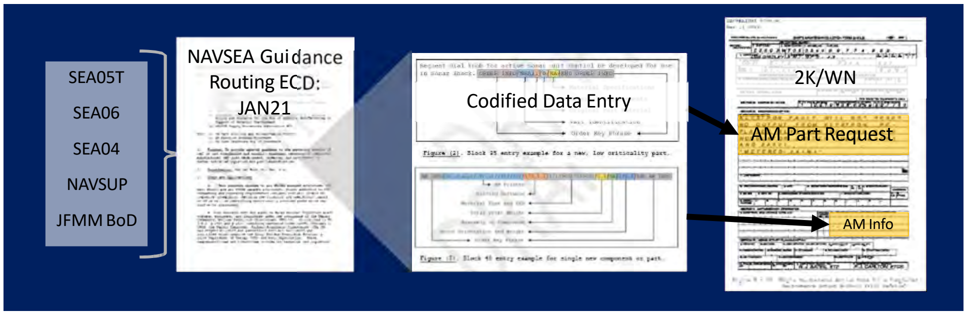
**Submitted For Approval**
Applications have been submitted for assessment.

**Approved Low Risk Applications**
Delegated to local technical authority (Chief Engineers - Waterfront or Ship).

**Received Tech Authority Approval**
Approved TDP which specifies materials and printers

## Additive Manufacturing Part Reporting Guidance

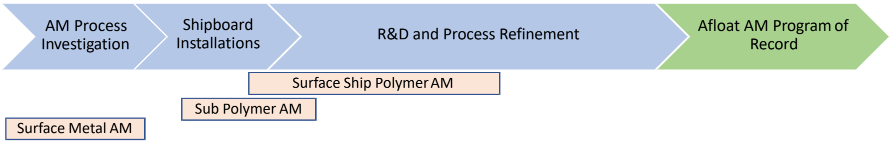
- Current tracking of AM part demand, AM parts produced is manual (reported via Excel spreadsheet and email/hand-carry hard drive)
- New approach takes advantage of established processes and systems with sailor and shipyard experience – OMMS-NG and Automated Work Notification (AWN)
- Reporting as maintenance provides traceability and time metrics to support logistics tracking without further burdening sailors
- Proposed process is being piloted with USS MAKIN ISLAND. Additional pilot will initiate with an AWN ship after MKI pilot completes. Results will be used to update reporting process outlined in guidance update



Automated data collection

## Afloat Advanced Manufacturing Overview

### Afloat Advanced Manufacturing Strategy



Results to Date

- 8 Surface Ship Installations (FY19/20)
- 3 Sub Kits Delivered and one requested (FY20)
- 1 FDRMC Rota Installation (IOC FY19, FOC FY20)
- 50+ Sailors Trained
- 3 Underways Supported
- AIRPAC Requested SOW to fund additional CVN Installations


CAT2 CASREP for Satellite IP Antenna


Night Ops Porthole Covers


Light Bracket Bridge

## Afloat Advanced Manufacturing

**Metal AM**
- Test candidate hybrid metal wire directed energy deposition (DED) and CNC systems
- Develop a requirements document and installation plan for shipboard installation
- Identify appropriate platform for FY21 install
- Preliminary R&D on melt pool effects from motion and vibration
- Development of preliminary SOPs and operator training/familiarization

**Polymer AM**
- Development of four AM packages for installation aboard CVNs
- Model development for vibration and motion effects on machines and materials
  - Influence of ship motion on printer components
  - Influence of shipboard vibration on printer components and parts and development of mitigation strategies
- Off-gas testing at NASA White Sands Test Facility
  - Determining emission products, amounts, and rates from processing thermoplastic with AM equipment

**Apollo Lab**
- Provide continued reach-back support for deployed equipment

## Afloat Advanced Manufacturing Capabilities
## Updated Polymer Equipment

**Tier 1 – Desktop Polymer**
- Non-critical shipboard repair applications and some NAVSEA-approved critical applications with corresponding technical data package
- Polymer desktop printer, laptop with design and AM processing software, reverse engineering kit and maintenance/feedstock sustainment for 1 year

**Tier 2 – Industrial Polymer**
- Suitable for non-critical and critical shipboard repair applications
- Expands to high temperature and engineering-grade plastics and composites
- Polymer desktop printer, engineering-grade (PEEK, PEKK, ULTEM, etc.) polymer printer, composite polymer printer, design and software suite (desktop / laptop computers)

- Leverages lessons learned from over 2 years of shipboard installation support while also continuing R&D to expand critical polymer applications
- Expands shipboard printable materials to higher strength engineering plastics and polymer composites
- All equipment must be "hatchable", either whole or disassembled, to enable installation

## Cybersecure Digital Manufacturing Enclave

- BLUF: Advanced Manufacturing capabilities on operational platforms is isolated and sub-optimal, due to inability to network AM computers or equipment. The development of a dedicated network enclave with a controlled interface to DoN networks will facilitate an appropriate security posture, enabling efficient utilization of AM capabilities.

- Notional Schedule:

| | |
|---|---|
| • Domain Specific Tailoring Guide Routing | 18 Aug |
| • Prototype enclave (shore) | Q3 FY21 |
| • Evaluate enclave during HacktheMachine-Atlanta | 21-23 March |
| • Enclave installation (afloat) | CY FY21 |

The DME will enable the secure transfer of Advanced Manufacturing Data between Ship and Shore to facilitate distributed manufacturing

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# U.S. Nuclear Industry Perspectives on Advanced Manufacturing Technologies

Hilary Lane

December 7, 2020

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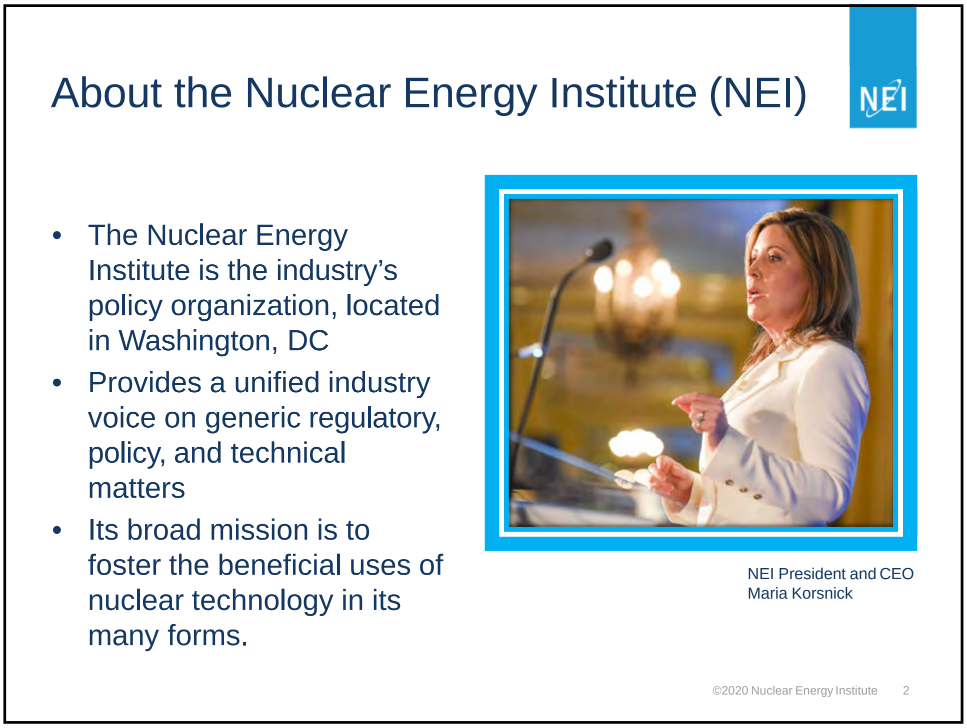


## About the Nuclear Energy Institute (NEI)

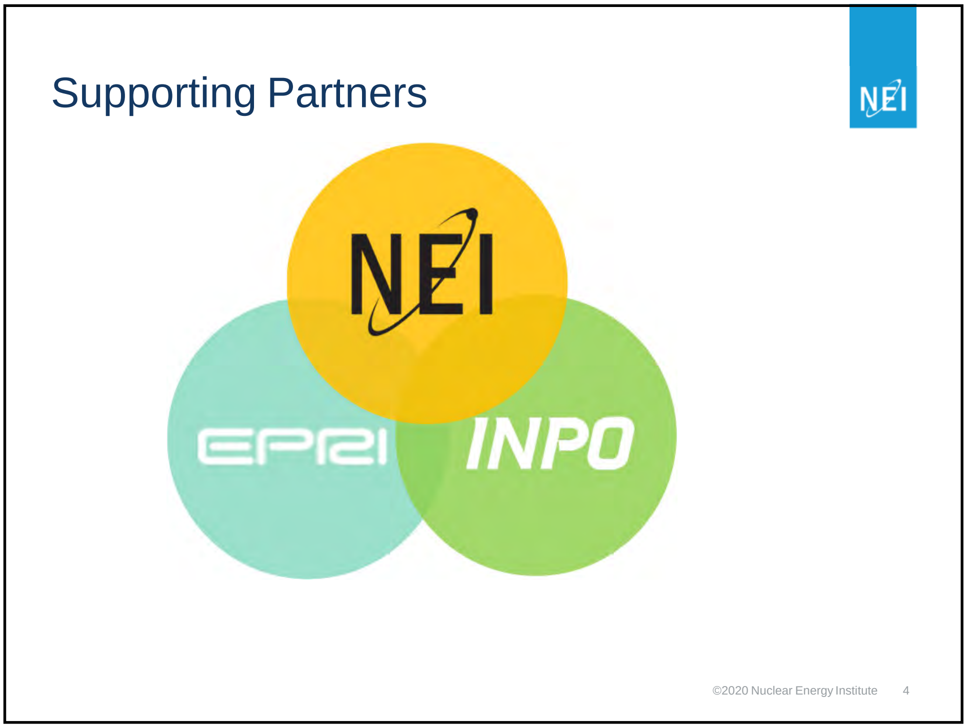
- The Nuclear Energy Institute is the industry's policy organization, located in Washington, DC
- Provides a unified industry voice on generic regulatory, policy, and technical matters
- Its broad mission is to foster the beneficial uses of nuclear technology in its many forms.

NEI President and CEO
Maria Korsnick

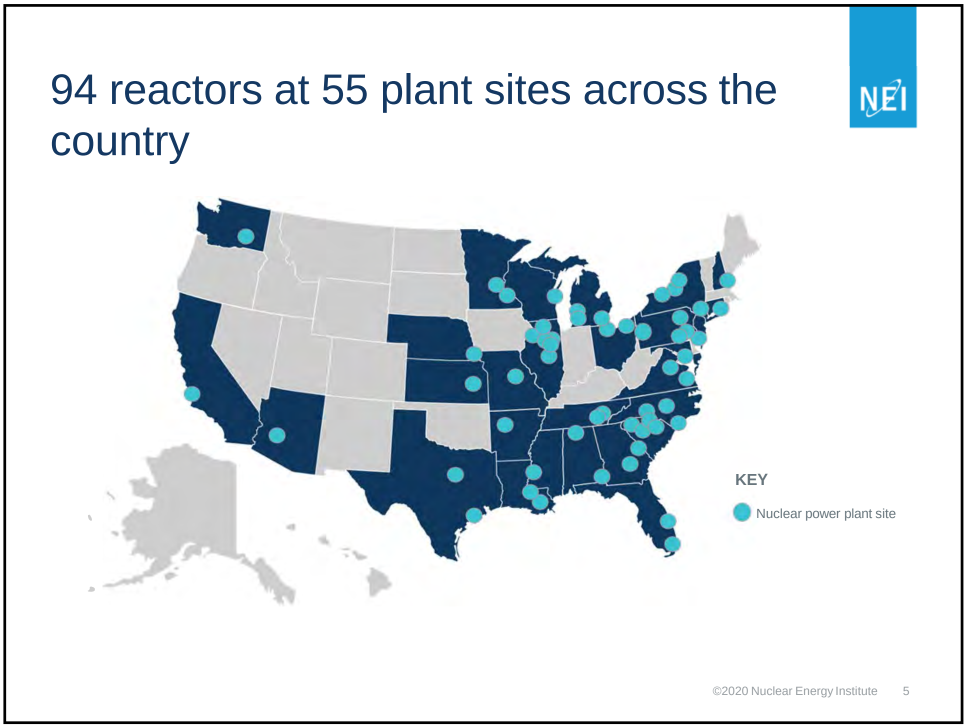
2

## In Collaboration with our Members:

**1,800 global member representatives serving on 140 committees, working groups and task forces (i.e. Advanced Manufacturing Task Force)**



## Supporting Partners

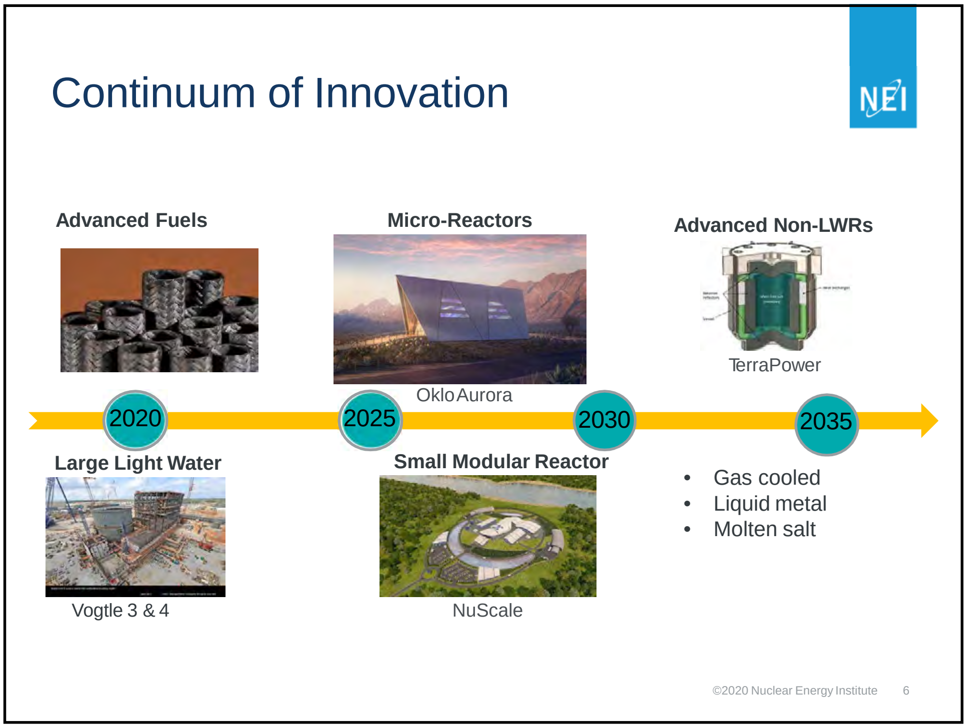


## 94 reactors at 55 plant sites across the country

NEI

KEY

● Nuclear power plant site



## Continuum of Innovation

NEI

**Advanced Fuels**

**Micro-Reactors**

Oklo Aurora

**Advanced Non-LWRs**

TerraPower

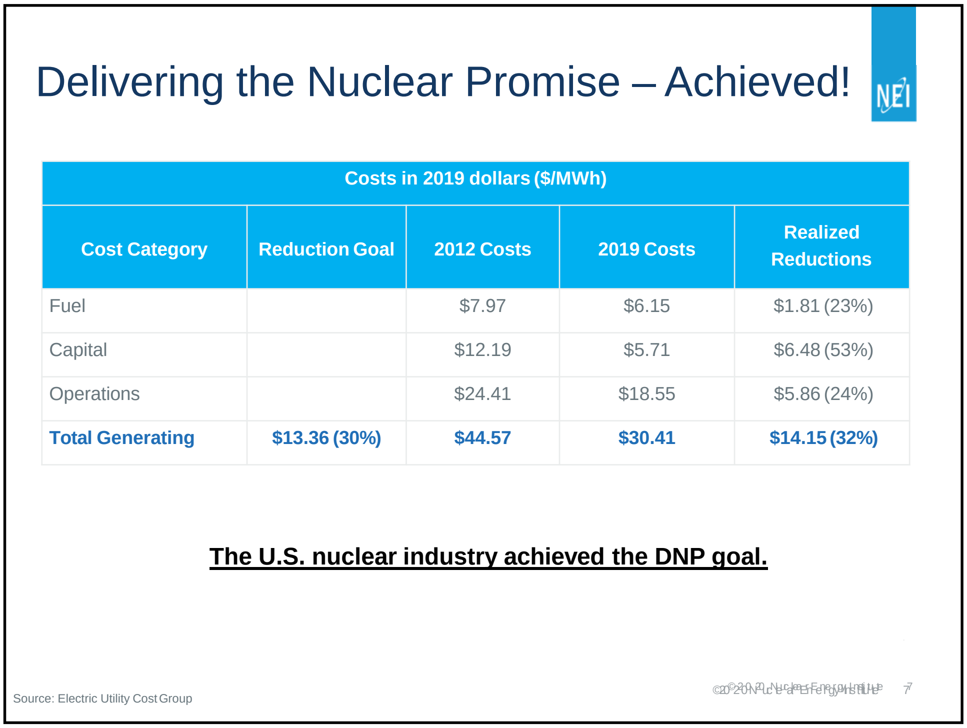
**Large Light Water**

Vogtle 3 & 4

**Small Modular Reactor**

NuScale

- Gas cooled
- Liquid metal
- Molten salt

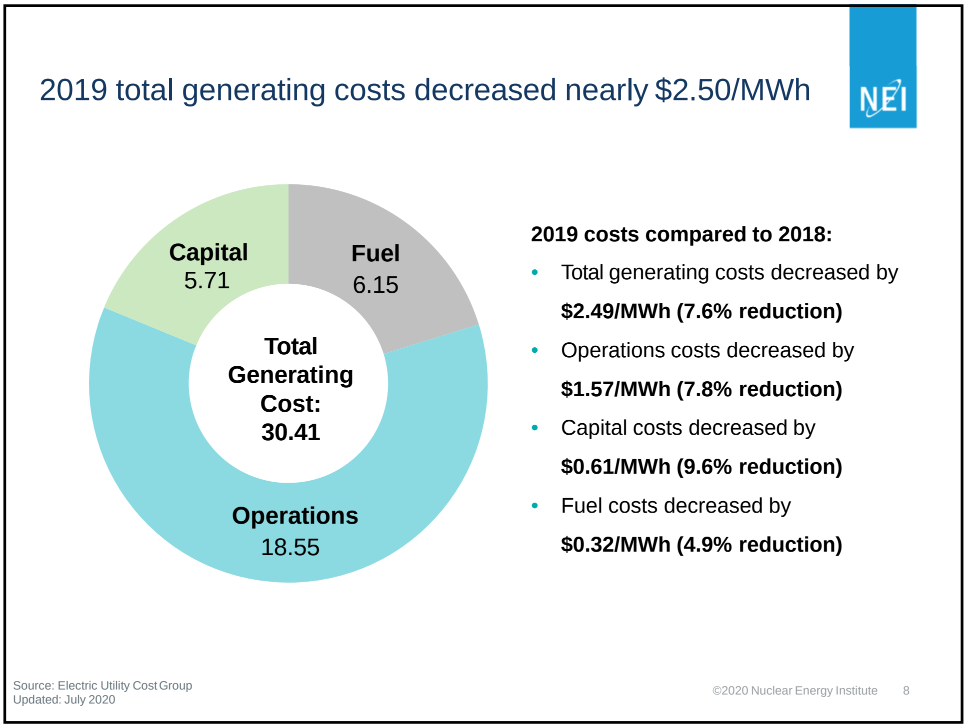


# Delivering the Nuclear Promise – Achieved!

| Costs in 2019 dollars ($/MWh) | | | | |
|---|---|---|---|---|
| **Cost Category** | **Reduction Goal** | **2012 Costs** | **2019 Costs** | **Realized Reductions** |
| Fuel | | $7.97 | $6.15 | $1.81 (23%) |
| Capital | | $12.19 | $5.71 | $6.48 (53%) |
| Operations | | $24.41 | $18.55 | $5.86 (24%) |
| **Total Generating** | **$13.36 (30%)** | **$44.57** | **$30.41** | **$14.15 (32%)** |

**The U.S. nuclear industry achieved the DNP goal.**

Source: Electric Utility Cost Group



# 2019 total generating costs decreased nearly $2.50/MWh

**2019 costs compared to 2018:**

- Total generating costs decreased by **$2.49/MWh (7.6% reduction)**
- Operations costs decreased by **$1.57/MWh (7.8% reduction)**
- Capital costs decreased by **$0.61/MWh (9.6% reduction)**
- Fuel costs decreased by **$0.32/MWh (4.9% reduction)**

Source: Electric Utility Cost Group
Updated: July 2020

## "The Big 3"

APPLICATIONS FOR BOTH THE CURRENT FLEET AND ADVANCED REACTOR DESIGNS

**Cost**
- Less labor; automated
- Less material; less waste

**Schedule**
- Reduced lead times; some up to 90%

**Quality**
- Excellent inspectibility
- Excellent material properties
- Homogenous

AMT Good Candidate For:
- ✓ Long lead time components
- ✓ High value components
- ✓ Complex geometries
- ✓ Obsolete parts
- ✓ Mitigation work
- ✓ High T environments
- ✓ Reduced weight
- ✓ Localizing the supply chain
- ✓ True "Nth-of-a-kind"
- ✓ And more…

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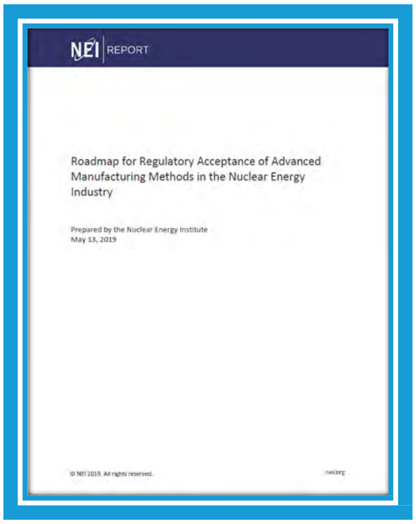
## NEI's Advanced Manufacturing Task Force



NEI | REPORT

Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry

Prepared by the Nuclear Energy Institute
May 13, 2019

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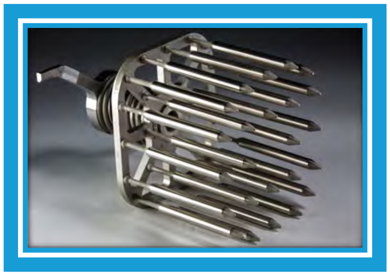
nei.org

- Broad membership to include:
  - Advanced Reactor designers/developers
  - Suppliers / manufacturers
  - Utilities
  - Law and consulting firms
  - EPRI
  - DOE-NE and DOE National Laboratories
  - Universities
  - Non-profits

# Advanced Manufacturing Technologies of Interest…

1) Laser Powder Bed Fusion
2) Powder Metallurgy – Hot Isostatic Pressing (PM-HIP)
3) Electron Beam Welding (EBW)
4) Cold Spray
5) Directed Energy Deposition (DED)
6) And many others…

# First of a Kind (FOAK) Deployments…

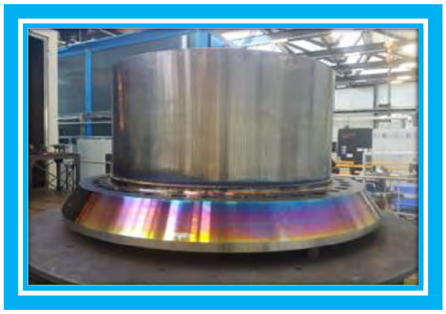


Courtesy: Westinghouse

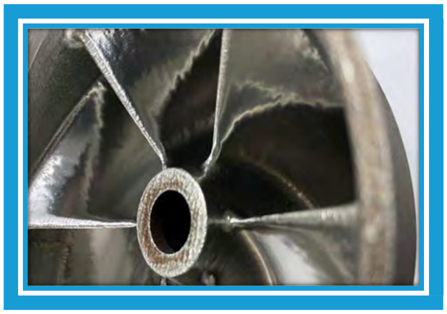
Courtesy: ORNL

Courtesy: Framatome

# First of a Kind (FOAK) Prototype Work…

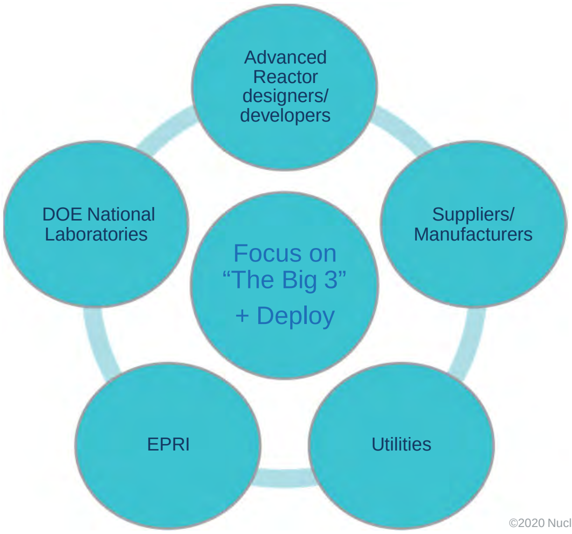


Courtesy: EPRI



Courtesy: Kairos

# Ongoing Collaboration Amongst the Industry, Supply Chain, & Research Arms



Advanced Reactor designers/ developers

Suppliers/ Manufacturers

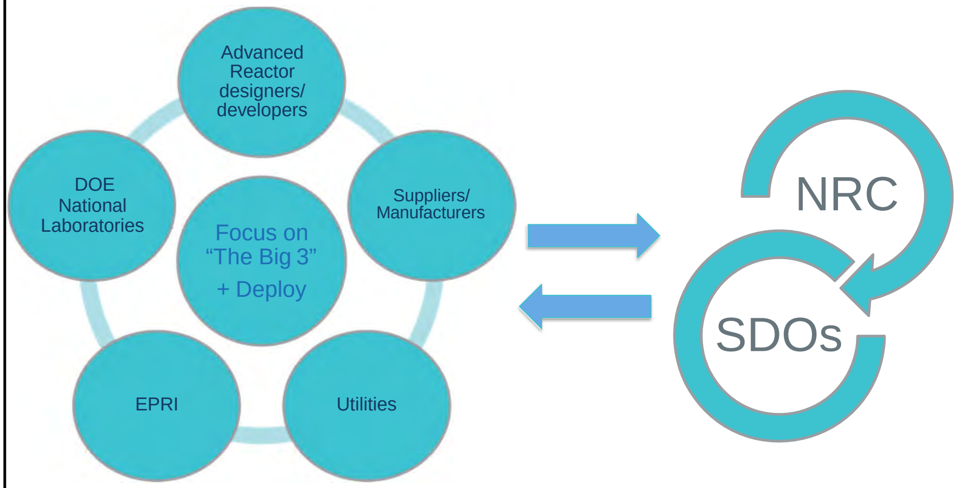
Utilities

EPRI

DOE National Laboratories

Focus on "The Big 3" + Deploy

## Continued Dialogue Needed



Advanced Reactor designers/ developers

Suppliers/ Manufacturers

Utilities

EPRI

DOE National Laboratories

Focus on “The Big 3” + Deploy

NRC

SDOs

---

## Codes & Standards

### ACCELERATED ACCEPTANCE NEEDED RE: AMT

- ASME Sec. III Code Case– Submitted Aug. 2019
  - Laser Powder Bed Fusion (316L)
- ASME Special Committee on Advanced Manufacturing (formed 2017)
- Draft Pressure Technology Book: “*Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing*”

## Where to go next?

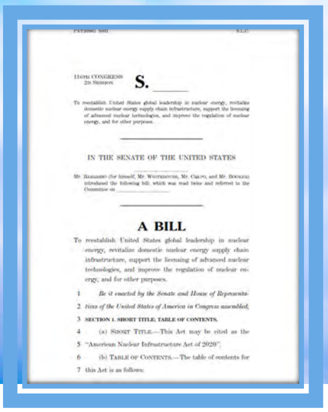
DEVELOPMENT & INTEREST IN THE FOLLOWING AREAS

- More fuel assembly focus (current fleet)
- Advanced reactor fuels
- Non-pressure boundary parts
- Pressure boundary parts (i.e. near net shape head)
- Replacement of obsolete parts
- New alloys
- Don’t forget about plastics!
- And more…

*Industry research & collaboration continues!*

## Legislative Works in Progress

*AMERICAN NUCLEAR INFRASTRUCTURE ACT (ANIA)*



116TH CONGRESS
2D SESSION **S.** ______

To reestablish United States global leadership in nuclear energy, revitalize domestic nuclear energy supply chain infrastructure, support the licensing of advanced nuclear technologies, and improve the regulation of nuclear energy, and for other purposes.

IN THE SENATE OF THE UNITED STATES

Mr. BARRASSO (for himself, Mr. WHITEHOUSE, Mr. CRAPO, and Mr. BOOKER) introduced the following bill; which was read twice and referred to the Committee on ______

**A BILL**

To reestablish United States global leadership in nuclear energy, revitalize domestic nuclear energy supply chain infrastructure, support the licensing of advanced nuclear technologies, and improve the regulation of nuclear energy, and for other purposes.

*Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,*

**SECTION 1. SHORT TITLE; TABLE OF CONTENTS.**

(a) SHORT TITLE.—This Act may be cited as the “American Nuclear Infrastructure Act of 2020”.

(b) TABLE OF CONTENTS.—The table of contents for this Act is as follows:

## Additional Takeaways

- Utilize the OPEX from other industries (aerospace, defense, etc.) to the extent practicable; **don’t re-invent the wheel**
- New-to-nuclear countries are looking to the U.S. to pave the way in AMT deployment
- Continue frequent dialogue amongst stakeholders (industry, NRC, SDOs, etc)

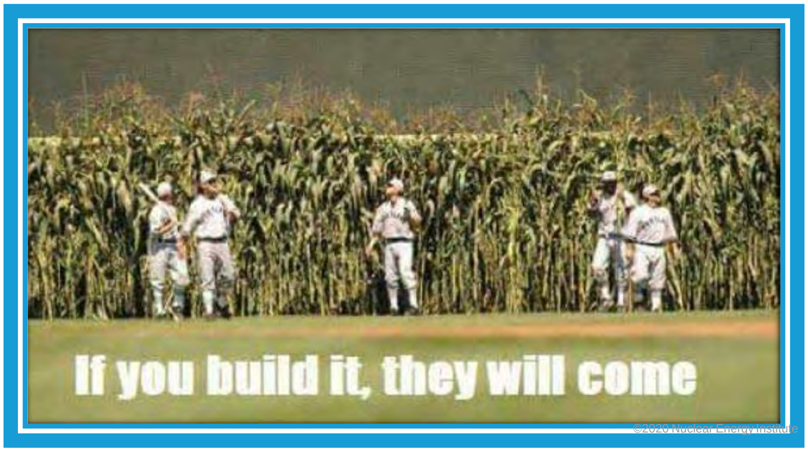
*Communicate, Communicate, Communicate!*

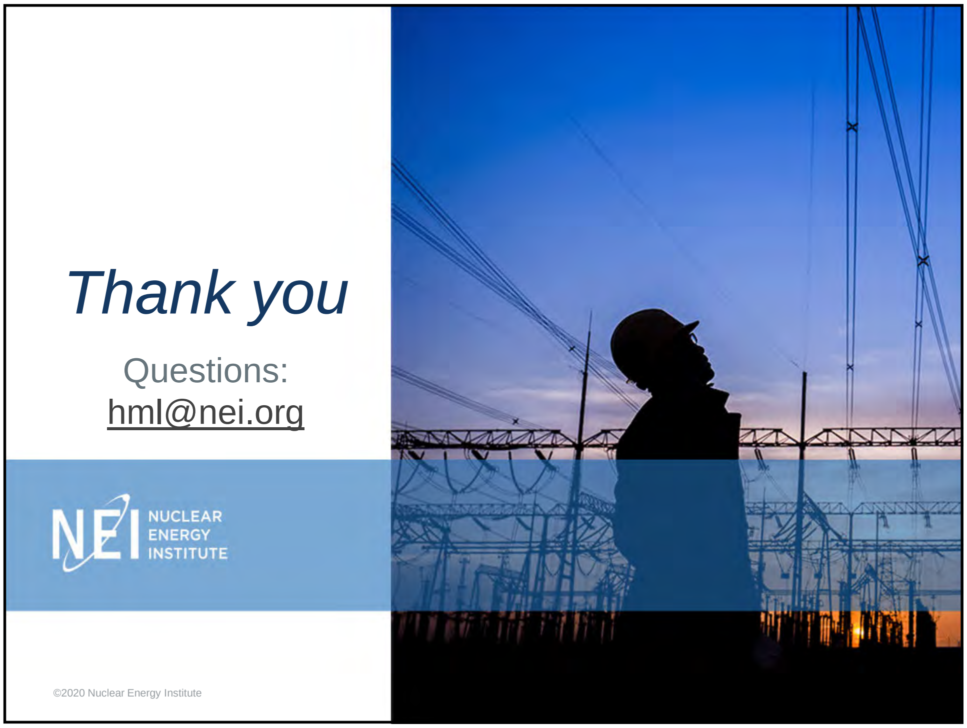
***Looking to NRC for a streamlined approach in line with their efforts to become a modern, risk-informed regulator***

## Advanced Manufacturing for the Nuclear Energy Industry

=

Innovate & Thrive





# *Thank you*

Questions:
hml@nei.org

NEI NUCLEAR ENERGY INSTITUTE

# Vision of Advanced Manufacturing Technology (AMT) Use in the Nuclear Industry

**Marc Albert, Senior Technical Leader**
Advanced Nuclear Technology
malbert@epri.com

**David Gandy, Senior Technical Executive**
Nuclear Materials

**NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications**
December 7-10, 2020

ELECTRIC POWER RESEARCH INSTITUTE

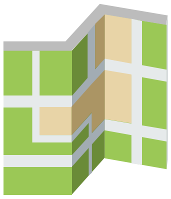
NUCLEAR

www.epri.com

Date: Add submission date and/or revision date & #

## Outline – Roadmapping EPRI's Vision to Deploy AMTs

- Advanced Manufacturing Technologies (AMT) Roadmap
- Additive Manufacturing Roadmap
- Additive Manufacturing for Obsolete and Replacement Components
- EPRI R&D Methodology to Deploy AMTs
  - Teaser for future presentations this week



**Collaboration Will Be Key within the Industry**

## EPRI AMT Roadmap – Background and Genesis

- Advanced ≠ Value Added
  - Numerous AMTs of interest for nuclear → where is the value/need?
    - Near net shapes, complex geometries (reduced machining and waste)
    - Flexible production, improved time to market
    - Improved material properties (in certain cases) = improved reliability
- Applicability
  - ALWRs and Repair/Maintenance of operating plants
  - Extends to advanced plants (SMRs, non-LWR ARs)
- Deployment Timeline: ⚖ Industry Needs
  - TRL level, lack of standards, reactor type applicability, ASME acceptance, regulatory approval

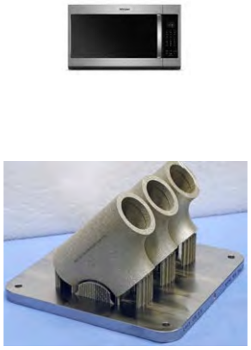
**Compliments/refines NEI *"Regulatory Acceptance of AMM in Nuclear Energy"* Roadmap & Technical Report**

## EPRI AMT Roadmap – Structure

**Aligns with "Approach to Codifying New Manufacturing Methods"**
- Dec. 8 discussion from GE-Hitachi and EPRI during NRC AMT Workshop

- Understanding AMTs and Applicability of Each
  - Component size often dictates AMT to be used
    - Review of LWR Component Opportunities for Powder Metallurgy-HIP (3002005432)
    - ALWR Primary System Candidates for Advanced Manufacturing Methods (Q1 2021)
    - SMR Candidate Components for Advanced Manufacturing Methods (2021)
    - Easily extends to advanced plants (SMRs, non-LWR ARs)
  - Process parameters and their impacts on properties (e.g., microstructure, etc.)
- Demonstrations of the AMTs at Scale
  - Understand applicability, advantages/disadvantages, prove-out implementation
- Development of ASME Data Packages and Code Cases to Support Implementation of Certain AMTs
- Development/Compilation of Environmental Effects for Regulatory Approval

# Size Often Dictates Advanced Manufacturing Process



**Laser Powder Bed Fusion Additive Manufacturing:**
<75 lbs (35 kg)

**Direct Energy Deposition Additive Manufacturing:**
<500 lbs (225 kg)

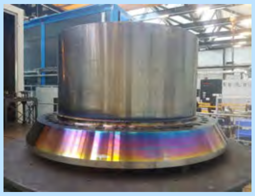
**Powder Metallurgy-HIP:**
100-10,000 lbs (45-4500 kg)

# Candidate AMT Processes for Nuclear Components

- Powder Metallurgy-Hot Isostatic Pressing: PM-HIP
  - ~4 ft (1.2m) diameter
    - Larger HIP allowing ~ 10ft (3.05m) diameter, est. completion 2023/24
- Directed Energy Deposition AM: DED-AM
  - < 500 lb. (227kg) max.
- Powder Bed Fusion AM: L-PBF or EB-PBF
  - ~75 lb. (34kg) max.
- Advanced Cladding Processes:
  - e.g., diode laser cladding, hot wire laser welding, friction stir additive, cold spray & laser assisted cold spray, PM-HIP
  - Further development/qualification needed
- Electron Beam Welding: EBW
  - For large components (RPVs, SGs, pressurizers, fusion components, etc.)
- Other AMTs of interest not included with the roadmap:
  - Advanced welding technologies, machining techniques, surfacing technologies

# Three AMT Roadmaps

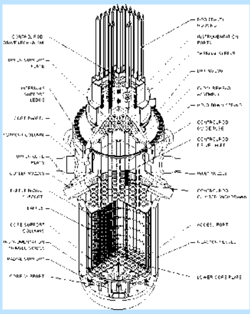
**Primary Pressure Boundary (Class 1) Components**



**Reactor Internals**


Courtesy of Westinghouse Electric Company LLC

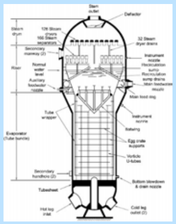

Photo credit: Fred List – ORNL, US DOE



**Other components** (Obsolete parts, Classes 2 & 3, etc.)


Courtesy of Siemens Power & Gas

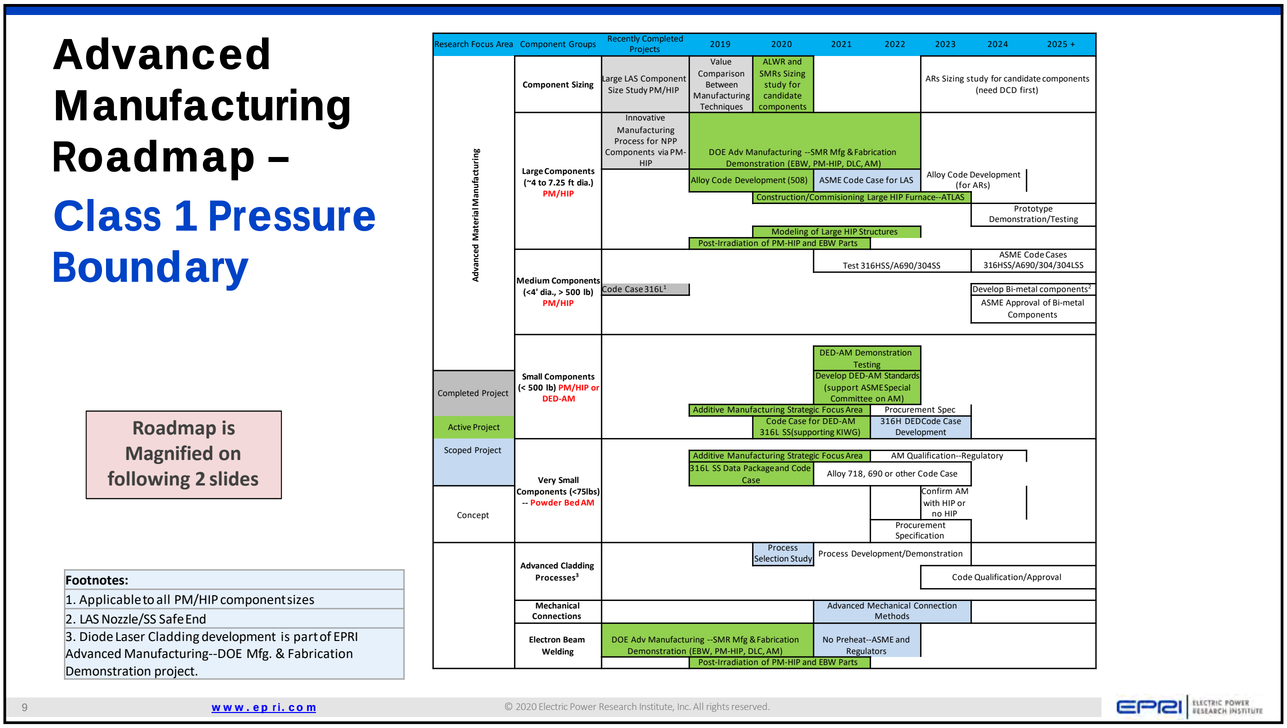

Courtesy of Westinghouse Electric Company LLC


Courtesy of US NRC

# 1. Primary Pressure Boundary (Class 1) Roadmap


16” BWR Feedwater Inlet Nozzle (LAS)

- Roadmap includes an initial sizing study to identify candidate components
  - Many large LWR Class 1 components exceed limitations of certain AMTs.
- Developments identified are specific to: size groups/processes/materials
  - **Larger Class 1 components** can be manufacture **using PM/HIP**
    - Demonstration pieces of LWR components already produced
    - 316L already accepted by ASME, but other alloys require qualification testing and ASME approval
  - **Smaller Class 1 components** may be produced **by DED-AM or Powder Bed-AM**
    - Process development, qualification testing, ASME approval shown
    - Few Class 1 components candidates for Powder Bed AM (size limitation)



# Advanced Manufacturing Roadmap – Class 1 Pressure Boundary

Roadmap is Magnified on following 2 slides

| Research Focus Area | Component Groups | Recently Completed Projects | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 + |
|---|---|---|---|---|---|---|---|---|---|
| Advanced Material Manufacturing | **Component Sizing** | Large LAS Component Size Study PM/HIP | Value Comparison Between Manufacturing Techniques | ALWR and SMRs Sizing study for candidate components | | | ARs Sizing study for candidate components (need DCD first) | | |
| | **Large Components (~4 to 7.25 ft dia.) PM/HIP** | Innovative Manufacturing Process for NPP Components via PM-HIP | DOE Adv Manufacturing --SMR Mfg & Fabrication Demonstration (EBW, PM-HIP, DLC, AM) | | | | | | |
| | | | Alloy Code Development (508) | | ASME Code Case for LAS | | Alloy Code Development (for ARs) | | |
| | | | | Construction/Commisioning Large HIP Furnace--ATLAS | | | | | |
| | | | | | | | | Prototype Demonstration/Testing | |
| | | | | Modeling of Large HIP Structures | | | | | |
| | | | Post-Irradiation of PM-HIP and EBW Parts | | | | | | |
| | **Medium Components (<4' dia., > 500 lb) PM/HIP** | | | | Test 316HSS/A690/304SS | | | ASME Code Cases 316HSS/A690/304/304LSS | |
| | | Code Case 316L[1] | | | | | | Develop Bi-metal components[2] | |
| | | | | | | | | ASME Approval of Bi-metal Components | |
| | **Small Components (< 500 lb) PM/HIP or DED-AM** | | | | DED-AM Demonstration Testing | | | | |
| | | | | | Develop DED-AM Standards (support ASME Special Committee on AM) | | | | |
| | | | Additive Manufacturing Strategic Focus Area | | | Procurement Spec | | | |
| | | | | Code Case for DED-AM 316L SS(supporting KIWG) | | 316H DEDCode Case Development | | | |
| | **Very Small Components (<75lbs) -- Powder Bed AM** | | Additive Manufacturing Strategic Focus Area | | | AM Qualification--Regulatory | | | |
| | | | 316L SS Data Package and Code Case | | Alloy 718, 690 or other Code Case | | | | |
| | | | | | | | Confirm AM with HIP or no HIP | | |
| | | | | | | Procurement Specification | | | |
| | **Advanced Cladding Processes[3]** | | | Process Selection Study | Process Development/Demonstration | | | | |
| | | | | | | | Code Qualification/Approval | | |
| | **Mechanical Connections** | | | | Advanced Mechanical Connection Methods | | | | |
| | **Electron Beam Welding** | DOE Adv Manufacturing --SMR Mfg & Fabrication Demonstration (EBW, PM-HIP, DLC, AM) | | | No Preheat--ASME and Regulators | | | | |
| | | | Post-Irradiation of PM-HIP and EBW Parts | | | | | | |

Completed Project
Active Project
Scoped Project
Concept

**Footnotes:**
1. Applicable to all PM/HIP component sizes
2. LAS Nozzle/SS Safe End
3. Diode Laser Cladding development is part of EPRI Advanced Manufacturing--DOE Mfg. & Fabrication Demonstration project.

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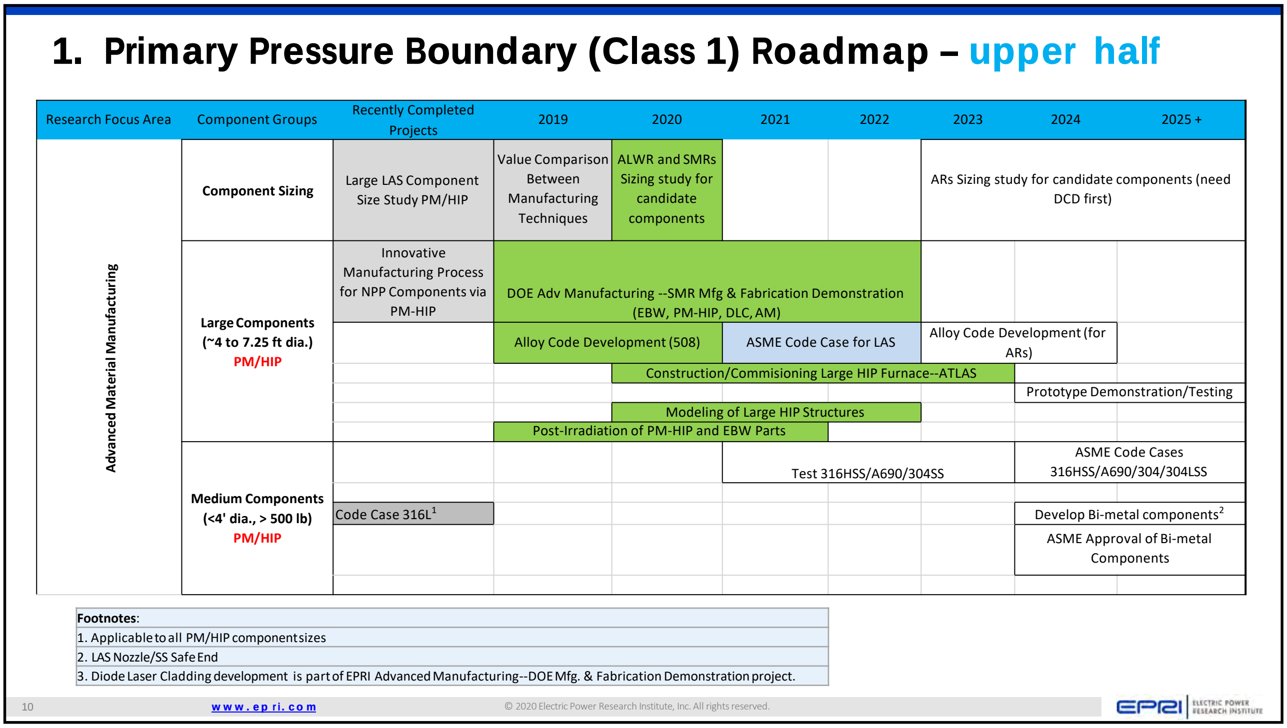
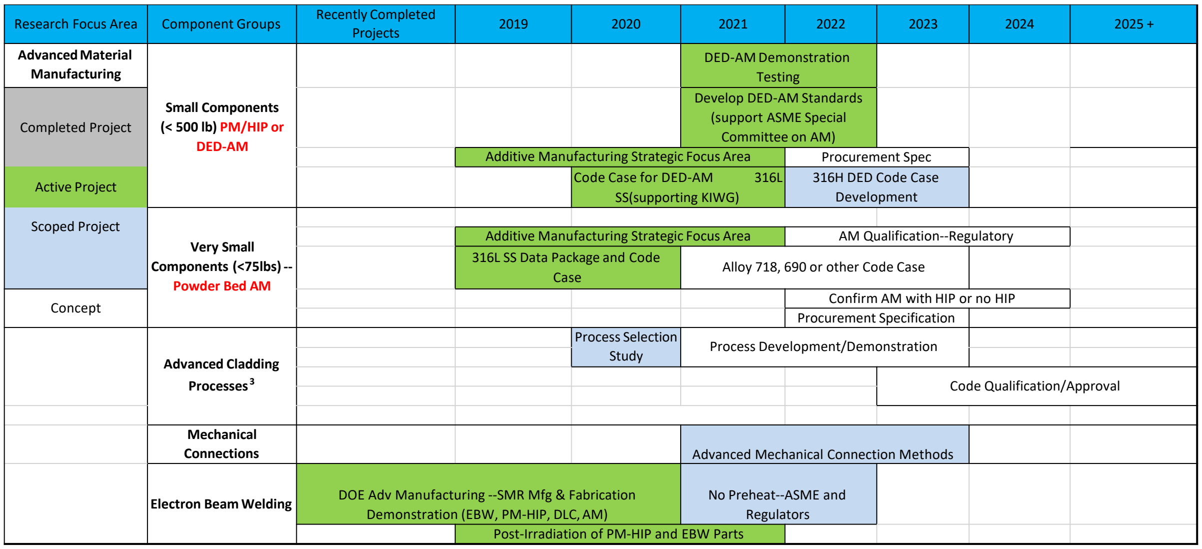


# 1. Primary Pressure Boundary (Class 1) Roadmap – upper half

| Research Focus Area | Component Groups | Recently Completed Projects | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 + |
|---|---|---|---|---|---|---|---|---|---|
| Advanced Material Manufacturing | **Component Sizing** | Large LAS Component Size Study PM/HIP | Value Comparison Between Manufacturing Techniques | ALWR and SMRs Sizing study for candidate components | | | ARs Sizing study for candidate components (need DCD first) | | |
| | **Large Components (~4 to 7.25 ft dia.) PM/HIP** | Innovative Manufacturing Process for NPP Components via PM-HIP | DOE Adv Manufacturing --SMR Mfg & Fabrication Demonstration (EBW, PM-HIP, DLC, AM) | | | | | | |
| | | | Alloy Code Development (508) | | ASME Code Case for LAS | | Alloy Code Development (for ARs) | | |
| | | | | Construction/Commisioning Large HIP Furnace--ATLAS | | | | | |
| | | | | | | | | Prototype Demonstration/Testing | |
| | | | | Modeling of Large HIP Structures | | | | | |
| | | | Post-Irradiation of PM-HIP and EBW Parts | | | | | | |
| | **Medium Components (<4' dia., > 500 lb) PM/HIP** | | | | Test 316HSS/A690/304SS | | | ASME Code Cases 316HSS/A690/304/304LSS | |
| | | Code Case 316L[1] | | | | | | Develop Bi-metal components[2] | |
| | | | | | | | | ASME Approval of Bi-metal Components | |

**Footnotes:**
1. Applicable to all PM/HIP component sizes
2. LAS Nozzle/SS Safe End
3. Diode Laser Cladding development is part of EPRI Advanced Manufacturing--DOE Mfg. & Fabrication Demonstration project.

# 1. Primary Pressure Boundary (Class 1) Roadmap – lower half



| Research Focus Area | Component Groups | Recently Completed Projects | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 + |
|---|---|---|---|---|---|---|---|---|---|
| **Advanced Material Manufacturing** | **Small Components (< 500 lb) PM/HIP or DED-AM** | | | | DED-AM Demonstration Testing | | | | |
| Completed Project | | | | | Develop DED-AM Standards (support ASME Special Committee on AM) | | | | |
| | | | Additive Manufacturing Strategic Focus Area | | | Procurement Spec | | | |
| Active Project | | | | Code Case for DED-AM 316L SS(supporting KIWG) | | 316H DED Code Case Development | | | |
| Scoped Project | **Very Small Components (<75lbs) -- Powder Bed AM** | | Additive Manufacturing Strategic Focus Area | | | AM Qualification--Regulatory | | | |
| | | | 316L SS Data Package and Code Case | | Alloy 718, 690 or other Code Case | | | | |
| Concept | | | | | | Confirm AM with HIP or no HIP | | | |
| | | | | | | Procurement Specification | | | |
| | **Advanced Cladding Processes**[3] | | | Process Selection Study | Process Development/Demonstration | | | | |
| | | | | | | | Code Qualification/Approval | | |
| | **Mechanical Connections** | | | | Advanced Mechanical Connection Methods | | | | |
| | **Electron Beam Welding** | DOE Adv Manufacturing --SMR Mfg & Fabrication Demonstration (EBW, PM-HIP, DLC, AM) | | | No Preheat--ASME and Regulators | | | | |
| | | | Post-Irradiation of PM-HIP and EBW Parts | | | | | | |

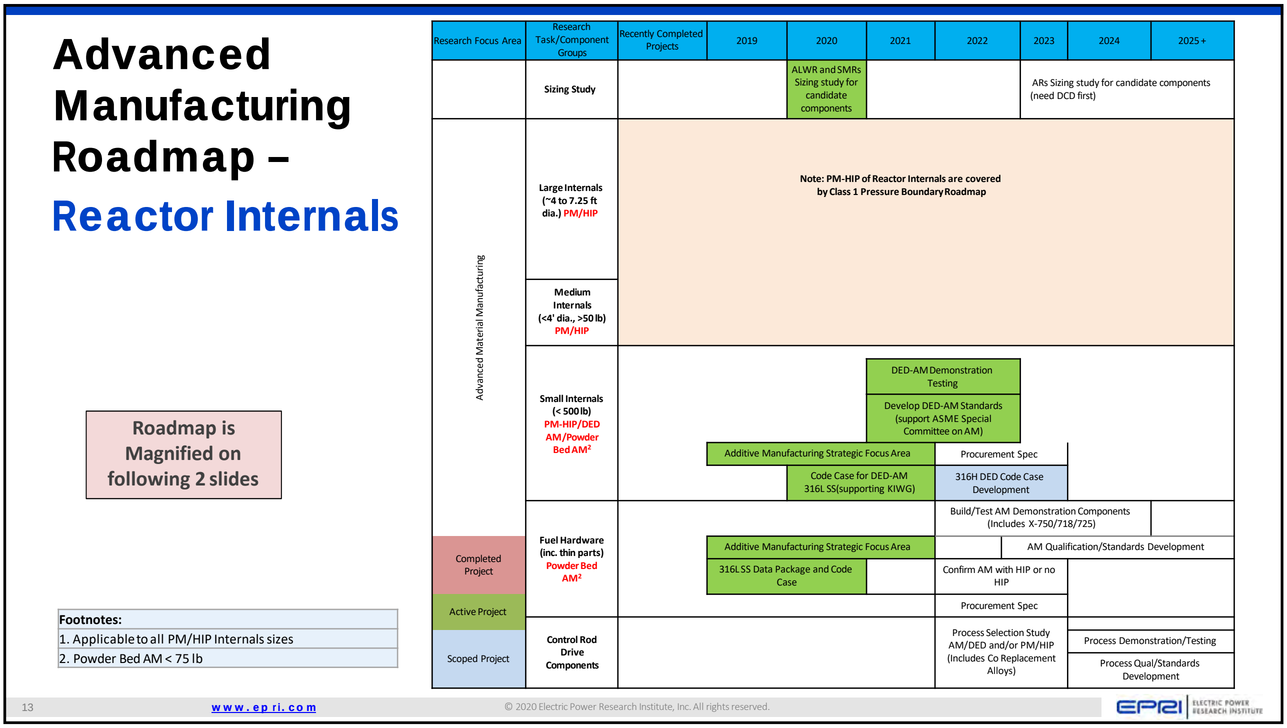
**Footnotes**:

2. LAS Nozzle/SS Safe End

3. Diode Laser Cladding development is part of EPRI Advanced Manufacturing--DOE Mfg. & Fabrication Demonstration project.

# 2. Reactor Internals Roadmap

- Internals Roadmap generally follows similar pattern set for Class 1
  - Up front sizing study
- Some significant differences:
  - No low alloy steel components
  - Fuel Hardware and Control Rod Drive components (unique shapes and materials)
  - High strength Ni-base alloys and cobalt-free alloys
- **Interaction with ASME is limited** for Internals Roadmap
  - Only core support structures require ASME approval
  - Interaction with NRC may be required for some Safety Related Internals
  - Other internals: free to use ASTM, AMS, etc. or no standard at all (a potential case for fuel hardware or control rod drive components)



# Advanced Manufacturing Roadmap – Reactor Internals

| Research Focus Area | Research Task/Component Groups | Recently Completed Projects | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 + |
|---|---|---|---|---|---|---|---|---|---|
| | **Sizing Study** | | | ALWR and SMRs Sizing study for candidate components | | | ARs Sizing study for candidate components (need DCD first) | | |
| Advanced Material Manufacturing | **Large Internals (~4 to 7.25 ft dia.) PM/HIP** | **Note: PM-HIP of Reactor Internals are covered by Class 1 Pressure Boundary Roadmap** | | | | | | | |
| | **Medium Internals (<4' dia., >50 lb) PM/HIP** | | | | | | | | |
| | **Small Internals (< 500 lb) PM-HIP/DED AM/Powder Bed AM²** | | | | DED-AM Demonstration Testing<br>Develop DED-AM Standards (support ASME Special Committee on AM) | | | | |
| | | | Additive Manufacturing Strategic Focus Area | | | Procurement Spec | | | |
| | | | | Code Case for DED-AM 316L SS(supporting KIWG) | | 316H DED Code Case Development | | | |
| Completed Project | **Fuel Hardware (inc. thin parts) Powder Bed AM²** | | | | | Build/Test AM Demonstration Components (Includes X-750/718/725) | | | |
| | | | Additive Manufacturing Strategic Focus Area | | | | AM Qualification/Standards Development | | |
| Active Project | | | 316L SS Data Package and Code Case | | | Confirm AM with HIP or no HIP | | | |
| | | | | | | Procurement Spec | | | |
| Scoped Project | **Control Rod Drive Components** | | | | | Process Selection Study AM/DED and/or PM/HIP (Includes Co Replacement Alloys) | | Process Demonstration/Testing<br>Process Qual/Standards Development | |

Roadmap is Magnified on following 2 slides

| **Footnotes:** |
|---|
| 1. Applicable to all PM/HIP Internals sizes |
| 2. Powder Bed AM < 75 lb |

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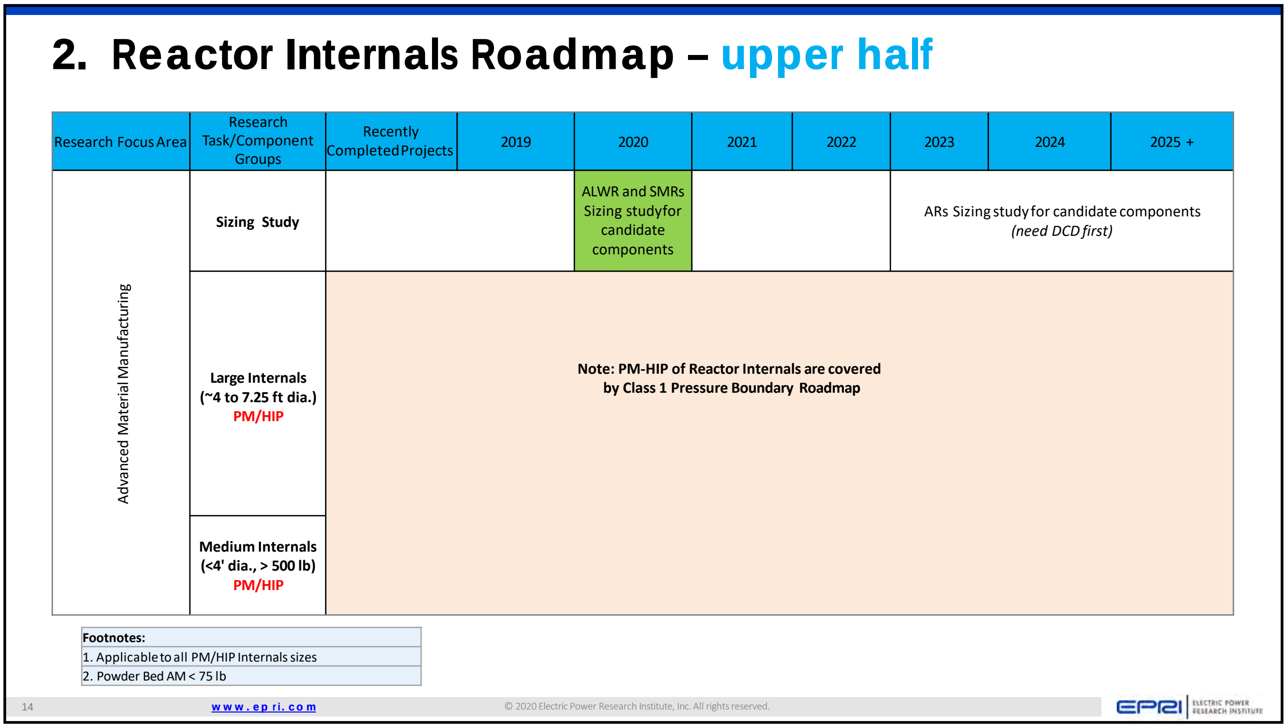
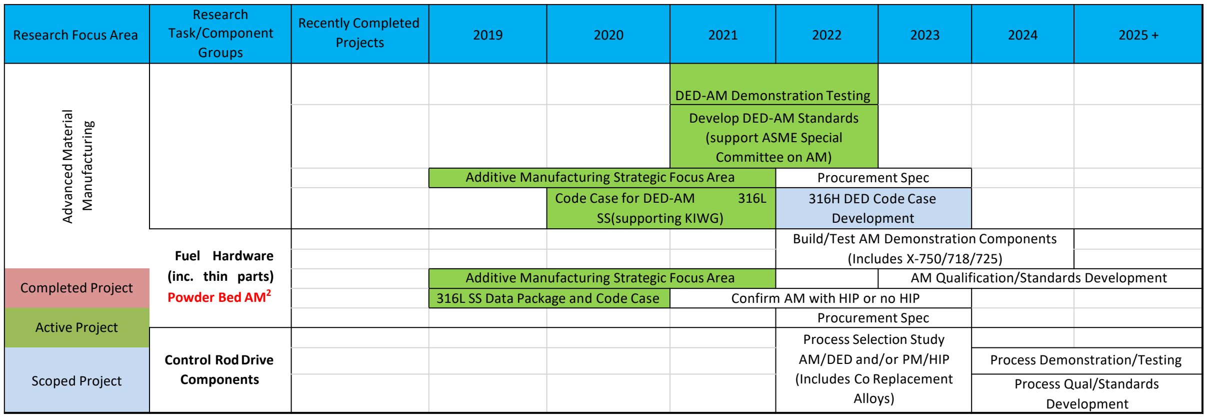


# 2. Reactor Internals Roadmap – upper half

| Research Focus Area | Research Task/Component Groups | Recently Completed Projects | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 + |
|---|---|---|---|---|---|---|---|---|---|
| Advanced Material Manufacturing | **Sizing Study** | | | ALWR and SMRs Sizing study for candidate components | | | ARs Sizing study for candidate components *(need DCD first)* | | |
| | **Large Internals (~4 to 7.25 ft dia.) PM/HIP** | **Note: PM-HIP of Reactor Internals are covered by Class 1 Pressure Boundary Roadmap** | | | | | | | |
| | **Medium Internals (<4' dia., > 500 lb) PM/HIP** | | | | | | | | |

| **Footnotes:** |
|---|
| 1. Applicable to all PM/HIP Internals sizes |
| 2. Powder Bed AM < 75 lb |

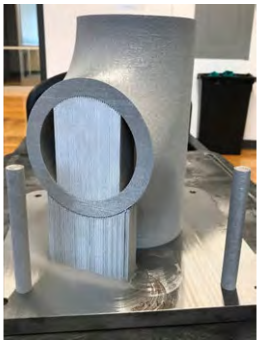
## 2. Reactor Internals Roadmap – lower half



| Research Focus Area | Research Task/Component Groups | Recently Completed Projects | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 + |
|---|---|---|---|---|---|---|---|---|---|
| Advanced Material Manufacturing | | | | | DED-AM Demonstration Testing | | | | |
| | | | | | Develop DED-AM Standards (support ASME Special Committee on AM) | | | | |
| | | | Additive Manufacturing Strategic Focus Area | | | Procurement Spec | | | |
| | | | | Code Case for DED-AM 316L SS(supporting KIWG) | | 316H DED Code Case Development | | | |
| | **Fuel Hardware (inc. thin parts)**<br>**Powder Bed AM[2]** | | | | | Build/Test AM Demonstration Components (Includes X-750/718/725) | | | |
| Completed Project | | | Additive Manufacturing Strategic Focus Area | | | | AM Qualification/Standards Development | | |
| | | | 316L SS Data Package and Code Case | | Confirm AM with HIP or no HIP | | | | |
| Active Project | | | | | | Procurement Spec | | | |
| Scoped Project | **Control Rod Drive Components** | | | | | Process Selection Study AM/DED and/or PM/HIP (Includes Co Replacement Alloys) | | | |
| | | | | | | | | Process Demonstration/Testing | |
| | | | | | | | | Process Qual/Standards Development | |

**Footnotes:**
1. Applicable to all PM/HIP Internals sizes
2. Powder Bed AM < 75 lb

## 3. All Other Components Roadmap
## --Obsolete Parts, Class 2 & 3, etc.



- Primary Pressure Boundary and Reactor Internals Roadmaps fully address needs of "Other Components" category
  - e.g., ASME acceptance of a process/material for Class 1 immediately applicable to Class 2 & 3
  - **Other "Components Roadmap" may not be required**
- Sizing study to identify potential AMM candidate components still required
  - Complicated by the broad range of components in this category
    - Potentially different materials of interest
  - Many likely Class 2 & 3 components and steam generator shell/internals
  - Outcome of sizing study may dictate development of separate Roadmap

# Examples of Candidate AMM Components

## Primary Pressure Boundary

| Reactor Type | Component | AMM Process | Material |
|---|---|---|---|
| AP1000 | Vessel Shell (Six ring segments) | PM/HIP | LAS |
| AP1000 | Pressurizer Shell (Four ring segments) | PM/HIP | LAS |
| US EPR | Pressurizer Shell (Four ring segments) | PM/HIP | LAS |
| US APWR | Pressurizer Shell (Four ring segments) | PM/HIP | LAS |
| BWR | CRD Stub Tubes | PM/HIP | CC N-580 |
| PWR | CRDM Housings | PM/HIP | A690 |
| ABWR | Reactor Internal Pump Case | PM/HIP | LAS |
| AP1000 | Recirculation Pump Case (top section) | PM/HIP | SS |
| BWR/PWR | Medium Size Valve Bodies and Bonnets | PM/HIP | SS |
| BWR/PWR | Reactor Vessel Nozzles | PM/HIP | LAS |
| BWR/PWR | Small Valves & Fittings | PM/HIP or DED | SS |
| BWR/PWR | Very Small Valves and Fittings | Powder Bed AM | SS |

## Reactor Internals

| Reactor Type | Component | AMM Process | Material |
|---|---|---|---|
| AP1000 | Core Barrel (Six ring segments) | PM/HIP | SS |
| Advanced PWRs | Core Barrel Nozzles | PM/HIP | SS |
| AP1000 | Upper Guide Tube Components | PM/HIP | SS |
| AP1000 | Control Rod Guide Cards | Powder Bed AM | SS |
| AP1000 | Core Barrel Support Lugs | PM/HIP | A690 |
| BWR/PWR | Dome Cooling Spray Nozzles | PM/HIP or DED | SS |
| EPR | Heavy Reflector Positioning Keys | PM/HIP | SS |
| ABWR/ESBWR | Control Rod Guide Tube Base Plate | PM/HIP | XM-19 |
| ABWR/ESBWR | Steam Separator Swirlers | PM/HIP | SS |
| ABWR | Shroud Head Bolt Tees | PM/HIP | CC N-580 |
| BWR | Fuel Spacers | Powder Bed AM | X-750 |
| BWR | Fuel Tie Plates | Powder Bed AM | SS |
| BWR/PWR | Fuel Debris Filters | Powder Bed AM | SS |
| BWR/PWR | Control Rod Drive Components | PM/HIP, DED, or Powder Bed AM | SS or Co-Free Alloys |

## Other Components

| Reactor Type | Component | AMM Process | Material |
|---|---|---|---|
| AP1000 | Steam Generator Upper Shell (Six ring segments) | PM/HIP | LAS |
| AP1000 | Steam Generator Lower Shell (Six ring segments) | PM/HIP | LAS |
| US EPR | Steam Generator Lower Shell (Six ring segments) | PM/HIP | LAS |
| US APWR | Steam Generator Lower Shell (Six ring segments) | PM/HIP | LAS |
| Advanced PWRs | Steam Generator Manways/Nozzles/ Handholes | PM/HIP | LAS |
| All LWRs | Class 2/3 Valve Bodies/Bonnets | PM/HIP or DED | SS |
| All LWRs | Class 2/3 Pipe Fittings | PM/HIP or DED | SS |
| Advanced PWRs | Steam Generator Internals | PM/HIP or DED | SS/A690 |
| Operating BWRs | Jet Pump Beams | PM/HIP | X-750/718 |
| All LWRs | Class 2/3 Small Valves and Fittings | Powder Bed AM | SS |
| BWR | Internals Repair Hardware | PM/HIP, DED, or Powder Bed AM | SS/XM-19/X-750 |
| BWR/PWR | Very Small Valves and Fittings | Powder Bed AM | SS |

# AMM Roadmap – Summary

- Two Roadmaps will likely cover >95% of components
  - Primary pressure boundary (Class 1) Roadmap
  - Reactor Internals Roadmap
- Roadmaps are focused on LWRs, ALWRs and SMRs
  - Easily expanded to ARs in future
- Roadmap development generated based on component size/materials
- Central feature of each is ASME BPVC standards development & regulatory approval

# Additive Manufacturing Roadmap for the Nuclear Industry

## AM Roadmap Contents

- Discuss state-of-the-art applications of additive manufacturing technologies for metallic materials.
- Discuss industry specifications and standards for AM
  - Current documents
  - Major documents in the pipeline
  - Availability and applicability to the nuclear power industry
- Identify key concerns for AM use in nuclear power applications
- Assessment of gaps in qualifying additive manufacturing techniques for AM components to be used in the nuclear power industry
- Develop a roadmap for additive manufacturing
  - highlights the identified gaps as well as steps to be taken to address those gaps

## Motivations for AM Adoption in Nuclear Industry

- Complex geometries not previously practical
  - Example: novel fuel assembly debris filters
- Reduce cost to build complex geometries
  - Examples: valve bodies, Transformational Challenge Reactor
- Simplify inventory management
  - Just-in-time manufacture of low-volume spares from digital library

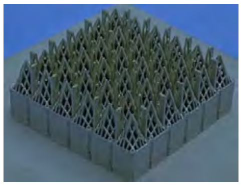


*Photo Credit: Westinghouse Electric Company, LLC*

*Photo Credit: Fred List/ORNL, U.S. DOE, Framatome*

*Photo Credit: ORNL*

## Motivations for AM Adoption in Nuclear Industry (cont'd)

- Increase reliability and decrease part count with integrated assemblies
  - Example: thimble plug assembly
- Simplify supply chain
  - Reduce number of active qualified vendors
- Manufacture in-kind replacements for obsolete parts
  - Example: fire protection pump impellers
- Other motivations
  - Reduce environmental footprint, functionally graded materials, infill lattices

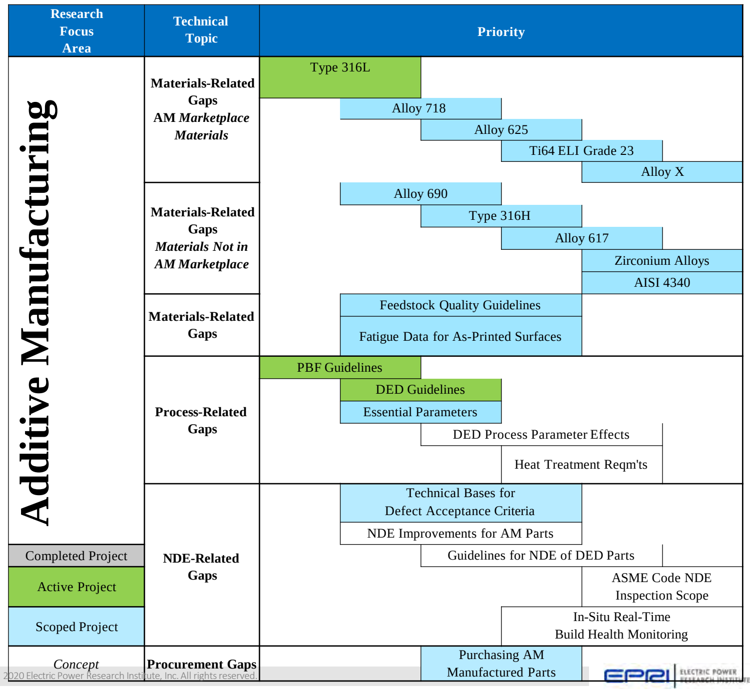
*Photo Credit: Westinghouse Electric Company, LLC*

*Photo Credit: NEI, Siemens, Krško*

# AM Roadmap

**EPRI Report: 3002018276**

- Material Development and ASME Code Case Priorities
  - AM Marketplace Materials
  - Non-AM Marketplace Materials
  - Feedstock Quality Guidelines
  - Fatigue Data
  - SCC and Irradiation Data
- Process Related Gaps
  - ASME PTB Guideline for DED
  - Industry consensus regarding minimum essential parameters for each AM process
  - Heat Treatment Effects (HIP and SA)
- Non-Destructive Examination Related Gaps
  - Technical Basis for Defect Acceptance Criteria
  - NDE Improvements for AM Parts
  - Guidelines for NDE of DED Parts
  - In-situ Real-Time Build Health Monitoring
- Recommended Practices for Purchases AM Parts



| Research Focus Area | Technical Topic | Priority |
|---|---|---|
| **Additive Manufacturing** | **Materials-Related Gaps** ***AM Marketplace Materials*** | 🟩 Type 316L<br>🟦 Alloy 718<br>🟦 Alloy 625<br>🟦 Ti64 ELI Grade 23<br>🟦 Alloy X |
| | **Materials-Related Gaps** ***Materials Not in AM Marketplace*** | 🟦 Alloy 690<br>🟦 Type 316H<br>🟦 Alloy 617<br>🟦 Zirconium Alloys<br>🟦 AISI 4340 |
| | **Materials-Related Gaps** | 🟦 Feedstock Quality Guidelines<br>🟦 Fatigue Data for As-Printed Surfaces |
| | **Process-Related Gaps** | 🟩 PBF Guidelines<br>🟩 DED Guidelines<br>🟦 Essential Parameters<br>⬜ DED Process Parameter Effects<br>⬜ Heat Treatment Reqm'ts |
| | **NDE-Related Gaps** | 🟦 Technical Bases for Defect Acceptance Criteria<br>⬜ NDE Improvements for AM Parts<br>⬜ Guidelines for NDE of DED Parts<br>⬜ ASME Code NDE Inspection Scope<br>⬜ In-Situ Real-Time Build Health Monitoring |
| | **Procurement Gaps** | 🟦 Purchasing AM Manufactured Parts |

▨ Completed Project

🟩 Active Project

🟦 Scoped Project

⬜ *Concept*

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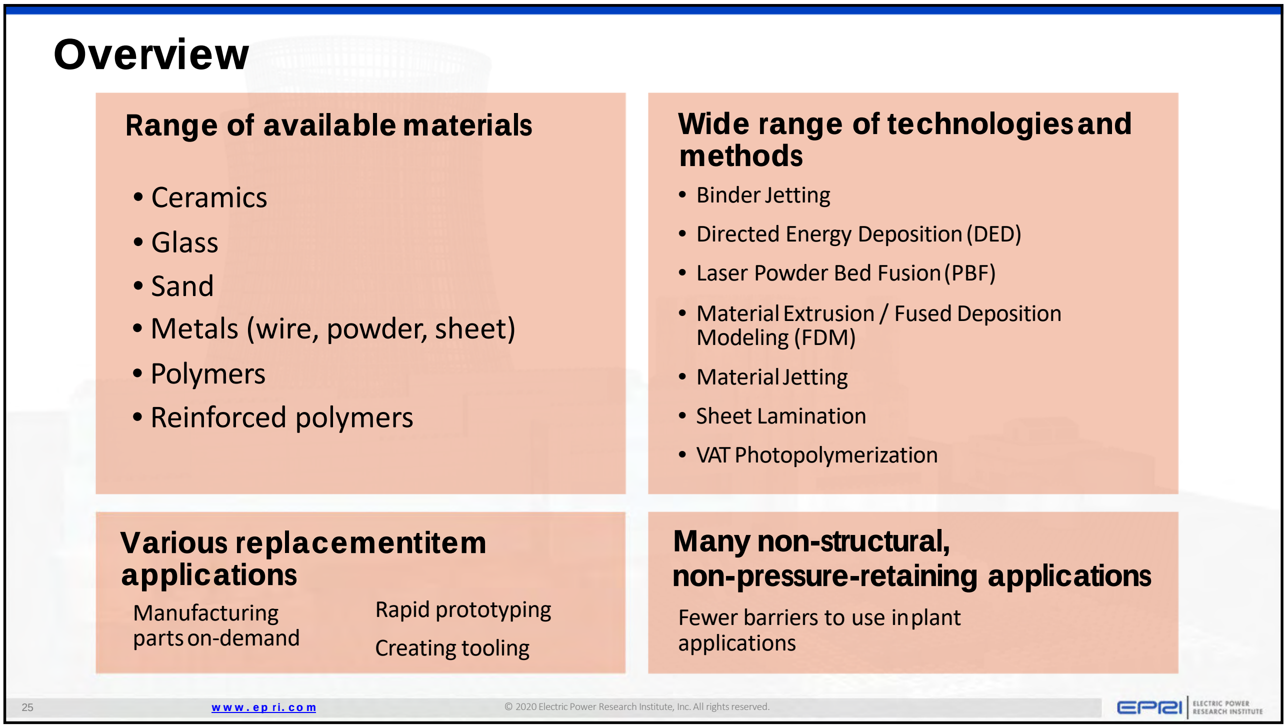
# Additive Manufacturing

## *To Support Spare and Replacement Items*

*Marc H. Tannenbaum*
*Technical Executive*

24



## Overview

### Range of available materials

- Ceramics
- Glass
- Sand
- Metals (wire, powder, sheet)
- Polymers
- Reinforced polymers

### Wide range of technologies and methods

- Binder Jetting
- Directed Energy Deposition (DED)
- Laser Powder Bed Fusion (PBF)
- Material Extrusion / Fused Deposition Modeling (FDM)
- Material Jetting
- Sheet Lamination
- VAT Photopolymerization

### Various replacement item applications

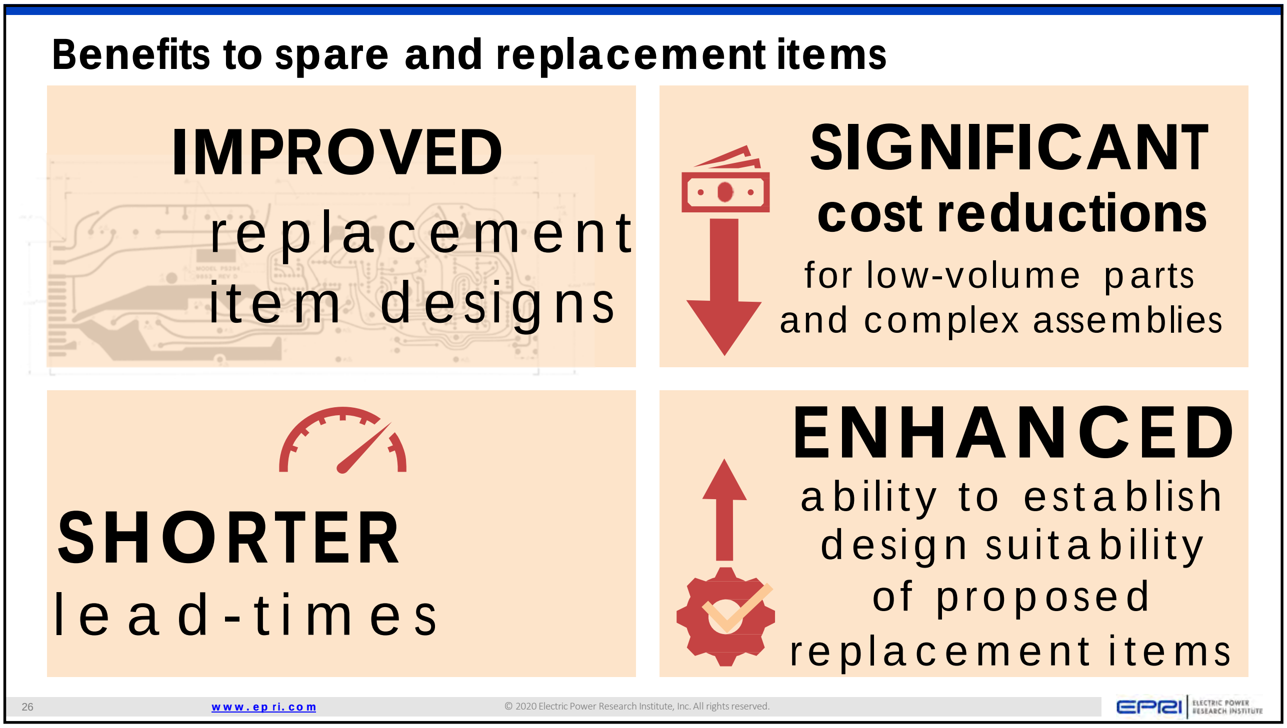
Manufacturing parts on-demand

Rapid prototyping

Creating tooling

### Many non-structural, non-pressure-retaining applications

Fewer barriers to use in plant applications



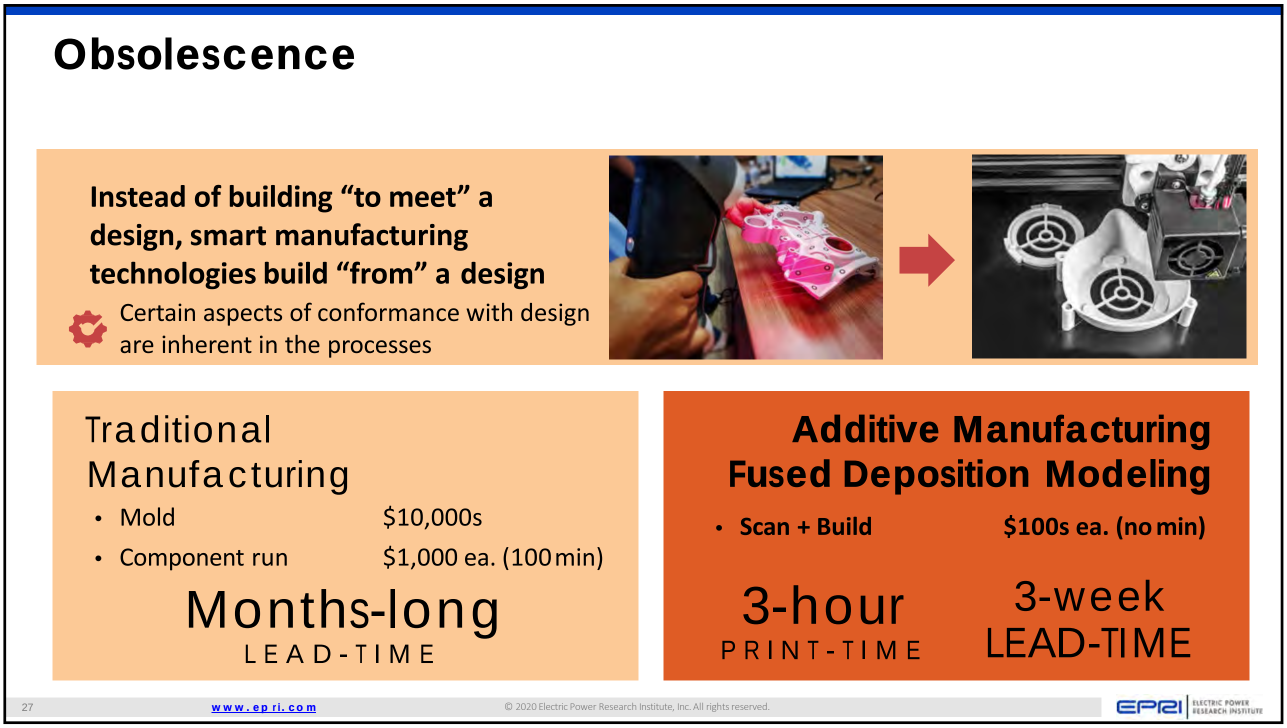
## Benefits to spare and replacement items

**IMPROVED** replacement item designs

**SIGNIFICANT cost reductions** for low-volume parts and complex assemblies

**SHORTER** lead-times

**ENHANCED** ability to establish design suitability of proposed replacement items



## Obsolescence

**Instead of building "to meet" a design, smart manufacturing technologies build "from" a design**

Certain aspects of conformance with design are inherent in the processes

Traditional Manufacturing

- Mold $10,000s
- Component run $1,000 ea. (100 min)

Months-long

LEAD-TIME

**Additive Manufacturing Fused Deposition Modeling**

- **Scan + Build** **$100s ea. (no min)**

3-hour

PRINT-TIME

3-week

LEAD-TIME

## Advanced Manufacturing Research Focus Area

# EPRI Advanced Manufacturing Research Focus Area

GOAL & VALUE

Identify, develop, qualify and implement more economical manufacturing technologies that enable:

**Higher Quality Components | Reduced Lead Times | Alternative Supply Chains | Cost Competitiveness**

## Additive Manufacturing

**316L LPBF Code Case & Data Package**
(submitted to ASME August 2020)

**Additive Manuf. Roadmap for Nuclear Applications** *(Q4 2020)*

**DED-AM Component Demonstration**

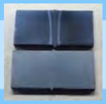
## Advanced Manufacturing Demonstration Project

**PM-HIP**

**EB Welding**

**DLC**

**Heat Treat**



## Advanced Welding Techniques

**Adaptive Feedback Welding**

ANT +
WRTC

**Modular In-Chamber EBW**

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# What's Next for the Nuclear Industry?

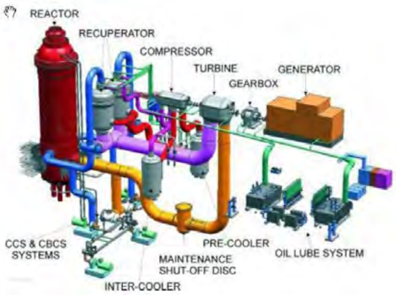
## SMRs and ARs Factory Manufacture/Fabrication

- Modular Construction
  - Have to get it right this time…
- Smaller unit size is ideal for factory production
- Economy of scale
- Must bring to bear new manufacturing and fabrication technologies to be cost effective.

*Reference: Bailey, J., "What's Nu and What's Next," April 2017.*

## Advanced Reactor Manufacturing/Fabrication

- **Micro-Reactors**
  - Heat pipe reactors will use AMTs to produce core
- **GEN IV Reactors**
  - Rely heavily on nickel-based alloys and complex cooling geometries.
  - HIP provides economic avenue to produce nickel-based components
  - Eliminates welds and minimizes machining due to near net-shape
  - Cladding of complex alloys (Moly or other)
  - Joining through EB Welding

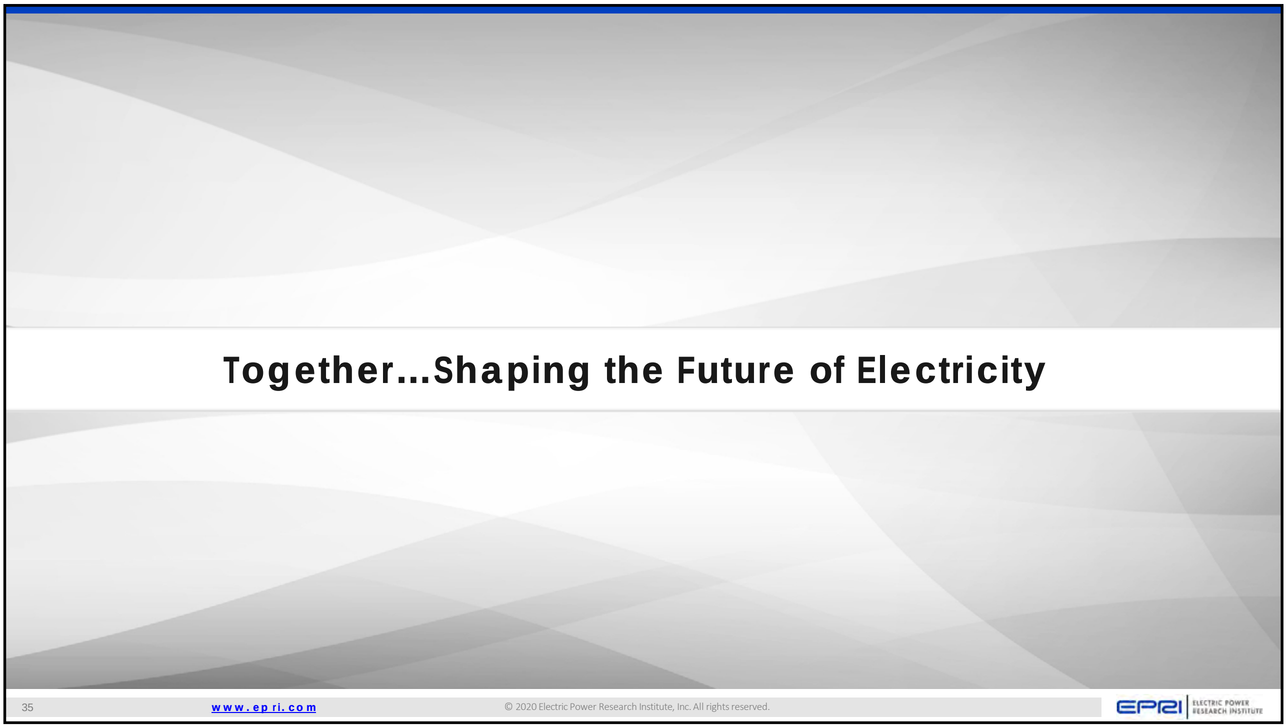


## What Is Required To Bring These Technologies Forward For SMR, Micro-Reactor, or AR Applications?

- Code Data Packages (mechanical, microstructural, welding data)
- ASME or RCC-M Code acceptance
- Regulatory Acceptance
- Corrosion Testing
- Irradiation Studies
- Clearly separate pressure retaining applications from structural applications

## Summary – EPRI Vision of AMT Use in Industry

- Advanced Manufacturing Technologies Roadmap
  - ALWRs → Easily extends to advanced plants (SMRs, non-LWR ARs)
  - Two Roadmaps will likely cover >95% of components
  - Development generated based on component size/materials
  - Central feature of each is ASME BPVC standards development & regulatory approval
- Additive Manufacturing Roadmap
  - Assesses key concerns/gaps for AM use in nuclear power applications
  - Develops a roadmap for AM to address the gaps identified
- Additive Manufacturing for Obsolete and Replacement Components
- EPRI R&D to Deploy AMTs
- What's Next



## Together…Shaping the Future of Electricity

www.epri.com

# Utility Perspective on Implementing on Advanced Manufacturing Technologies in LWRs

Lee Friant, PhD
Sr. Staff Engineer
Exelon Nuclear

Exelon Generation

## Utility View of New Technologies - Inertia

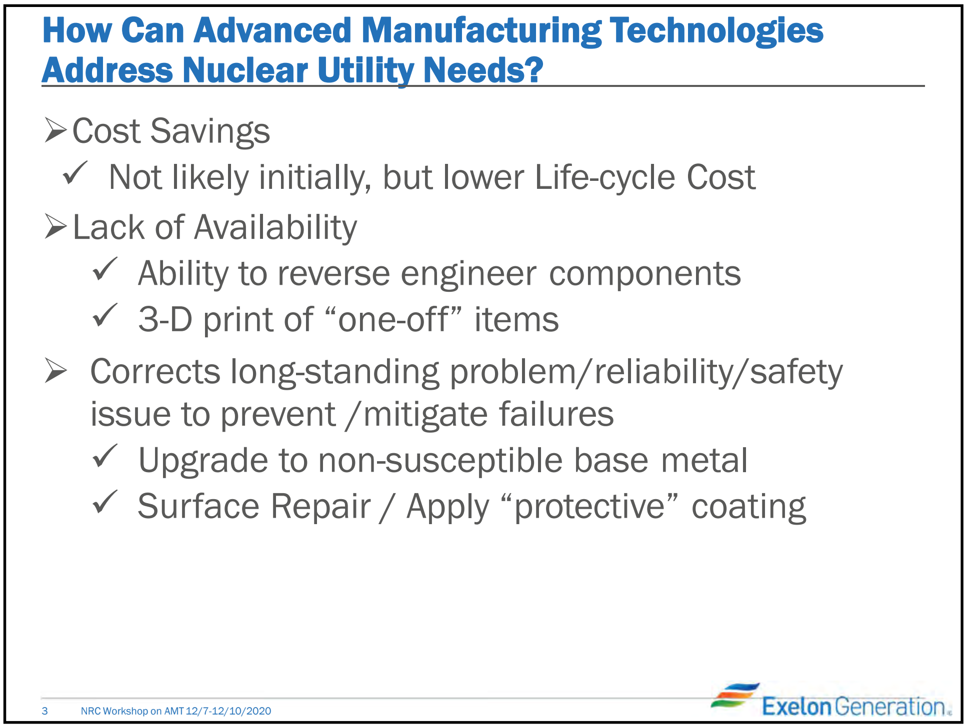
Governing Law:

Newton's first law states that every “object” (read “Nuclear Utility”) will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an *external force.*

Exelon Generation

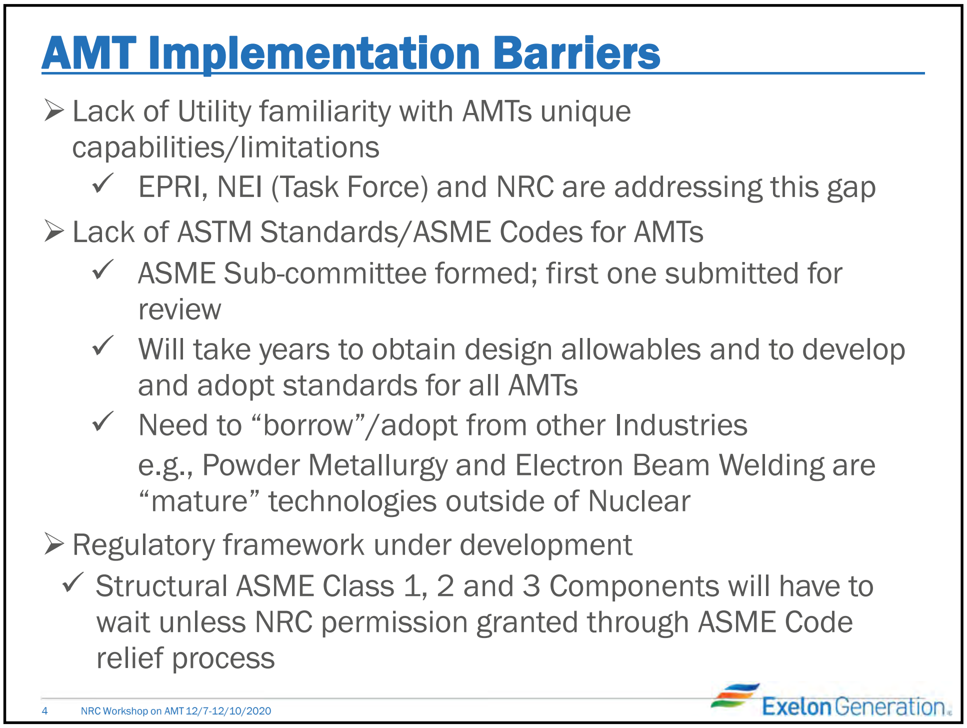
## External Forces Driving New Technology in Nuclear

- ➢ Cost Savings
  - ✓ Purchase Price
  - ✓ Maintenance
  - ✓ Radiological Dose
- ➢ Lack of Availability
  - ✓ Obsolescence/Supplier out of business
  - ✓ Too long lead time to deliver
  - ✓ Only off-shore suppliers (unknown quality)
- ➢ Corrects long-standing problem/reliability/safety issue with an existing component design
  - ✓ Material failures; e.g., cracking, erosion, corrosion, wear, etc.
  - ✓ Regulatory Compliance



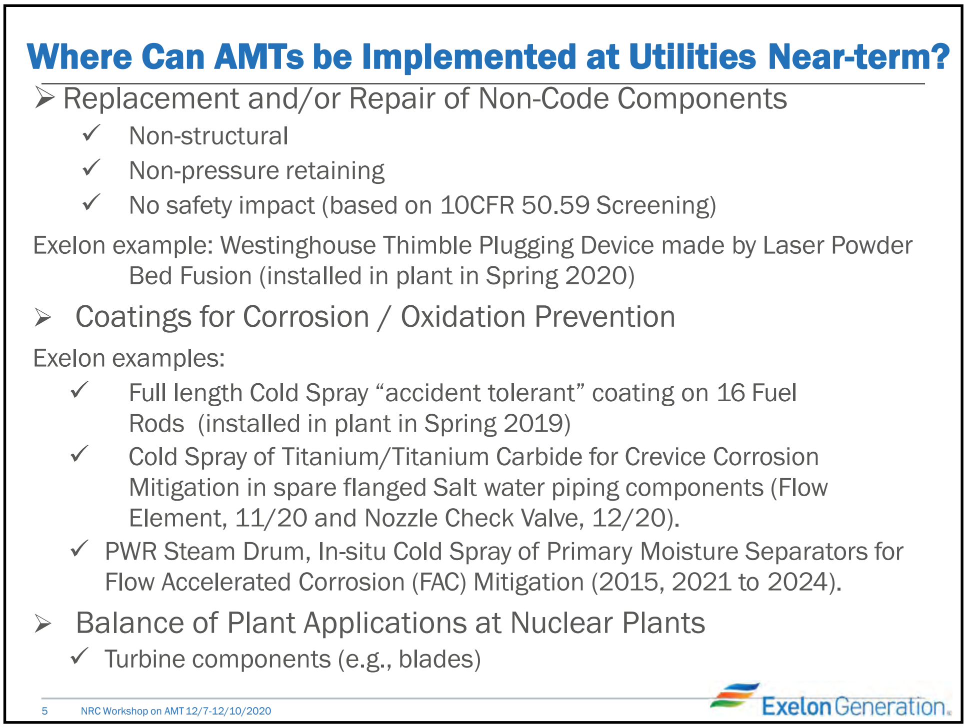
## How Can Advanced Manufacturing Technologies Address Nuclear Utility Needs?

- ➢ Cost Savings
  - ✓ Not likely initially, but lower Life-cycle Cost
- ➢ Lack of Availability
  - ✓ Ability to reverse engineer components
  - ✓ 3-D print of "one-off" items
- ➢ Corrects long-standing problem/reliability/safety issue to prevent /mitigate failures
  - ✓ Upgrade to non-susceptible base metal
  - ✓ Surface Repair / Apply "protective" coating



## AMT Implementation Barriers

- ➢ Lack of Utility familiarity with AMTs unique capabilities/limitations
  - ✓ EPRI, NEI (Task Force) and NRC are addressing this gap
- ➢ Lack of ASTM Standards/ASME Codes for AMTs
  - ✓ ASME Sub-committee formed; first one submitted for review
  - ✓ Will take years to obtain design allowables and to develop and adopt standards for all AMTs
  - ✓ Need to "borrow"/adopt from other Industries
    e.g., Powder Metallurgy and Electron Beam Welding are "mature" technologies outside of Nuclear
- ➢ Regulatory framework under development
  - ✓ Structural ASME Class 1, 2 and 3 Components will have to wait unless NRC permission granted through ASME Code relief process



## Where Can AMTs be Implemented at Utilities Near-term?

- ➢ Replacement and/or Repair of Non-Code Components
  - ✓ Non-structural
  - ✓ Non-pressure retaining
  - ✓ No safety impact (based on 10CFR 50.59 Screening)

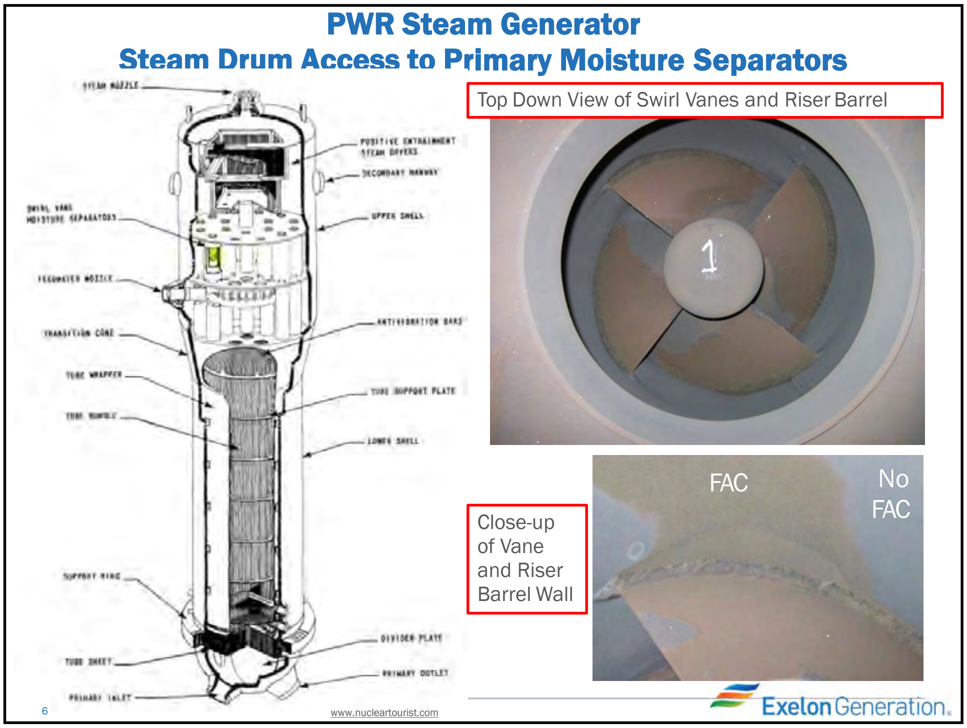
Exelon example: Westinghouse Thimble Plugging Device made by Laser Powder Bed Fusion (installed in plant in Spring 2020)

- ➢ Coatings for Corrosion / Oxidation Prevention

Exelon examples:

- ✓ Full length Cold Spray "accident tolerant" coating on 16 Fuel Rods (installed in plant in Spring 2019)
- ✓ Cold Spray of Titanium/Titanium Carbide for Crevice Corrosion Mitigation in spare flanged Salt water piping components (Flow Element, 11/20 and Nozzle Check Valve, 12/20).
- ✓ PWR Steam Drum, In-situ Cold Spray of Primary Moisture Separators for Flow Accelerated Corrosion (FAC) Mitigation (2015, 2021 to 2024).

- ➢ Balance of Plant Applications at Nuclear Plants
  - ✓ Turbine components (e.g., blades)

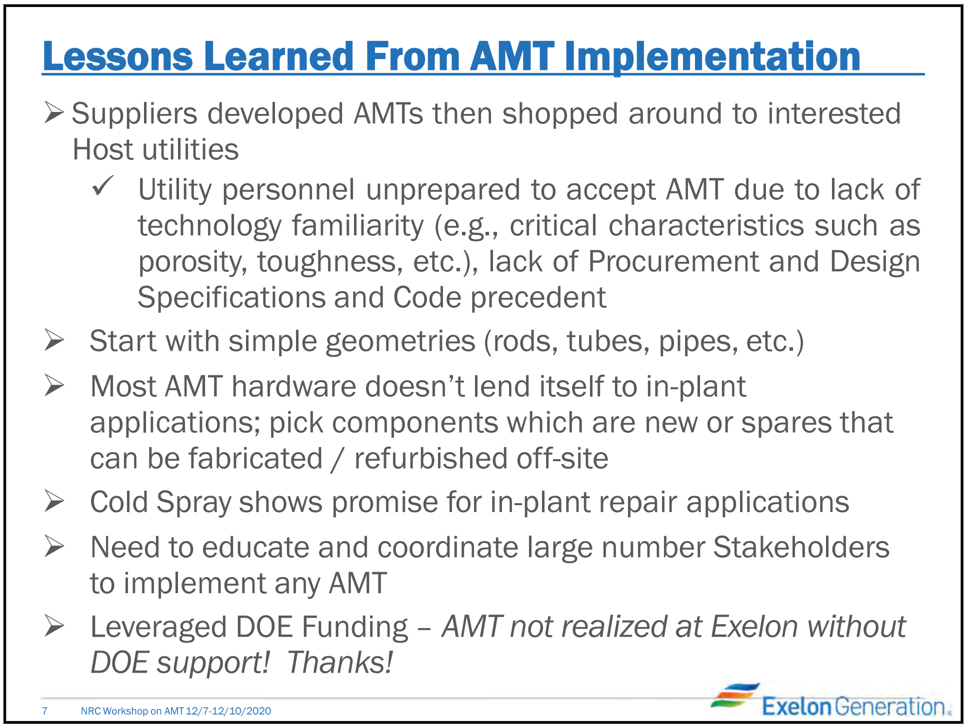


## PWR Steam Generator
## Steam Drum Access to Primary Moisture Separators

Top Down View of Swirl Vanes and Riser Barrel

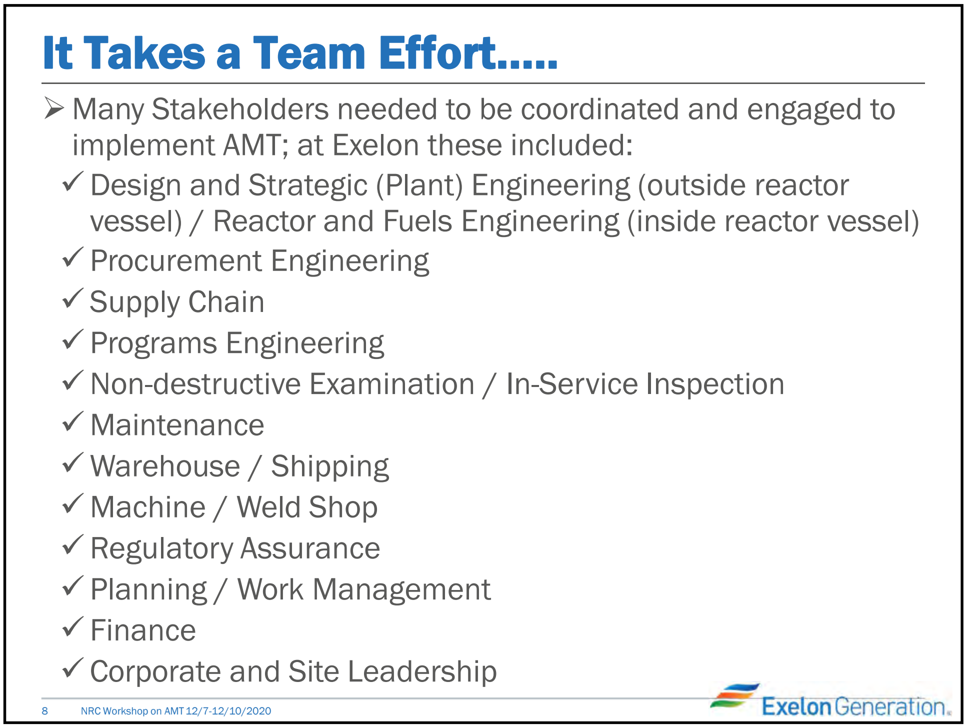
Close-up of Vane and Riser Barrel Wall

www.nucleartourist.com



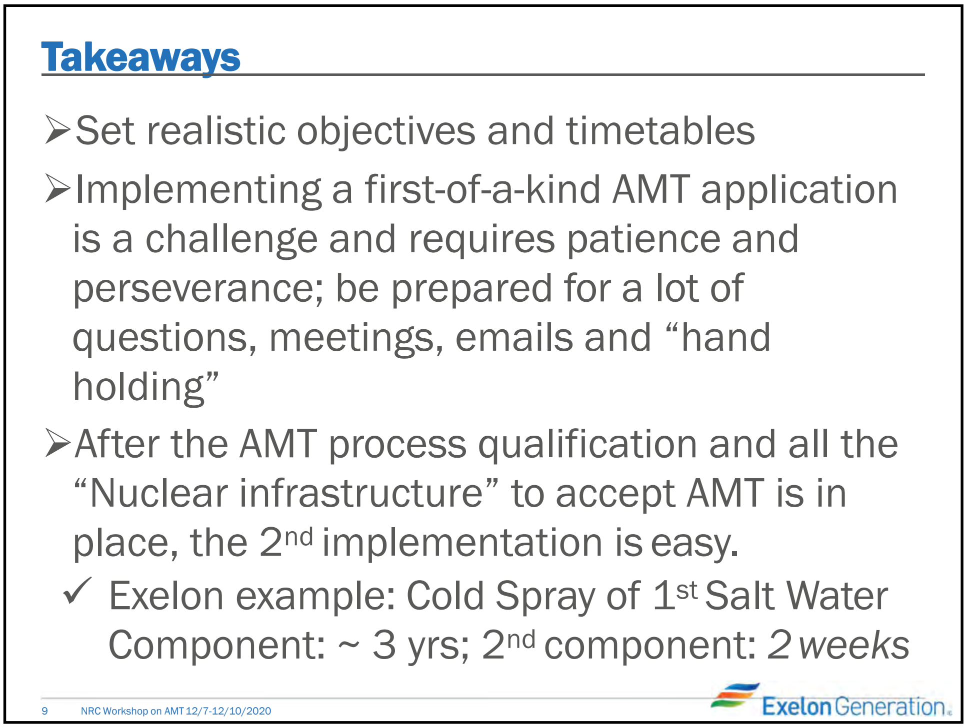
## Lessons Learned From AMT Implementation

- ➢ Suppliers developed AMTs then shopped around to interested Host utilities
  - ✓ Utility personnel unprepared to accept AMT due to lack of technology familiarity (e.g., critical characteristics such as porosity, toughness, etc.), lack of Procurement and Design Specifications and Code precedent
- ➢ Start with simple geometries (rods, tubes, pipes, etc.)
- ➢ Most AMT hardware doesn’t lend itself to in-plant applications; pick components which are new or spares that can be fabricated / refurbished off-site
- ➢ Cold Spray shows promise for in-plant repair applications
- ➢ Need to educate and coordinate large number Stakeholders to implement any AMT
- ➢ Leveraged DOE Funding – *AMT not realized at Exelon without DOE support! Thanks!*



## It Takes a Team Effort.....

- Many Stakeholders needed to be coordinated and engaged to implement AMT; at Exelon these included:
  - ✓ Design and Strategic (Plant) Engineering (outside reactor vessel) / Reactor and Fuels Engineering (inside reactor vessel)
  - ✓ Procurement Engineering
  - ✓ Supply Chain
  - ✓ Programs Engineering
  - ✓ Non-destructive Examination / In-Service Inspection
  - ✓ Maintenance
  - ✓ Warehouse / Shipping
  - ✓ Machine / Weld Shop
  - ✓ Regulatory Assurance
  - ✓ Planning / Work Management
  - ✓ Finance
  - ✓ Corporate and Site Leadership



## Takeaways

- Set realistic objectives and timetables
- Implementing a first-of-a-kind AMT application is a challenge and requires patience and perseverance; be prepared for a lot of questions, meetings, emails and “hand holding”
- After the AMT process qualification and all the “Nuclear infrastructure” to accept AMT is in place, the 2nd implementation is easy.
  - ✓ Exelon example: Cold Spray of 1st Salt Water Component: ~ 3 yrs; 2nd component: 2 *weeks*

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WAPP-11867

# WESTINGHOUSE ADVANCED MANUFACTURING DEVELOPMENT AND IMPLEMENTATION EFFORTS

## U.S. NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications

December 7, 2020

**Clint Armstrong**: armstrcb@westinghouse.com
Advanced Manufacturing Subject Matter Expert
Westinghouse Global Technology Office

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## Westinghouse Advanced Manufacturing Program Objectives

**Improve industry competitiveness, through the development and implementation of advanced manufacturing technologies**

- Drive cost reductions in component manufacturing
- Enable new products and services that provide innovative customer solutions
- Leverage collaborative development and external funding sources

2

2

# ADDITIVE MANUFACTURING DEVELOPMENT EFFORTS

# Additive Manufacturing (AM) Objectives

## Exploiting the Benefits of Additive Manufacturing Technologies

- Producing components with: Powder Bed Fusion (PBF), Binder Jetting (BJ), and Directed Energy Deposition (DED) AM technologies
- Complex components required for performance gains
- Advanced reactor components – eVinci, LFR
- Obsolete and high value / lead-time components
- Tooling / jigs / fixture, prototypes, mockups

## Enabling AM for Nuclear Component Construction

- Leading material development & testing for in reactor use, including irradiation and PIE of 316L, 718 and Zirc-2
- Parameter development and material testing for 304L, 17-4 PH, Haynes 230 & 282, MS1, AFA and FeCrAl ODS alloys
- Supporting the development of ASTM and ASME codes and standards

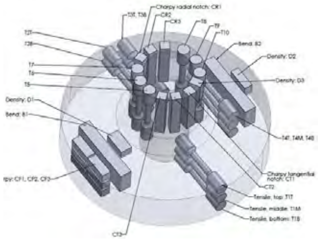
WAPP-11867

# ASME Engagement – L-PBF AM 316L Code Case

## FIRST ASME CODE CASE SUBMITTAL FOR ADDITIVE MANUFACTURING

### Laser-PBF AM 316L Code Case

- Submitted the Section III Code Case for L-PBF AM in August
  - ASME Record 20-254
  - Requesting implementation ASTM F3184-16 with addition requirements, for Section III, Division 1, Subsection NB/NC/ND, Class 1, 2 and 3 components construction
  - Presented Code Case and Data Package at the Section III MF&E Sub-Committee and AM Special Committee
- EPRI consolidated the 316L AM Data Package to support the AM Code Case
  - AM test components were supplied by Westinghouse, Rolls-Royce, ORNL, Auburn University and Oerlikon
  - EPRI coordinated material testing and analysis
  - Funded under DOE NEET-1 AMM Program (DE-NE0008521)



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WAPP-11867

# Reactor Ready Component Development Efforts

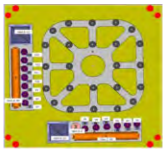
## AM COMPONENT INSTALL IN COMMERCIAL NUCLEAR REACTOR CORE

### Advanced Manufacturing Kaizen – Dec. 2014

- Project initiated for development of AM reactor ready component

### Thimble Plugging Device (TPD) selected as first component to test in core

- Low risk component, moderate complexity
- Produced hybrid 304/316L TPD
  - Manufacturing qualification……..2017-2018
  - Production units…………………2018-2019
  - Delivered Byron 1……………….Spring 2020



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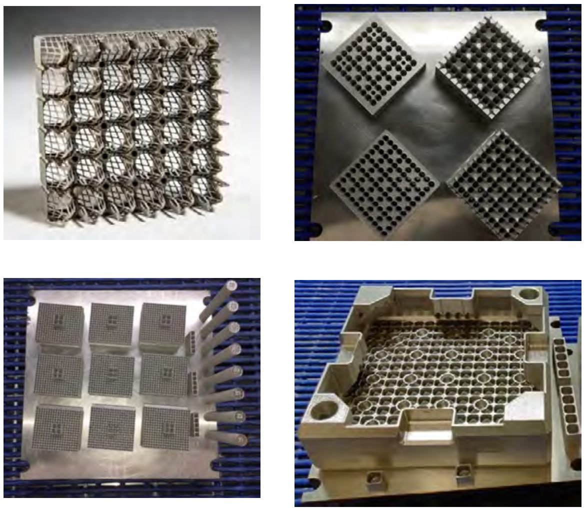
# Fuel Debris Filtering Bottom Nozzle Development

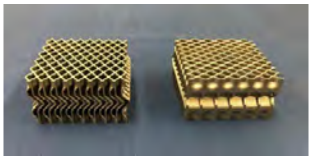
**AM Benefits:**

- Improved debris filtration
  - BWR Testing: Up to 100% debris capture in testing
- Reduced pressure drop

**AM Development:**

- Multiple complex designs / features enabled by AM
- Significant mechanical and performance testing
- PWR: LUAs in Fall 2021
- BWR: LUAs in Spring 2022





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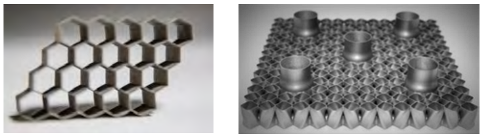
# Fuel Spacer Grid Development Efforts

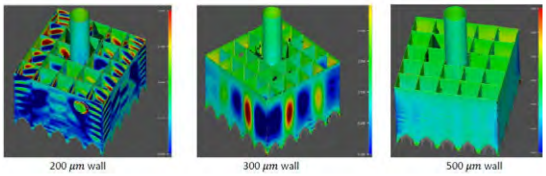
**AM Benefits:**

- Stronger support of fuel rods
- Improved mixing characteristics

**Additive Manufacturing of Spacer Grids for Nuclear Reactors**

- $1.25M, 3 year, ARPA-E Funded Project
- Collaborative effort with Carnegie Mellon University
- Primary Tasks Include:
  - Establish baseline capability
  - Enable low-cost fabrication
  - Improve the spacer grid quality and performance
  - Improve spacer grid performance
  - Exploring potential opportunities for redesign of spacer grid geometries





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WAPP-11867

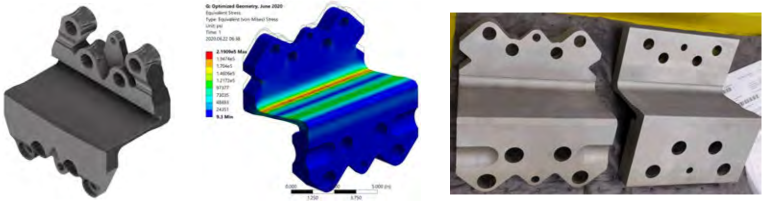
# Innovation Projects

## eVinci™ Microreactor

- Utilizing of Design for Manufacturability approach and developing Adv Mfg technologies, where appropriate
- Primary Heat Exchanger (PHX), heat pipe end plugs and fittings, and small parts and structural components are the leading candidates

## Salem Thermal Shield Flexure

- Completed topology and AM optimization efforts
- Successfully complete fatigue testing of topology optimized AM flexure



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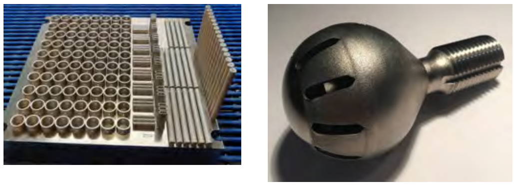
# Replacement Parts

## Replacement Parts Identification Efforts

- Currently working to identify, demonstrate and qualify AM applications
- Data and expert review for application down-selection
- Development of detailed estimates / business cases for top candidates
- Utilizing laser scanning and reverse engineering software to develop editable 3D models for obsolete parts



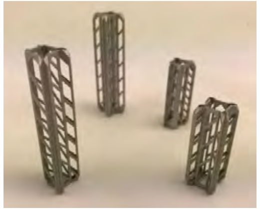
# Tooling

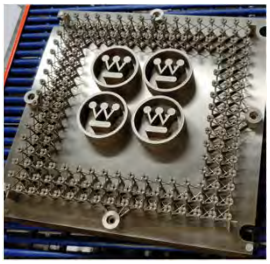
**Immediate benefit from tooling applications**

- Lower the costs and improve performance

**Improved safety for operators**

- Reduction of leak points
- Two hands touch control
- Ergonomic designs resulting in less fatigue injuries





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# HOT ISOSTATIC PRESSING (HIP) DEVELOPMENT EFFORTS

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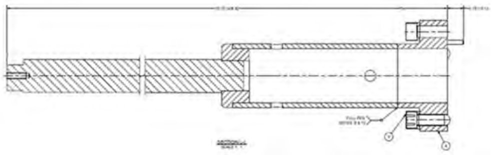
# Hot Isostatic Pressing (HIP) Development Efforts

**NEER Project (Innovate UK-funded): Completed in May 2018**

- Focused on reusable tooling, HIP development and demonstration of nuclear components, and UK supply based development
- Produced demonstration components
    - Reactor Vessel Internals (RVIs): Quickloc Upper Support Assembly
    - Control Rod Drive Mechanisms (CRDMs): Guide Funnel Extension
    - Valves: 4” Motor Operated Gate Valve Body



**Producing Prototypes / Mockups for Next Generation Plants**

**Completing Cost-Benefit Analysis for Reactor Coolant Loop Components**

**Collaborating on Auburn led DOE AMM funded project**

- 3 year, $1M effort focused on HIP of dissimilar metal joints, materials, and modeling

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# ADVANCED WELDING AND COATING DEVELOPMENT EFFORTS

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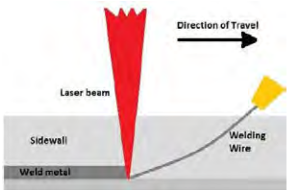
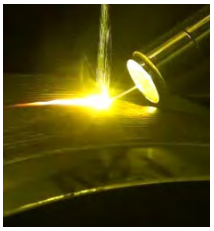
# Advanced Welding and Coating Development Efforts

## Collaborating on welding development efforts

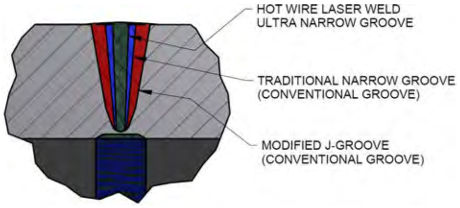
- Hot wire laser welding (HWLW)
- Hybrid laser GMAW
- Laser welding of irradiated materials
- Laser metal deposition for component repair
- Cold Spray & Plasma Arc Spray





## Using emergent technologies to solve fabrication and repair challenges and reduce manufacturing costs

- RCP, RVI and CRDM cost reduction opportunities
- Module fabrication
- Weld distortion reduction and modeling
- In-field component repair



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Westinghouse Electric Company

@WECNuclear

Westinghouse Electric Company

wecchinanuclear

westinghousenuclear.com

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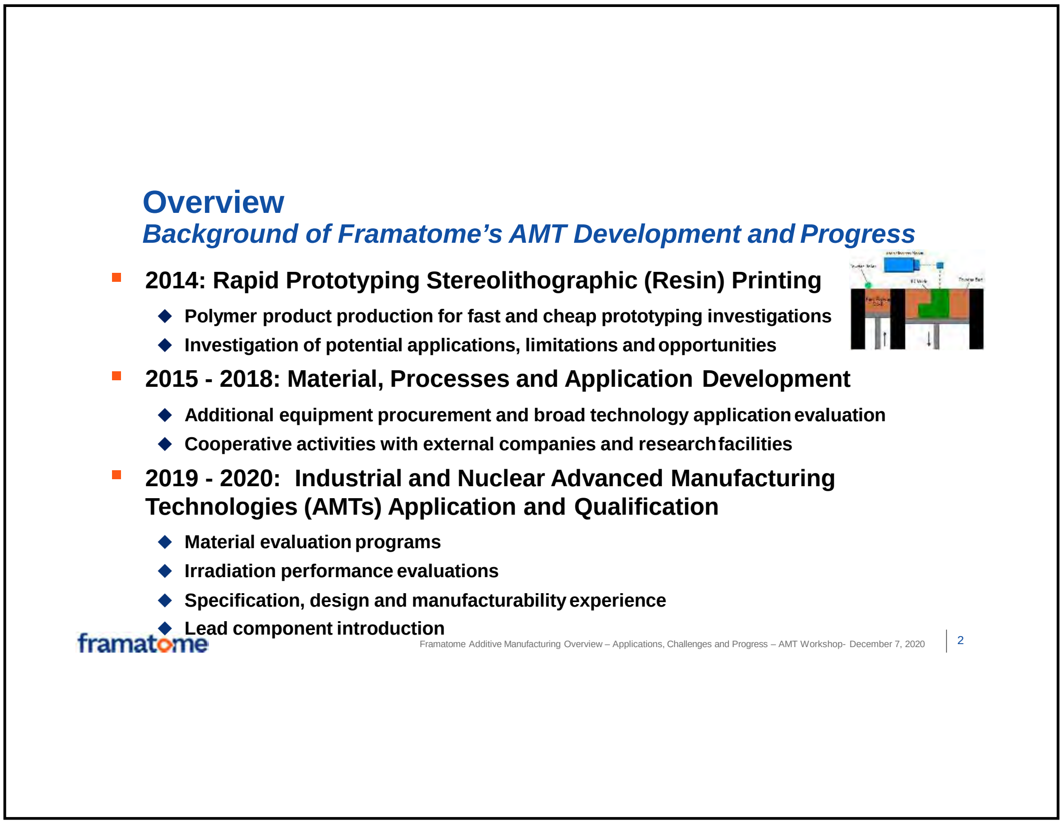
# Framatome Additive Manufacturing Overview

## Applications, Challenges and Progress

Thomas Genevés - R&D Engineer - AMT, Framatome Technical Center
Chris Wiltz - Design to Cost / Design to Manufacture Manager, Fuel

Advanced Manufacturing Technologies Workshop

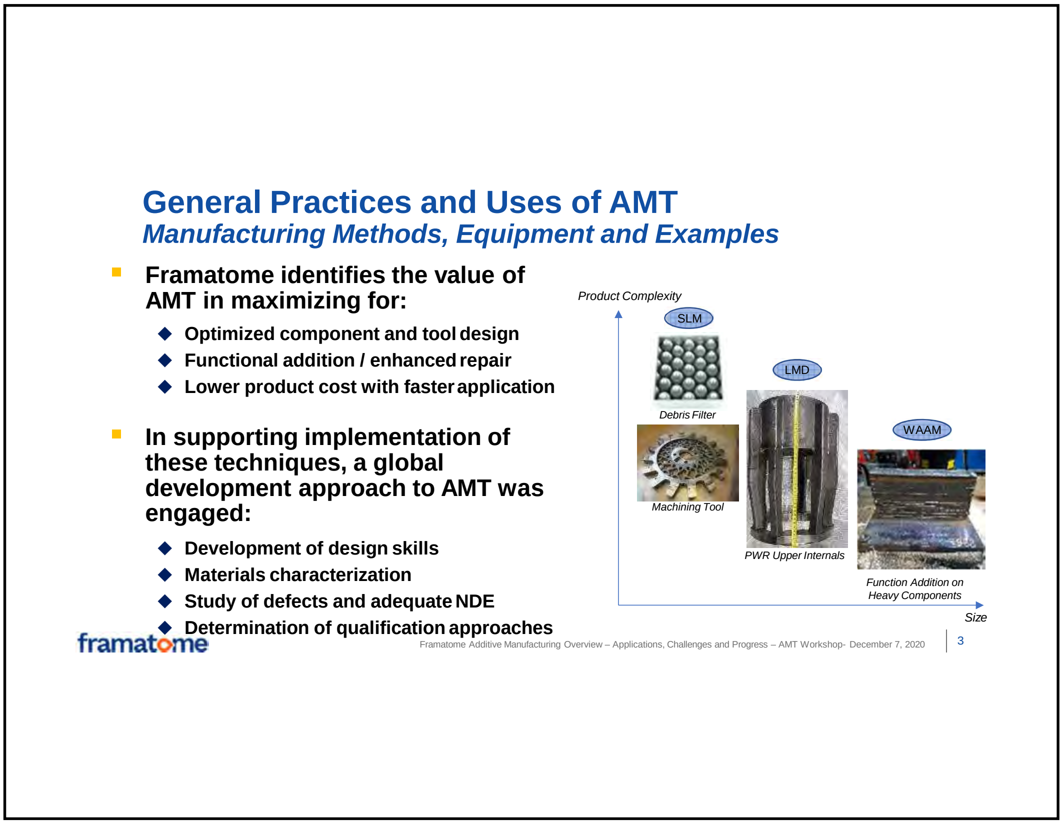
December 7, 2020



## Overview

### *Background of Framatome's AMT Development and Progress*

- 2014: Rapid Prototyping Stereolithographic (Resin) Printing
  - Polymer product production for fast and cheap prototyping investigations
  - Investigation of potential applications, limitations and opportunities
- 2015 - 2018: Material, Processes and Application Development
  - Additional equipment procurement and broad technology application evaluation
  - Cooperative activities with external companies and research facilities
- 2019 - 2020: Industrial and Nuclear Advanced Manufacturing Technologies (AMTs) Application and Qualification
  - Material evaluation programs
  - Irradiation performance evaluations
  - Specification, design and manufacturability experience
  - Lead component introduction



## General Practices and Uses of AMT

### *Manufacturing Methods, Equipment and Examples*

- **Framatome identifies the value of AMT in maximizing for:**
  - Optimized component and tool design
  - Functional addition / enhanced repair
  - Lower product cost with faster application
- **In supporting implementation of these techniques, a global development approach to AMT was engaged:**
  - Development of design skills
  - Materials characterization
  - Study of defects and adequate NDE
  - Determination of qualification approaches

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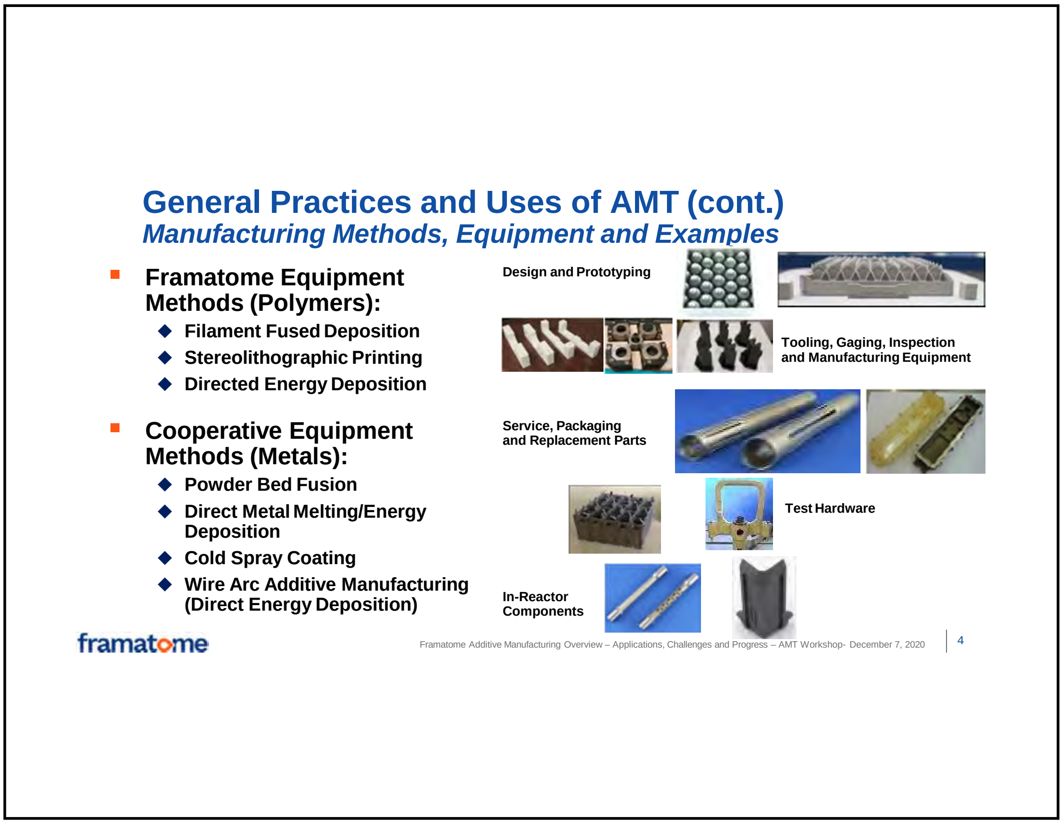

## General Practices and Uses of AMT (cont.)

### *Manufacturing Methods, Equipment and Examples*

- **Framatome Equipment Methods (Polymers):**
  - Filament Fused Deposition
  - Stereolithographic Printing
  - Directed Energy Deposition
- **Cooperative Equipment Methods (Metals):**
  - Powder Bed Fusion
  - Direct Metal Melting/Energy Deposition
  - Cold Spray Coating
  - Wire Arc Additive Manufacturing (Direct Energy Deposition)

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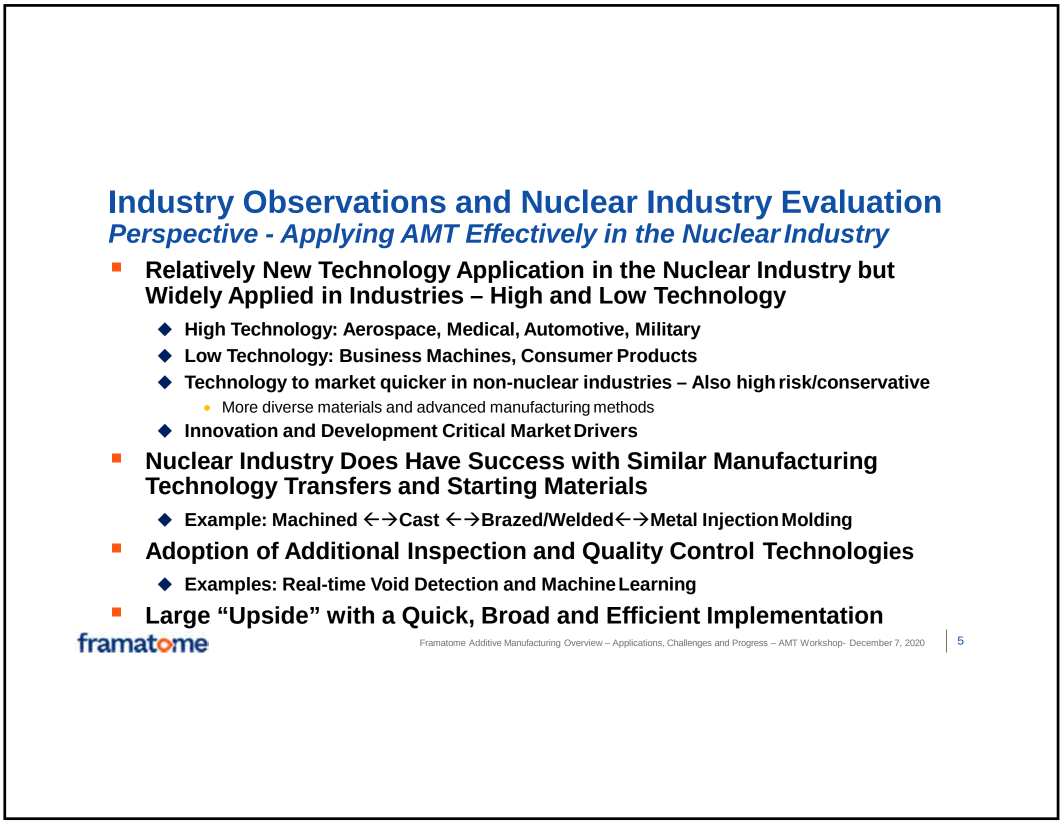
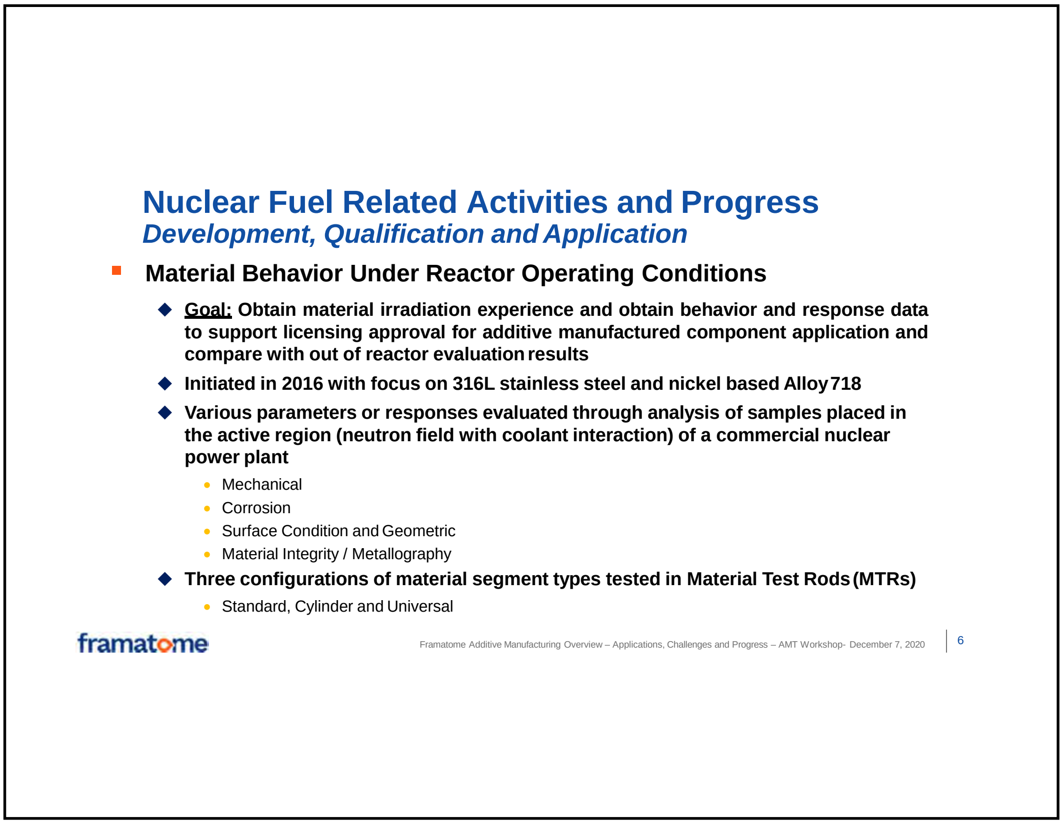


## Industry Observations and Nuclear Industry Evaluation

### *Perspective - Applying AMT Effectively in the Nuclear Industry*

- **Relatively New Technology Application in the Nuclear Industry but Widely Applied in Industries – High and Low Technology**
  - **High Technology: Aerospace, Medical, Automotive, Military**
  - **Low Technology: Business Machines, Consumer Products**
  - **Technology to market quicker in non-nuclear industries – Also high risk/conservative**
    - More diverse materials and advanced manufacturing methods
  - **Innovation and Development Critical Market Drivers**
- **Nuclear Industry Does Have Success with Similar Manufacturing Technology Transfers and Starting Materials**
  - **Example: Machined ←→Cast ←→Brazed/Welded←→Metal Injection Molding**
- **Adoption of Additional Inspection and Quality Control Technologies**
  - **Examples: Real-time Void Detection and Machine Learning**
- **Large “Upside” with a Quick, Broad and Efficient Implementation**



## Nuclear Fuel Related Activities and Progress

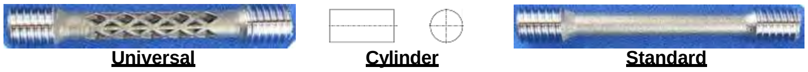
### *Development, Qualification and Application*

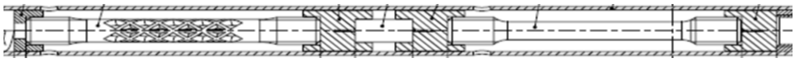
- **Material Behavior Under Reactor Operating Conditions**
  - **Goal: Obtain material irradiation experience and obtain behavior and response data to support licensing approval for additive manufactured component application and compare with out of reactor evaluation results**
  - **Initiated in 2016 with focus on 316L stainless steel and nickel based Alloy 718**
  - **Various parameters or responses evaluated through analysis of samples placed in the active region (neutron field with coolant interaction) of a commercial nuclear power plant**
    - Mechanical
    - Corrosion
    - Surface Condition and Geometric
    - Material Integrity / Metallography
  - **Three configurations of material segment types tested in Material Test Rods (MTRs)**
    - Standard, Cylinder and Universal

## Nuclear Fuel Related Activities and Progress

### *Development, Qualification and Application (cont.)*

- **Material Behavior Under Reactor Operating Conditions (cont.)**
  - **Test samples manufactured using Selective Laser Melting and placed in Material Test Rods for irradiation testing**





**Test Sample Orientation in MTR Segment – Multiple Segments in Multiple Rods**

  - **Samples to be analyzed after 1, 3 and 5 cycles of operation**

| | | | | | | |
|---|---|---|---|---|---|---|
| Three Sample Sets Inserted | Sample Set #1 (1 Cycle) Removed | Sample Set #1 Hot Cell Examination | Sample Set #2 (3 Cycles) Removed | Sample Set #2 Hot Cell Examination | Sample Set #3 (5 Cycles) Removed | Sample Set #3 Hot Cell Examination |
| 2019 | 2020 | 2021/22 | 2022 | 2023/24 | 2024 | 2025/26 |

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## Nuclear Fuel Related Activities and Progress

### *Development, Qualification and Application (cont.)*

- **Fuel Assembly Component Implementation - Channel Fastener**
  - **Goal: Gain experience, demonstrate competency and introduce in reactor nuclear fuel assembly components produced using additive manufacturing**
  - **Accomplished in collaboration with Oak Ridge National Laboratory and TVA as part of the Transformational Challenge Reactor (TCR) program**
  - **Full scope basic product development and implementation project accomplished**
    - Design modification and control for Direct Metal Laser Melting (Powder Bed Fusion) AM technique
      - Drawings, product specifications, material specifications, inspection requirements, etc.
    - Additive manufacturing process/configuration control and optimization – Product manufacturability
    - Qualification and quality control establishment for manufacturing process and final product
    - Licensing and commercial operation of a safety related fuel assembly component in reactor
  - **Four channel fasteners completed and delivered to TVA for Spring 2021 insertion in Browns Ferry Nuclear Power Plant - Unit 2 (Cycle 22) for three cycles of operation**
    - Full pre-irradiation characterizations accomplished – Dimensional, mechanical, chemical and NDE

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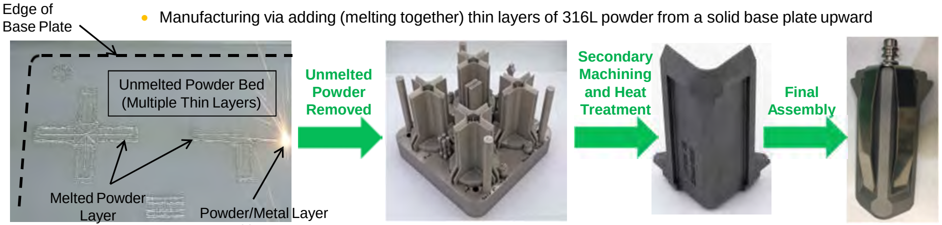
## Nuclear Fuel Related Activities and Progress
### *Development, Qualification and Application (cont.)*

- **Fuel Assembly Component Implementation - Channel Fastener (cont.)**
  - **Anticipated post-irradiation examination plan beginning in 2023 – To be finalized**
    - Poolside visual examination after each cycle of operation
    - Hot cell examinations – visual, dimensional, metallography, tensile tests, fraction toughness, etc.
  - **Direct Metal Laser Melting Manufacturing Process – Directed Energy Deposition**
    - Manufacturing via adding (melting together) thin layers of 316L powder from a solid base plate upward



Edge of Base Plate

Unmelted Powder Bed (Multiple Thin Layers)

Melted Powder Layer (Component Build-up)

Powder/Metal Layer Melting Laser

**Unmelted Powder Removed**

**Secondary Machining and Heat Treatment**

**Final Assembly**

## Nuclear Fuel Related Activities and Progress
### *Development, Qualification and Application (cont.)*

- **Direction Forward for Additive Manufacturing Application**
  - **Near Term – Additional Experience and Industrial/Commercial Application Feedback**
    - Completion of reactor operation material behavior evaluation programs
    - Introduction of additional "existing" fuel assembly components produced using additive manufacturing technologies and materials as additional PWR and BWR fuel assembly lead type programs
      - 316L stainless steel and nickel based Alloy 718 material applications
    - Technology influenced product boundary conditions and performance enhancement capabilities
  - **Product Innovation and Additive Manufacturing Technology Application Optimization**

**Fuel Lower Debris Filters**

**Fuel Upper Grids and Filters**

**Tooling and Reactor Components**

  - **Goal: Industrial product delivery beginning in 2026**

## Questions, Comments and/or Opinions

# Thank You!

# Advanced Manufacturing with Advanced Materials for Nuclear Applications

ROBERT OELRICH

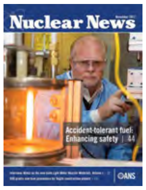
Fuels and Materials Performance, National Security Directorate, PNNL
NRC Public Workshop on Advanced Manufacturing - December 7-10, 2020

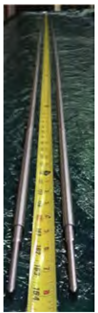
IR# PNNL-SA-158421

## Advanced Materials with Advanced Manufacturing

- Additive Manufacturing: Components are now being introduced into commercial LWRs
  - PWR thimble plug assembly installed at Exelon's Byron Unit 1 in Spring 2020
  - BWR channel fasteners to be installed at Brown's Ferry in Spring 2021
- Advanced Manufacturing: Accident Tolerant Fuel (ATF) coated cladding also being introduced in PWRs and BWRs
  - GNF Armor-coated Zirconium at Plant Hatch
  - Framatome EATF Chromium-coated M5® into Vogtle 2
  - Westinghouse EnCore® Chromium-coated rods in Byron 2

Westinghouse – PBF Thimble Plug
Source: World Nuclear News May 5, 2020





GE Armor-Coated Cladding
Source: Power Magazine April 1, 2018

Framatome/TVA/ORNL TCR – AM Channel Fasteners
Source: ORNL Press Release October 19, 2020

## Advanced Materials with Advanced Manufacturing

Pacific Northwest NATIONAL LABORATORY
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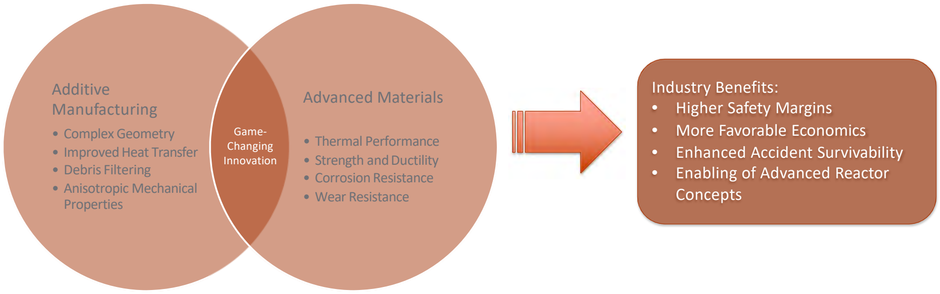
The combination of Additive Manufacturing flexibility with advanced materials can result in innovation that was previously unachievable.



Additive Manufacturing
- Complex Geometry
- Improved Heat Transfer
- Debris Filtering
- Anisotropic Mechanical Properties

Game-Changing Innovation

Advanced Materials
- Thermal Performance
- Strength and Ductility
- Corrosion Resistance
- Wear Resistance

Industry Benefits:
- Higher Safety Margins
- More Favorable Economics
- Enhanced Accident Survivability
- Enabling of Advanced Reactor Concepts

## Advanced Materials with Advanced Manufacturing

Pacific Northwest NATIONAL LABORATORY
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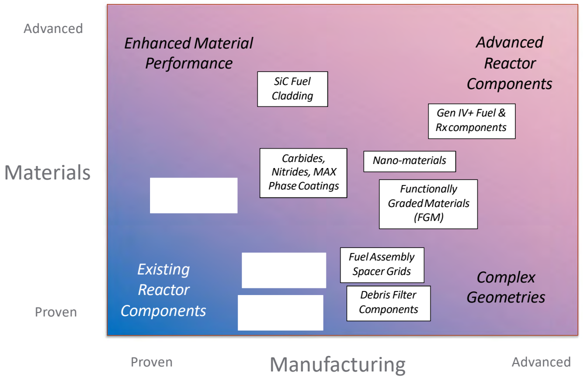
- **Advanced Manufacturing**
  - Complex geometries not possible with traditional manufacturing
  - Material and weight savings
  - Materials: SS 316L, Inconel 718, Zirconium, Titanium & Aluminum alloys
- **Advanced Materials**
  - Improved thermal and mechanical properties
  - Enhanced radiation, wear and corrosion resistance
  - Materials: new alloys, carbides, nitrides, MAX phase, ceramics, ODS steels
- **Advanced Manufacturing with Advanced Materials**
  - Functionally Graded Materials (FGM)
  - Applications of some new non-traditional reactor materials
  - New components for advanced reactors (unrestricted by existing environments and configurations)

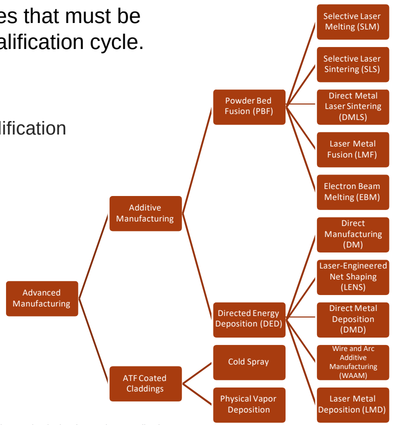
## Advanced Materials with Advanced Manufacturing

- Advanced Manufacturing (AM) can be useful for direct component replacement, and/or to implement evolutionary improvements in performance or weight
  - However, costs may not justify AM for high volume parts or for long qualification processes
- Strongest opportunities may be for totally new concepts for future advanced reactor components which may not be constrained by pre-existing requirements: enveloping geometry, thermal and other environmental conditions, licensing bases, etc…



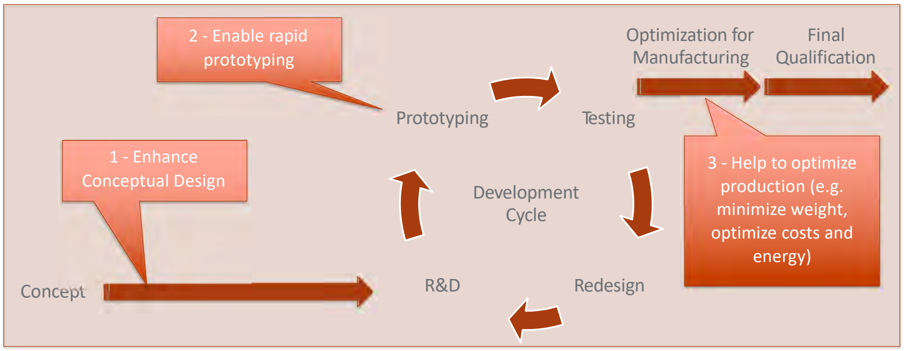
## Advanced Materials with Advanced Manufacturing

- Additive Manufacturing introduces new variables that must be controlled throughout the development and qualification cycle.
- Parameters
  - Energy, speed of deposition
  - Thermal conditions, temperature gradients, solidification velocities, localized annealing rates
  - Powder characteristics
  - Alloys, impurities
- Material Properties
  - Isotropic/Anisotropic performance
  - Strength, Ductility
  - Production Rates
  - Surface Finish
  - Microstructure
  - Composition Homogenity



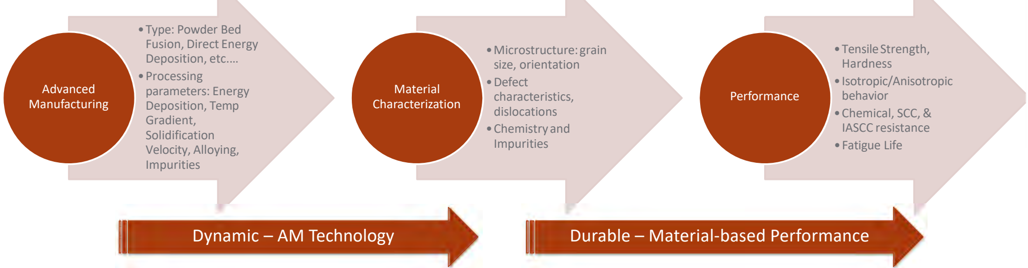
## Advanced Manufacturing in the Development Process

- There are at least three separate opportunities to introduce Advanced Manufacturing into the development and qualification process…



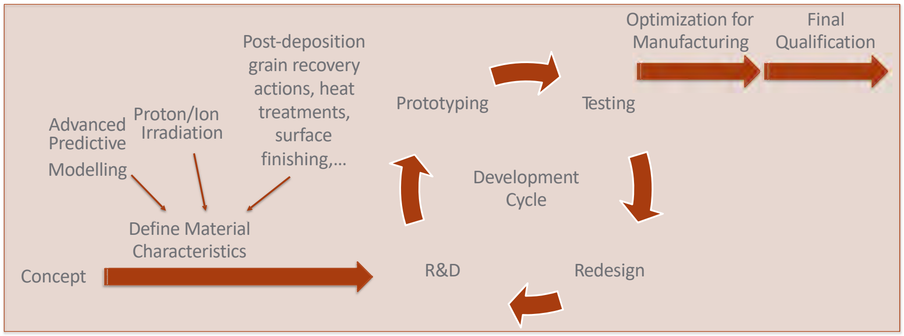
## Advanced Manufacturing in the Development Process

- The many forms of Advanced Manufacturing introduces new flexibility into the development and qualification process. Also, AM technology continues to evolve at a fast pace.
  - Technology can outpace the qualification and licensing process.
  - Traditional certification and qualification processes need to be improved.
- To retain the most flexibility from AM, consider qualifying material and irradiation performance as much as possible based on material characterization - specific AM technology can/will evolve.



## Advanced Manufacturing in the Development Process

- Evolving AM technology can disrupt material performance, jeopardizing the qualification process.
- Define and control basic material characteristics early in the process.
- Also inform regulators in advance of new technology as early as possible.



Advanced Predictive Modelling

Proton/Ion Irradiation

Post-deposition grain recovery actions, heat treatments, surface finishing,…

Define Material Characteristics

Concept

R&D

Prototyping

Testing

Development Cycle

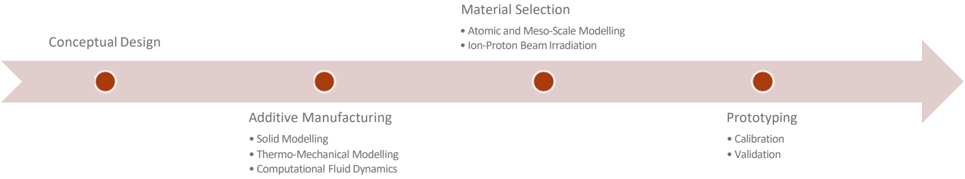
Redesign

Optimization for Manufacturing

Final Qualification

## Advanced Manufacturing in the Development Process

- The third “AM”, Advanced Modelling, supports Additive Manufacturing and Advanced Materials
  - Additive Manufacturing can enable rapid prototyping in the testing phase
  - However, it also introduces additional variables into the prototyping/testing process
  - So, empirical modelling and qualification can be much more challenging
- Advanced modelling can be utilized to better predict and control the governing AM parameters influencing the product performance
- Finally, with so much more computer-based modelling earlier in the development cycle, Cyber Security becomes even that much more critical to protect Intellectual Property.



Conceptual Design

Additive Manufacturing
- Solid Modelling
- Thermo-Mechanical Modelling
- Computational Fluid Dynamics

Material Selection
- Atomic and Meso-Scale Modelling
- Ion-Proton Beam Irradiation

Prototyping
- Calibration
- Validation

## Case Study – Accident Tolerant Fuels

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- ATF coated cladding development represent a similar qualification and licensing challenge as other AM development programs
  - Material properties are heavily dependent upon new but controllable process parameters, such as temperature, speed, carrier gas, energy of deposition, impurities
- Critical to understand and control desired microstructure characteristics, not just process parameters
  - Qualification and licensing based on fundamental material properties, not simply deposition process parameters
  - Key modelling and material characterization must be brought forward in the process

## Case Study – Accident Tolerant Fuels

IL TROVATORE

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- IL TROVATORE:
  - An international collaboration with strong academic input & industrial support
  - Beneficiaries: 28 from Europe, 1 from the US, and 1 from Japan
  - External Expert Advisory Committees:
    - Scientific Advisory Committee
    - End Users Group (Oelrich member)
    - Standardization Advisory Committee (ASTM/C28, CEN/TC 430, ISO/TC 85)

## Case Study – Accident Tolerant Fuels

- Goal: Help to address the global societal & industrial need for improved nuclear energy safety by optimizing and validating select ATF cladding material concepts in an industrially relevant environment (i.e., under neutron irradiation in PWR-like water in the BR2 research reactor)
- Candidate ATF Cladding Material Concepts:
  - SiC/SiC composite clads, different concepts
  - Coated clads (e.g., Cr-coated zircaloys); innovative coating materials: MAX phases, doped oxides
  - GESA surface-modified clads
  - ODS-FeCrAl alloy clads

## Case Study – Accident Tolerant Fuels

- Goal: Help to address the global societal & industrial need for improved nuclear energy safety by optimizing and validating select ATF cladding material concepts in an industrially relevant environment (i.e., under neutron irradiation in PWR-like water in the BR2 research reactor)

| SiC/SiC Composite Clads | Coated & Surface-Modified Clads | ODS-FeCrAl Clads |
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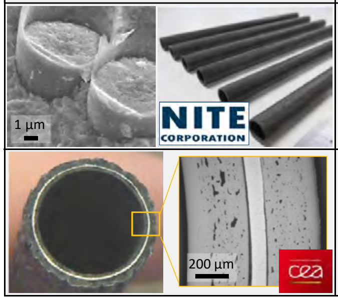
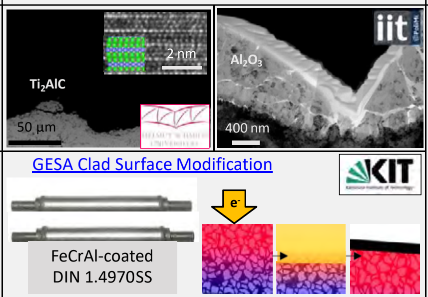
|  |  |  |

## Case Study – Accident Tolerant Fuels

IL TROVATORE

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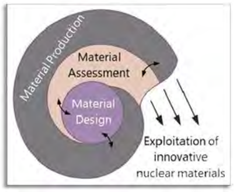

- The accelerated development of nuclear materials entails:
  - Interconnectivity of *application-driven material design*, *material production* *and material performance assessment* in application-relevant conditions
  - Development of *reliable high-throughput material screening tools*, e.g., use of *ion/proton irradiation* to assess radiation tolerance; *select modelling approaches* (atomic scale, FE, etc.) to predict in-service material behavior

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## Case Study – Accident Tolerant Fuels

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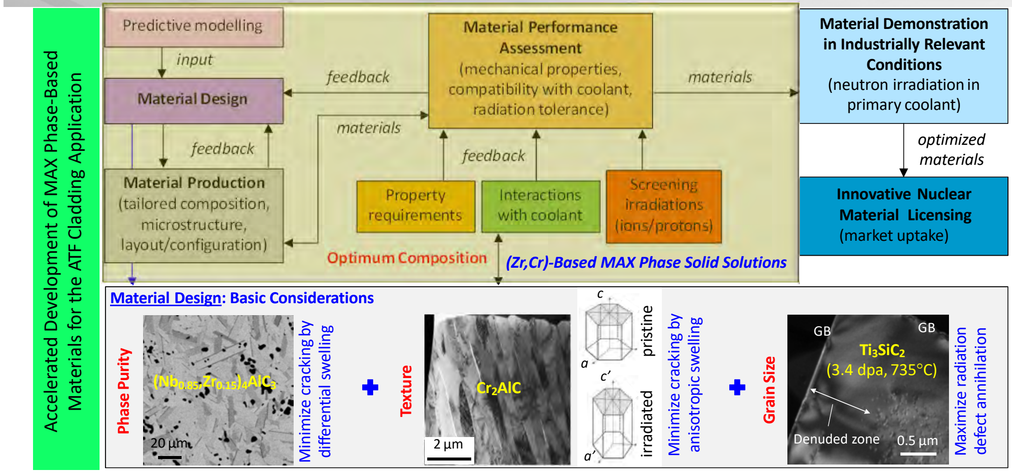


Accelerated Development of MAX Phase-Based Materials for the ATF Cladding Application

Predictive modelling

*input*

**Material Design**

*feedback*

**Material Production** (tailored composition, microstructure, layout/configuration)

*feedback*

*materials*

**Material Performance Assessment** (mechanical properties, compatibility with coolant, radiation tolerance)

*feedback*

Property requirements

Interactions with coolant

Screening irradiations (ions/protons)

*materials*

**Material Demonstration in Industrially Relevant Conditions** (neutron irradiation in primary coolant)

*optimized materials*

**Innovative Nuclear Material Licensing** (market uptake)

**Optimum Composition**

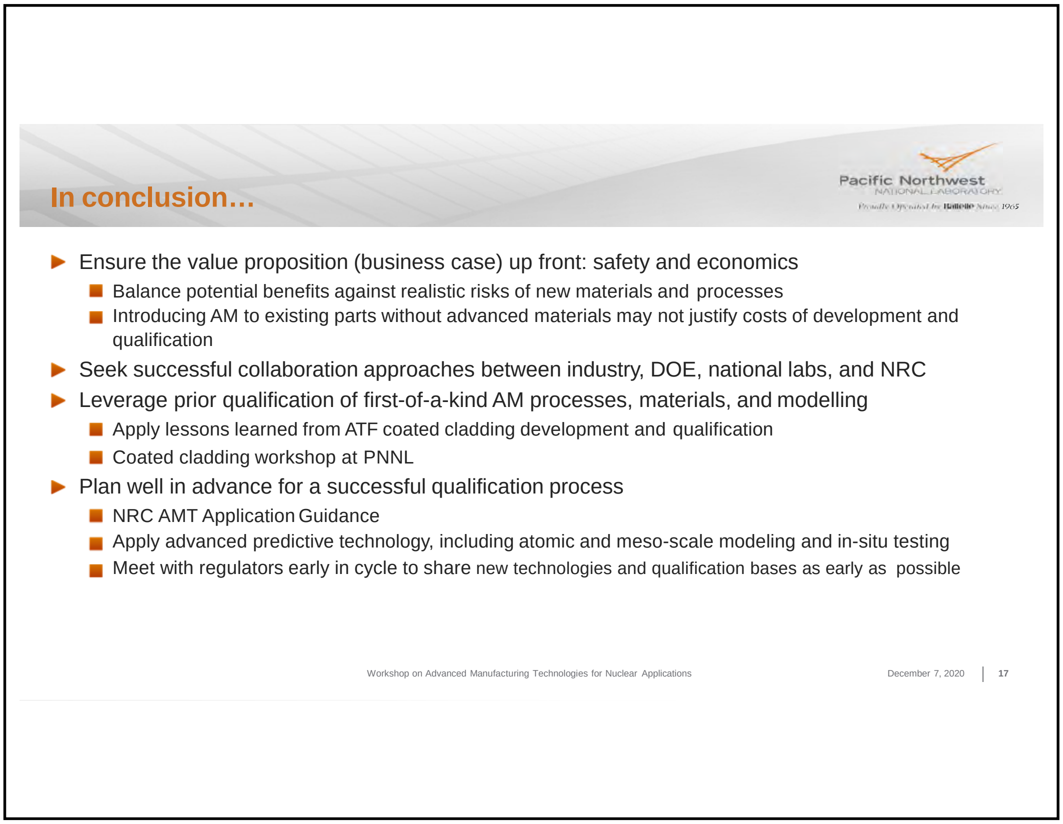
***(Zr,Cr)-Based MAX Phase Solid Solutions***

**Material Design: Basic Considerations**

**Phase Purity** — $(Nb_{0.85},Zr_{0.15})_4AlC_3$ — Minimize cracking by differential swelling

**Texture** — $Cr_2AlC$ — pristine, irradiated — Minimize cracking by anisotropic swelling

**Grain Size** — $Ti_3SiC_2$ (3.4 dpa, 735°C) — Maximize radiation defect annihilation



## In conclusion…

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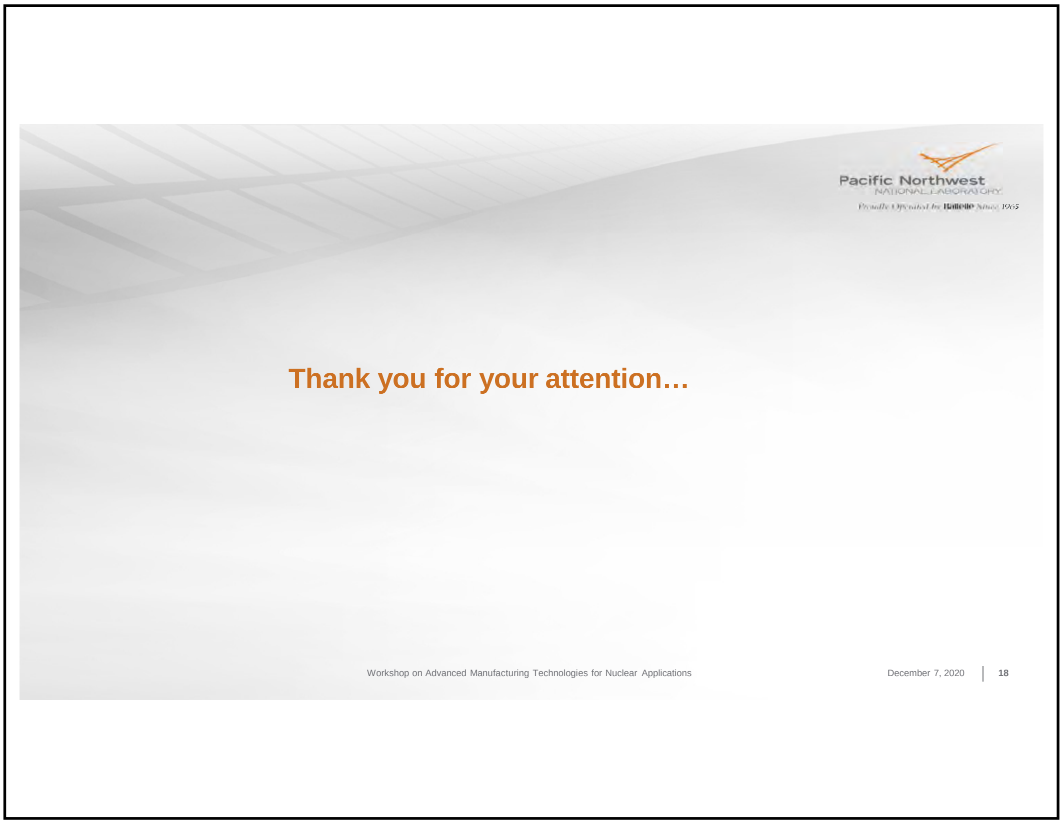
- Ensure the value proposition (business case) up front: safety and economics
  - Balance potential benefits against realistic risks of new materials and processes
  - Introducing AM to existing parts without advanced materials may not justify costs of development and qualification
- Seek successful collaboration approaches between industry, DOE, national labs, and NRC
- Leverage prior qualification of first-of-a-kind AM processes, materials, and modelling
  - Apply lessons learned from ATF coated cladding development and qualification
  - Coated cladding workshop at PNNL
- Plan well in advance for a successful qualification process
  - NRC AMT Application Guidance
  - Apply advanced predictive technology, including atomic and meso-scale modeling and in-situ testing
  - Meet with regulators early in cycle to share new technologies and qualification bases as early as possible



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## Thank you for your attention…

# Additive Manufacturing

## Justification and Implementation

Dave Poole, Additive Manufacturing Engineering Manager
Bill Press, Technical Specialist

December 2020

## Agenda

01 **Implementation Strategy**
Substitution > Enhanced Substitution > One-way-choice

02 **The Lead Application**
Primary Circuit Manual Globe Valve

03 **Justification Strategy**
'Beyond code' multi-legged TAGSI approach

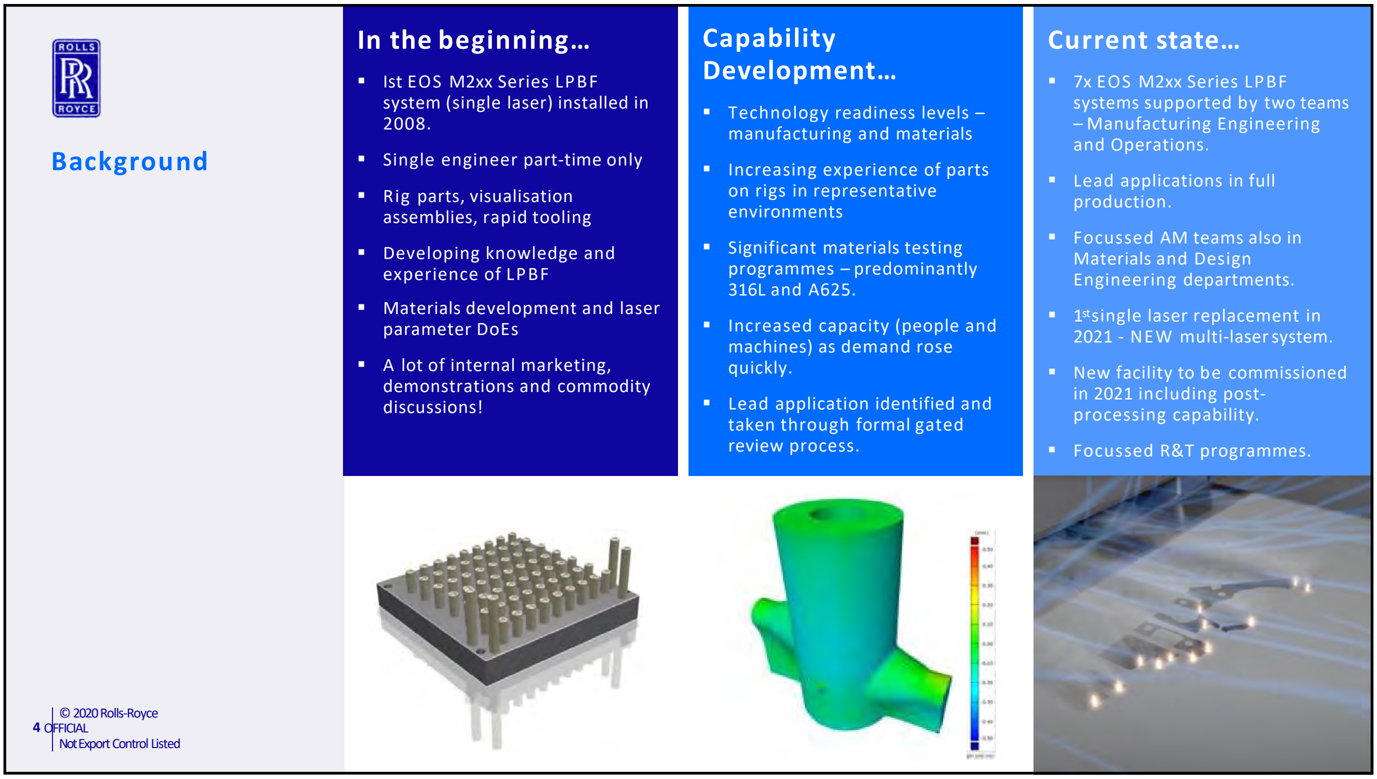
04 **Where next?**
Robust production, new applications and R&T

05 **Questions**
and discussions

# 01

# Implementation Strategy

*"The Additive Manufacturing Team will be the Rolls-Royce Nuclear and Defence centre of competence for additive manufacture; delivering improvements to cost, quality & delivery through innovative & effective implementation of additive manufacturing technology"*



## Background

### In the beginning…

- Ist EOS M2xx Series LPBF system (single laser) installed in 2008.
- Single engineer part-time only
- Rig parts, visualisation assemblies, rapid tooling
- Developing knowledge and experience of LPBF
- Materials development and laser parameter DoEs
- A lot of internal marketing, demonstrations and commodity discussions!

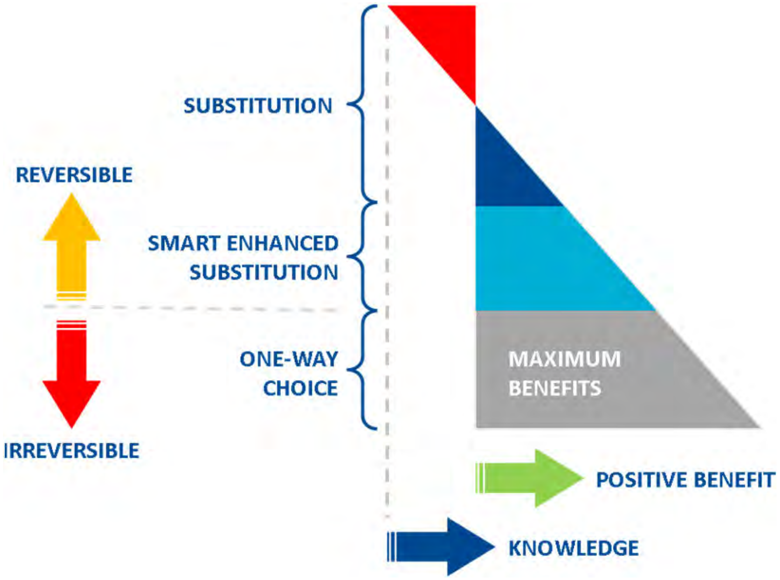
### Capability Development…

- Technology readiness levels – manufacturing and materials
- Increasing experience of parts on rigs in representative environments
- Significant materials testing programmes – predominantly 316L and A625.
- Increased capacity (people and machines) as demand rose quickly.
- Lead application identified and taken through formal gated review process.

### Current state…

- 7x EOS M2xx Series LPBF systems supported by two teams – Manufacturing Engineering and Operations.
- Lead applications in full production.
- Focussed AM teams also in Materials and Design Engineering departments.
- 1st single laser replacement in 2021 - NEW multi-laser system.
- New facility to be commissioned in 2021 including post-processing capability.
- Focussed R&T programmes.

## Implementation Strategy



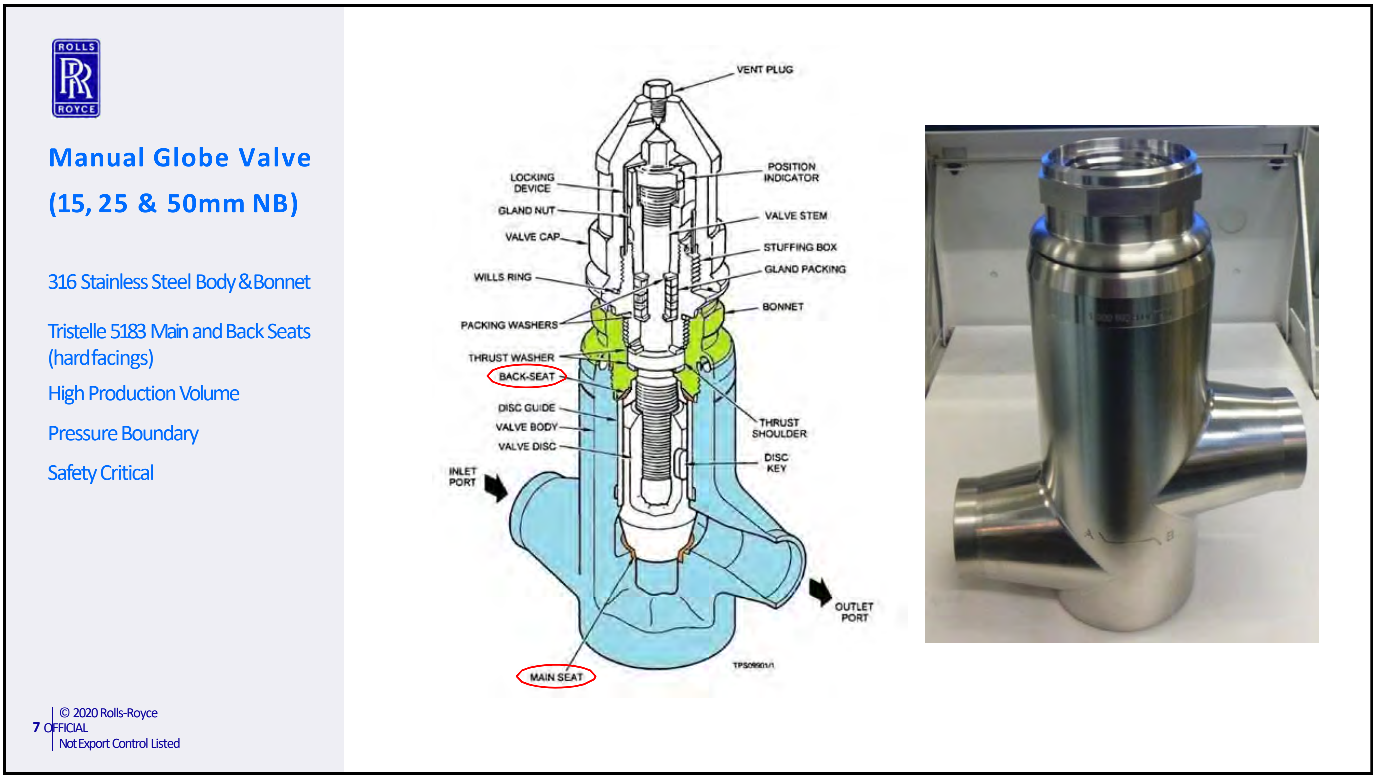
# 02

# The Lead Application

High volume manual globe valve

Safety critical

Pressure boundary



## Manual Globe Valve (15, 25 & 50mm NB)

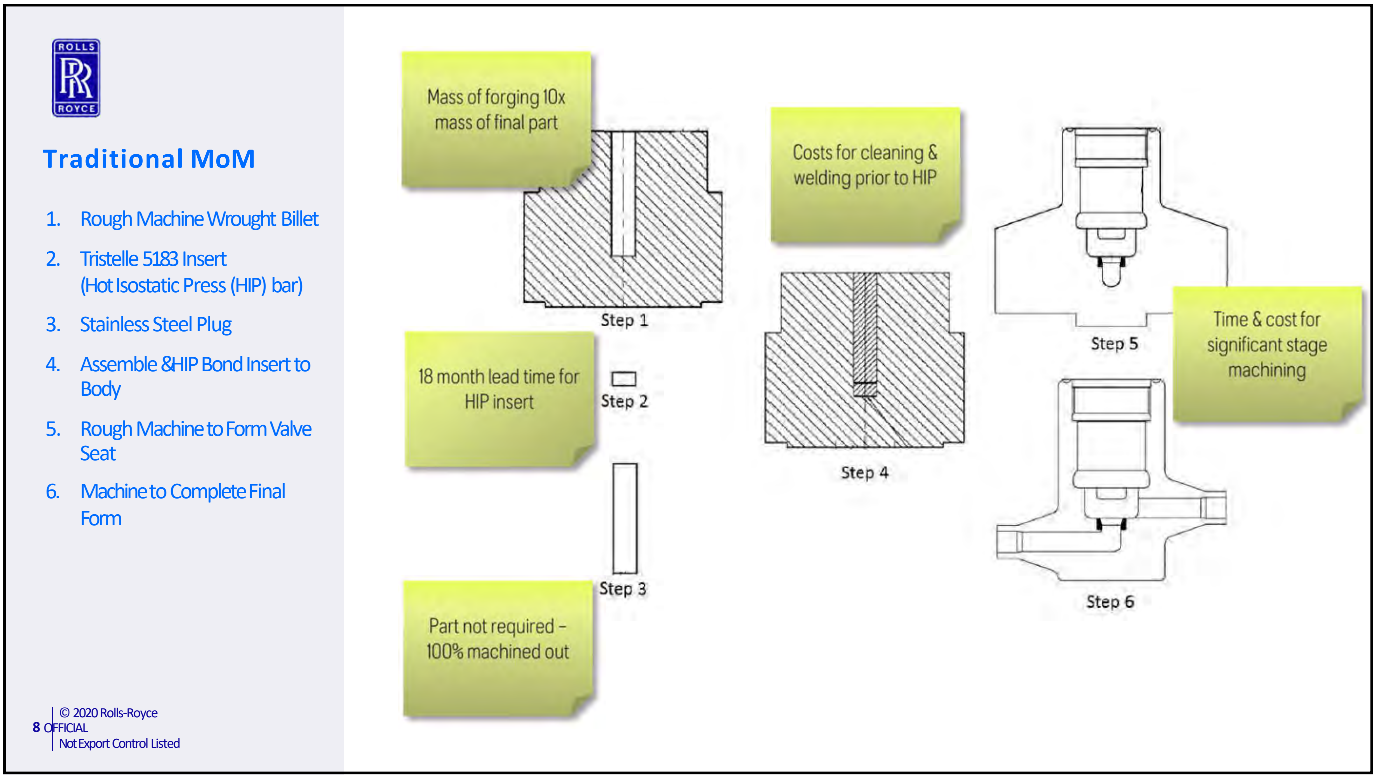
316 Stainless Steel Body & Bonnet

Tristelle 5183 Main and Back Seats (hard facings)

High Production Volume

Pressure Boundary

Safety Critical



## Traditional MoM

1. Rough Machine Wrought Billet
2. Tristelle 5183 Insert (Hot Isostatic Press (HIP) bar)
3. Stainless Steel Plug
4. Assemble & HIP Bond Insert to Body
5. Rough Machine to Form Valve Seat
6. Machine to Complete Final Form

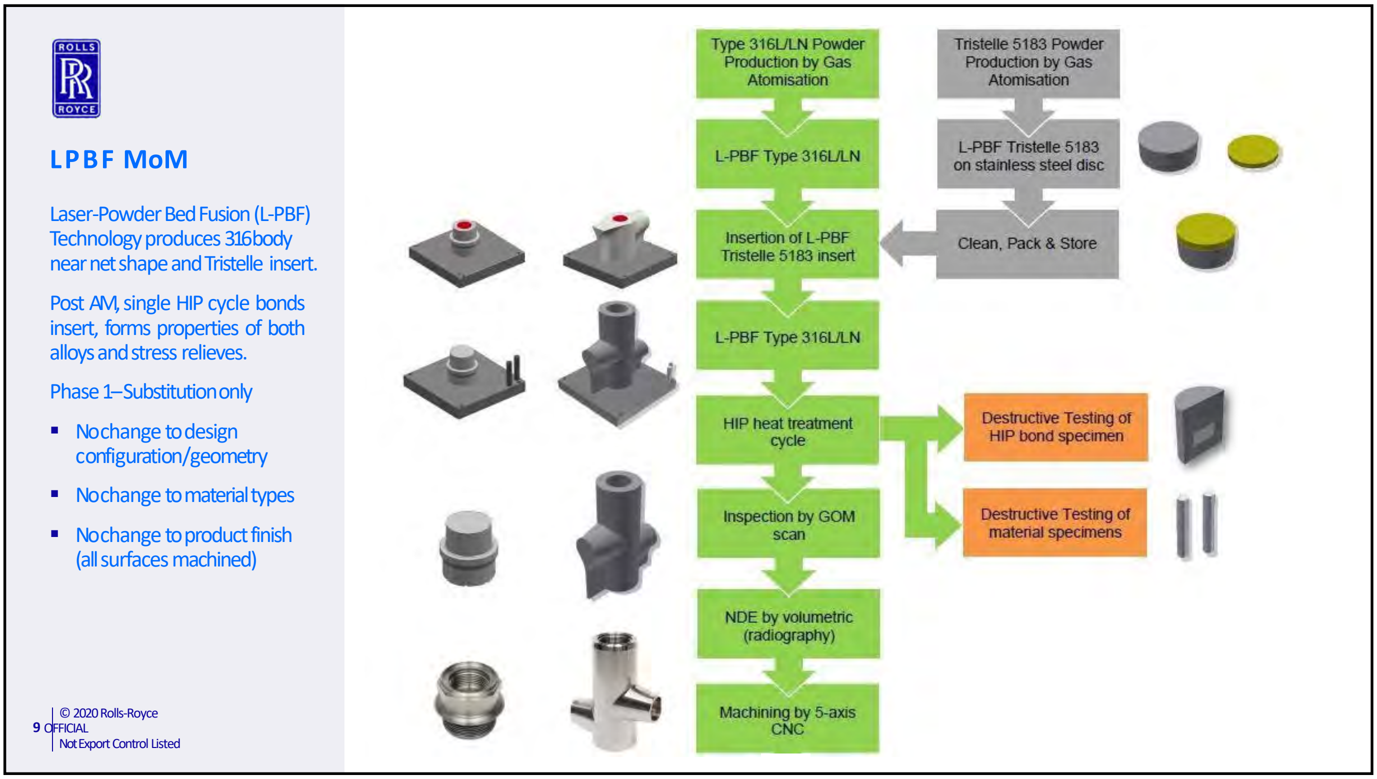
Mass of forging 10x mass of final part

18 month lead time for HIP insert

Part not required – 100% machined out

Costs for cleaning & welding prior to HIP

Time & cost for significant stage machining



ROLLS ROYCE

## LPBF MoM

Laser-Powder Bed Fusion (L-PBF) Technology produces 316body near net shape and Tristelle insert.

Post AM, single HIP cycle bonds insert, forms properties of both alloys and stress relieves.

Phase 1–Substitution only

- No change to design configuration/geometry
- No change to material types
- No change to product finish (all surfaces machined)

Type 316L/LN Powder Production by Gas Atomisation

L-PBF Type 316L/LN

Insertion of L-PBF Tristelle 5183 insert

L-PBF Type 316L/LN

HIP heat treatment cycle

Inspection by GOM scan

NDE by volumetric (radiography)

Machining by 5-axis CNC

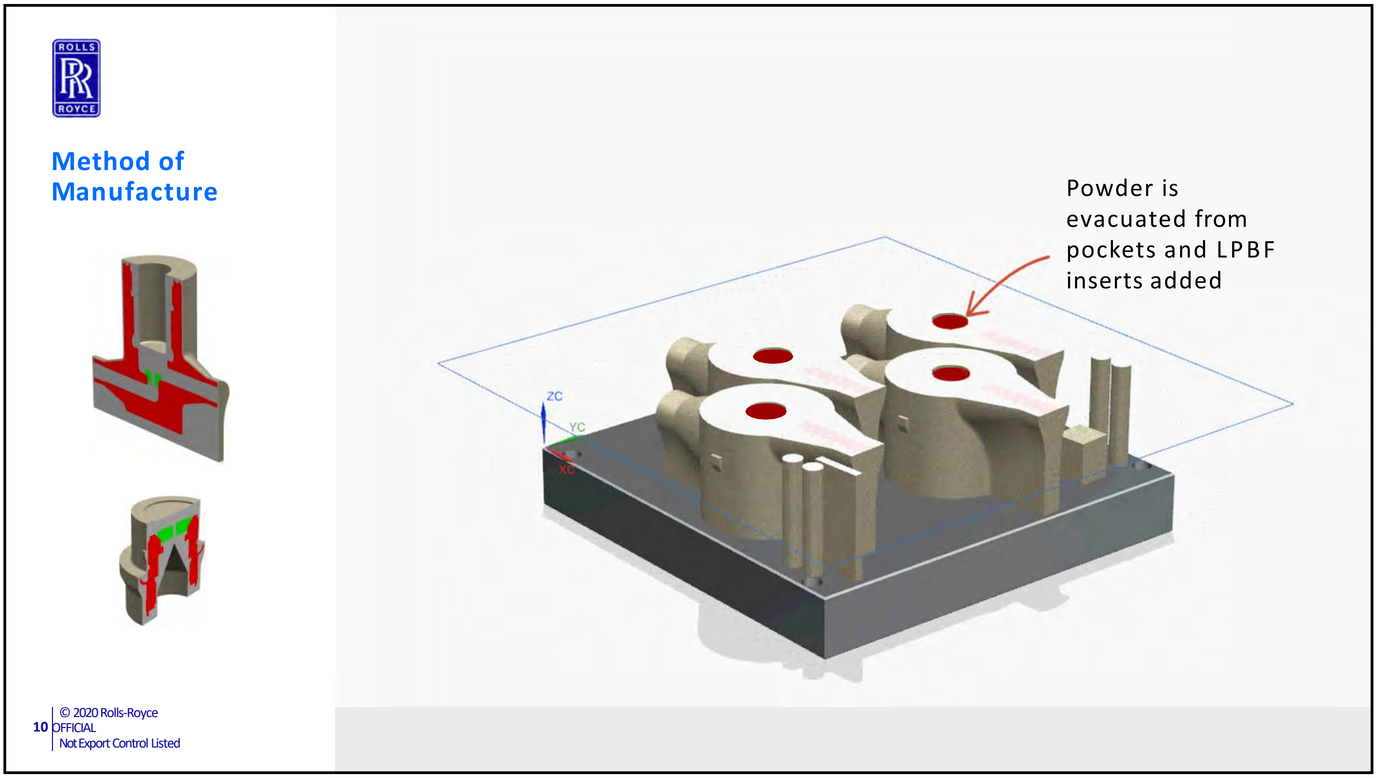
Tristelle 5183 Powder Production by Gas Atomisation

L-PBF Tristelle 5183 on stainless steel disc

Clean, Pack & Store

Destructive Testing of HIP bond specimen

Destructive Testing of material specimens



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## Method of Manufacture

Powder is evacuated from pockets and LPBF inserts added

## What are the benefits?

Still at Phase 1–simple substitution only.

Phase 2–Enhanced substitution programmes will deliver further benefits to cost and delivery.

- In-process monitoring
- Justification of as-built surfaces

**Leadtime Reduction**

- Removal of a HIP cycle
- Reduced machining steps and timescales

**Cost Reduction**

- Simplification of manufacturing method
- Removal of extensive machining operations
- Reduced raw material inventory

**Collaboration**

Rolls-Royce leading on AM with key partners across exchange programme

**Materials**

- AM material properties meet specification requirements
- Materials types applicable to broad product range

**Quality Assurance**

Quality assurance of metallic powder and product (control samples/HIP bond specimens)

**Innovation**

Encapsulation principle patent – exploitation opportunities against broad product range

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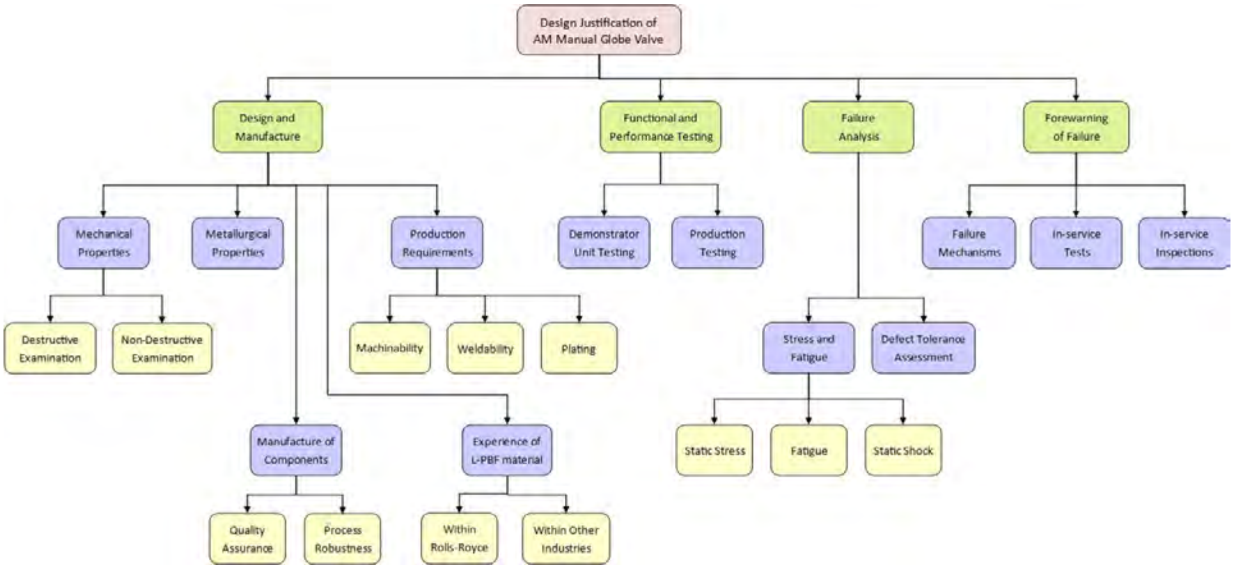
# 03

# Justification Strategy

Beyond-code approach to justification based on TAGSI multi-legged structure: design and manufacture, functional testing, failure analysis & forewarning of failure.

## Design Justification Strategy



Design Justification of AM Manual Globe Valve

Design and Manufacture

Functional and Performance Testing

Failure Analysis

Forewarning of Failure

Mechanical Properties

Metallurgical Properties

Production Requirements

Demonstrator Unit Testing

Production Testing

Failure Mechanisms

In-service Tests

In-service Inspections

Destructive Examination

Non-Destructive Examination

Machinability

Weldability

Plating

Stress and Fatigue

Defect Tolerance Assessment

Manufacture of Components

Experience of L-PBF material

Static Stress

Fatigue

Static Shock

Quality Assurance

Process Robustness

Within Rolls-Royce

Within Other Industries

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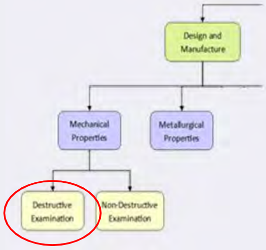
## Leg 1 - Design & Manufacture

Mechanical, metallurgical & corrosion testing



Design and Manufacture

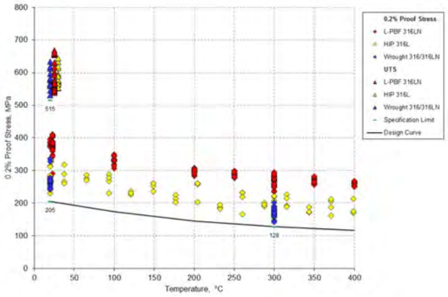
Mechanical Properties

Metallurgical Properties

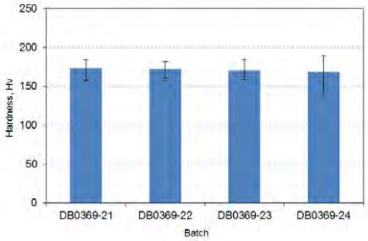
Destructive Examination

Non-Destructive Examination

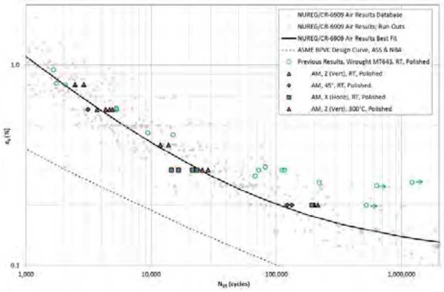
### UTS and Proof Stress



### Hardness



### Fatigue



### Tristelle 5183 to 316 St St Bond Line

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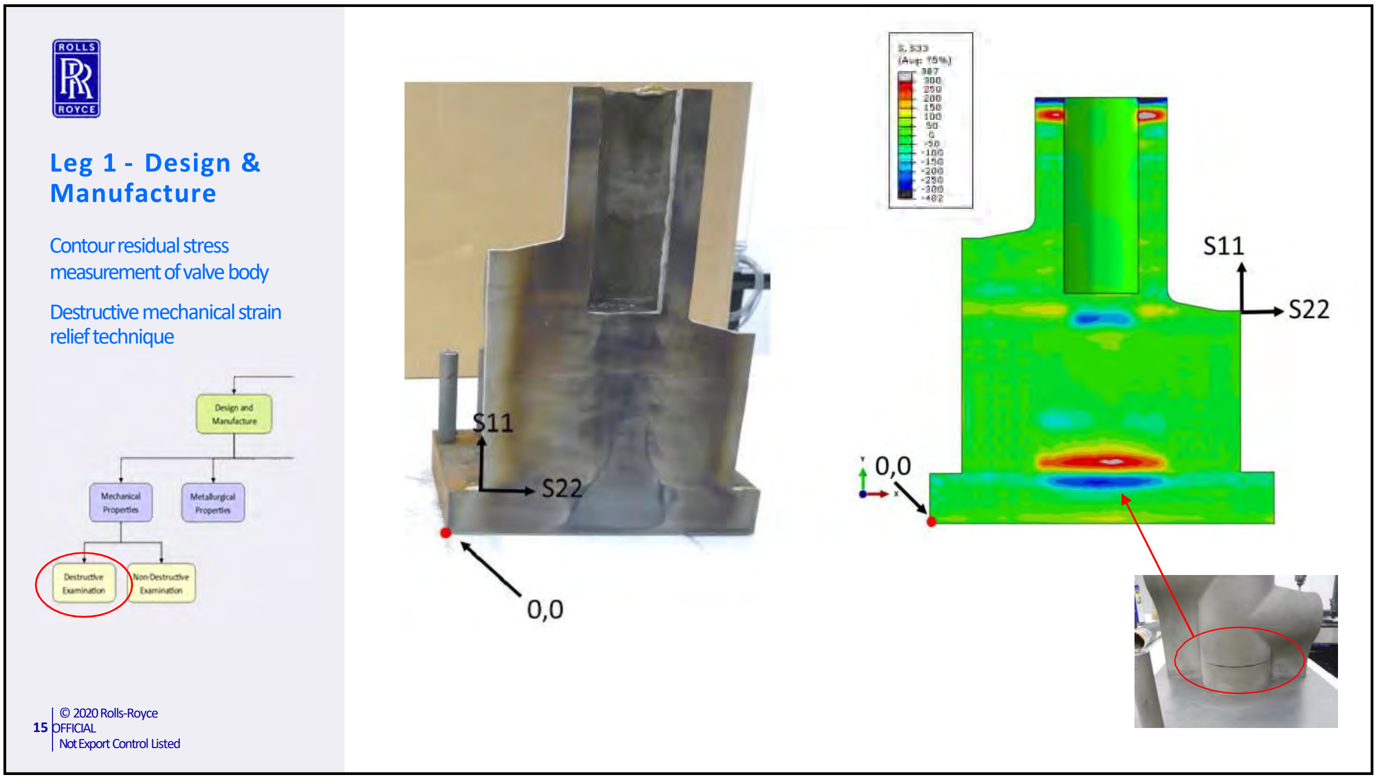
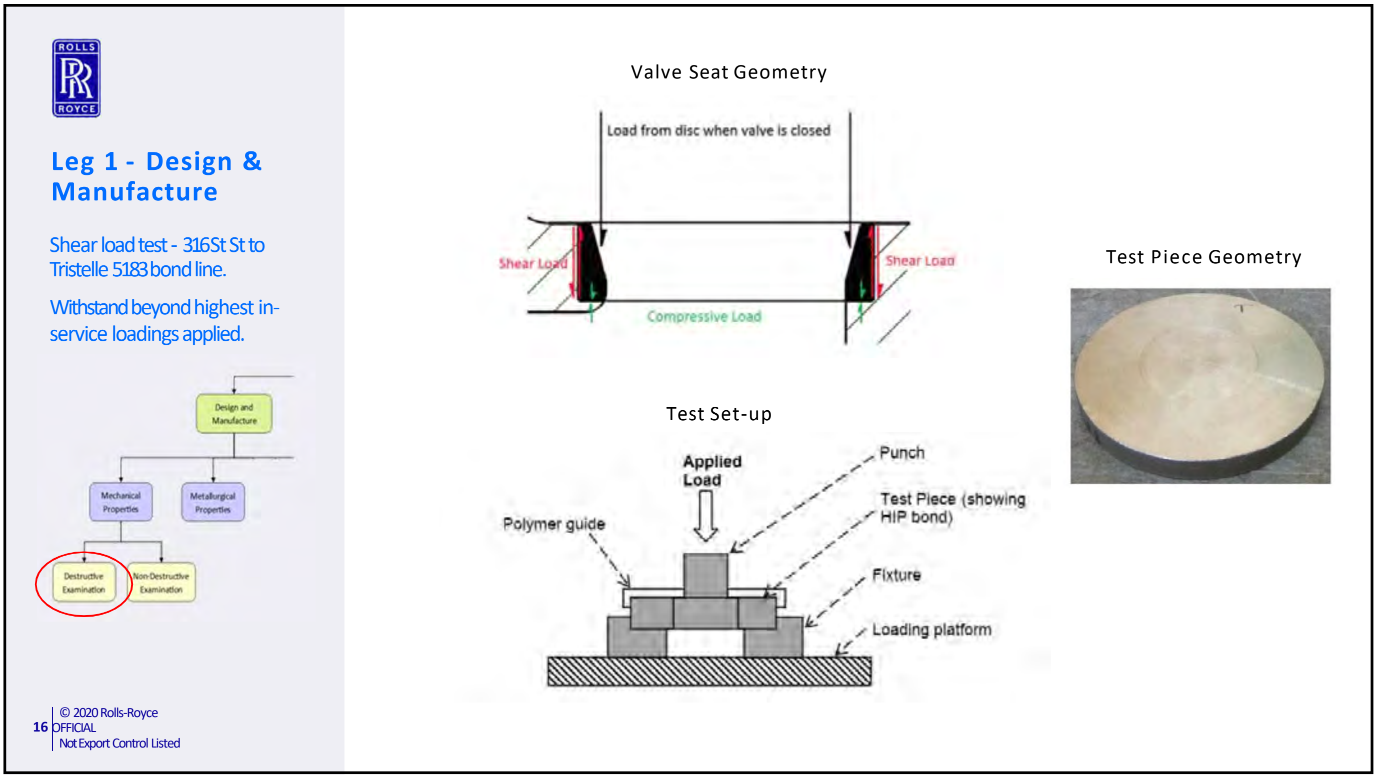


## Leg 1 - Design & Manufacture

Contour residual stress measurement of valve body

Destructive mechanical strain relief technique

15



## Leg 1 - Design & Manufacture

Shear load test - 316St St to Tristelle 5183 bond line.

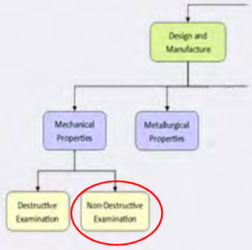
Withstand beyond highest in-service loadings applied.

16

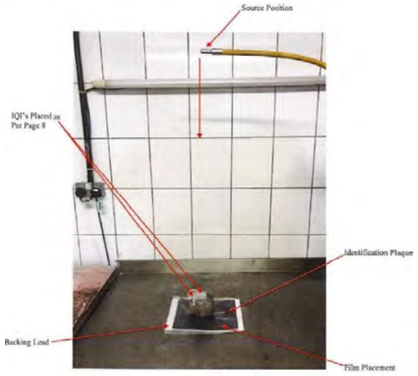
## Leg 1 - Design & Manufacture

Volumetric on-destructive testing – radiography

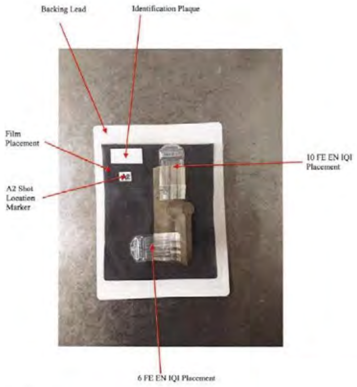
Surface visual examination



50mm MGV Bonnet



15mm MGV Body

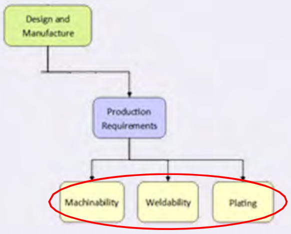


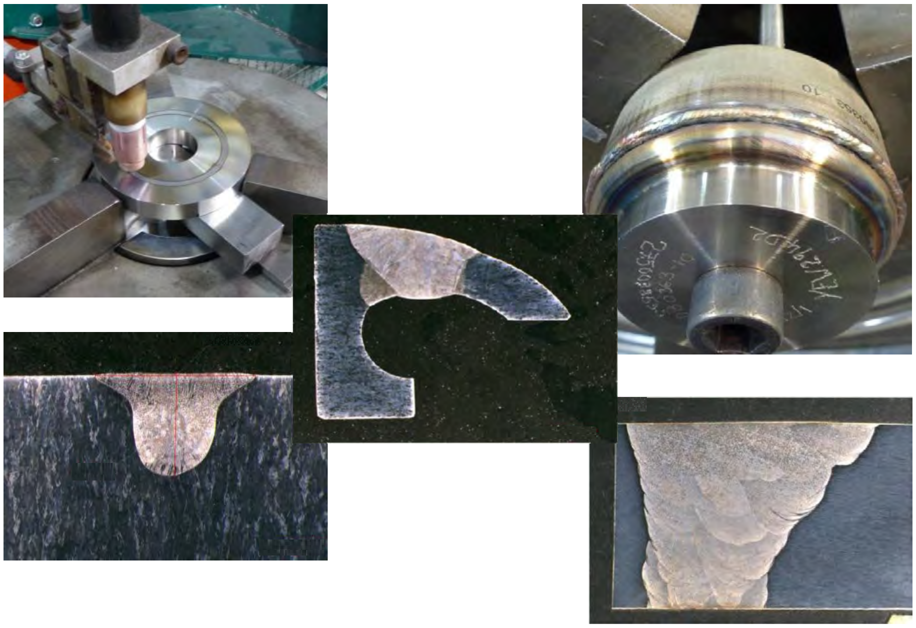
- Current Method – Wrought/HIP bar examined using Ultrasonic Testing
- AM Method – Radiographic Testing based on near-net-shape and start-of-Life defect characterisation
- Defect characterisation by expert elicitation used to guide inspection technique and inspection acceptance criteria
- Future expectation for though-process melt pool monitoring to remove traditional volumetric examination

## Leg 1 - Design & Manufacture

Production Requirements:

- Weldability Trials
- Canopy Weld Trials
- Pipework Stub Trials
- Machining, grinding, plating methods trialled





## Leg 2 – Functional & Performance Testing

| Test Type | Description | Component | Size | Comparison Wrought Valve | Production Test |
|---|---|---|---|---|---|
| Hydrostatic | Standard Hydro | Body only | 15mm✓<br>25mm✓<br>50mm✓ | No | Yes |
| | Valve Half Open | Full Assembly | 15mm✓<br>50mm✓ | No | Yes |
| | Valve Closed | Full Assembly | 15mm✓<br>50mm✓ | No | Yes |
| Ultimate Hydrostatic | Ultimate Pressure Test | Body only | 50mm only✓ | Yes | No |
| Performance | Cold | Full Assembly | 15mm✓<br>50mm✓ | No | Yes |
| | Hot | Full Assembly | 15mm✓<br>50mm✓ | No | No |
| | Repeat Cold | Full Assembly | 15mm✓<br>50mm✓ | No | No |
| Endurance | Hot | Full Assembly | 15mm only✓ | No | No |
| Shock | Cold | Full Assembly | 50mm only✓ | Yes | No |
| Fatigue | Thermal Shock | Full Assembly | 50mm only✓ | Yes | No |

---

## Leg 2 – Functional & Performance Testing

Ultimate Pressure Tests

Explore full capability of AM pressure boundary on MGV body

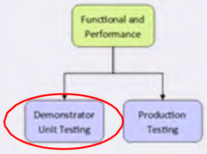
>2000bar applied without failure

Representative material strain rates

### Wrought and AM MGV Bodies Pre-burst Test

### Wrought and AM MGV Bodies Post-burst Test

## Leg 2 – Functional & Performance Testing



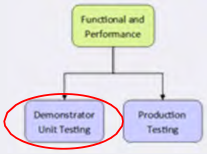
Shock Loading Tests

Shock test to assess integrity of key MGV regions during shock event

Three test orientations on both AM and Wrought MGVs

Pre and post test functional checks successful on each MGV

## Leg 2 – Functional & Performance Testing

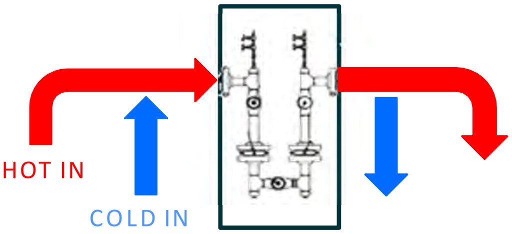


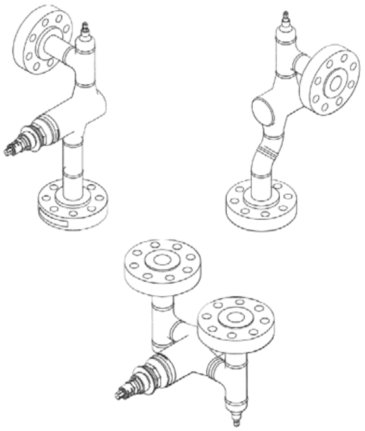
Thermal Fatigue Test

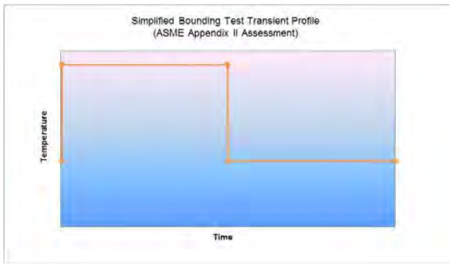
ASME III, Appendix II assessment used to specify extended thermal cycle test

2x AM and 1x Wrought MGV tested

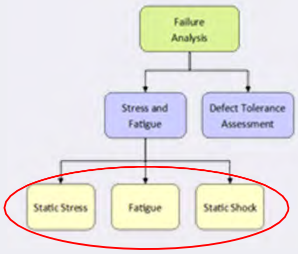
Valves functionally tested after extended life simulation

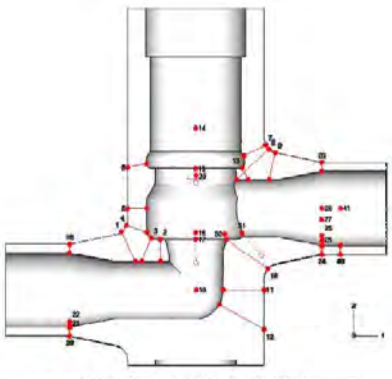




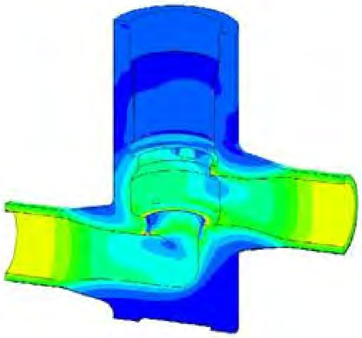


## Leg 3 – Failure Analysis



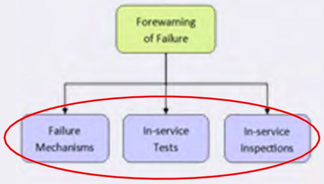


Location of Stress Classification Lines for ASME Assessment



- Design, hydrostatic and level A conditions assessed for limiting valve location
- Fatigue assessment using cycling counting method and static shock assessment
- Leg 1 – Material test data confirms analysis inputs remain appropriate
- Leg 2 – Functional/performance testing provides further assurance in theoretical analysis

## Leg 4 – Forewarning of Failure



- FMEA Review
- System Hydrostatic and Valve Functional Tests
- In-service Inspections
  - External for evidence of corrosion/EAC
  - Internal for evidence of bond line corrosion and condition of seat contact line
- Potential for additional volumetric NDE in-service (Remote RT, Phased Array UT)
  - Development of Techniques
  - ALARP study

# 04

## Where Next?

Increasing applications across plant

Strategic alloy development

Facility commissioning

Increased size, capacity and build speed

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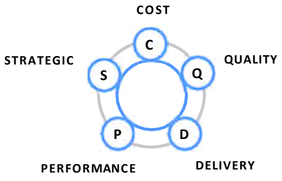
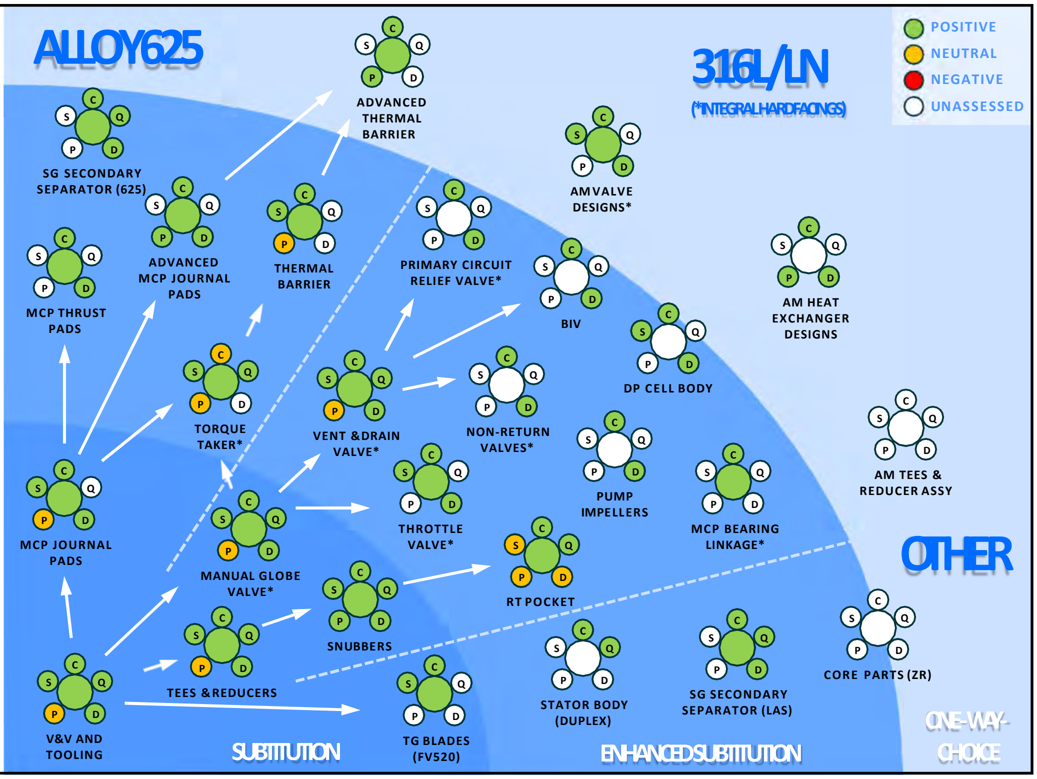
## LPBF Component Strategy

Commodities engaged on opportunities for AM to deliver benefits





ALLOY625

316L/LN

(*INTEGRAL HARDFACINGS)

OTHER

- 🟢 POSITIVE
- 🟡 NEUTRAL
- 🔴 NEGATIVE
- ○ UNASSESSED

ADVANCED THERMAL BARRIER

SG SECONDARY SEPARATOR (625)

ADVANCED MCP JOURNAL PADS

THERMAL BARRIER

PRIMARY CIRCUIT RELIEF VALVE*

AM VALVE DESIGNS*

MCP THRUST PADS

BIV

AM HEAT EXCHANGER DESIGNS

DP CELL BODY

TORQUE TAKER*

VENT & DRAIN VALVE*

NON-RETURN VALVES*

PUMP IMPELLERS

AM TEES & REDUCER ASSY

MCP JOURNAL PADS

MANUAL GLOBE VALVE*

THROTTLE VALVE*

MCP BEARING LINKAGE*

RT POCKET

SNUBBERS

TEES & REDUCERS

V&V AND TOOLING

TG BLADES (FV520)

STATOR BODY (DUPLEX)

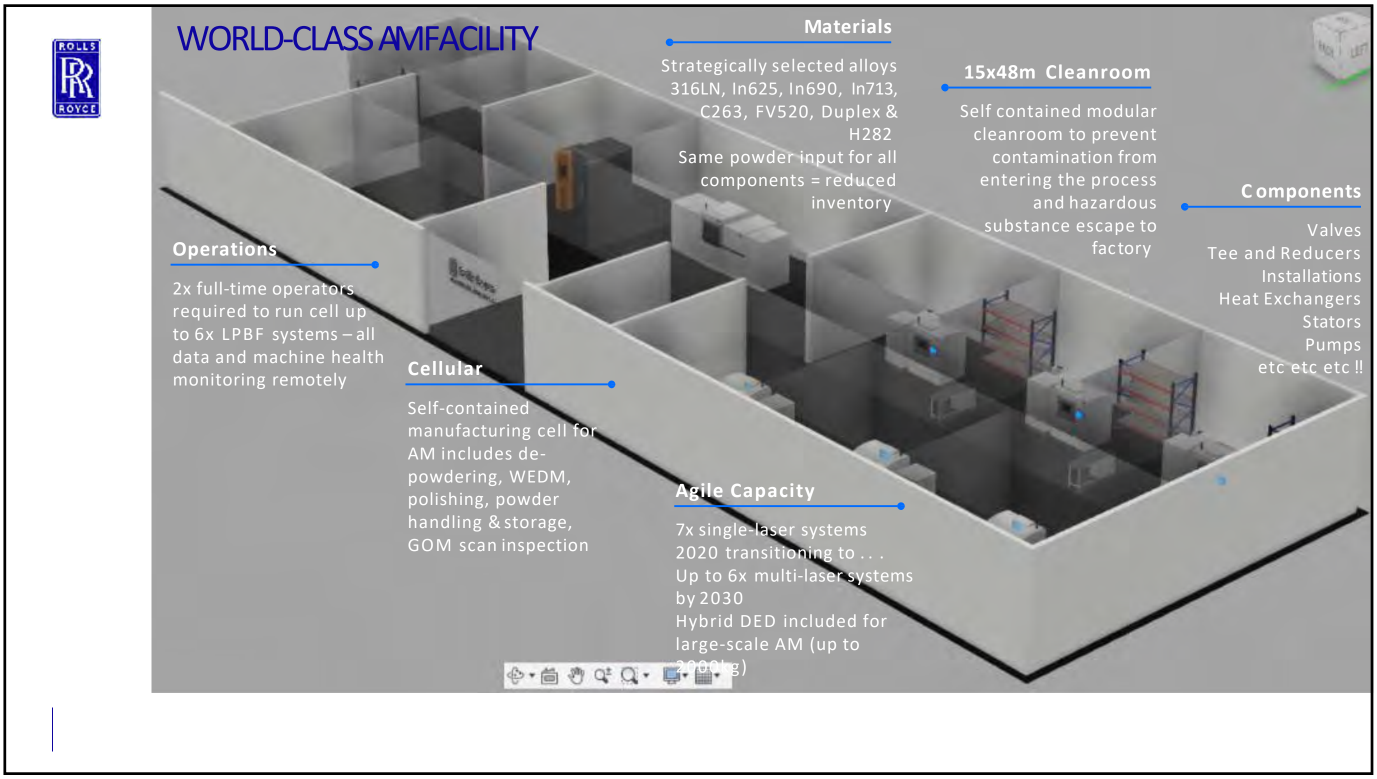
SG SECONDARY SEPARATOR (LAS)

CORE PARTS (ZR)

SUBTITUTION

ENHANCED SUBTITUTION

ONE-WAY-CHOICE



## WORLD-CLASS AMFACILITY

**Materials**

Strategically selected alloys 316LN, In625, In690, In713, C263, FV520, Duplex & H282
Same powder input for all components = reduced inventory

**15x48m Cleanroom**

Self contained modular cleanroom to prevent contamination from entering the process and hazardous substance escape to factory

**Components**

- Valves
- Tee and Reducers
- Installations
- Heat Exchangers
- Stators
- Pumps
- etc etc etc !!

**Operations**

2x full-time operators required to run cell up to 6x LPBF systems – all data and machine health monitoring remotely

**Cellular**

Self-contained manufacturing cell for AM includes de-powdering, WEDM, polishing, powder handling & storage, GOM scan inspection

**Agile Capacity**

7x single-laser systems
2020 transitioning to . . .
Up to 6x multi-laser systems by 2030
Hybrid DED included for large-scale AM (up to 2000kg)

# 05

# Questions & Discussion

**Thank you**

NAVAL NUCLEAR LABORATORY | Technology

# Fatigue and Mechanical Properties of Laser Powder Bed Fusion 316L Stainless Steel

**Steve Attanasio, Chelsea Snyder, and Tressa White**
*Naval Nuclear Laboratory – Schenectady, NY*

**NRC workshop on Advanced Manufacturing**
*December 7-10, 2020*

The Naval Nuclear Laboratory is operated for the U.S. Department of Energy by Fluor Marine Propulsion, LLC,
a wholly owned subsidiary of Fluor Corporation.

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# Naval Nuclear Propulsion Program:

## *A History of Success*

**Over 80 Nuclear-Powered Ships**

**Over 167 Million Miles Safely Steamed**

# Naval Nuclear Laboratory (NNL) Research Laboratory Sites

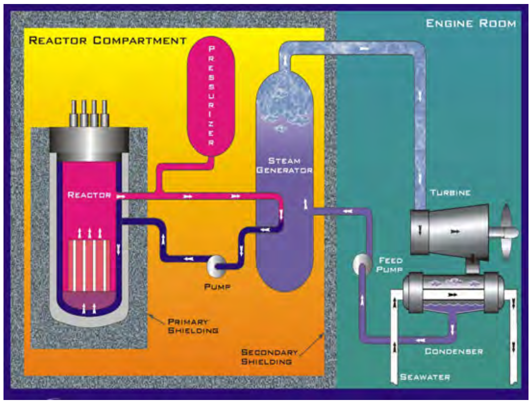
Two Laboratory Sites:

- **Headquarters for NNL Operations**
- **Centers for Design and Engineering**
- **Laboratory, Testing and Experimental Facilities**
- **Operated by FMP**

# Naval Nuclear Laboratory Expertise

## NNPP Reactor and Propulsion Plant Designs, Equipment, and Support Require Expertise In:

- **Acoustics**
- **Materials Science**
- **Reactor Engineering**
- **Instrumentation & Control**



- **Power Electronics and Distribution**
- **Experimental Engineering**
- **Scientific Computations**
- **Information Technology**

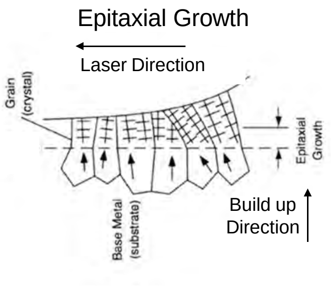
# NNL Interests in Metal Additive Manufacturing (AM)

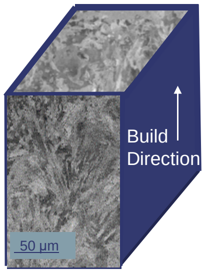
- **The capabilities of metal AM processes have spurred changes to fabrication methods in industries such as aerospace and medical**
  - *More modest changes to date in other areas such as the nuclear industry*
- **Prospective benefits include manufacturing and performance gains**
  - *Delivery time, hard-to-source parts, part consolidation, improved design*
  - *Tooling, rapid prototyping, repairs, hard-to-fabricate parts, tailored design*

*Materials of interest include 316L SS and Alloy 625*
*Components of interest include valves and pump hardware*

# Laser Powder Bed Fusion (L-PBF)

- L-PBF 316L contains long grains and crystallographic texture in the build direction due to epitaxial growth across layers





# Build Parameters and Chemistry for 316L Build

**Naval Nuclear Laboratory (NNL) Build**
**20 µm layer**
**EOS M290**
**Hot Isostatic Press (HIP)**
**Porosity – Witness cylinder <0.05%**

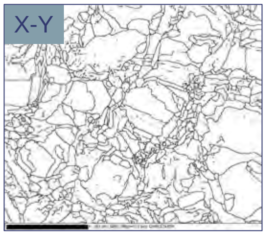
**External Vendor (EV) Build**
**40 µm layer**
**EOS M290**
**Hot Isostatic Press (HIP)**
**Porosity – Witness cylinder <0.03%**

| | ASTM F3184 | ASTM A182 | EV As-Built | NNL As-Built | Bar Stock |
|---|---|---|---|---|---|
| Iron | Balance | Balance | Balance | Balance | Balance |
| Chromium | 16.0 – 18.0 | 16.0 – 18.0 | 17.88 - 17.92 | 17.64 - 17.98 | 16.68 |
| Nickel | 10.0 – 14.0 | 10.0 – 15.0 | 12.95-12.99 | 13.15 - 13.40 | 10.62 |
| Carbon | 0.030, max. | 0.030, max. | 0.013 | 0.015 - 0.017 | 0.018 |
| Copper | – | – | 0.02 | 0.03 | 0.36 |
| Manganese | 2.00, max. | 2.00, max. | 1.22 | 0.84 - 0.87 | 1.38 |
| Molybdenum | 2.00 – 3.00 | 2.00 - 3.00 | 2.37 | 2.38 - 2.43 | 2.05 |
| Nitrogen | – | 0.10, max. | 0.083 - 0.084 | 0.090 - 0.091 | 0.045 |
| Oxygen | – | – | 0.014 - 0.015 | 0.020 - 0.026 | -- |
| Phosphorus | 0.045, max. | 0.045, max. | 0.009 | 0.005 - 0.007 | 0.026 |
| Sulfur | 0.030, max. | 0.030, max. | 0.004 - 0.005 | 0.004 - 0.005 | 0.0285 |
| Silicon | 1.00, max. | 1.00, max. | 0.78 - 0.80 | 0.70 - 0.72 | 0.28 |
| Cobalt | – | – | 0.02 | 0.03 | 0.28 |
| Boron | – | – | <0.005 | <0.005 | -- |
| Tantalum | – | – | <0.01 | <0.01 | -- |

# Microstructure

- Similar grain size and structure between builds
- Precipitate size and locations (primarily along grain boundaries) similar between builds
- Texture was stronger in the NNL build

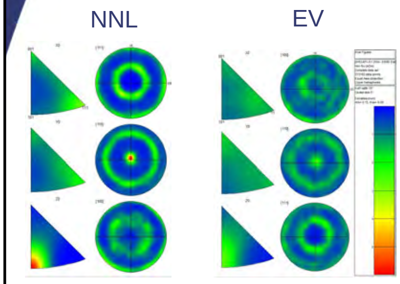
Grain Sizing

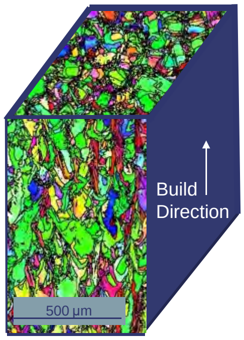


Grain Size 19.5 µm
Aspect Ratio 3.4

Grain Size 25 µm
Aspect Ratio 3.4

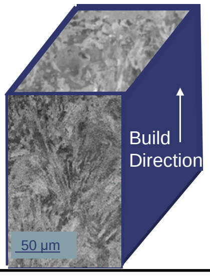
Texture

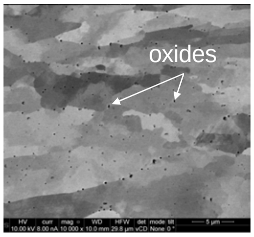


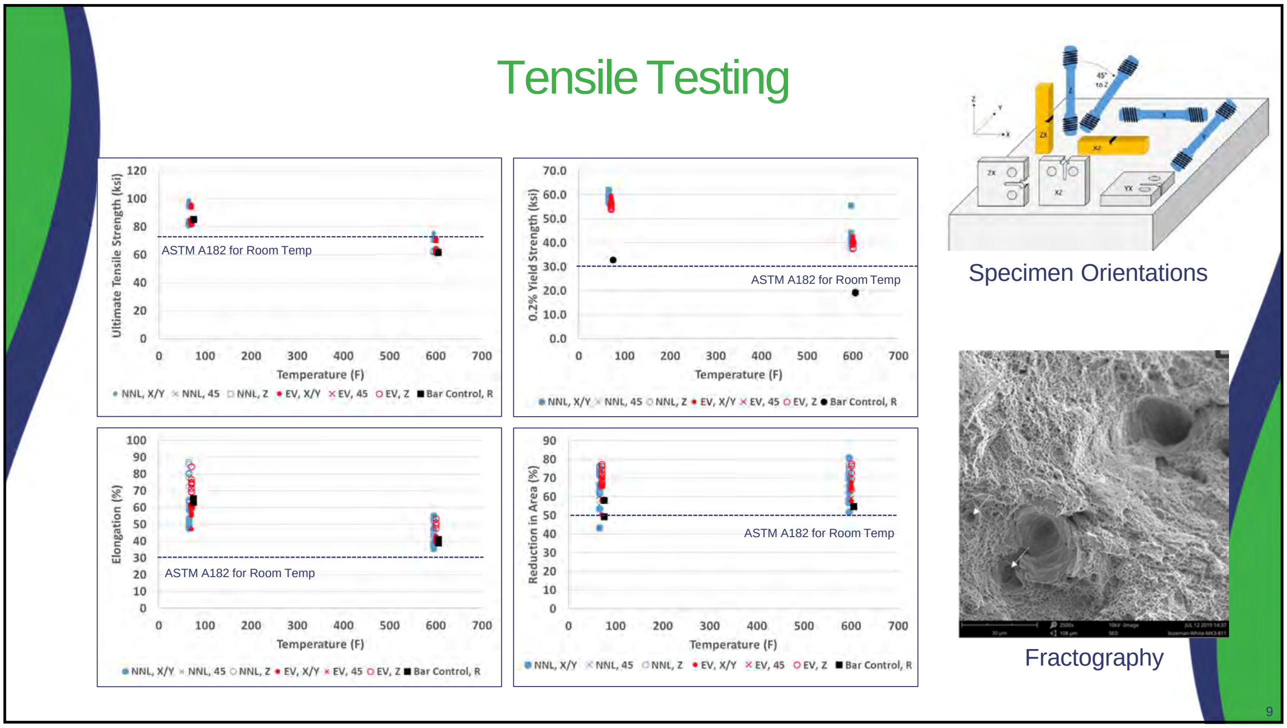


IPF-Z

Microstructure



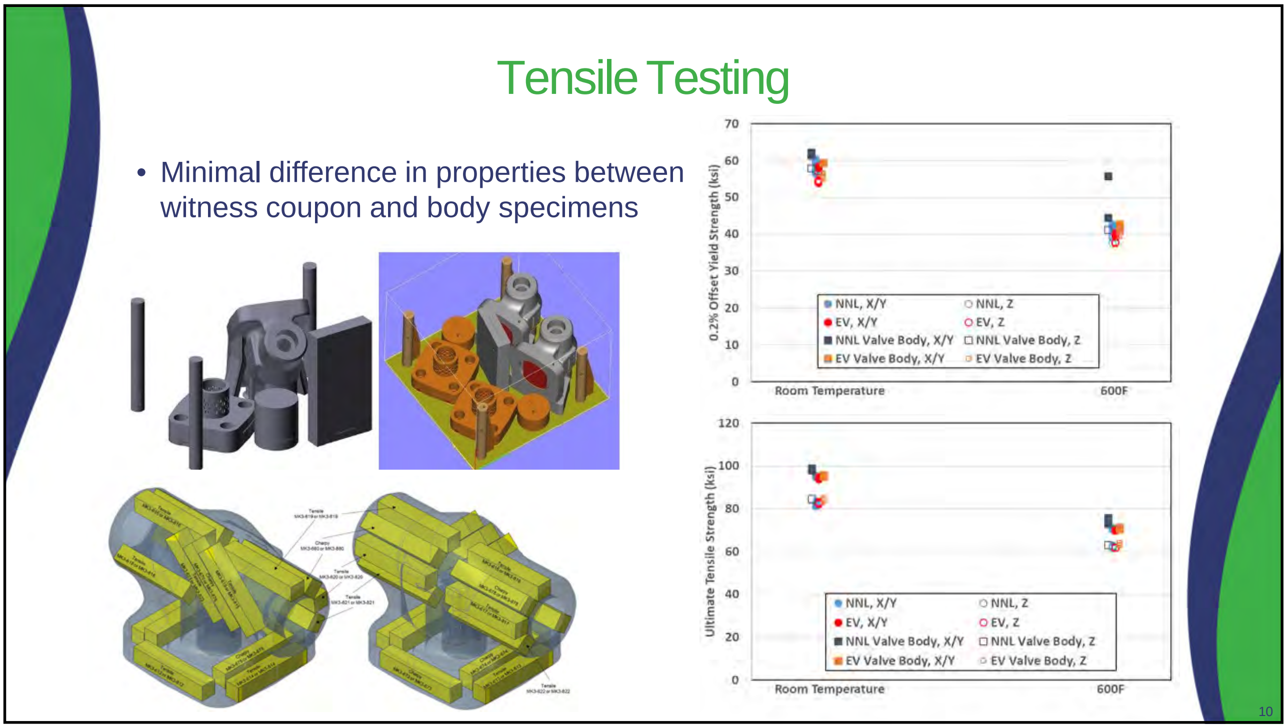




# Tensile Testing

Specimen Orientations

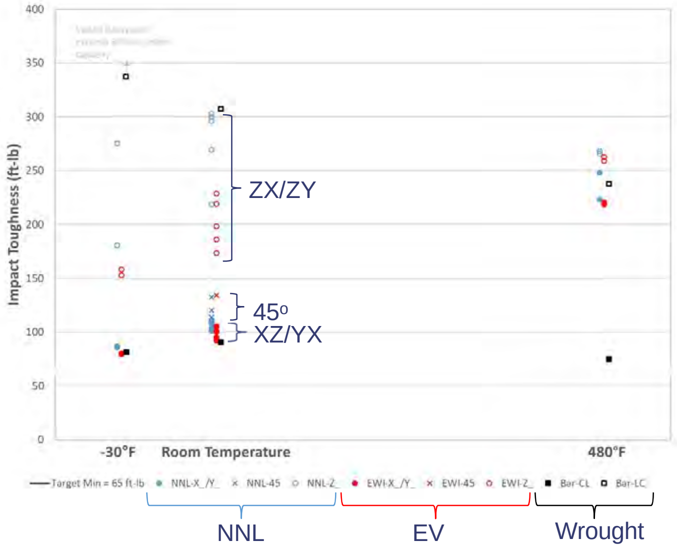
Fractography

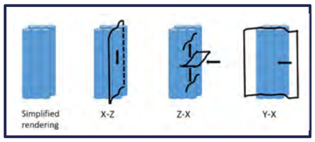


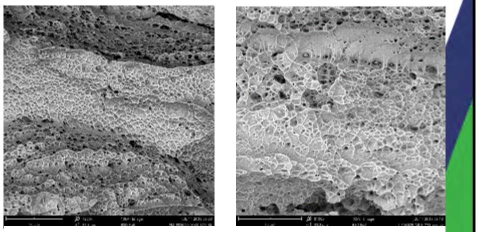
# Tensile Testing

- Minimal difference in properties between witness coupon and body specimens

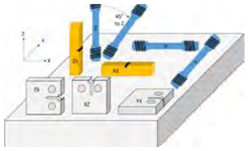
# Charpy Impact Toughness







Secondary Electron Microscopy (SEM) images of lowest energy fracture surfaces



Testing according to ASTM E23-16b

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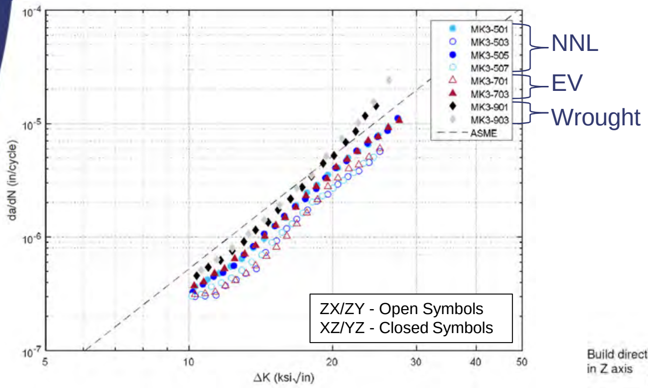
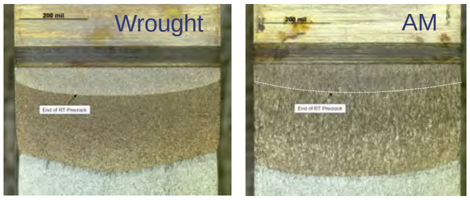
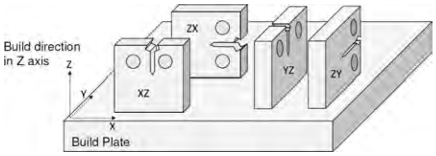
# 480°F Air Fatigue Crack Growth Testing

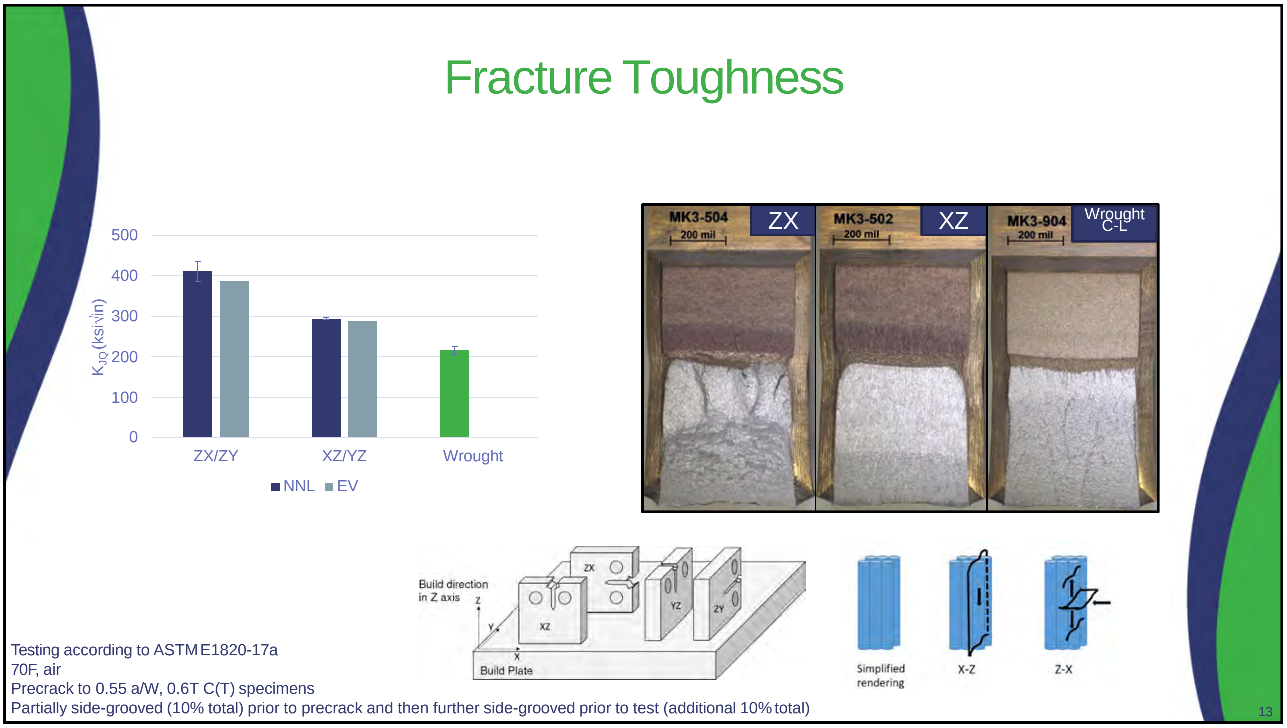




*Heat tint more difficult to see in AM material*

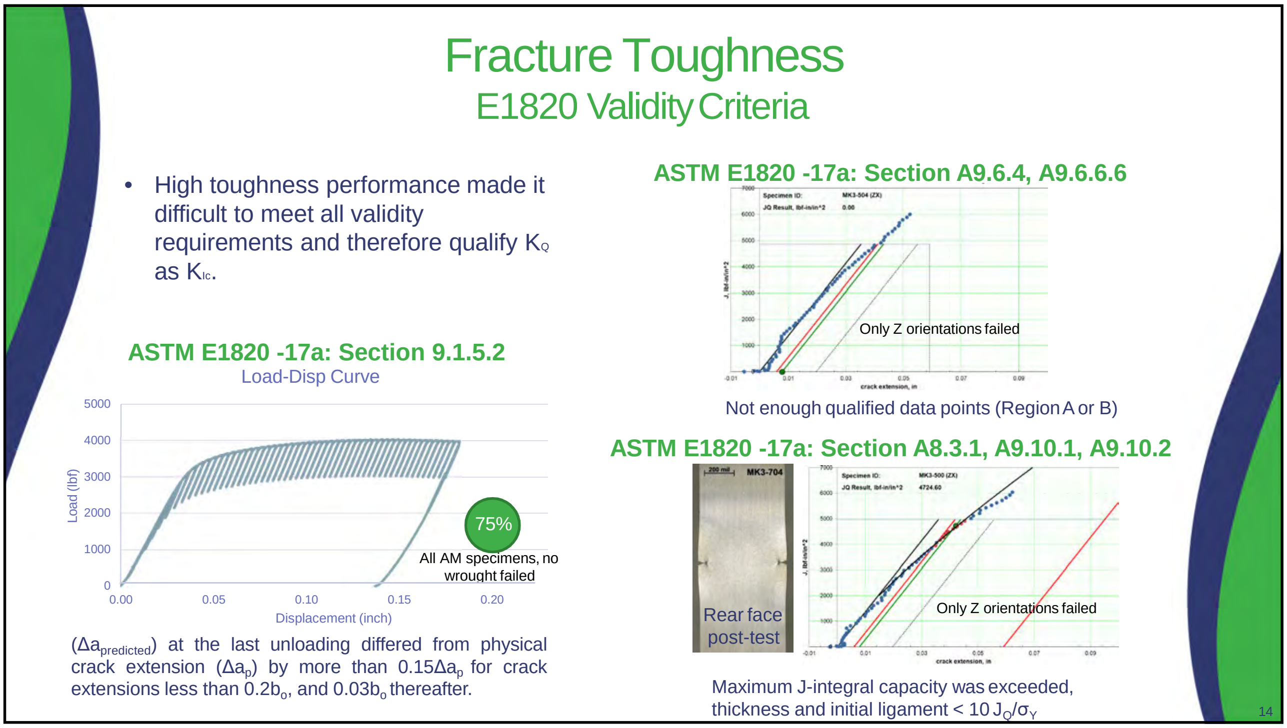


Testing according to ASTM E647-15ε1
Temperature: Precrack 70 °F air, Test 480 °F air
Stress Ratio: Precrack R = 0.1, Test R=0.3
Clip gage compliance method used
ASME Boiler and Pressure Code, Section XI, Article C-8410 for Austenitic Steels



# Fracture Toughness

Testing according to ASTM E1820-17a
70F, air
Precrack to 0.55 a/W, 0.6T C(T) specimens
Partially side-grooved (10% total) prior to precrack and then further side-grooved prior to test (additional 10% total)



# Fracture Toughness

## E1820 Validity Criteria

- High toughness performance made it difficult to meet all validity requirements and therefore qualify $K_Q$ as $K_{Ic}$.

### ASTM E1820 -17a: Section 9.1.5.2

Load-Disp Curve

All AM specimens, no wrought failed

($\Delta a_{predicted}$) at the last unloading differed from physical crack extension ($\Delta a_p$) by more than $0.15\Delta a_p$ for crack extensions less than $0.2b_o$, and $0.03b_o$ thereafter.

### ASTM E1820 -17a: Section A9.6.4, A9.6.6.6

Only Z orientations failed

Not enough qualified data points (Region A or B)

### ASTM E1820 -17a: Section A8.3.1, A9.10.1, A9.10.2

Rear face post-test

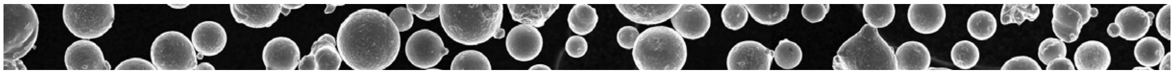
Only Z orientations failed

Maximum J-integral capacity was exceeded, thickness and initial ligament < 10 $J_Q/\sigma_Y$

# Summary

- Similar microstructure and properties were observed across vendors and when comparing test blocks to components
- Orientation effects caused by deposition process could be traced back to microstructural differences and texture in material
- Despite orientation effects, AM material performed as good as or better than wrought material
- Satisfactory performance of AM material gives confidence in qualification of methods for component fabrication and use of this material in applications

# Impact of Powder Supply Variation on Mechanical Properties for Additive Manufacture of Alloy 718



**Christopher Kantzos**

**NASA John H. Glenn Research Center at Lewis Field**
**Cleveland Ohio**

NRC Workshop on Advanced Manufacturing, Dec 2020

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## *SLM 718 Feedstock Variability Project – Intraagency Team:*
## *Supplier-to-supplier comparison 18 powders and 194 variables measured*

**Project Coordination**
- Chantal Sudbrack, Team Lead
- Cheryl Bowman, Team Lead
- Brian West

**Powder Characterization**
- Richard Boothe
- David Ellis
- Alejandro Hinojos (OSU)
- Chantal Sudbrack

**MSFC AM Fabrication**
- James Lydon
- Omar Mireles
- Ken Cooper

**Analytical Characterization**
- Rick Rogers
- Dereck Johnson
- Joy Buehler

**Heat Treat & Machining**
- Will Tilson
- MSFC Heat Treat Facility
- GRC Specimen Shop

**Microstructural Evaluation**
- Ivan Locci
- Tim Smith
- Chantal Sudbrack
- Alejandro Hinojos (OSU)
- Michael Kloesel (Cal Poly)
- Bethany Cook (CWRU)
- Jonathan Healy (CWRU)

**Mechanical Testing**
- Brad Lerch
- Aaron Thompson
- Jonathan Woolley
- GRC Testing Facility

**Fractography**
- Paul Chao (CMU)
- Ben Richards (NU)
- Ivan Locci

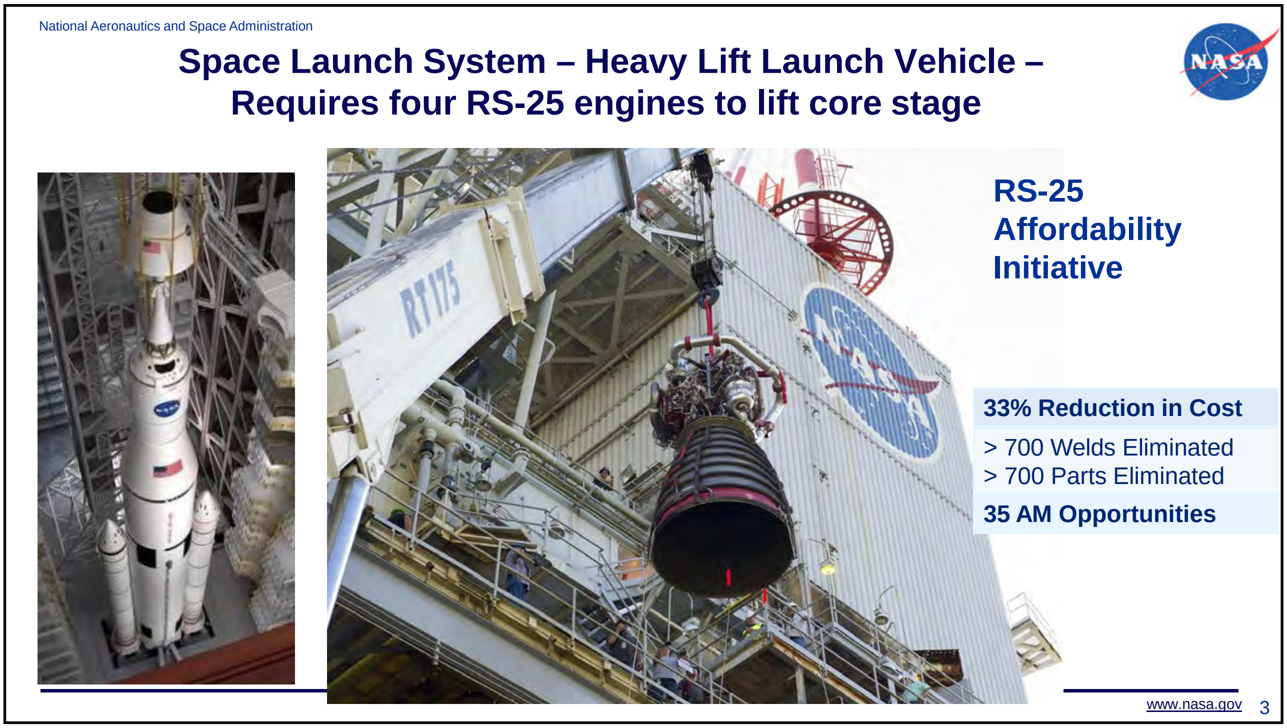
**Flammability (Flam.) Analysis**
- Jon Tylka (WSTF)
- White Sands Test Facility (WSTF)

**Flam. Characterization**
- Tim Smith
- Michael Kloesel (Cal Poly)

**PCA analysis**
- David Ellis

**Program Advisors**
- Kristin Morgan, Program Manager
- David Ellis
- Doug Wells
- Robert Carter

Published: Proceedings Superalloy 718 & Derivatives: E. Ott et al (Eds.), TMS (Pittsburgh), 89-113 (2018)



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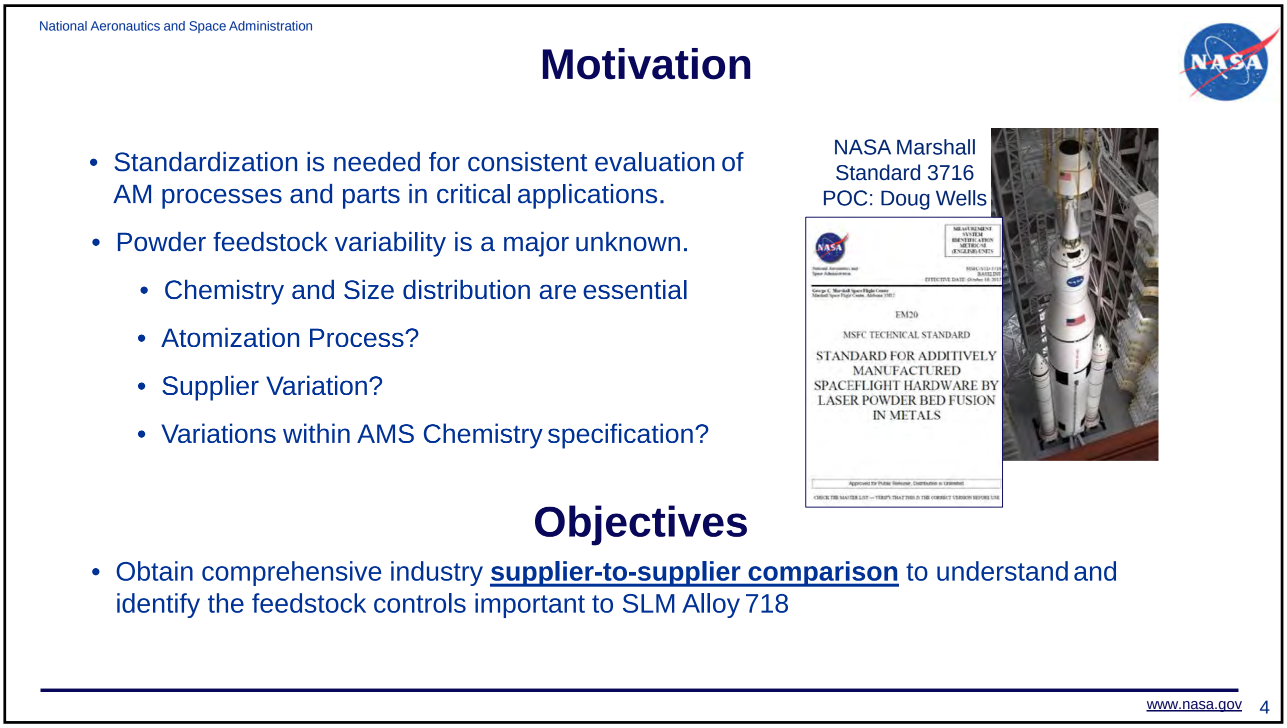
## Space Launch System – Heavy Lift Launch Vehicle – Requires four RS-25 engines to lift core stage

**RS-25 Affordability Initiative**

**33% Reduction in Cost**

> 700 Welds Eliminated
> 700 Parts Eliminated

**35 AM Opportunities**



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## Motivation

- Standardization is needed for consistent evaluation of AM processes and parts in critical applications.
- Powder feedstock variability is a major unknown.
    - Chemistry and Size distribution are essential
    - Atomization Process?
    - Supplier Variation?
    - Variations within AMS Chemistry specification?

NASA Marshall
Standard 3716
POC: Doug Wells

EM20

MSFC TECHNICAL STANDARD

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

## Objectives

- Obtain comprehensive industry **supplier-to-supplier comparison** to understand and identify the feedstock controls important to SLM Alloy 718

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# **Approach**: Survey wide range of off-the-shelf Alloy 718 powders

16 total powders acquired

- Supplier-to-supplier
- Lot-to-lot
- Gas and rotary atomized
- Ar and N cover gas
- Cut Size
- Once Reuse

**Standard ~10-45 µm SLM cuts (8 powders)**

**Standard ~15-45 µm SLM cuts (6 powders)**

**Undersized / oversized cuts**

**- G1: 0-22 Did not build**

**- G4: 45-90 Did not build well**

| ID | | Cut | Atomization | Gas |
|---|---|---|---|---|
| A1 | Supplier 1, Powder 1 | 15-45 | Gas | Ar |
| A2 | Supplier 1, Powder 2 | 10-45 | Gas | Ar |
| A3 | Supplier 1, Powder 3 | 10-45 | Gas | Ar |
| B1 | Supplier 2, Powder 1 | 15-45 | **Rotary** | Ar |
| C1 | Supplier 3, Powder 1 | 15-45 | Gas | **N** |
| D1 | Supplier 4, Powder 1 | 16-45 | Gas | Ar |
| D2 | Supplier 4, Powder 2 | 11-45 | Gas | Ar |
| E1 | Supplier 5, Powder 1 | 10-45 | Gas | **N** |
| E2 | Supplier 5, Powder 2 | 10-45 | Gas | **N** |
| F1 | Supplier 6, Powder 1 | 15-45 | Gas | Ar |
| F2 | Supplier 6, Powder 2 | 10-45 | Gas | Ar |
| G | Supplier 7: **G2:11-45** | **G3: 16 -45** | Gas | Ar |
| H1 | Supplier 8, Powder 1 | 10-45 | Gas | Ar |

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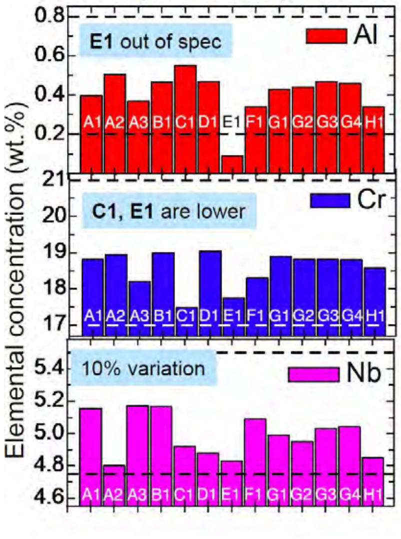
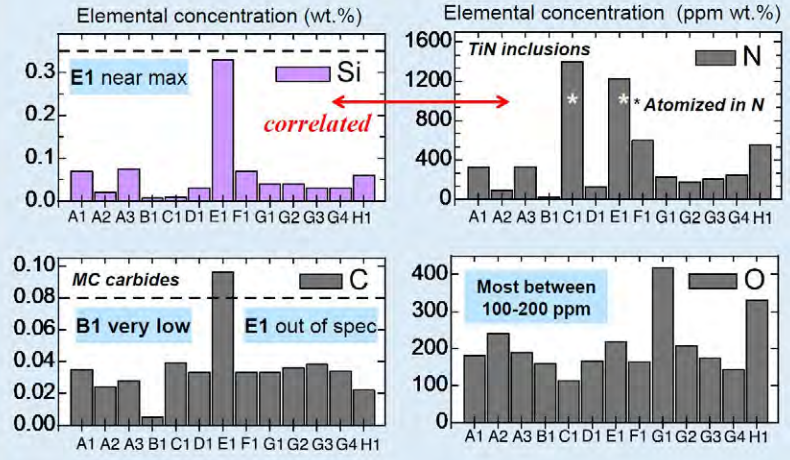
# Majority of powder compositions within AMS 5664 chemistry specification **B1** low C, **E1** high C, low Al

**Precipitate strengtheners**



**High trace impurity could lead to segregation, inclusions, & weldability issues**



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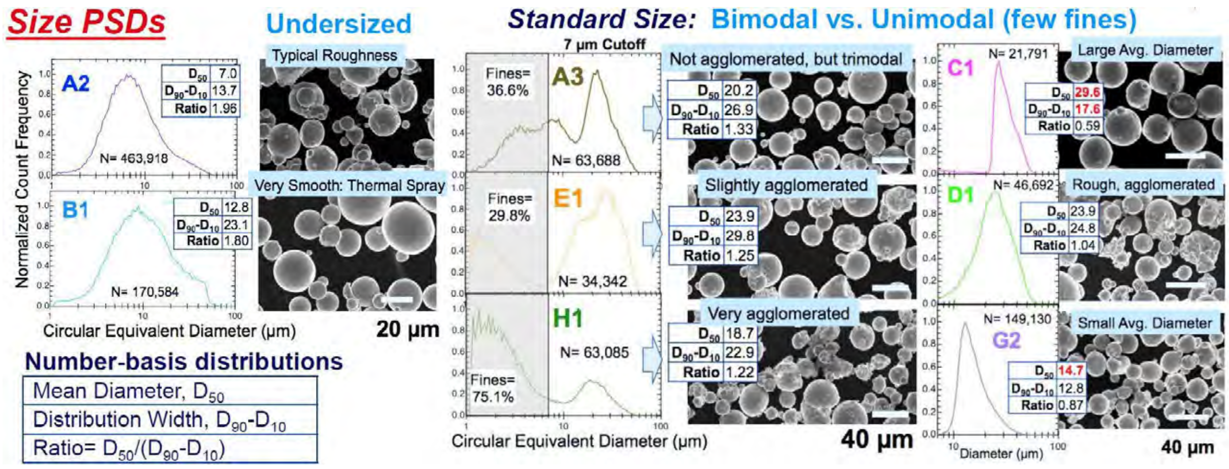
# Particles are all highly regular spheroids from all suppliers; Show distinct differences in roughness, fines, & agglomeration



*Powders with higher percentage of fines and agglomeration more prone to unplanned stops*

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# Processing Details

**NASA MSFC Concept Laser M1 machine:**

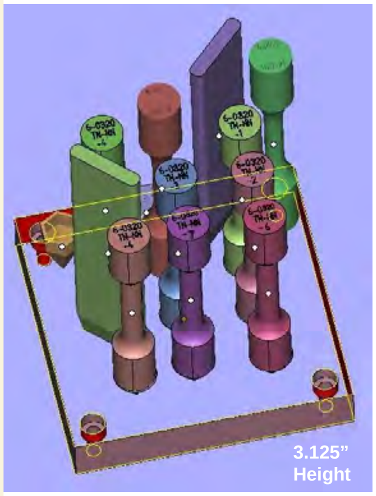
- Customized SLM 718 parameters for MSFC RS-25 projects
- Layer thickness: 30 µm
- Continuous scan strategy plus contours

***Visible refill lines***

Green-state "met" bar

**Small box configuration requires start /stop to refill piston with powder**

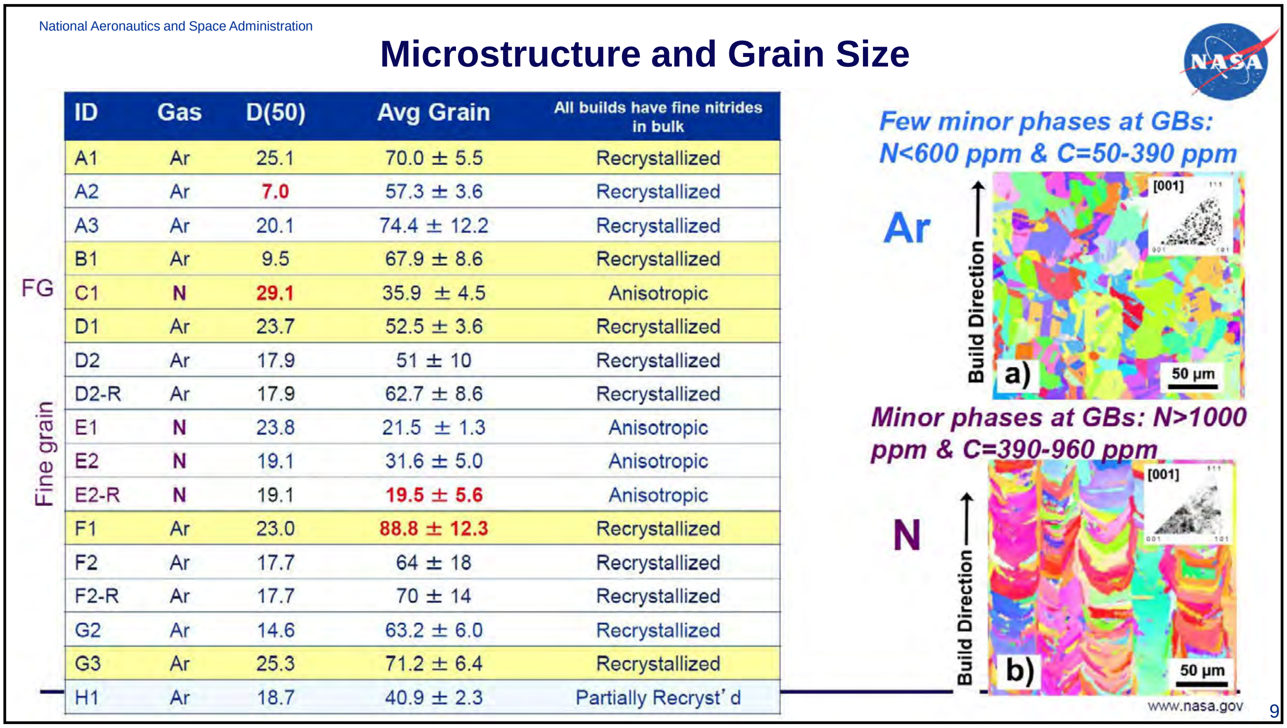
**Planned restarts**



- **Custom Build Parameters**
- **10 cm height**
- **Snap off construction; no stress relief**
- **HIP: >1100 C hot isostatic press**
- **AMS 5664 heat treat schedule**

- **Two microstructure bars**
  - **Green-state bar** → inherent to the process
  - **HIP + heat treated bar** → post process response

- **Eight Mechanical Test Specimens**
  - **Two Tensile specimen**
  - **Six High Cycle Fatigue specimens**
- **Six Flammability specimens**



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## Microstructure and Grain Size

| ID | Gas | D(50) | Avg Grain | All builds have fine nitrides in bulk |
|---|---|---|---|---|
| A1 | Ar | 25.1 | 70.0 ± 5.5 | Recrystallized |
| A2 | Ar | **7.0** | 57.3 ± 3.6 | Recrystallized |
| A3 | Ar | 20.1 | 74.4 ± 12.2 | Recrystallized |
| B1 | Ar | 9.5 | 67.9 ± 8.6 | Recrystallized |
| C1 | **N** | **29.1** | 35.9 ± 4.5 | Anisotropic |
| D1 | Ar | 23.7 | 52.5 ± 3.6 | Recrystallized |
| D2 | Ar | 17.9 | 51 ± 10 | Recrystallized |
| D2-R | Ar | 17.9 | 62.7 ± 8.6 | Recrystallized |
| E1 | **N** | 23.8 | 21.5 ± 1.3 | Anisotropic |
| E2 | **N** | 19.1 | 31.6 ± 5.0 | Anisotropic |
| E2-R | **N** | 19.1 | **19.5 ± 5.6** | Anisotropic |
| F1 | Ar | 23.0 | **88.8 ± 12.3** | Recrystallized |
| F2 | Ar | 17.7 | 64 ± 18 | Recrystallized |
| F2-R | Ar | 17.7 | 70 ± 14 | Recrystallized |
| G2 | Ar | 14.6 | 63.2 ± 6.0 | Recrystallized |
| G3 | Ar | 25.3 | 71.2 ± 6.4 | Recrystallized |
| H1 | Ar | 18.7 | 40.9 ± 2.3 | Partially Recryst’d |

FG

Fine grain

*Few minor phases at GBs: N<600 ppm & C=50-390 ppm*

*Minor phases at GBs: N>1000 ppm & C=390-960 ppm*

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## Mechanical Property Evaluation

**Screen room temperature mechanical behavior**

**As-Fabricated (AF) vs. Low Stress-Ground (LSG) Surface Conditions**

- **One tensile test per surface condition**
  - **Strain control up to 2% then stroke control at equivalent strain rate**

- **Three HCF tests per surface condition at 20 Hz and $R_\sigma$= -1**
  - **Targeted 1 million cycle averages, Runouts above 10 million**
  - **Stress amplitudes of 271 MPa (40 ksi) for AF and 464 MPa (67 ksi) for LSG**

**All mechanical testing performed after HIP (1160 C) + Soln (1065 C) + Precipitation Aging (760 C, 650 C)**

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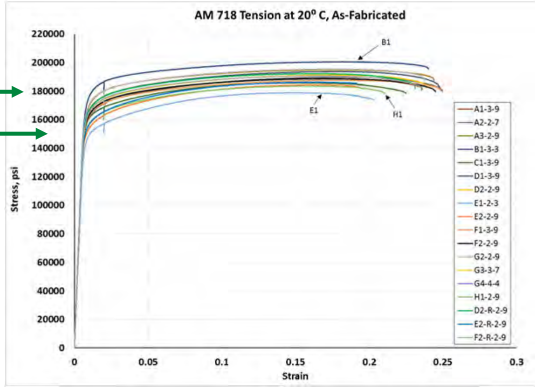
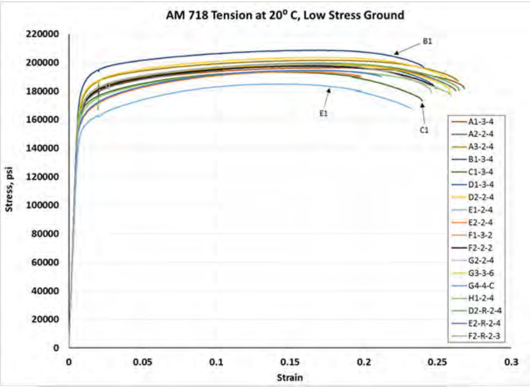
# Room Temperature Tensile Meets Minimum Standard

**AMS 5664E spec.**

**UTS**

**YS**





| As-fabricated | UTS (ksi) | 0.2% YS Offset (ksi) |
|---|---|---|
| B1 | 200.5 | 171.1 |
| Avg | 183.5-195.5 | 151.6-165.4 |
| E1 (Low Al, Hi C) | 178.8 | 144.9 |

| Low Stress Ground | UTS (ksi) | 0.2% YS Offset (ksi) |
|---|---|---|
| B1 | 208.8 | 179.3 |
| Avg | 193.4-203.6 | 160.8-165.4 |
| E1 (Low Al, Hi C) | 185.0 | 150.6 |

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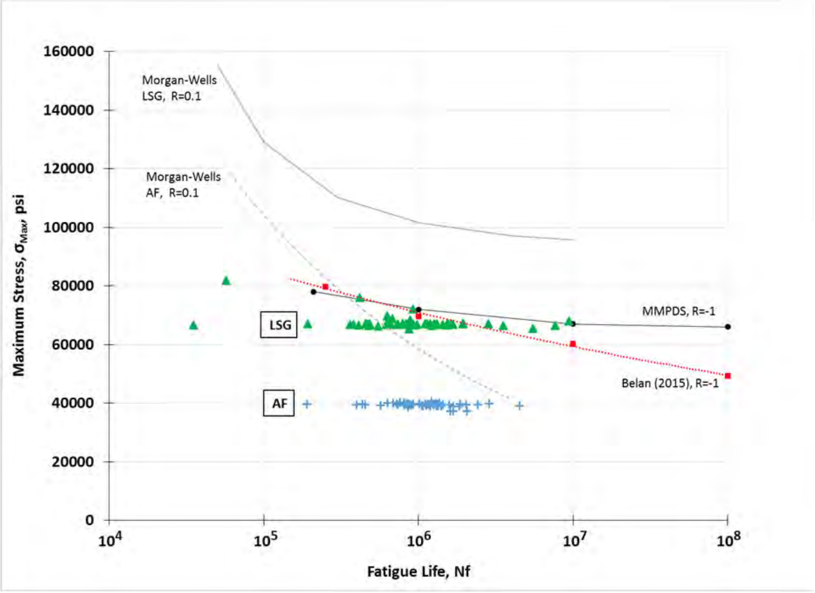
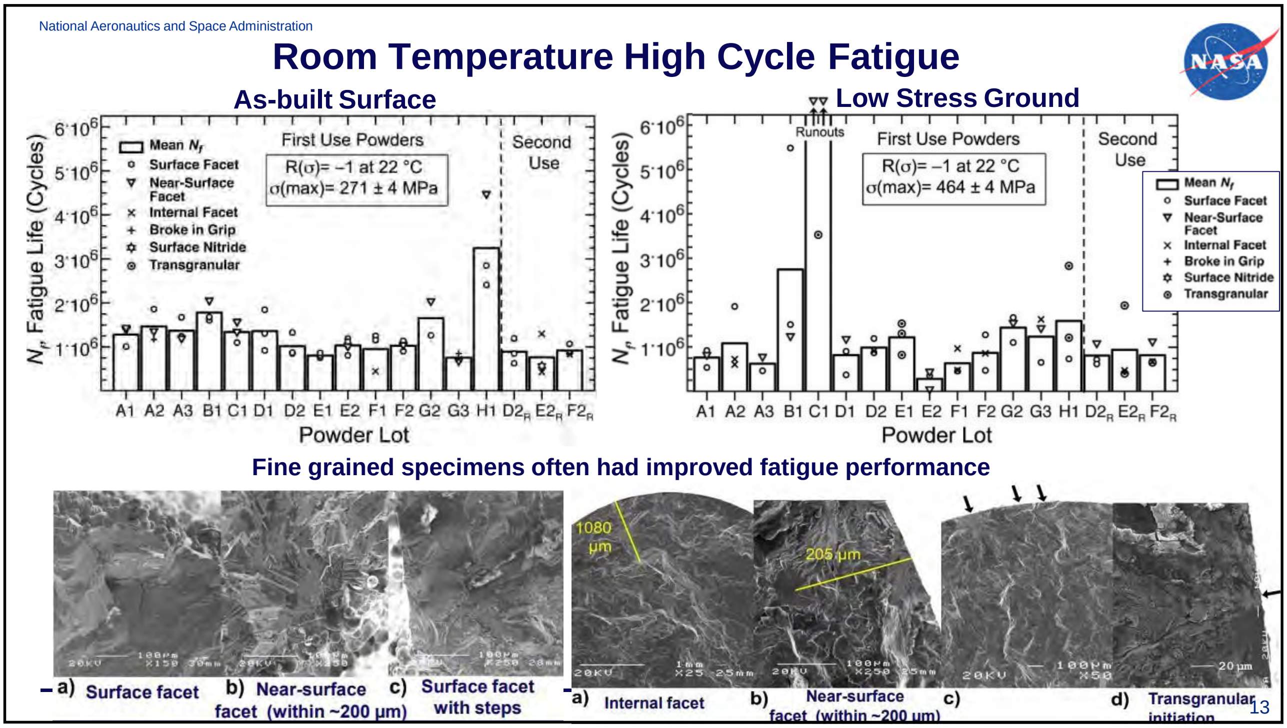
# Room Temperature High Cycle Fatigue



- **Low stress ground compares well to literature**
- **Statistical analysis shows two populations: C1 & B1 had highest lives, G4 and E2 the lowest**
- **As Fabricated has less scatter, but 40% lower stress for comparable life**
- **Only H1 lot was significantly different, with higher lives**

6



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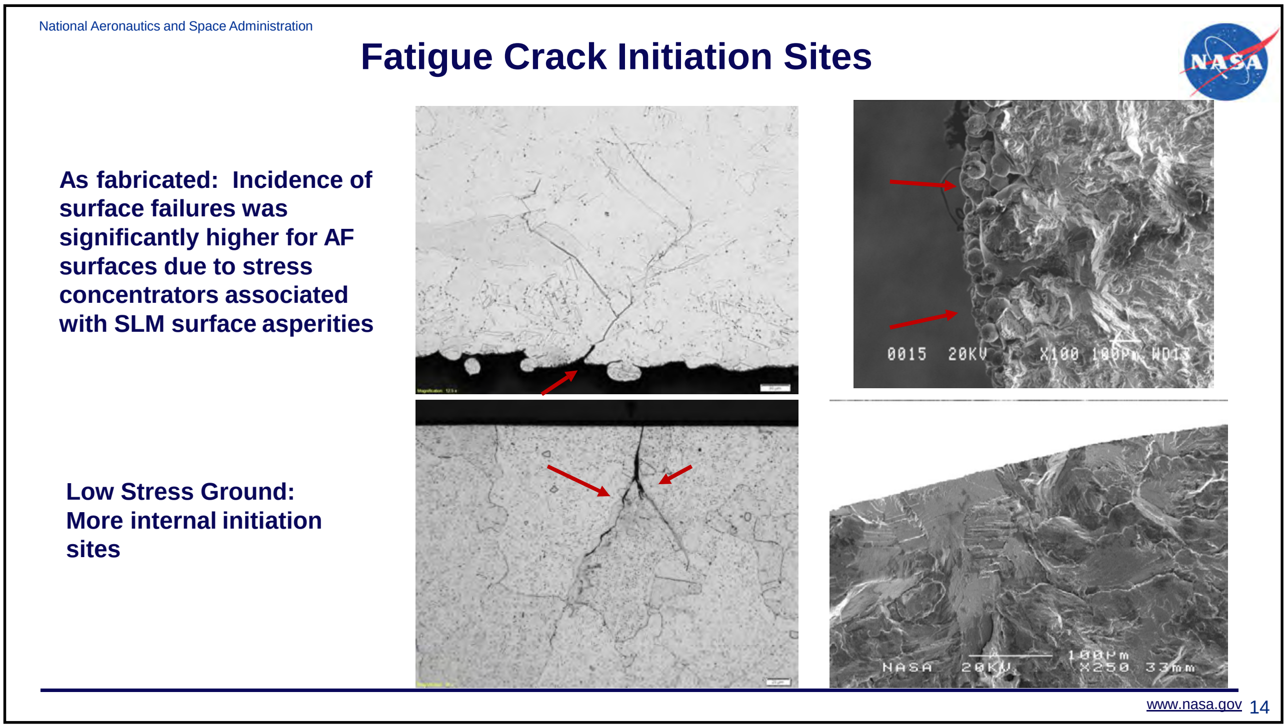
## Room Temperature High Cycle Fatigue

**As-built Surface** | **Low Stress Ground**

**Fine grained specimens often had improved fatigue performance**

a) Surface facet b) Near-surface facet (within ~200 µm) c) Surface facet with steps

a) Internal facet b) Near-surface facet (within ~200 µm) c) d) Transgranular initiation



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## Fatigue Crack Initiation Sites

**As fabricated: Incidence of surface failures was significantly higher for AF surfaces due to stress concentrators associated with SLM surface asperities**

**Low Stress Ground: More internal initiation sites**

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# Powder and Build Quality Summary

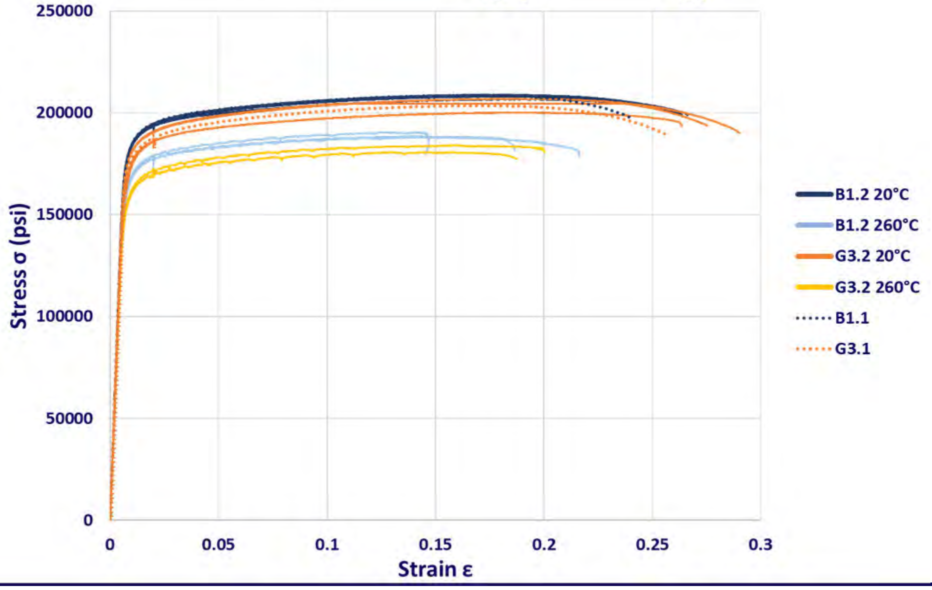
- **Majority of powder compositions within AMS 5664 chemistry specification** (E1 out)
- **Powders evaluated are distinct** – similar in that particles are highly regular spheroids; differences in N; Particle Size Distributions; degree of agglomeration and surface roughness
- **Optimized SL M parameters for 718 yielded high quality builds** with low porosity and full recrystallization across many distinct powder lots
- **Compositional differences had strongest impact on SLM 718 microstructure**
  - ➢ High N and C contents form TiN-nitrides and MC carbides on GBs that suppresses recrystallization during HT → 400 ppm N content a good rule of thumb cutoff to ensure equiaxed grain distribution
- **As-Fabricated surfaces met minimum tensile strength** except for E1 which was chemically out-of-spec
- **Low stress ground surface produced high cycle fatigue lives comparable with literature**
- **Fatigue strength reduced 40 percent for as-fabricated surface**

# (In-Progress) Phase 2: Downselection

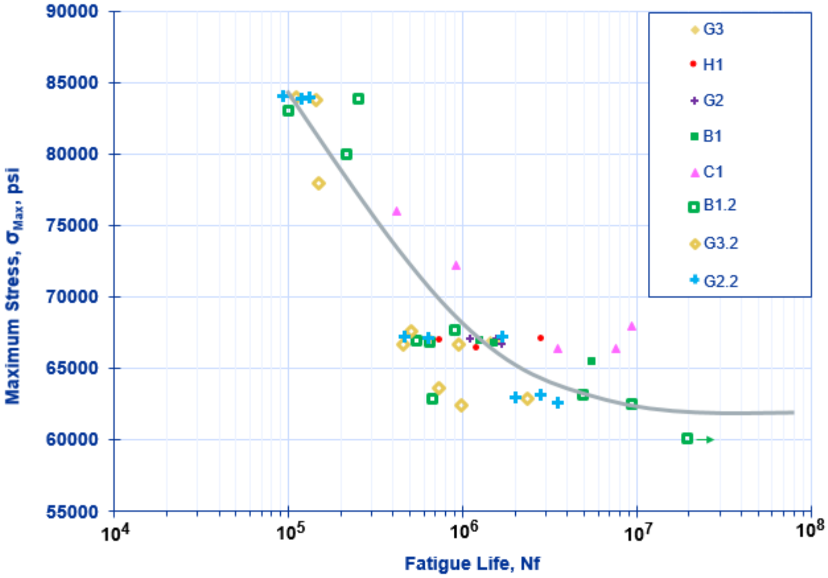
- **Five powder lots selected for a further investigation:** ***B1, C1, G2, G3, H1***
- **Powder, chemistry, and microstructure analysis**
- **Expanded Mechanical Testing**
  - **Cryogenic and Elevated Temperature Tensile**
  - **Room and Elevated Temperature High Cycle Fatigue**
  - **Creep**
  - **Crack Growth and Fracture Toughness**
  - **Broader As-built and Ground Surface Flammability**

| ID | Cut | Atomization | Gas | Note |
|---|---|---|---|---|
| B1 | 15-45 | Rotary | Ar | Low C/N, V. Smooth |
| C1 | 15-45 | Gas | N | High N, Narrow PSD |
| G2 | 11-45 | Gas | Ar | Good PSD |
| G3 | 16-45 | Gas | Ar | Good PSD |
| H1 | 10-45 | Gas | Ar | Moderate N, High Fines |

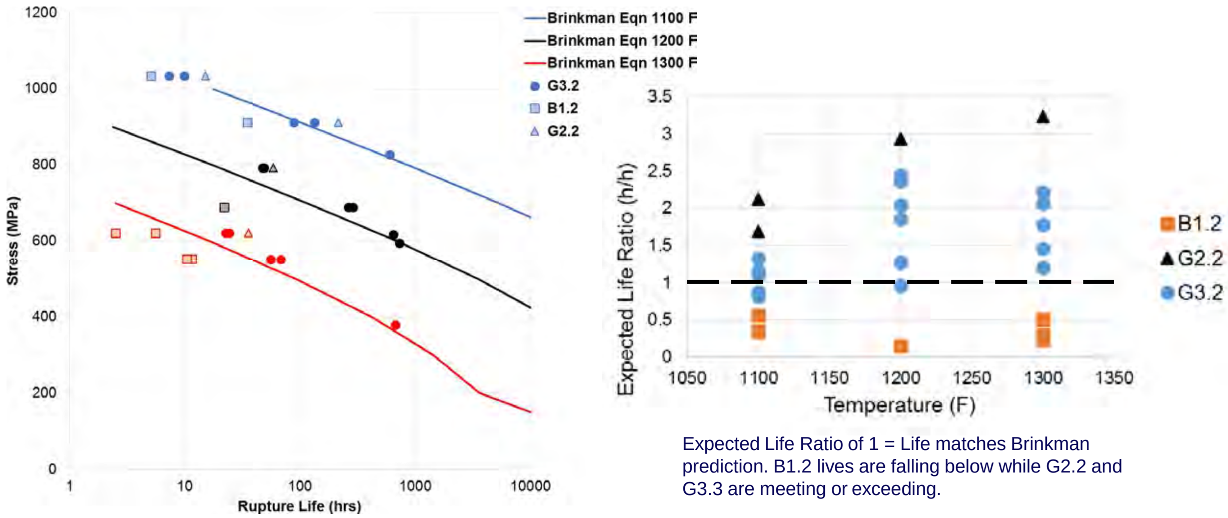
# Round 2 Mechanical Testing (On-Going) - Tensile



# Round 2 Mechanical Testing (On-Going) - Fatigue



# Round 2 Mechanical Testing (On-Going) - Creep

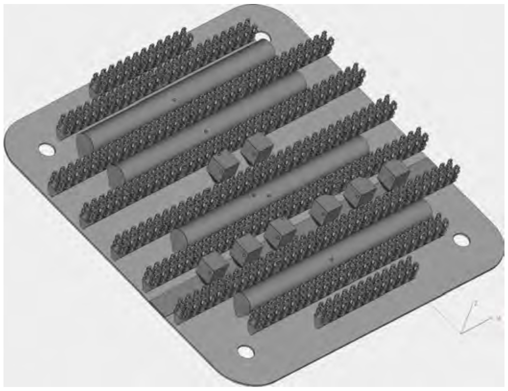


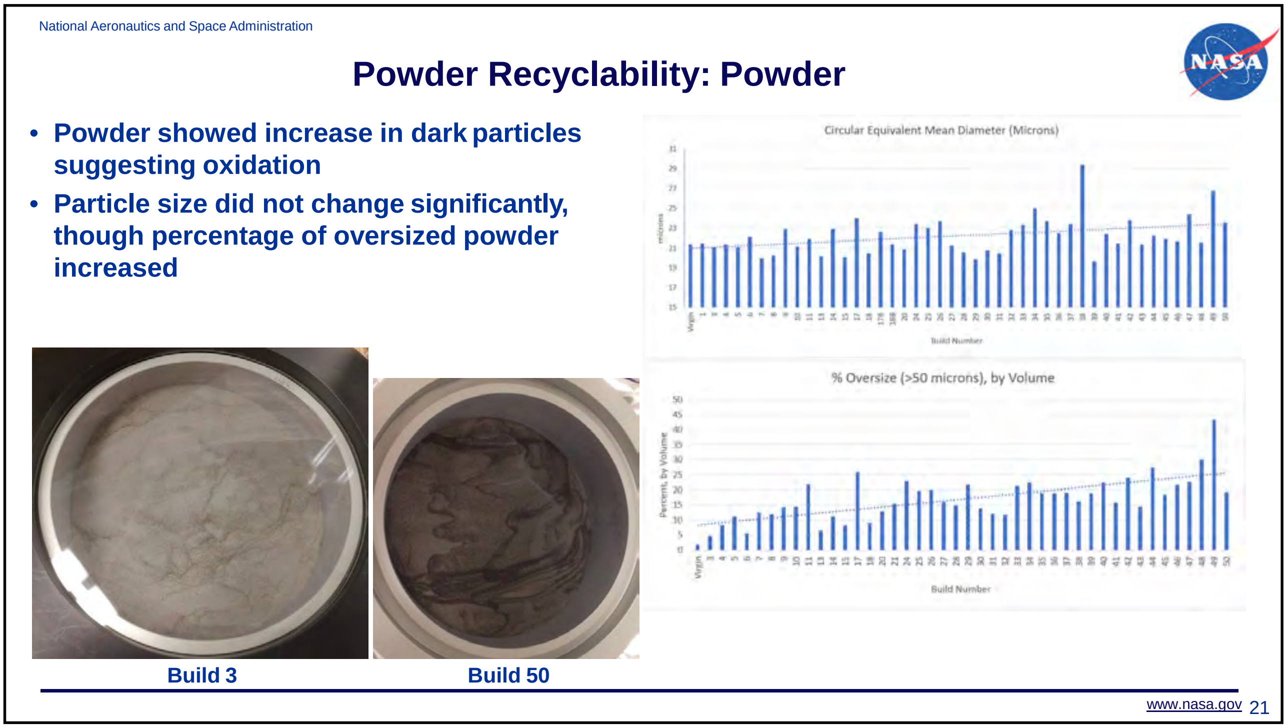
Expected Life Ratio of 1 = Life matches Brinkman prediction. B1.2 lives are falling below while G2.2 and G3.3 are meeting or exceeding.

Colors correspond to test temperature; Symbol shapes represent build batches

# Phase 3: Powder Recyclability

- **One powder lot selected for a further investigation: *G2***
- **Recycling Study: 50 builds reusing powder**
  1. **Virgin powder sieved -270/+500**
  2. **Complete build**
  3. **Leftover powder sieved again to -270/+500**
  4. **Recycled powder is blended with as much virgin powder necessary to complete next build**
  5. **Repeat steps 2-4 49 times for a total of 50 builds**
- **Builds included**
  - **8 cubes for microstructural/defect analysis**
  - **4 bars for mechanical testing.**
- **Horizontal test bars to keep build short**
- **Lattice “Fences” to increase laser-powder interaction**
- **Everything HIPed and heat treated**





National Aeronautics and Space Administration

## Powder Recyclability: Powder

- Powder showed increase in dark particles suggesting oxidation
- Particle size did not change significantly, though percentage of oversized powder increased

**Build 3** **Build 50**

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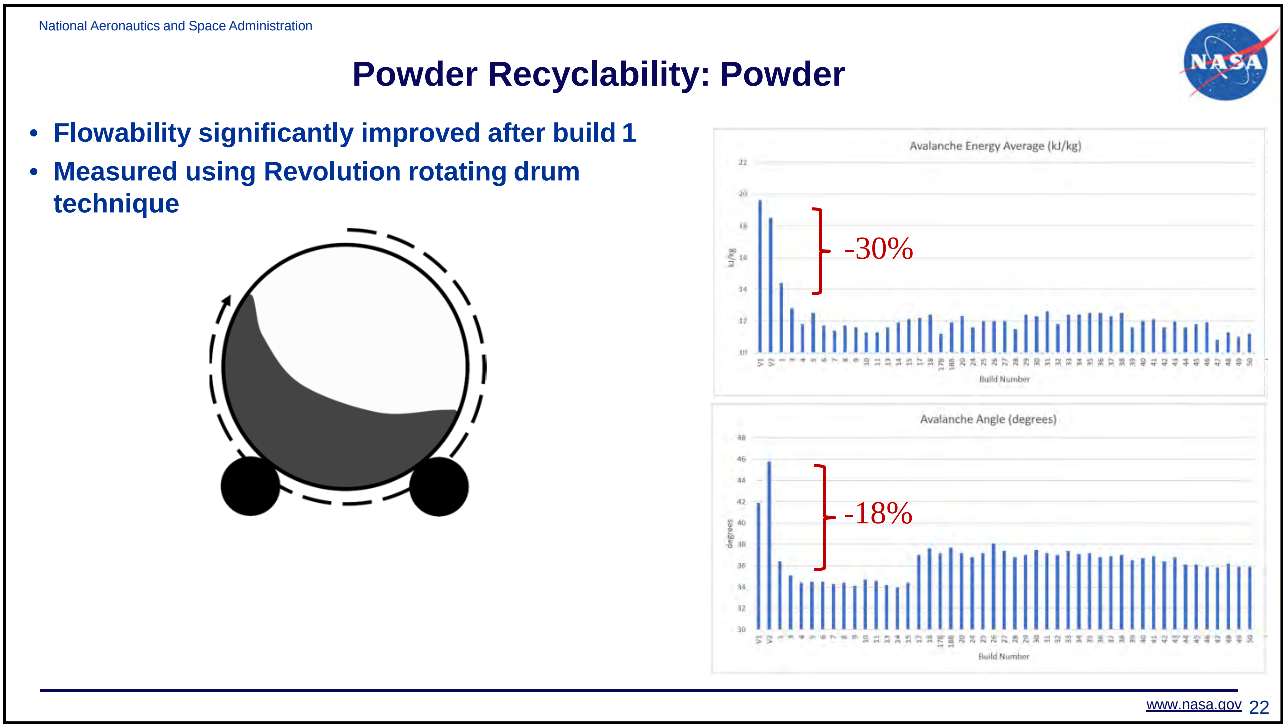

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## Powder Recyclability: Powder

- Flowability significantly improved after build 1
- Measured using Revolution rotating drum technique

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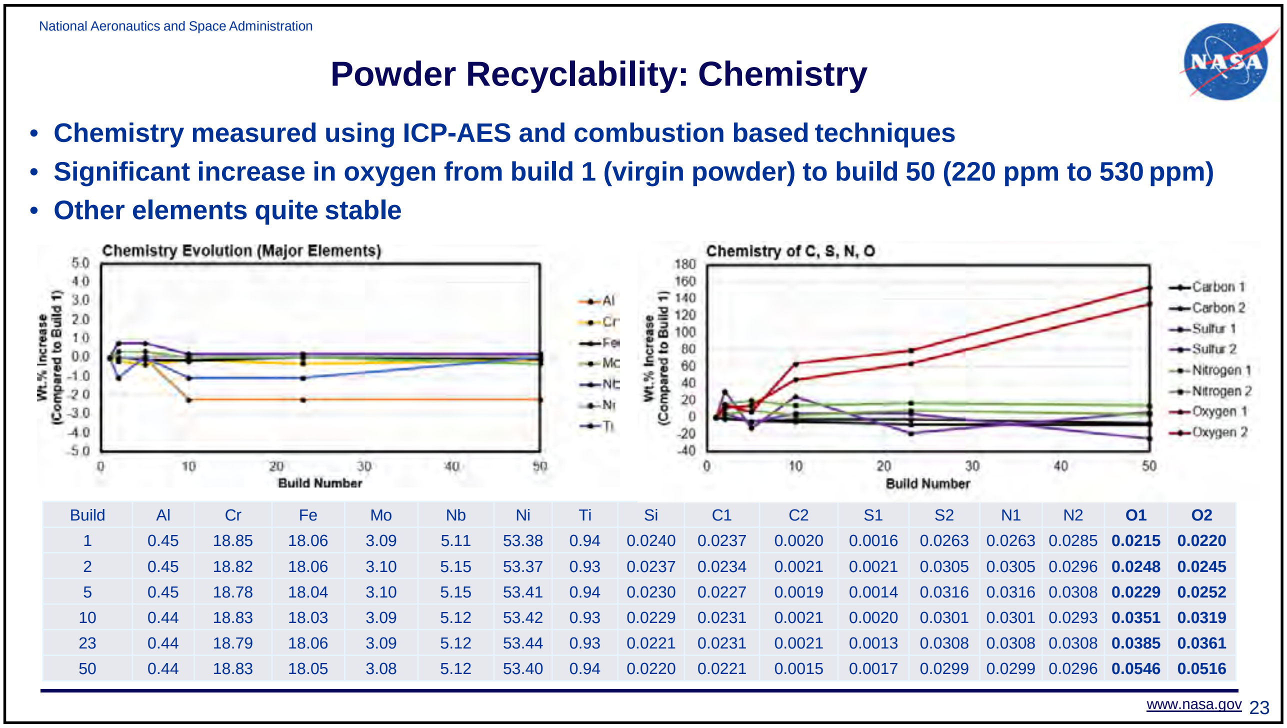

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## Powder Recyclability: Chemistry

- Chemistry measured using ICP-AES and combustion based techniques
- Significant increase in oxygen from build 1 (virgin powder) to build 50 (220 ppm to 530 ppm)
- Other elements quite stable

| Build | Al | Cr | Fe | Mo | Nb | Ni | Ti | Si | C1 | C2 | S1 | S2 | N1 | N2 | **O1** | **O2** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.45 | 18.85 | 18.06 | 3.09 | 5.11 | 53.38 | 0.94 | 0.0240 | 0.0237 | 0.0020 | 0.0016 | 0.0263 | 0.0263 | 0.0285 | **0.0215** | **0.0220** |
| 2 | 0.45 | 18.82 | 18.06 | 3.10 | 5.15 | 53.37 | 0.93 | 0.0237 | 0.0234 | 0.0021 | 0.0021 | 0.0305 | 0.0305 | 0.0296 | **0.0248** | **0.0245** |
| 5 | 0.45 | 18.78 | 18.04 | 3.10 | 5.15 | 53.41 | 0.94 | 0.0230 | 0.0227 | 0.0019 | 0.0014 | 0.0316 | 0.0316 | 0.0308 | **0.0229** | **0.0252** |
| 10 | 0.44 | 18.83 | 18.03 | 3.09 | 5.12 | 53.42 | 0.93 | 0.0229 | 0.0231 | 0.0021 | 0.0020 | 0.0301 | 0.0301 | 0.0293 | **0.0351** | **0.0319** |
| 23 | 0.44 | 18.79 | 18.06 | 3.09 | 5.12 | 53.44 | 0.93 | 0.0221 | 0.0231 | 0.0021 | 0.0013 | 0.0308 | 0.0308 | 0.0308 | **0.0385** | **0.0361** |
| 50 | 0.44 | 18.83 | 18.05 | 3.08 | 5.12 | 53.40 | 0.94 | 0.0220 | 0.0221 | 0.0015 | 0.0017 | 0.0299 | 0.0299 | 0.0296 | **0.0546** | **0.0516** |

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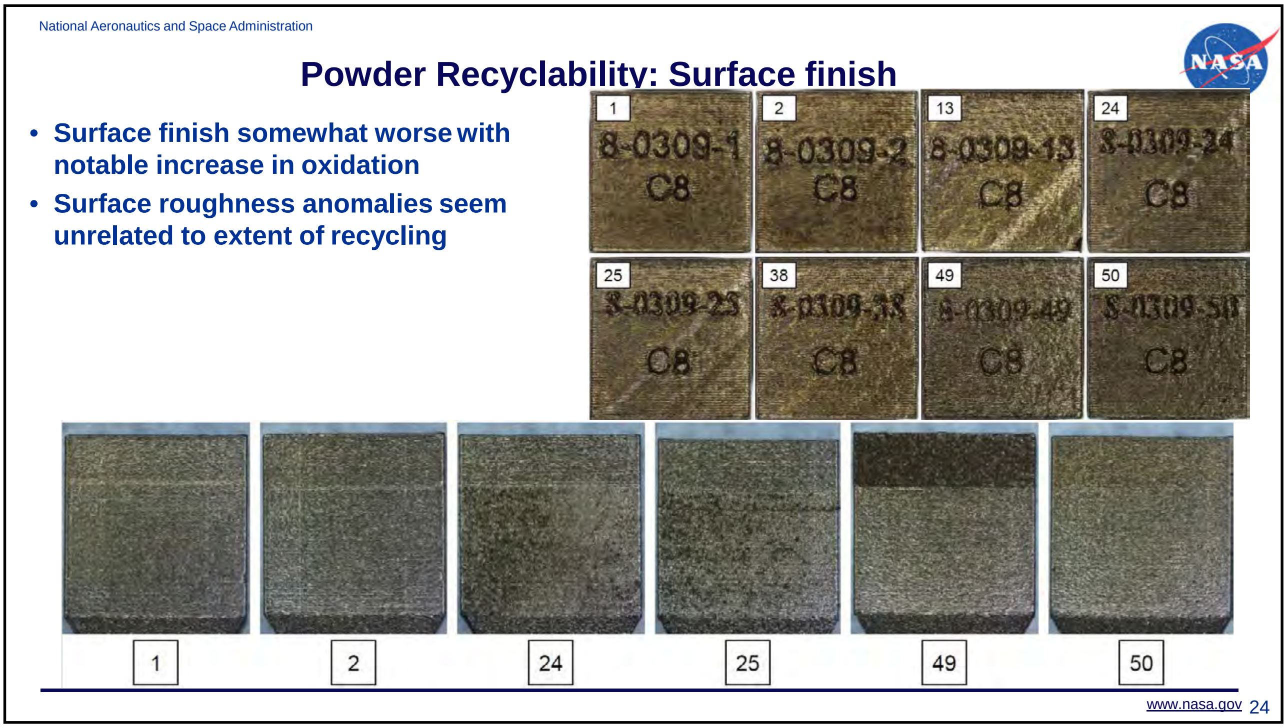

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## Powder Recyclability: Surface finish

- Surface finish somewhat worse with notable increase in oxidation
- Surface roughness anomalies seem unrelated to extent of recycling

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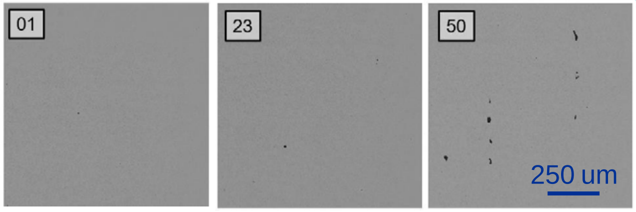
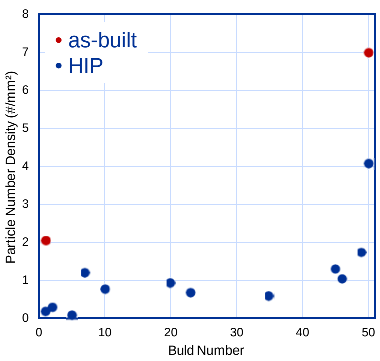
# Powder Recyclability: Defects

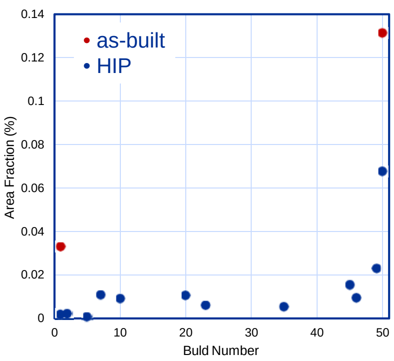
- Increase in defects found internally, though a lot of scatter
- For quantitative analysis particles with area<50µm2 (diameter<8µm) ignored



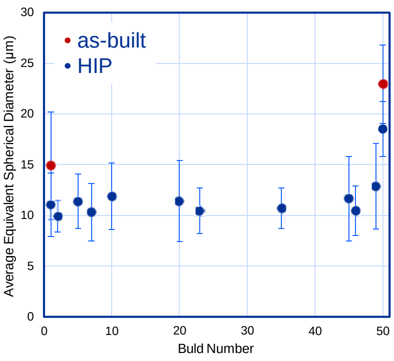
Number Density of Particles



Area Fraction of Particles



Particle Size



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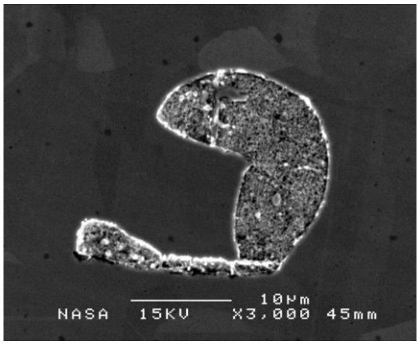
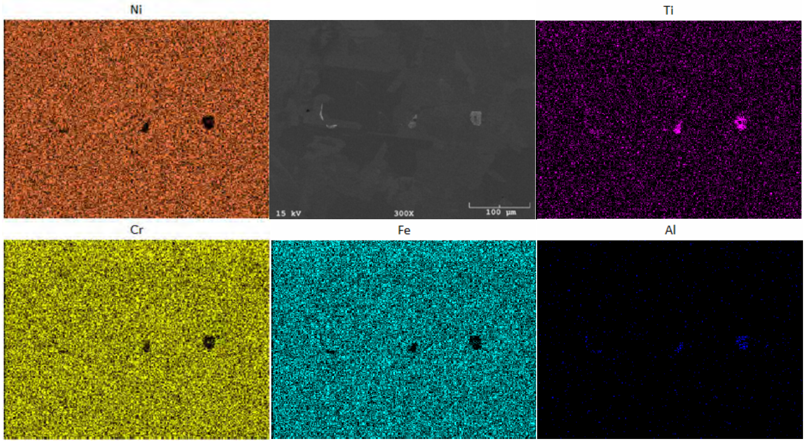
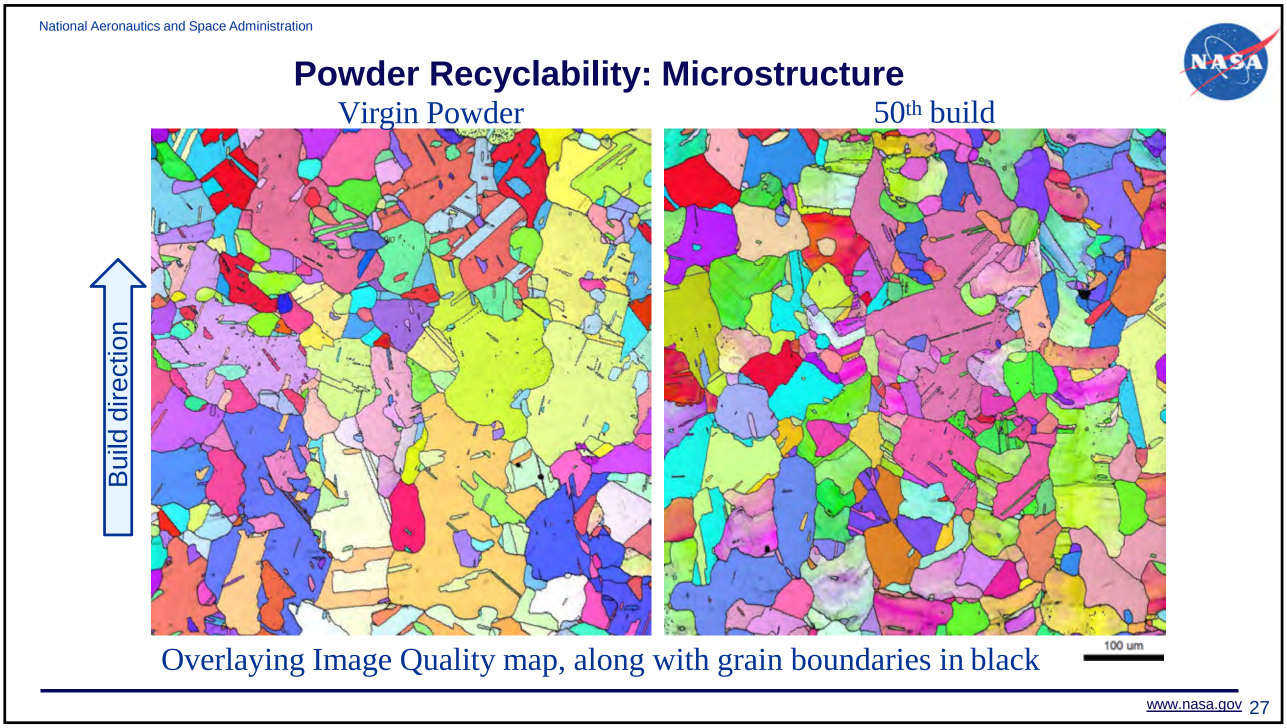
# Powder Recyclability: Defects

- A lot of defects confirmed to be Al/Ti oxides







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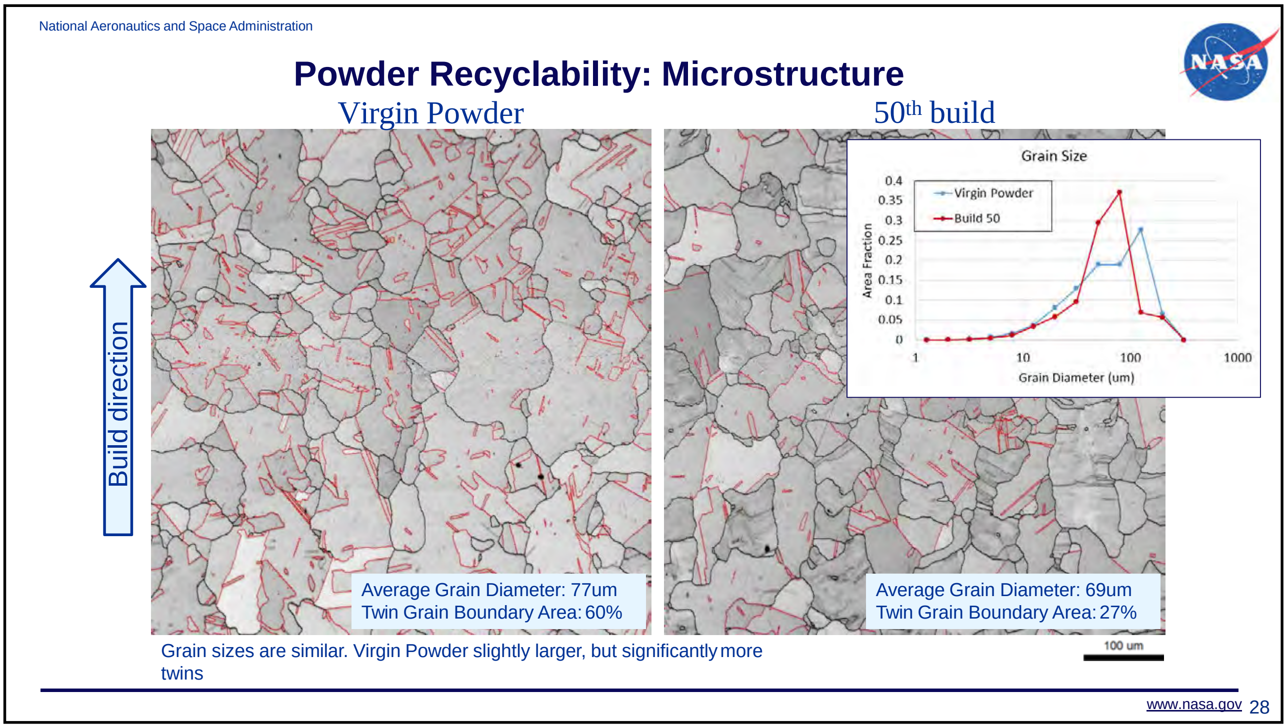
## Powder Recyclability: Microstructure

Overlaying Image Quality map, along with grain boundaries in black



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## Powder Recyclability: Microstructure

Average Grain Diameter: 77um
Twin Grain Boundary Area: 60%

Average Grain Diameter: 69um
Twin Grain Boundary Area: 27%

Grain sizes are similar. Virgin Powder slightly larger, but significantly more twins

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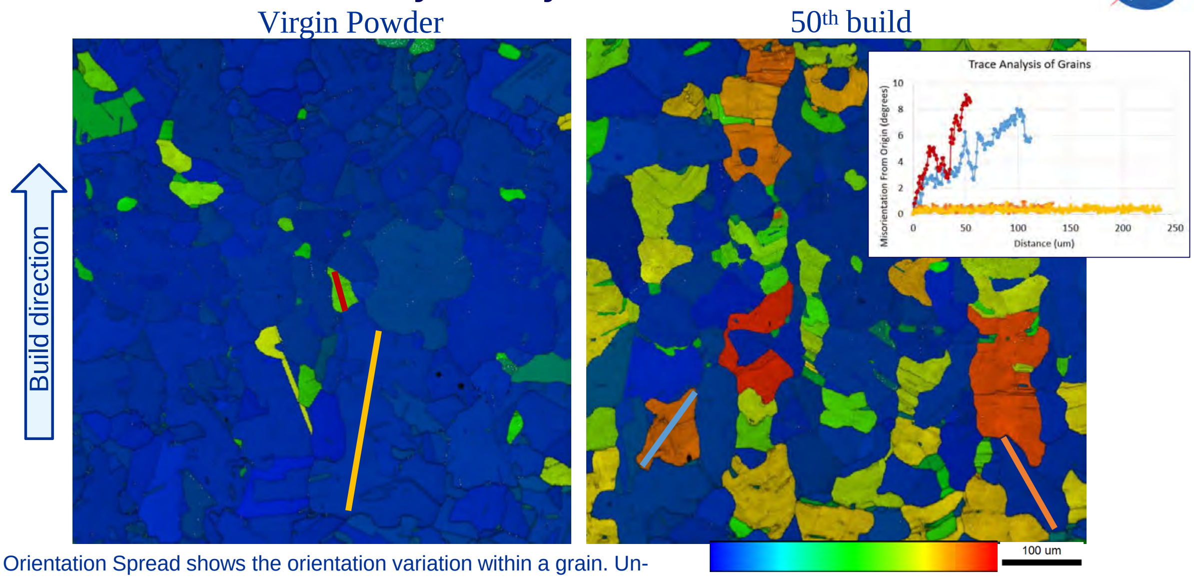
## Powder Recyclability: Microstructure



Grain Orientation Spread shows the orientation variation within a grain. Un-recrystallized (as-built) grains show high GOS. The recycled powder (with high oxide volume fraction) recrystallizes poorly.

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## Powder Recyclability: Summary

- **Mechanical testing results soon to come (tensile and fatigue)**
- **Both the powder and printed parts pick up Oxygen with increased reuse.**
- **This manifests in the surface finish, and in ~10 um oxide particles in the bulk.**
- **Significant impacts on microstructure and extent of recrystallization during HIP + HT**
- **Reused powder leads to less recrystallized microstructures with fewer twin boundaries.**

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## *SLM 718 Feedstock Variability Project – Intraagency Team: Supplier-to-supplier comparison 18 powders and 194 variables measured*

**Project Coordination**
- Chantal Sudbrack, Team Lead
- Cheryl Bowman, Team Lead
- Brian West

**Powder Characterization**
- Richard Boothe
- David Ellis
- Alejandro Hinojos (OSU)
- Chantal Sudbrack

**MSFC AM Fabrication**
- James Lydon
- Omar Mireles
- Ken Cooper

**Analytical Characterization**
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- Dereck Johnson
- Joy Buehler

**Heat Treat & Machining**
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- MSFC Heat Treat Facility
- GRC Specimen Shop

**Microstructural Evaluation**
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- Tim Smith
- Chantal Sudbrack
- Alejandro Hinojos (OSU)
- Michael Kloesel (Cal Poly)
- Bethany Cook (CWRU)
- Jonathan Healy (CWRU)

**Mechanical Testing**
- Brad Lerch
- Aaron Thompson
- Jonathan Woolley
- GRC Testing Facility

**Fractography**
- Paul Chao (CMU)
- Ben Richards (NU)
- Ivan Locci

**Flammability (Flam.) Analysis**
- Jon Tylka (WSTF)
- White Sands Test Facility (WSTF)

**Flam. Characterization**
- Tim Smith
- Michael Kloesel (Cal Poly)

**PCA analysis**
- David Ellis

**Program Advisors**
- Kristin Morgan, Program Manager
- David Ellis
- Doug Wells
- Robert Carter

Published: Proceedings Superalloy 718 & Derivatives: E. Ott et al (Eds.), TMS (Pittsburgh), 89-113 (2018)

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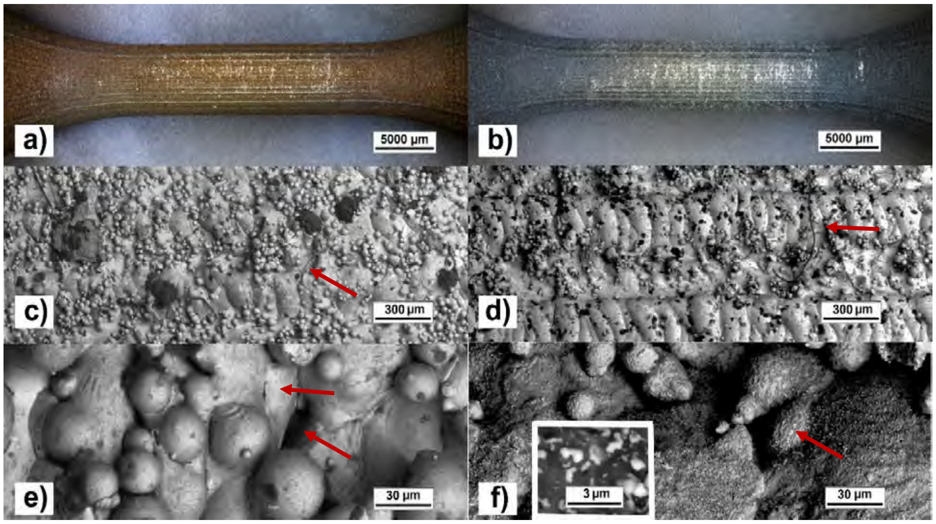
## As Fabricated Surface Finish



**Evidence of pre-existing flaws, surface cracking**

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# Effect of Plasma Spheroidization on the Corrosion Performance of Additively Manufactured 316L Stainless Steel

Department of Mechanical Engineering
Unites States Naval Academy
Annapolis, MD

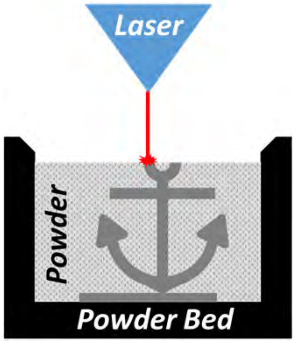
Prof R.J. Santucci, Prof Elizabeth Getto, Prof Michelle Koul

CAPT Brad Baker, CDR Jon Gibbs, Prof Rick Link,

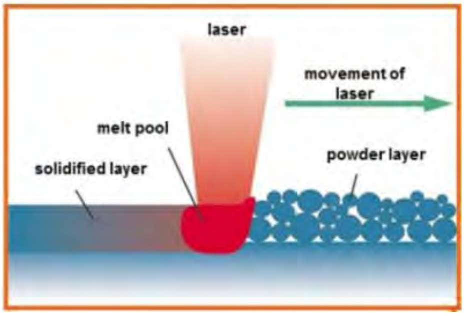
Midn 1/C Andrew Shumway, Midn 1/C Jordan McLaughlin

## Motivation

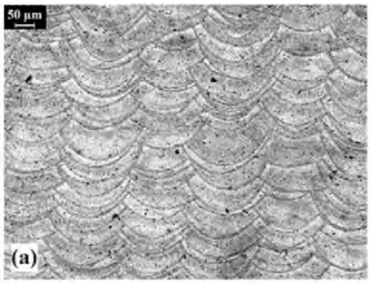
- 316L stainless steel is essential to U.S. Naval applications from ship parts to weapon systems.
- Additive manufacturing (AM), the stepwise construction of a part layer by layer, is used extensively with 316L and shows promise for use in the Navy.



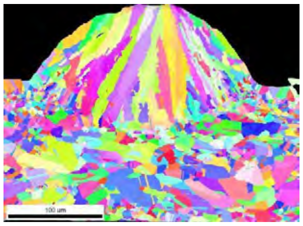
# Additive Manufacturing (AM) Process



***SLM**: Fraunhofer Institute for Machine Tools and Forming Technology



AM AlSi10Mg specimen, etched cross section, M. Krishnan, PhD Thesis, Politecnico di Torino; 2014

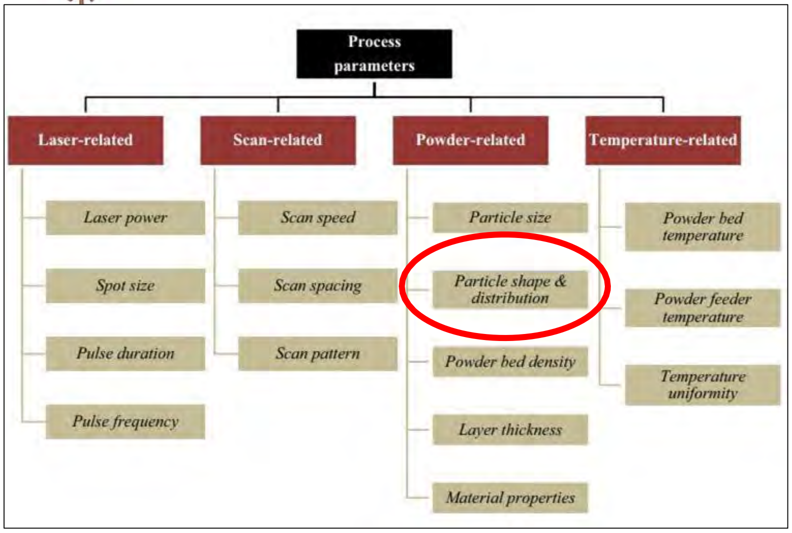


Inconel 600 specimen, EBSD of single track, Nicolas D. Hart, CAPT Brad W. Baker, US Naval Academy

Non-equilibrium solidification can result in microstructures that differ significantly from wrought materials

The same is true for the unique processing strategy employed with AM

# Additive Manufacturing (AM)



Process parameters

- Laser-related
  - Laser power
  - Spot size
  - Pulse duration
  - Pulse frequency
- Scan-related
  - Scan speed
  - Scan spacing
  - Scan pattern
- Powder-related
  - Particle size
  - Particle shape & distribution
  - Powder bed density
  - Layer thickness
  - Material properties
- Temperature-related
  - Powder bed temperature
  - Powder feeder temperature
  - Temperature uniformity

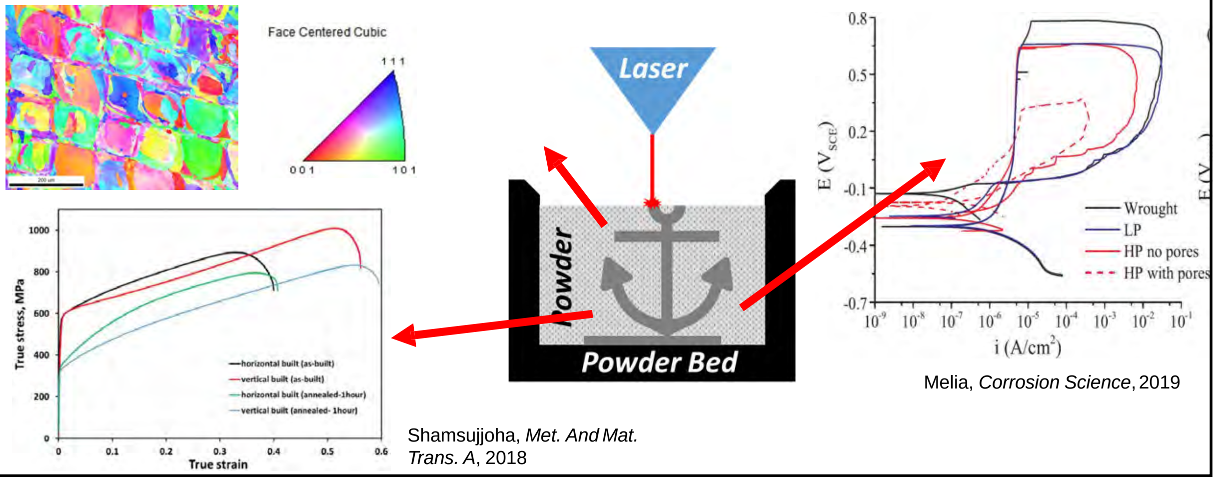
**From: Aboulkhair et. al., Additive Manufacturing 1–4 (2014) 77–86**

<u>AM Processing</u>:

With so many degrees of freedom in selecting processing variables, it is important to gain a mechanistic understanding of each variable

## Motivation

It is critical to determine the effects of AM on the properties of stainless steel parts: Microstructure, Strength, and Corrosion Resistance.



Shamsujjoha, *Met. And Mat. Trans. A*, 2018

Melia, *Corrosion Science*, 2019

## Motivation

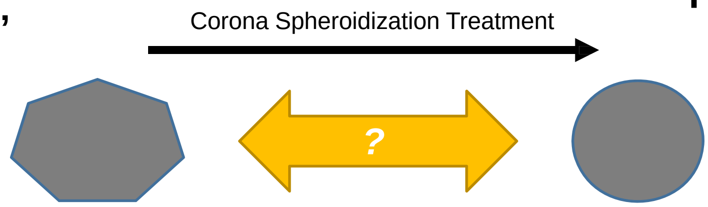
NSWC Corona has provided two separate 316L base powders to compare, one normal and one spheroidized, to make the particles more regular

**Untreated**

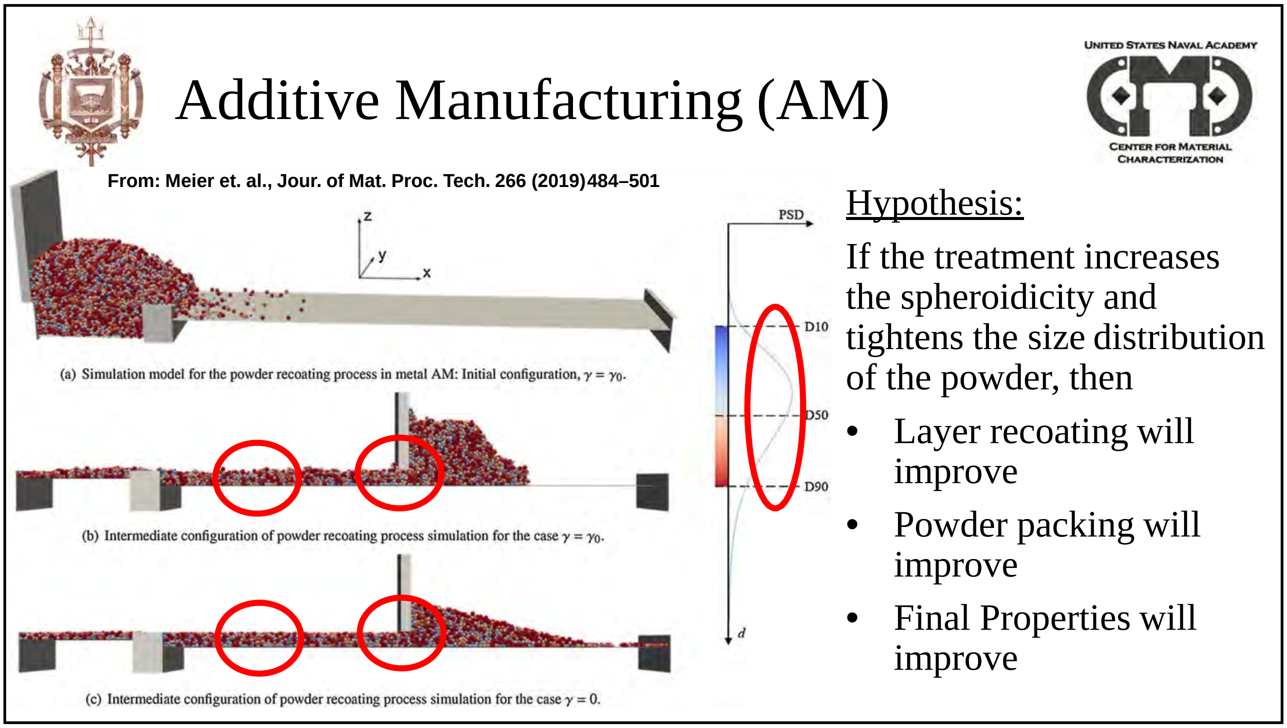
**"Normal"**

**Plasma Treated**
**or**
**Plasma Spheroidized**

**"Spheroidized"**



Specifically, what is the role of powder morphology?



# Additive Manufacturing (AM)

From: Meier et. al., Jour. of Mat. Proc. Tech. 266 (2019)484–501

(a) Simulation model for the powder recoating process in metal AM: Initial configuration, $\gamma = \gamma_0$.

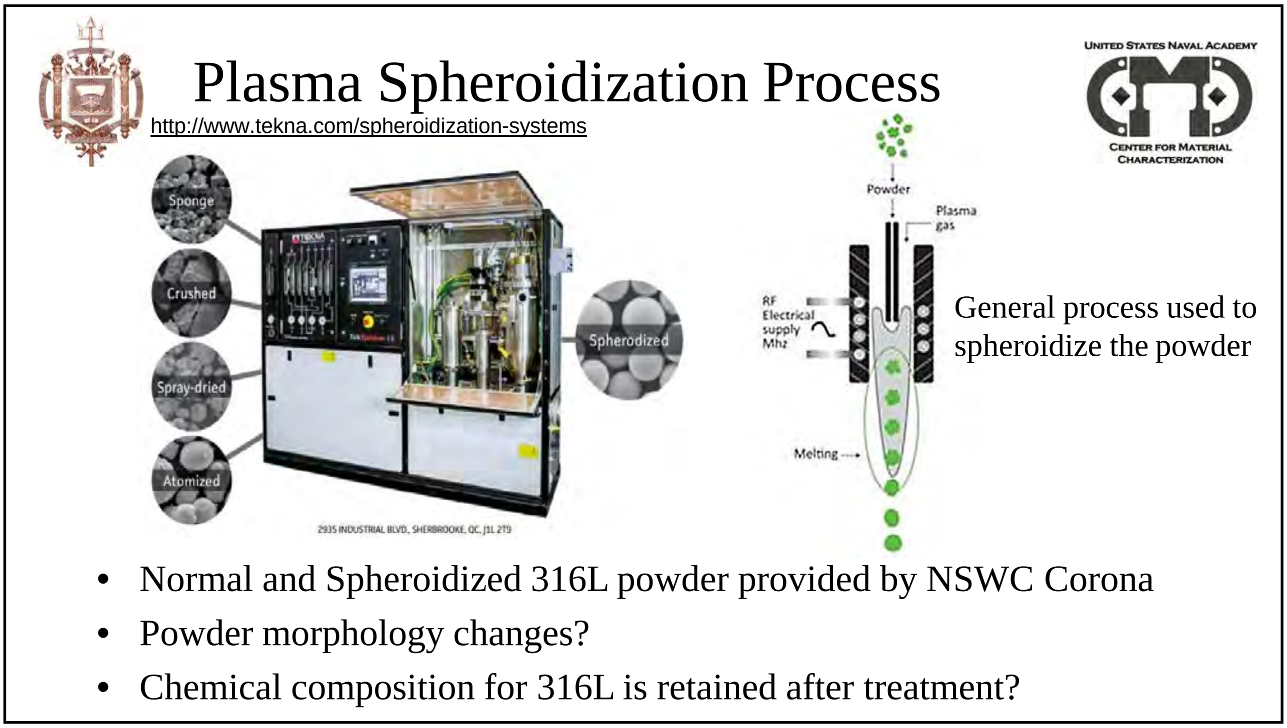
(b) Intermediate configuration of powder recoating process simulation for the case $\gamma = \gamma_0$.

(c) Intermediate configuration of powder recoating process simulation for the case $\gamma = 0$.

Hypothesis:

If the treatment increases the spheroidicity and tightens the size distribution of the powder, then

- Layer recoating will improve
- Powder packing will improve
- Final Properties will improve



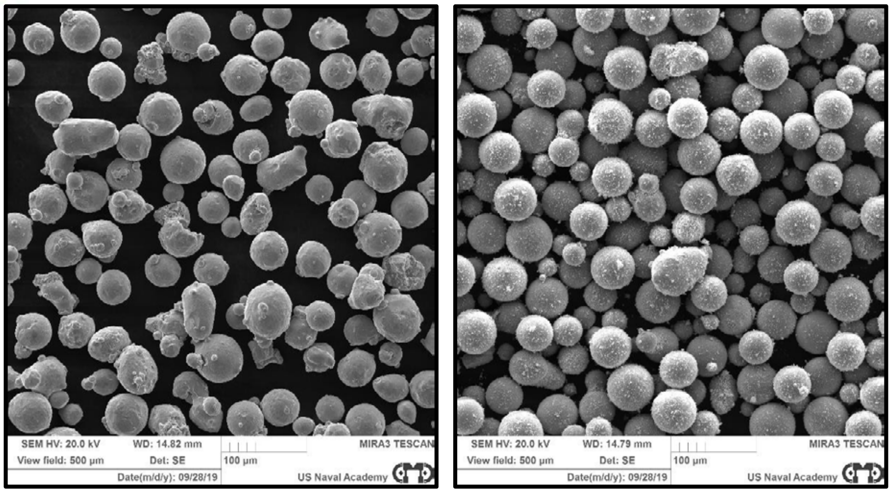
# Plasma Spheroidization Process

http://www.tekna.com/spheroidization-systems

General process used to spheroidize the powder

- Normal and Spheroidized 316L powder provided by NSWC Corona
- Powder morphology changes?
- Chemical composition for 316L is retained after treatment?

# Powder Morphology Characterization



Powder becomes more spherical after treatment

Size distribution largely invariant

Spheroidized powder exhibits satellite artifacts on surface

Virgin Normal

100 µm

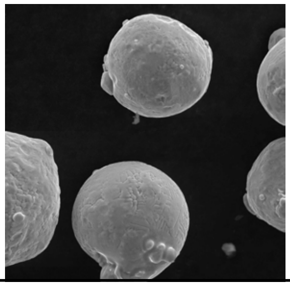
Virgin Spher.

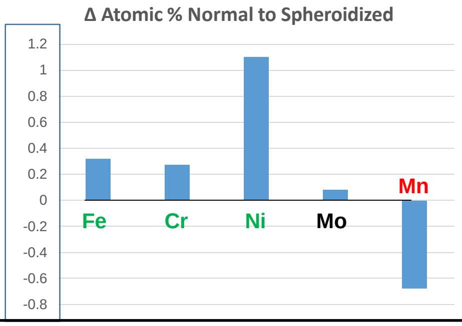
# Powder Elemental Characterization

Bulk composition is relatively unchanged – still SS316L

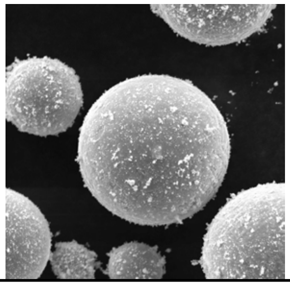
| | **Weight Percent** | | | | | |
|---|---|---|---|---|---|---|
| **Powder** | **Mo** | **Cr** | **Mn** | **Fe** | **Co** | **Ni** |
| Normal | 1.91 | 18.39 | 2.46 | 62.99 | 1.15 | 13.10 |
| Spheroidized | 2.04 | 18.63 | 1.79 | 63.29 | 0.00 | 14.25 |

**Normal**





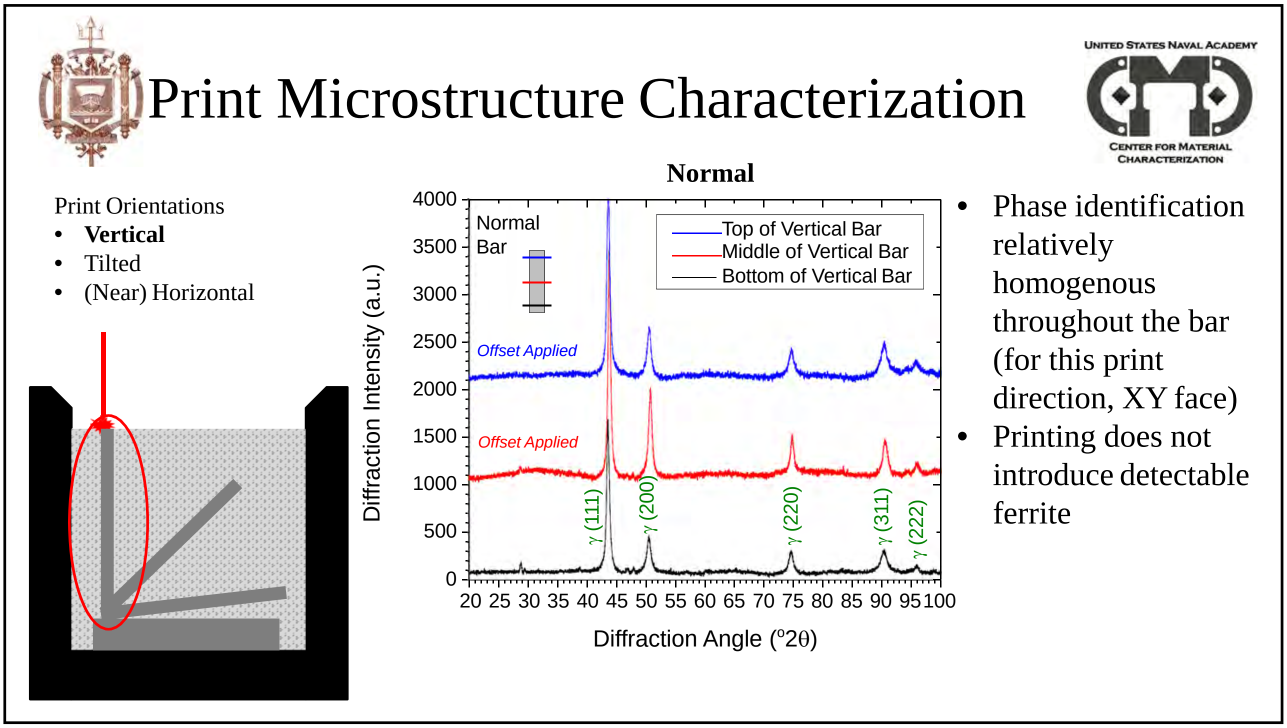
**Treated**



20 µm

Virgin Normal

Virgin Spher.

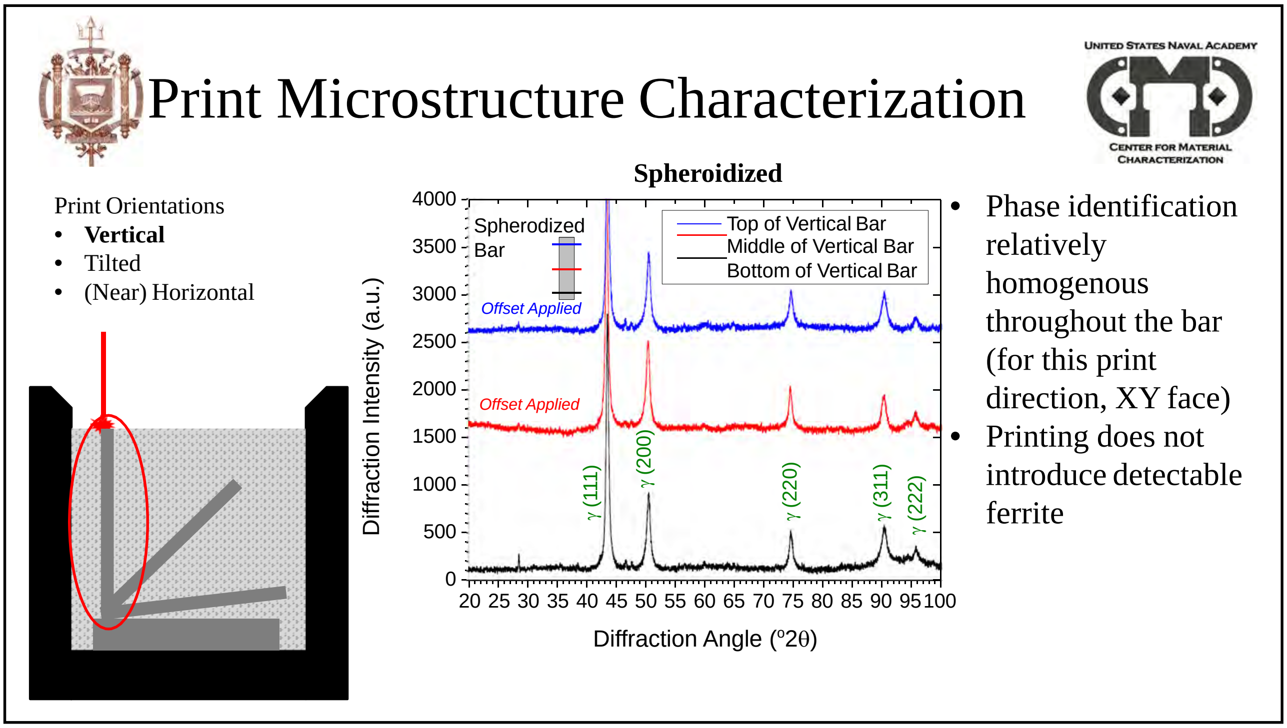


# Print Microstructure Characterization

Print Orientations

- **Vertical**
- Tilted
- (Near) Horizontal

- Phase identification relatively homogenous throughout the bar (for this print direction, XY face)
- Printing does not introduce detectable ferrite



# Print Microstructure Characterization

Print Orientations

- **Vertical**
- Tilted
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- Phase identification relatively homogenous throughout the bar (for this print direction, XY face)
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# Print Microstructure Characterization

Print Orientations
- **Vertical**
- Tilted
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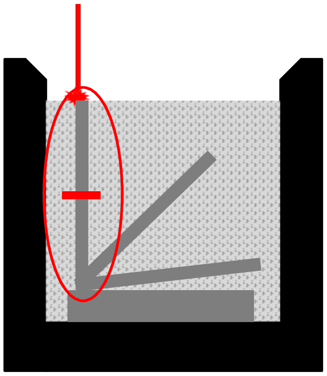
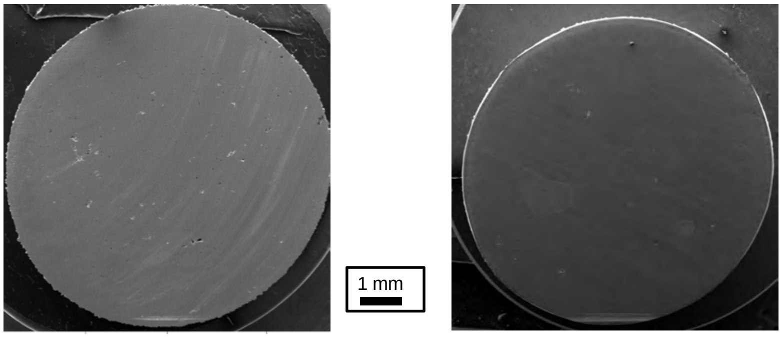


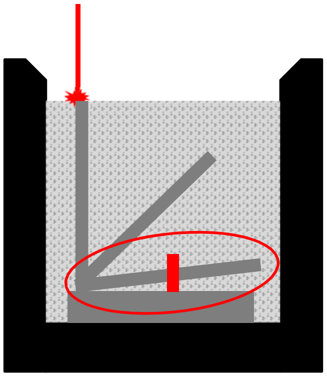
**Normal** **Spheroidized**



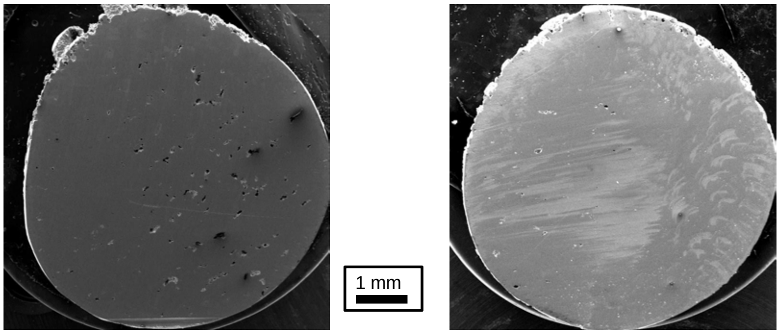
- Few macro pores overall for vertical print orientation
- Normal powder qualitatively has fewer defects or pores

# Print Microstructure Characterization

Print Orientations
- Vertical
- Tilted
- **(Near) Horizontal**



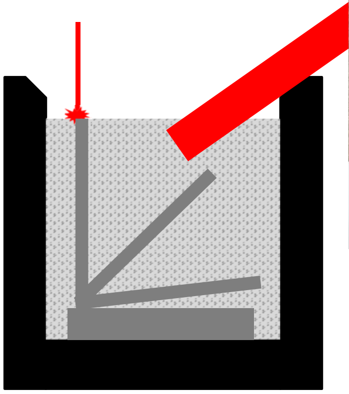
**Normal** **Spheroidized**

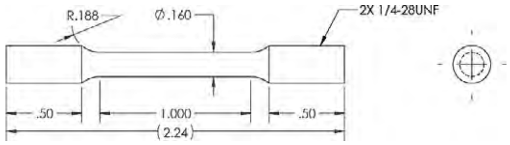


- Many more large pores and defects with normal powder
- Difference much more obvious than for Vertical build

# Print Tensile Properties

Print Orientations
- Vertical
- Tilted
- (Near) Horizontal





All dimensions in inches

- ASTM E8 – Standard Test Methods for Tension Testing of Metallic Materials
- Elastic Strain Rate of 3 x $10^{-5}$ /s - displacement control
- Elongation at fracture taken at 10% load drop from maximum load

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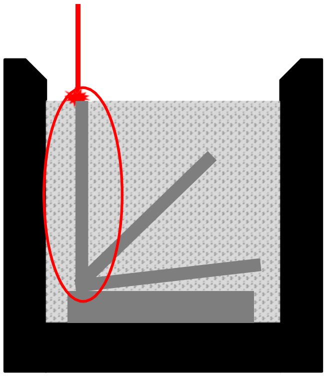
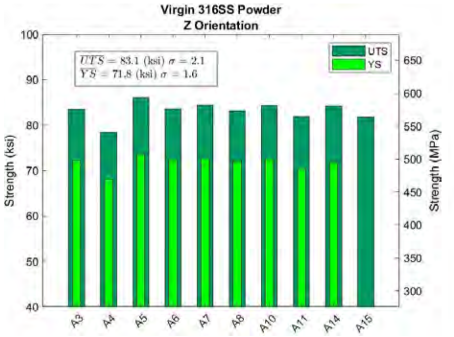
# Print Tensile Properties

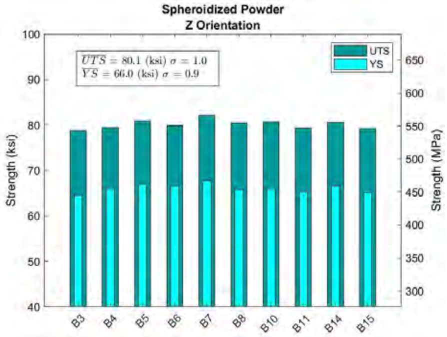
Print Orientations
- **Vertical**
- Tilted
- (Near) Horizontal



**Normal**



**Spheroidized**

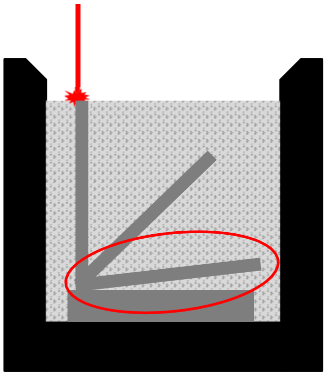


- The Ultimate Tensile Strength of the printed normal (83 ksi) and spheroidized (80 ksi) powder samples is similar
- The Yield Strength of the printed normal (72 ksi) powder sample is slightly higher than the spheroidized (66 ksi) powder sample
- The results for the spheroidized powder samples are less variable

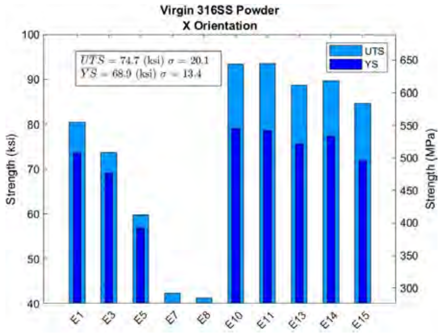
# Print Tensile Properties

United States Naval Academy
Center for Material Characterization

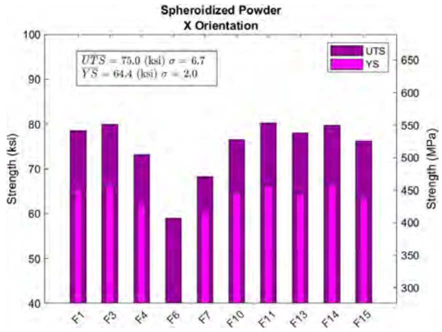
Print Orientations
- Vertical
- Tilted
- **(Near) Horizontal**



**Normal**



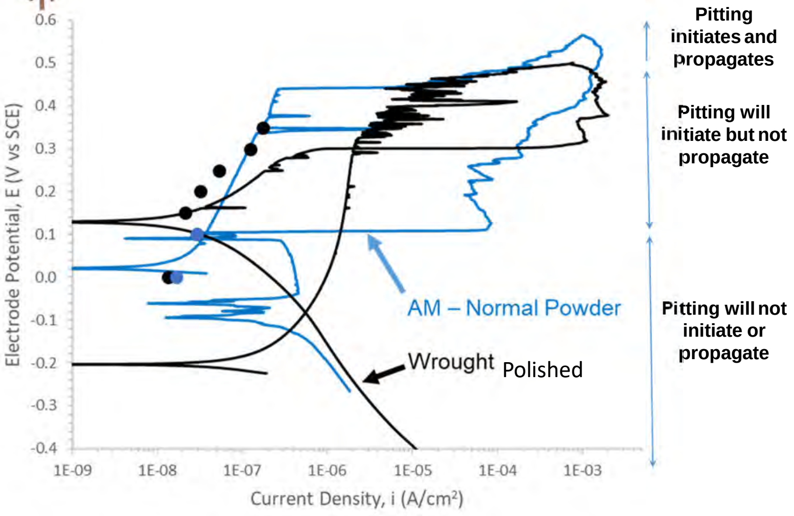
**Spheroidized**



- The Ultimate Tensile Strength is similar (at 75 ksi) for both the printed normal and spheroidized powder samples
- The Yield Strength of the printed normal (69 ksi) powder sample is slightly higher than the spheroidized (64 ksi) powder sample
- The results for the spheroidized powder samples are less variable

# Print Corrosion Testing

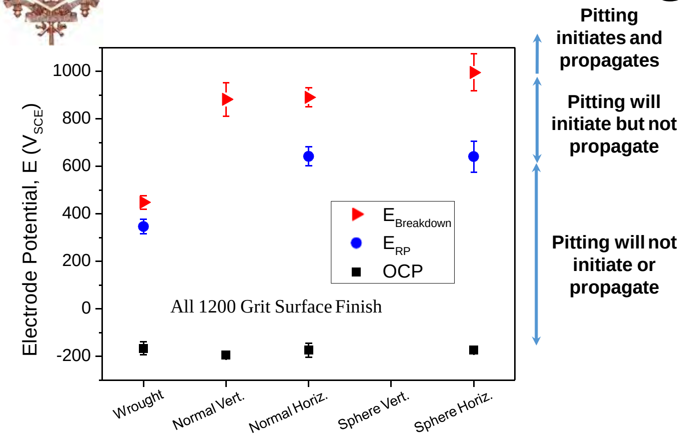
United States Naval Academy
Center for Material Characterization

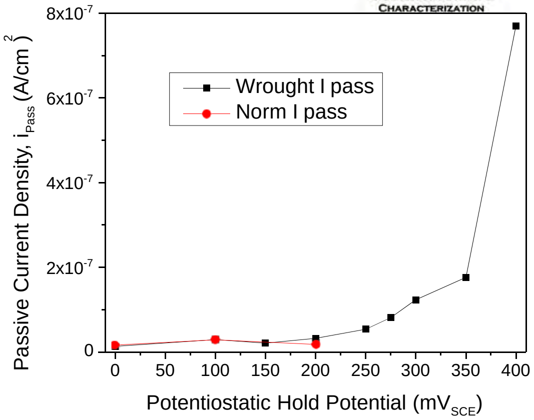


- Testing conducted in 0.6 M NaCl solution
- Wrought and AM (as-printed and polished) are evaluated
- Potentiodynamic and Potentiostatic Testing

- As-printed surface native oxide is passivating

# Print Corrosion Testing





- The passive window is extended for AM samples compared to wrought
- All critical potentials are more positive for the AM samples compared to wrought

- The stable film passive dissolution kinetics are similar between wrought and the printed normal powder samples

---

# Thank you

Questions?

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# Linking 3D Microstructural Analysis of Additive Manufactured 316L to Performance and Properties in LPBF 316L

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NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications 8 Dec 2020

## Outline

- Brief introduction to the NRL ICME approach to AM
- 3D Serial Sectioning Analysis: Qualitative to Quantitive
  - Why Serial Sectioning?
  - Automated Serial Sectioning
- 3D Analysis of 316L LPBF
  - Defect characterization and grain initiation
  - Localized crystallographic orientation
  - Grain Boundary Character Distribution
- Conclusions

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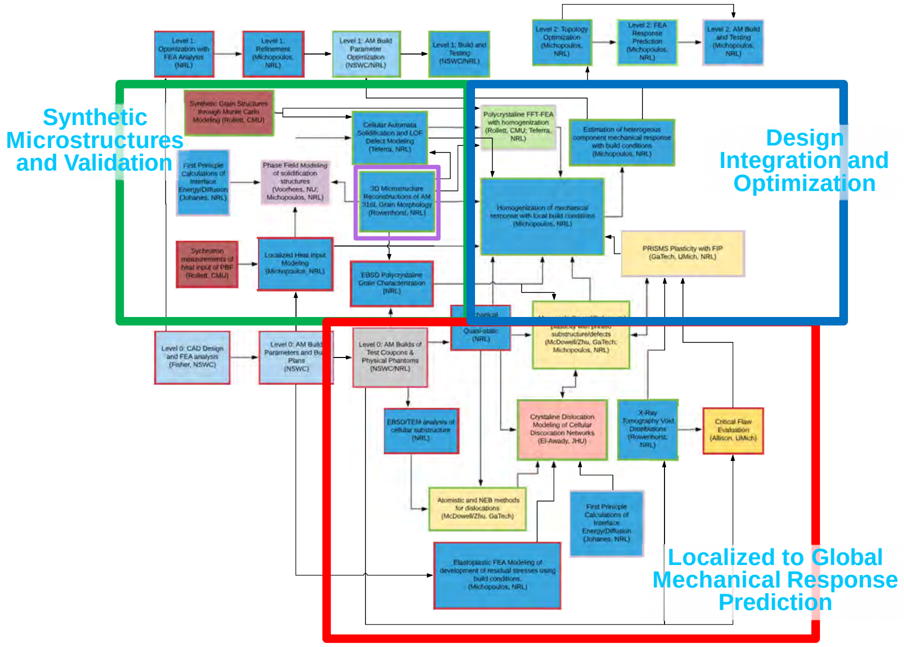
# Agile ICME AM Data Flow



Level 1: Optimization with FEA Analysis (NRL)

Level 1: Refinement (Michopoulos, NRL)

Level 1: AM Build Parameter Optimization (NSWC/NRL)

Level 1: Build and Testing (NSWC/NRL)

Level 2: Topology Optimization (Michopoulos, NRL)

Level 2: FEA Response Prediction (Michopoulos, NRL)

Level 2: AM Build and Testing (Michopoulos, NRL)

Synthetic Microstructures and Validation

Synthetic Grain Structures through Monte Carlo Modeling (Rollett, CMU)

Cellular Automata Solidification and LOF Defect Modeling (Teferra, NRL)

First Prinicple Calculations of Interface Energy/Diffusion (Johanes, NRL)

Phase Field Modeling of solidification structures (Voorhees, NU; Michopoulos, NRL)

3D Microstructure Reconstructions of AM 316L Grain Morphology (Rowenhorst, NRL)

Sychrotron measurements of heat input of PBF (Rollett, CMU)

Localized Heat Input Modeling (Michopoulos, NRL)

EBSD Polycrystaline Grain Characterization (NRL)

Design Integration and Optimization

Polycrystaline FFT-FEA with homogenization (Rollett, CMU; Teferra, NRL)

Estimation of heterogeous component mechanical response with build conditions (Michopoulos, NRL)

Homogenization of mechanical response with local build conditions (Michopoulos, NRL)

PRISMS Plasticity with FIP (GaTech, UMich, NRL)

Level 0: CAD Design and FEA analysis (Fisher, NSWC)

Level 0: AM Build Parameters and Build Plans (NSWC)

Level 0: AM Builds of Test Coupons & Physical Phantoms (NSWC/NRL)

Mechanical Quasi-static (NRL)

plasticity with printed substructure/defects (McDowell/Zhu, GaTech; Michopoulos, NRL)

EBSD/TEM analysis of cellular substructure (NRL)

Crystaline Dislocation Modeling of Cellular Discocation Networks (El-Awady, JHU)

X-Ray Tomography Void Distributions (Rowenhorst, NRL)

Critical Flaw Evaluation (Allison, UMich)

Atomistic and NEB methods for dislocations (McDowell/Zhu, GaTech)

First Prinicple Calculations of Interface Energy/Diffusion (Johanes, NRL)

Elastoplastic FEA Modeling of development of residual stresses using build conditions. (Michopoulos, NRL)

Localized to Global Mechanical Response Prediction

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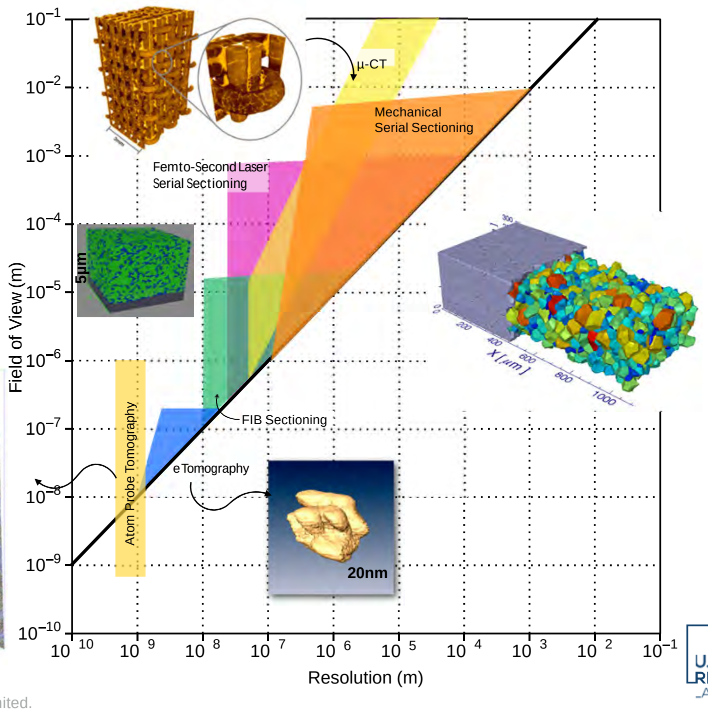
# 3D techniques for materials characterization

Serial sectioning is the method that can:

Capture very large volumes (~1mm$^3$)

At a relatively high resolution (≤1µm) for a wide class of materials.



2

# Robotic Serial Sectioning System (RS3D)*

*Inspired by Mike Uchic (AFRL) LEROY system "Good artists copy, great artists steal" — Pablo Picasso

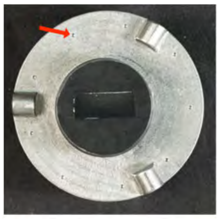
24 Hour, 7 Days/week operation, automated polishing, automated electron imaging.

Kuka six axis robot to transfer sample between devices

Mira Tescan SEM that allows for full automation of controls/data collection SE/EBSD/EDS/BSE...

RoboMet automatic polishing w/ 8 polishing pads, ultra sonic cleaning, two etching stations.

Controlled material removal from 0.2 - 10 micron using well developed material preparation techniques.



# 316L AM Build

OAK RIDGE National Laboratory

Special Thanks to Mike Kirka: ORNL

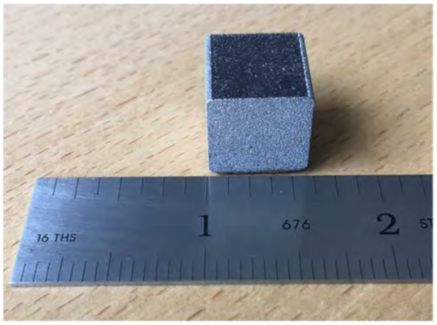
316L PBF on an SLM 280

15 x 15 x 15 mm cubes

**30µm layers ; 67° Raster Direction Rotation**

**Hatch distance: 0.12mm**

175W @750mm/sec



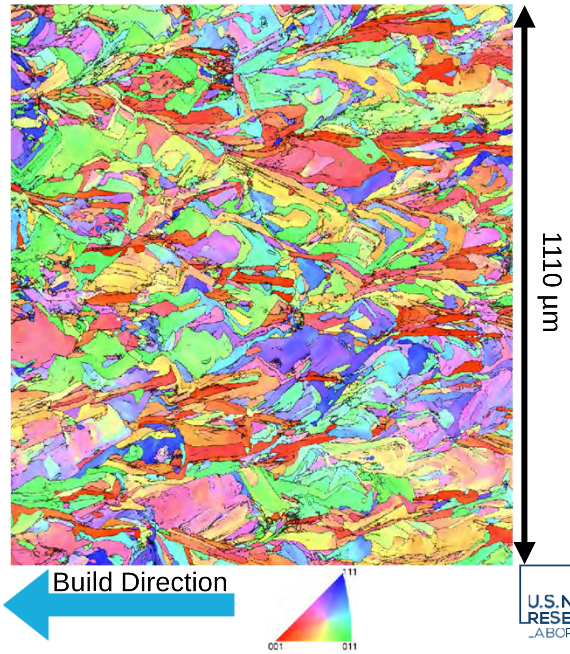
# Automated Serial Sectioning

308 Sections, 1.44µm spacing
  2-step polish: 1µm diamond; 0.04 $SiO_2$
BSE/SE: (0.586µm/px) 2048x2048
EBSD: 2x2 Montage 0.75µm/px ~ 1600 x1600
  Every Kikuchi Pattern saved, post-indexed
~2.5 hrs/section (30min removal/cleaning)

Total data set ~10TB. 10 sections/day

Image stacks aligned
- BSE - translations
- EBSD - high-order polynomials for stitching
  - Affine for stack alignment

Final dataset: 994 x 1110 x 444 $\mu m^3$
  >10,000 Grains in the volume



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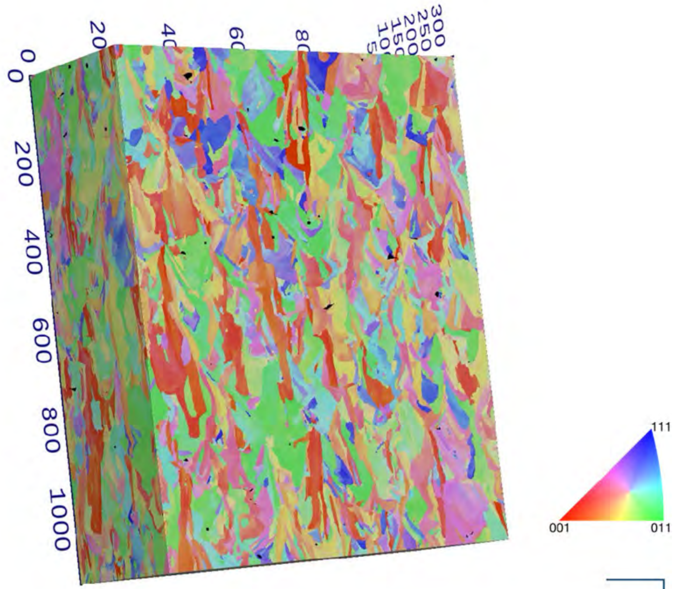
# Automated Serial Sectioning

308 Sections, 1.1µm spacing
  2-step polish: 1µm diamond; 0.04 $SiO_2$
BSE/SE: (0.586µm/px) 2048x2048
EBSD: 2x2 Montage 0.75µm/px ~ 1600 x1600
  Every Kikuchi Pattern saved, post-indexed
~2.5 hrs/section (30min removal/cleaning)

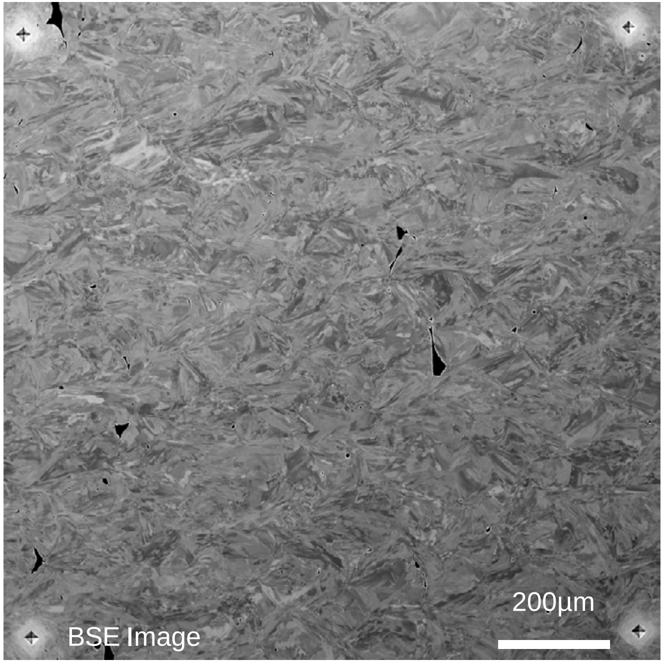
Total data set ~10TB. 10 sections/day

Image stacks aligned
- BSE - translations
- EBSD - high-order polynomials for stitching
  - Affine for stack alignment

Final dataset: 994 x 1110 x 339 $\mu m^3$
  30,000 Grains in the volume
  1,800 pore defects

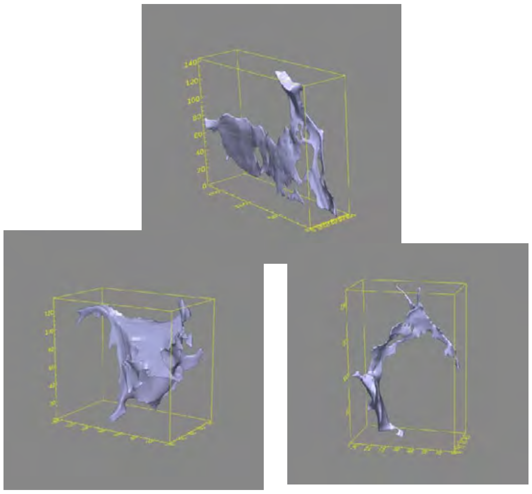


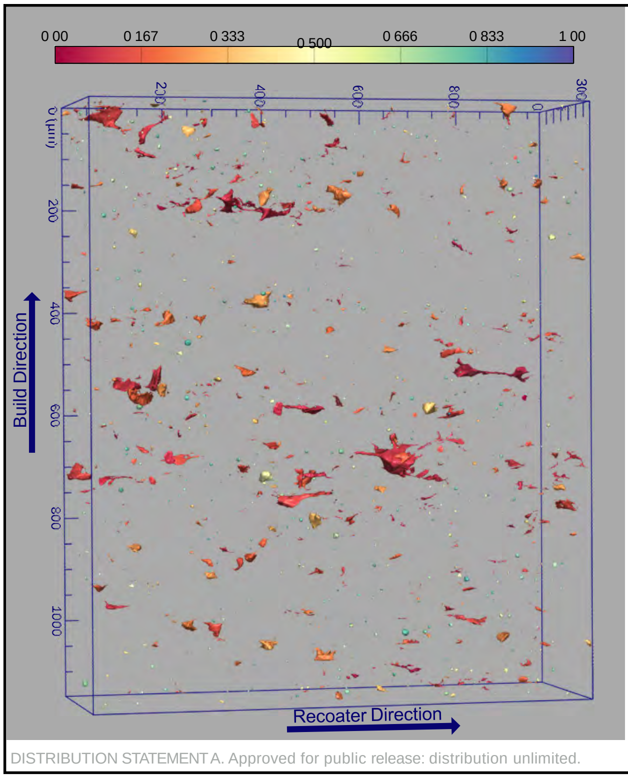
# Porosity using mechanical serial sectioning



0.28 %  Volume Fraction Pores (consistent with large area optical microscopy)

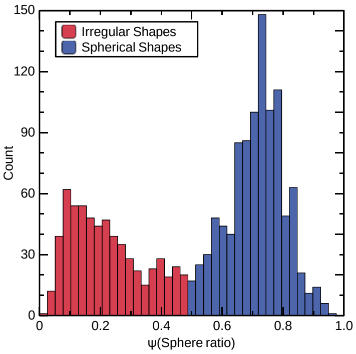
Largest pores are irregular in shape and have features that are much below the resolution of tomography.





# Pore Reconstruction

D. J. Rowenhorst, L. Nguyen, A. D. Murphy-Leonard, and R. W. Fonda. Characterization of microstructure in additively manufactured 316l using automated serial sectioning. Current Opinion in Solid State and Materials Science, page 100819, Jul 2020. DOI: 10.1016/j.cossms.2020.100819

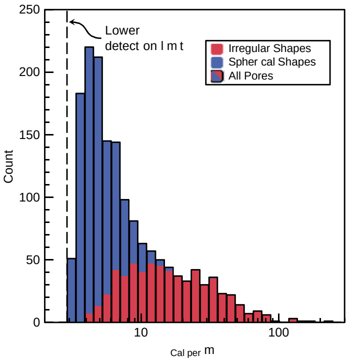


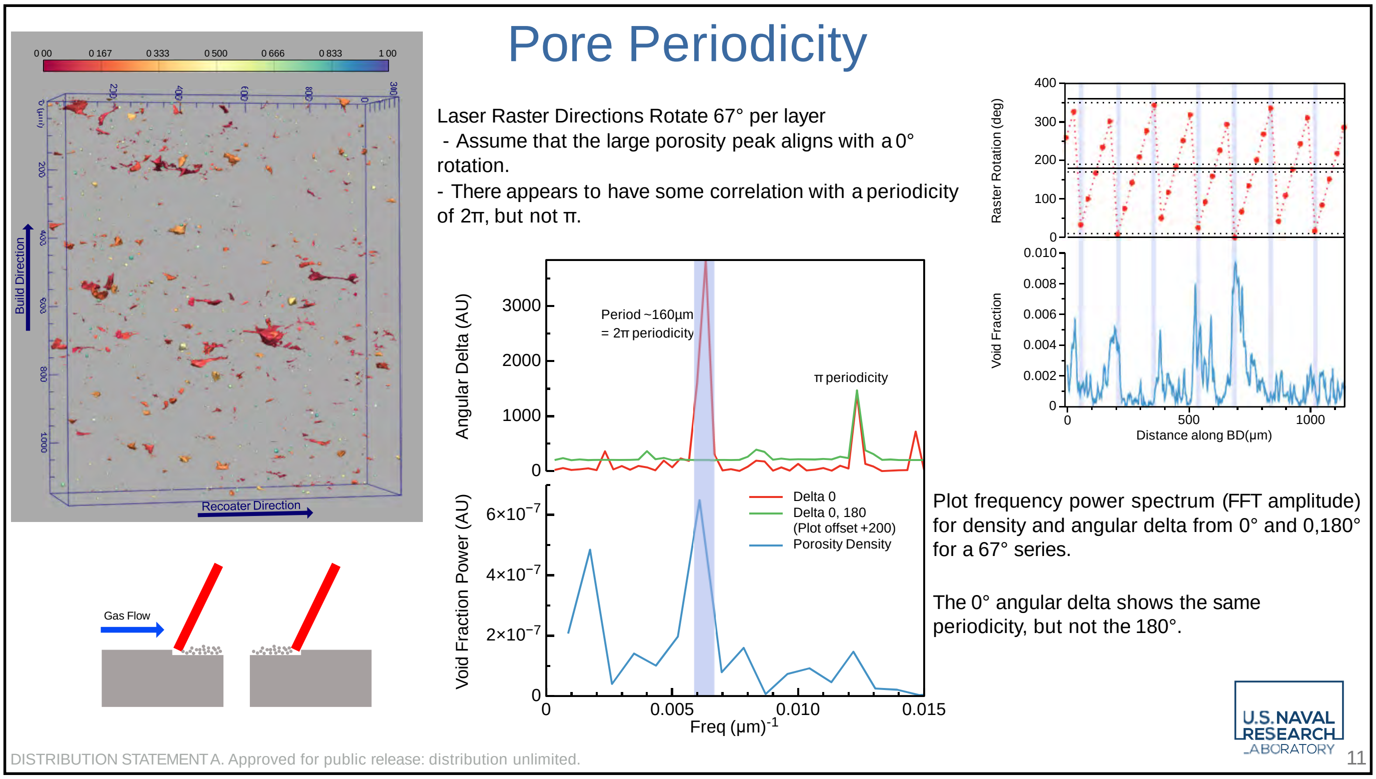
$$I = \frac{D_{Inscribed}}{D_{Caliper}}$$

$\psi$ is advantageous over sphericity in that is does not require measurement of surface area.

Irregular Pores -> LOF

- Elongation along the recoater direction
- LOF pores are denser in particular layers





## Pore Periodicity

Laser Raster Directions Rotate 67° per layer
- Assume that the large porosity peak aligns with a 0° rotation.
- There appears to have some correlation with a periodicity of 2π, but not π.

Plot frequency power spectrum (FFT amplitude) for density and angular delta from 0° and 0,180° for a 67° series.

The 0° angular delta shows the same periodicity, but not the 180°.

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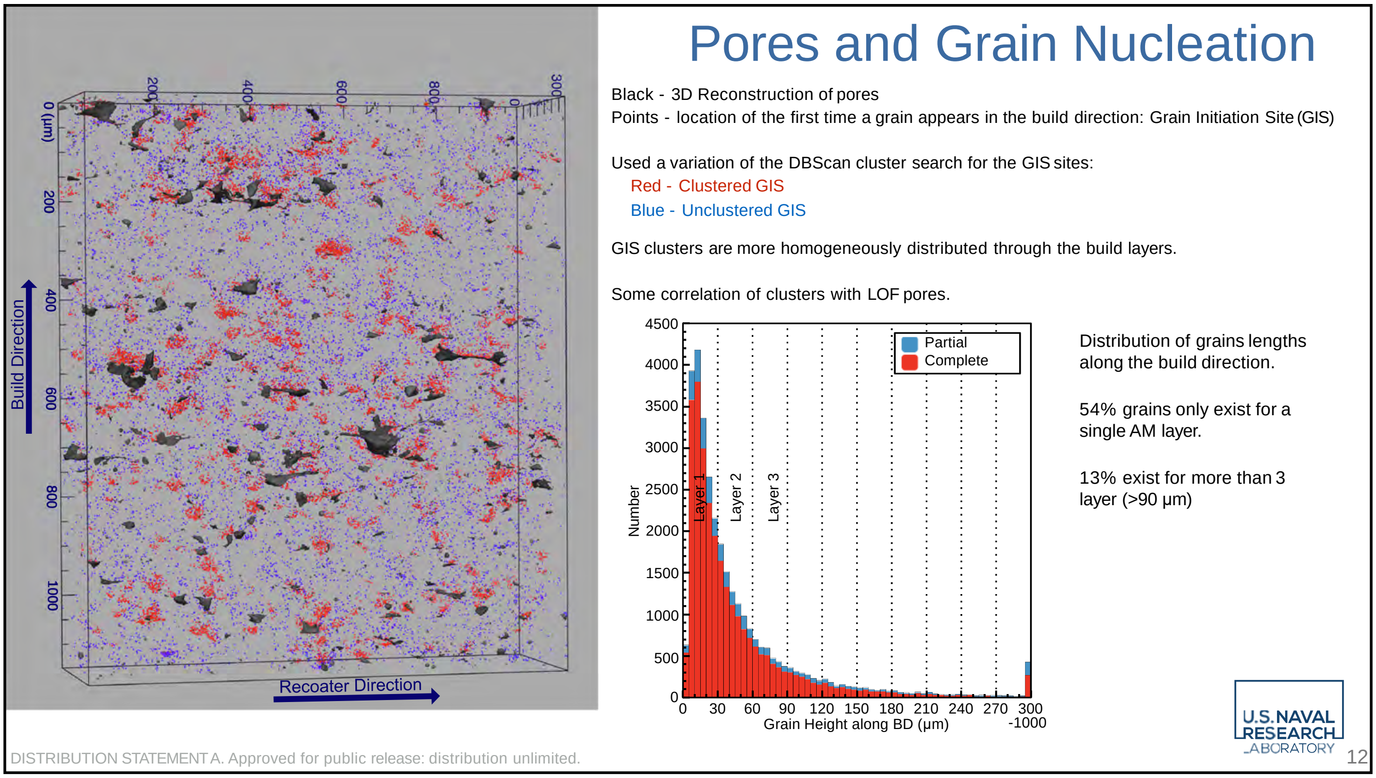

## Pores and Grain Nucleation

Black - 3D Reconstruction of pores
Points - location of the first time a grain appears in the build direction: Grain Initiation Site (GIS)

Used a variation of the DBScan cluster search for the GIS sites:
- Red - Clustered GIS
- Blue - Unclustered GIS

GIS clusters are more homogeneously distributed through the build layers.

Some correlation of clusters with LOF pores.

Distribution of grains lengths along the build direction.

54% grains only exist for a single AM layer.

13% exist for more than 3 layer (>90 μm)

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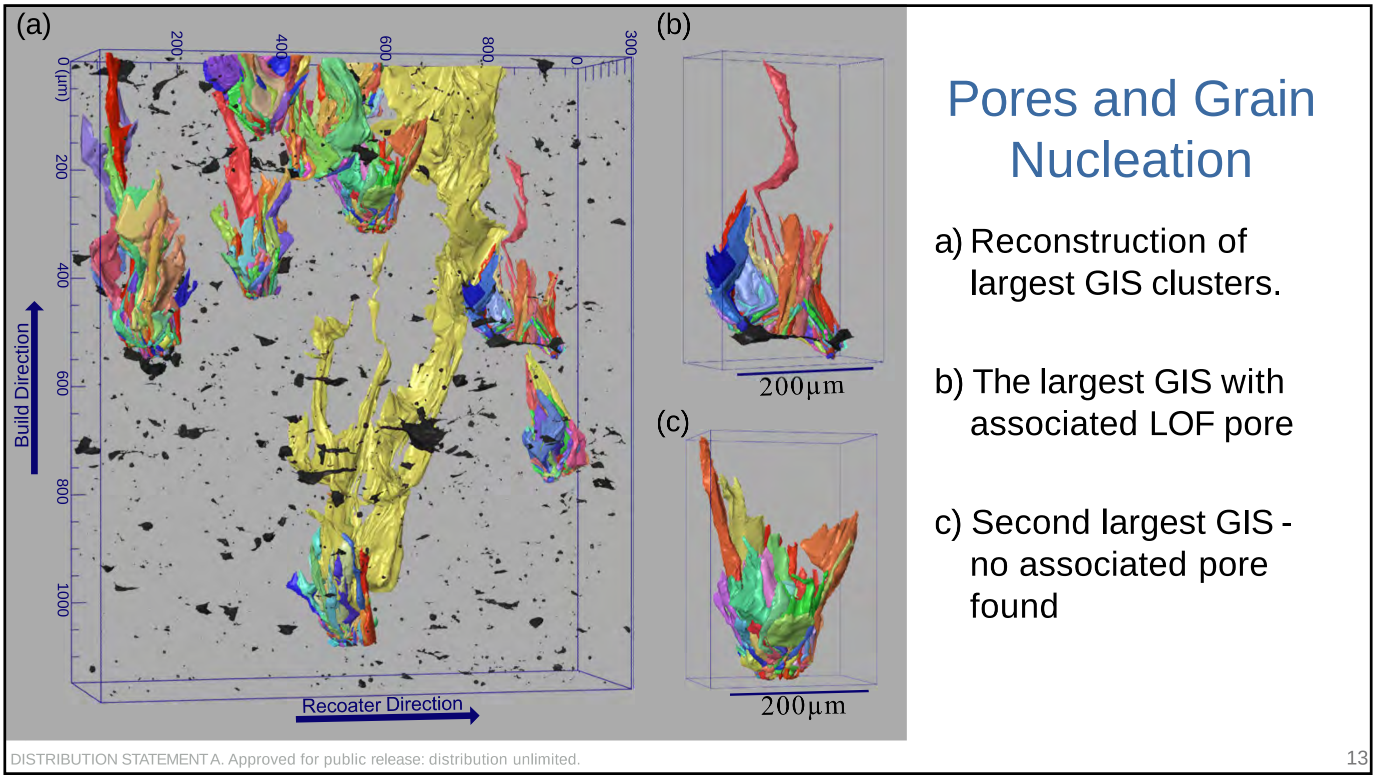


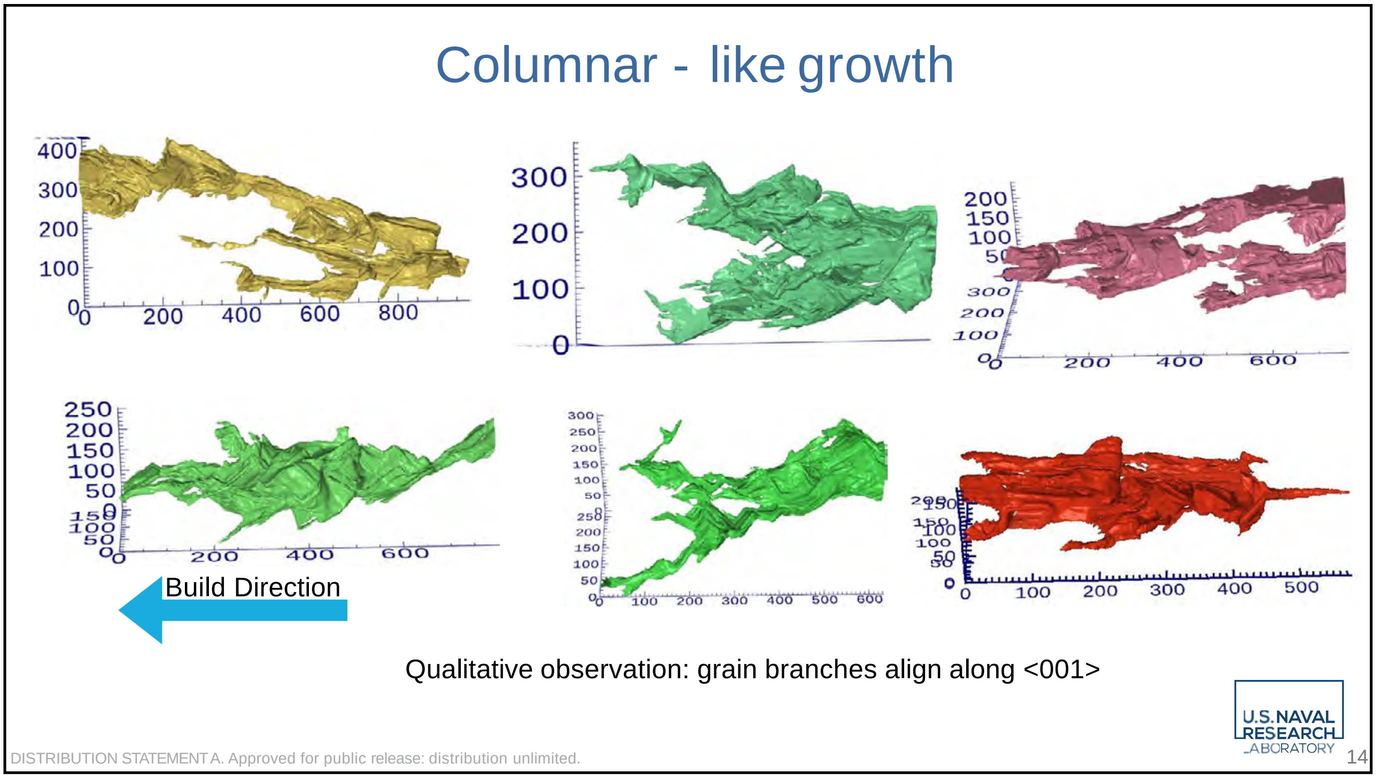
## Pores and Grain Nucleation

a) Reconstruction of largest GIS clusters.

b) The largest GIS with associated LOF pore

c) Second largest GIS - no associated pore found

## Columnar - like growth



Qualitative observation: grain branches align along <001>

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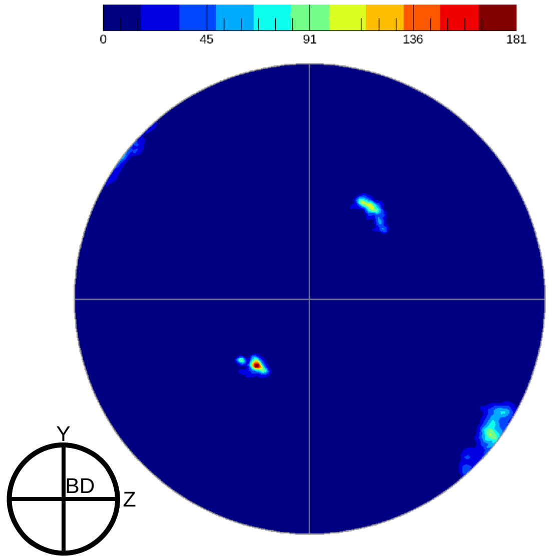
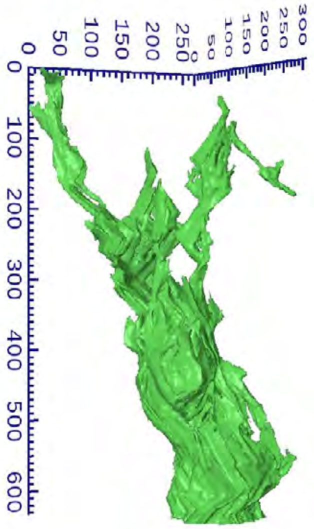
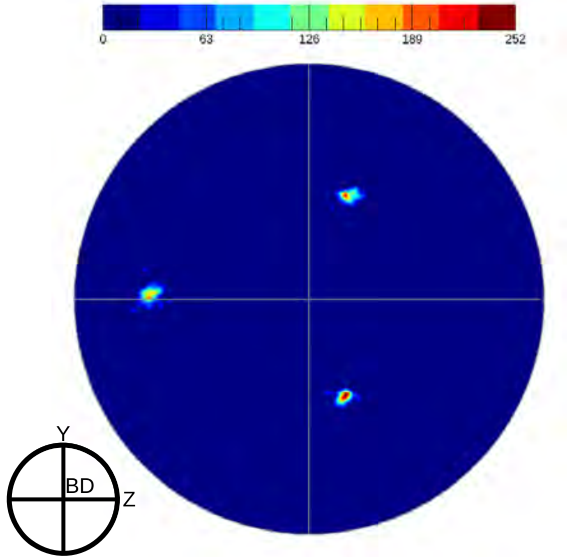
# Single Grain Textures - BD || [011]

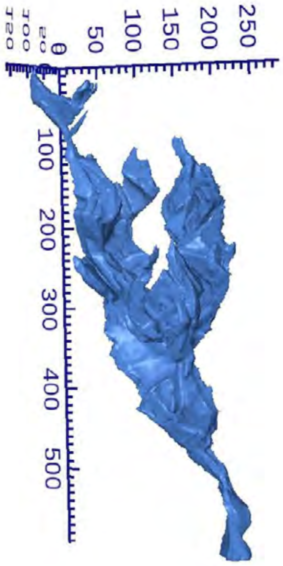




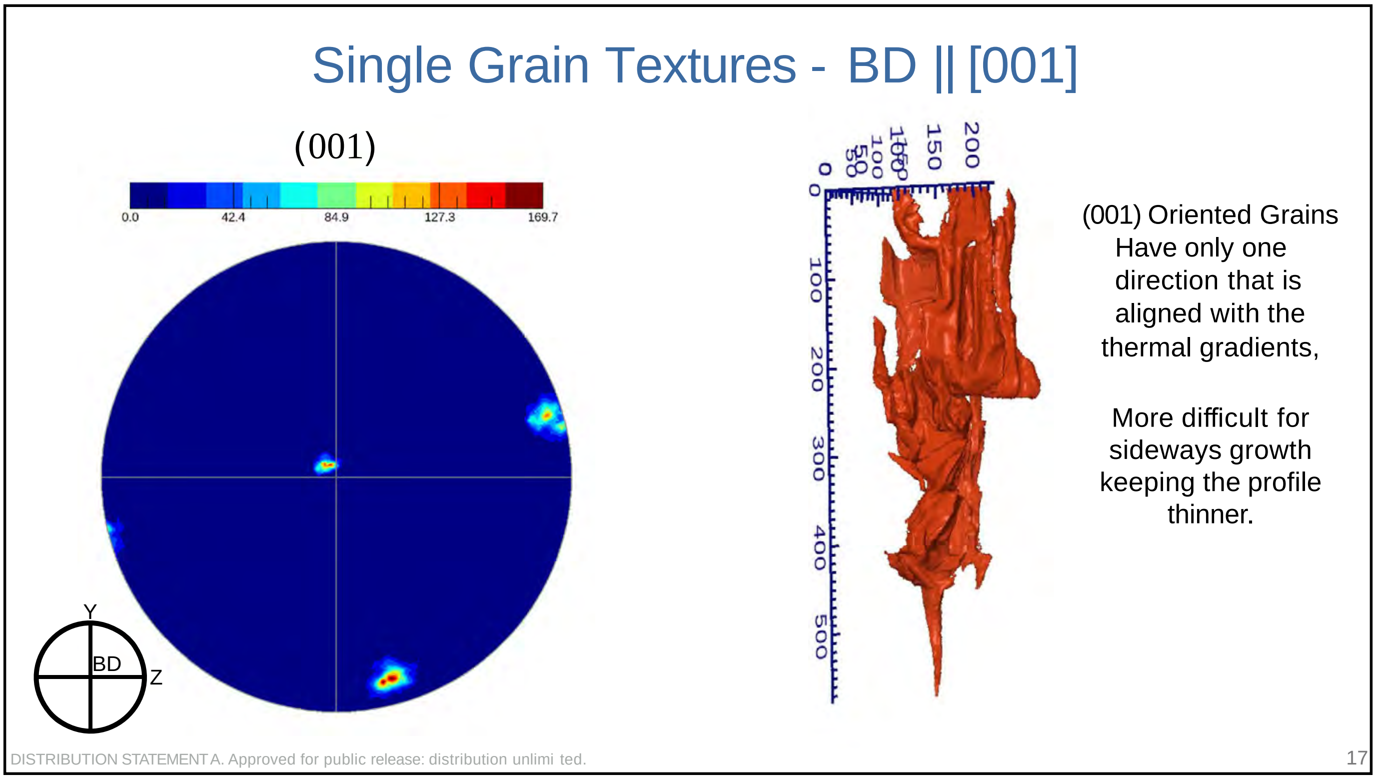
# Single Grain Textures - BD || [111]

(001)





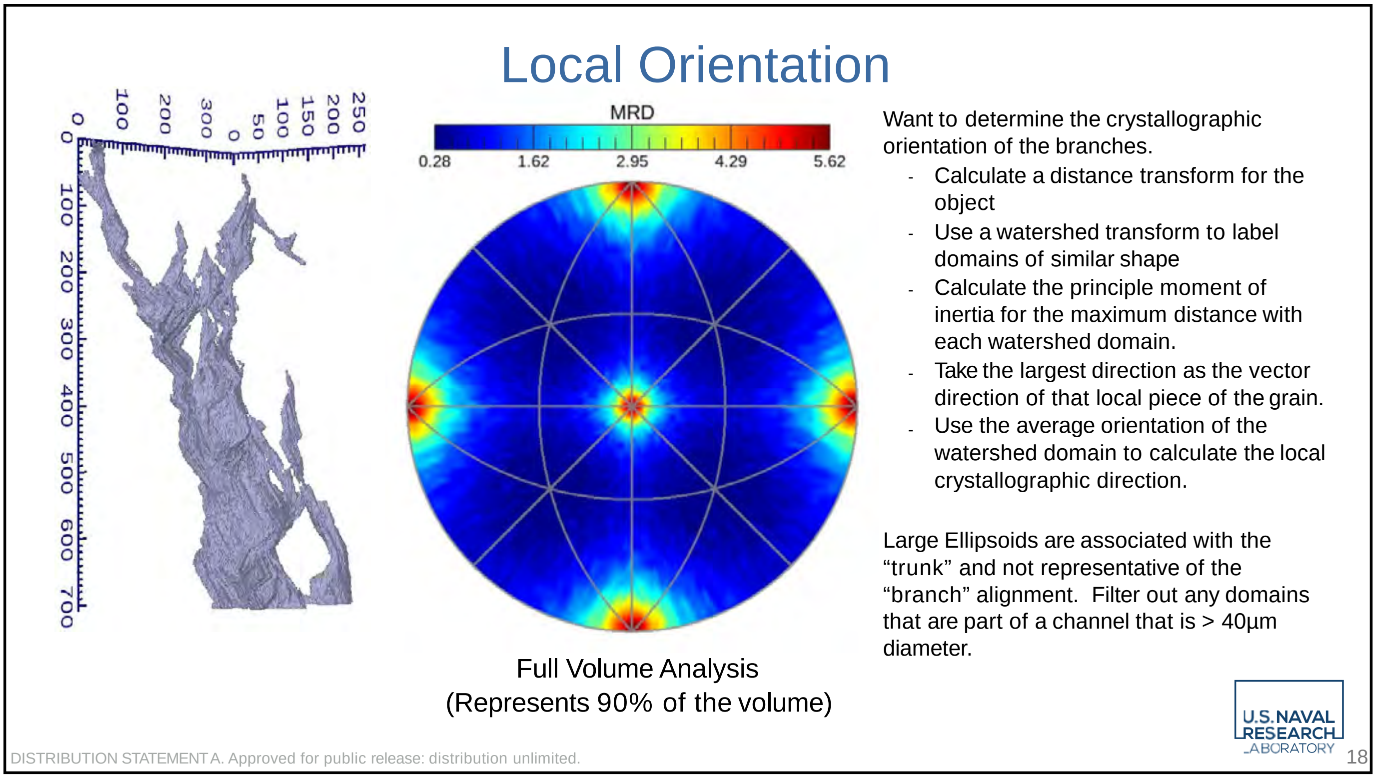
(111) Oriented Grains
Can poorly align three
(1)directions with
the raster directions.



# Single Grain Textures - BD || [001]

(001) Oriented Grains Have only one direction that is aligned with the thermal gradients,

More difficult for sideways growth keeping the profile thinner.



# Local Orientation

Full Volume Analysis
(Represents 90% of the volume)

Want to determine the crystallographic orientation of the branches.

- Calculate a distance transform for the object
- Use a watershed transform to label domains of similar shape
- Calculate the principle moment of inertia for the maximum distance with each watershed domain.
- Take the largest direction as the vector direction of that local piece of the grain.
- Use the average orientation of the watershed domain to calculate the local crystallographic direction.

Large Ellipsoids are associated with the "trunk" and not representative of the "branch" alignment. Filter out any domains that are part of a channel that is > 40µm diameter.

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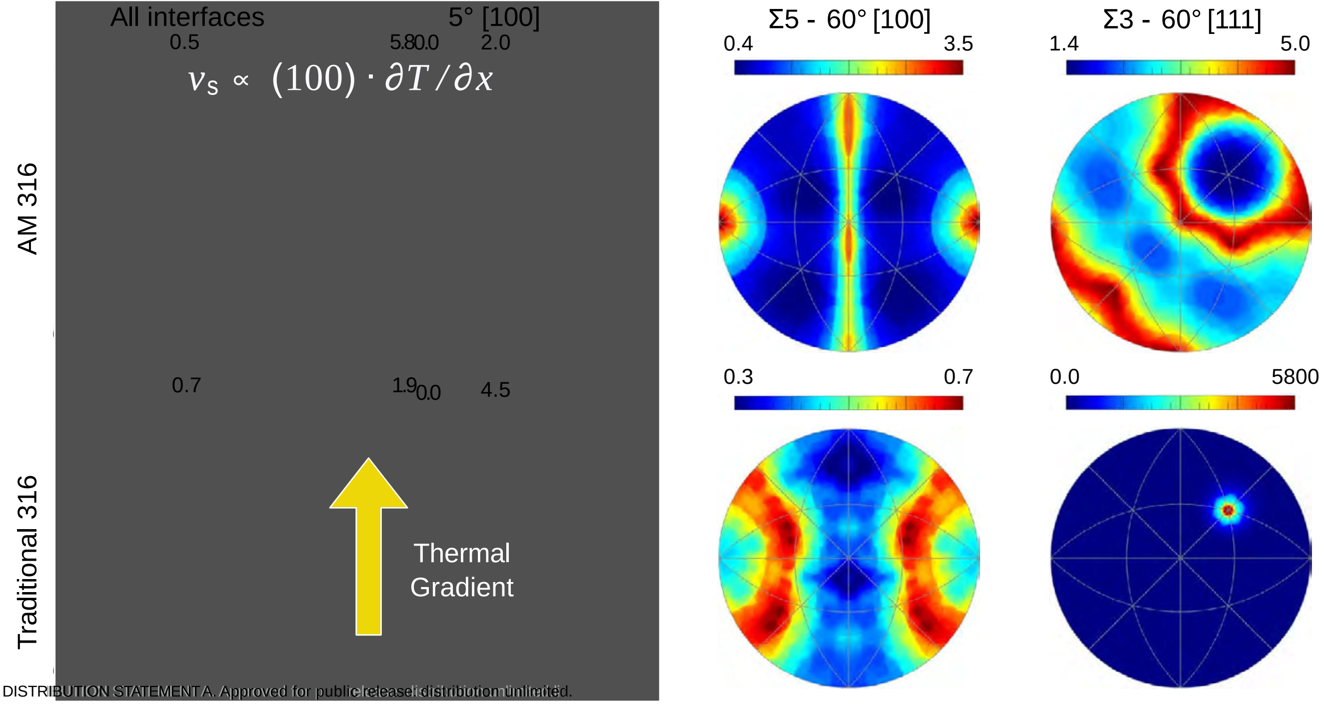
## Grain Boundary Interface Texture



$$v_s \propto (100) \cdot \partial T / \partial x$$

---

## Conclusions

New advances in automation have made large scale serial sectioning a feasible process, allowing for direct visualization of the 3D structures formed during AM processing.

- Incredibly useful for initial conditions of simulations and modeling
- Essential for validation of simulation and modeling

In 316L PBF material has a complex columnar growth. The grains are larger than expected, and contain complex shapes and branching features.

The sample textures are a function of preferred growth directions aligning with raster directions and the local morphology reflects the crystal symmetry.

This directional solidification structure leads to an elimination of Σ3 boundaries within the AM 316L Grain Boundary Character Distribution.

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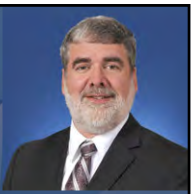

# The Effects of Post-Processing on Mechanical Properties and Corrosion Behavior of AM 316L Stainless Steel

Richard Fonda, Scott Olig, David Rowenhorst, Jerry Feng, Adelina Ntiros, Beth Stiles, Krystaufeux Williams, Roy Rayne, and Charles Hart
US Naval Research Laboratory
Codes 6350 and 6130

Supported by NRL and the NAVSEA Technology Office
Cross Platform Systems Development (CPSD) Program

# Objective

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**Objectives: Systematically determine the microstructure, corrosion behavior, and mechanical properties of AM 316L stainless steel in the as-built and post-processed conditions**

**Approach: Take advantage of the outstanding capabilities and expertise in microstructural characterization and corrosion behavior at NRL:**

- **Advanced 2D and 3D microscopy techniques**
- **Corrosion testing**
- **Mechanical property testing**

# 316L AM Steel is ***NOT*** Stainless

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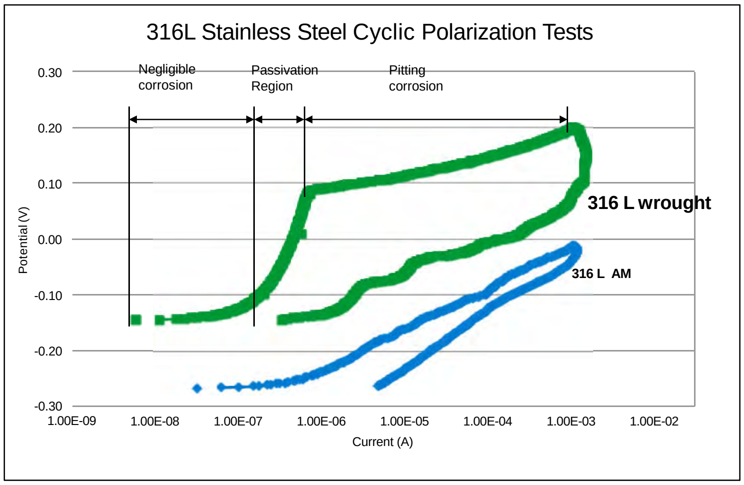
- **As-built 316L sample does not exhibit any passivity**
- **AM sample corrodes three orders of magnitude faster than wrought sample at -100mV**



**Polarization response comparison, Courtesy Dr. J. Moran 6130**

# Porosity in As-Built Material

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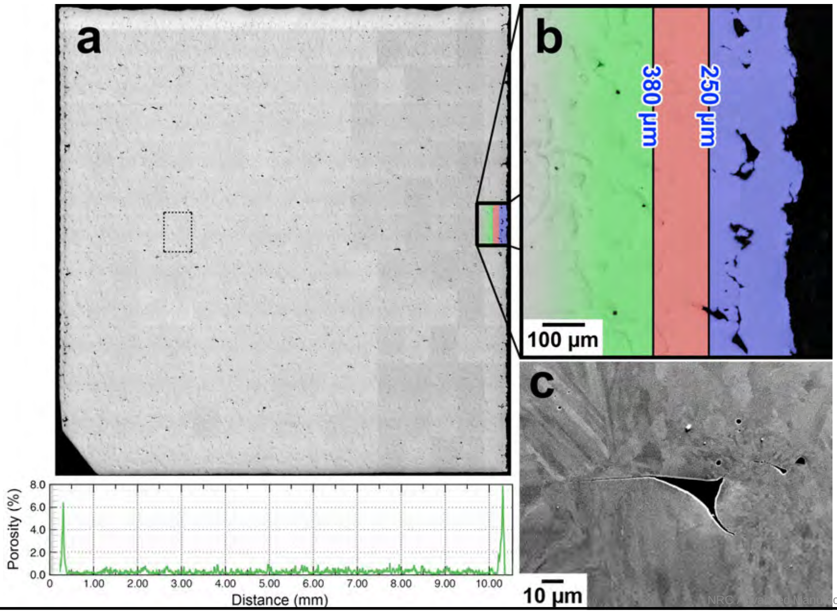
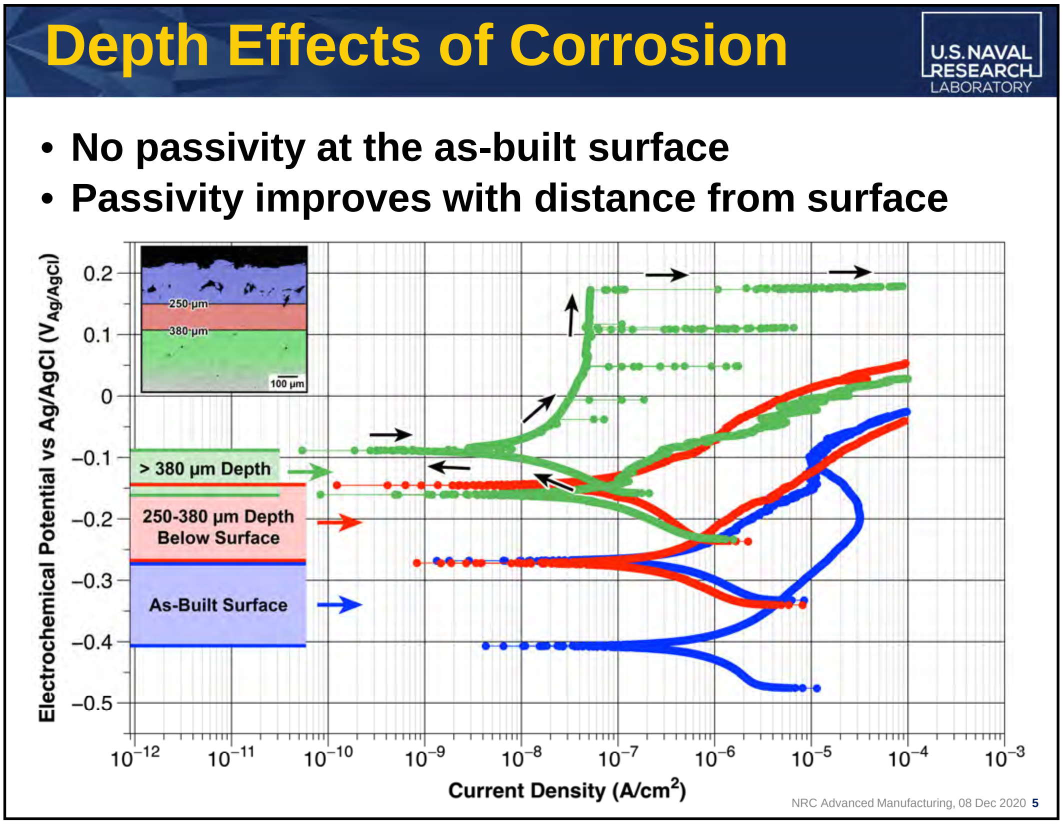
**Both LOF and gas porosity present**

**Enhanced porosity between fill and border scans**





## Depth Effects of Corrosion

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- **No passivity at the as-built surface**
- **Passivity improves with distance from surface**

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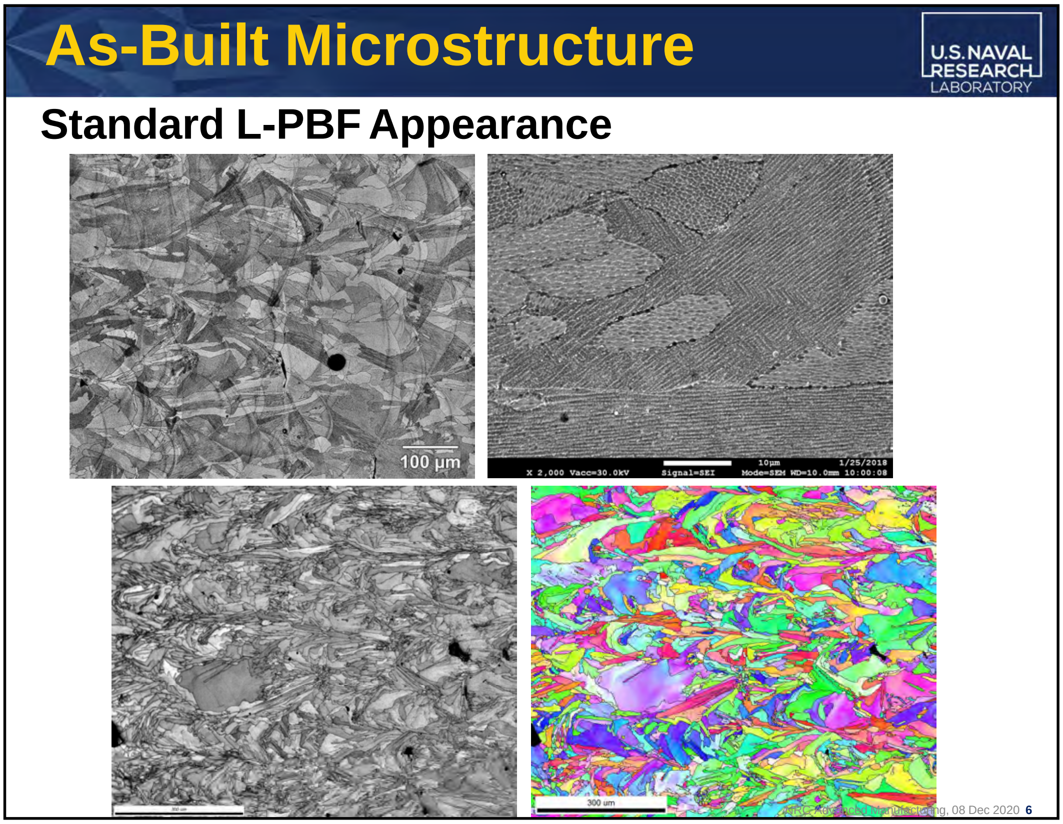

## As-Built Microstructure

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### Standard L-PBF Appearance

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# Samples

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- **As-Received Sample:**
  - 316L Stainless Steel
  - EOS M270
  - Stress Relief: 790 °C, 1 h
- **Additional Heat Treatments:**

| | |
|---|---|
| **500 °C, 1h** | **1100 °C, 1h** |
| **700 °C, 1h** | **1200 °C, 1h** |
| **800 °C, 1h** | **1300 °C, 1h** |
| **900 °C, 1h** | **1300 °C, 15h** |
| **1000 °C, 1h** | |

- **HIP Treatments—15 ksi (100 Mpa):**

| | | |
|---|---|---|
| **1000 °C, 3h** | **1100 °C, 3h** | **1200 °C, 3h** |

# Microhardness Variations

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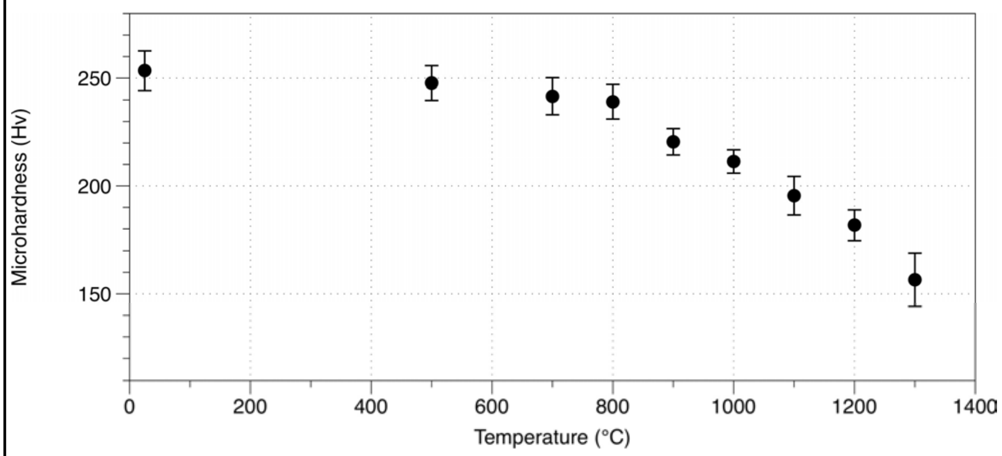
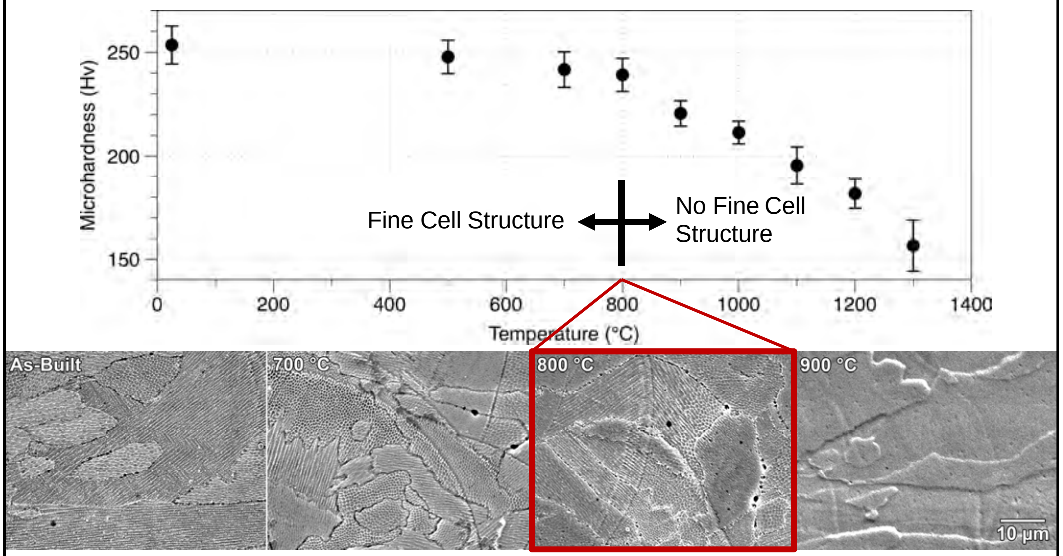


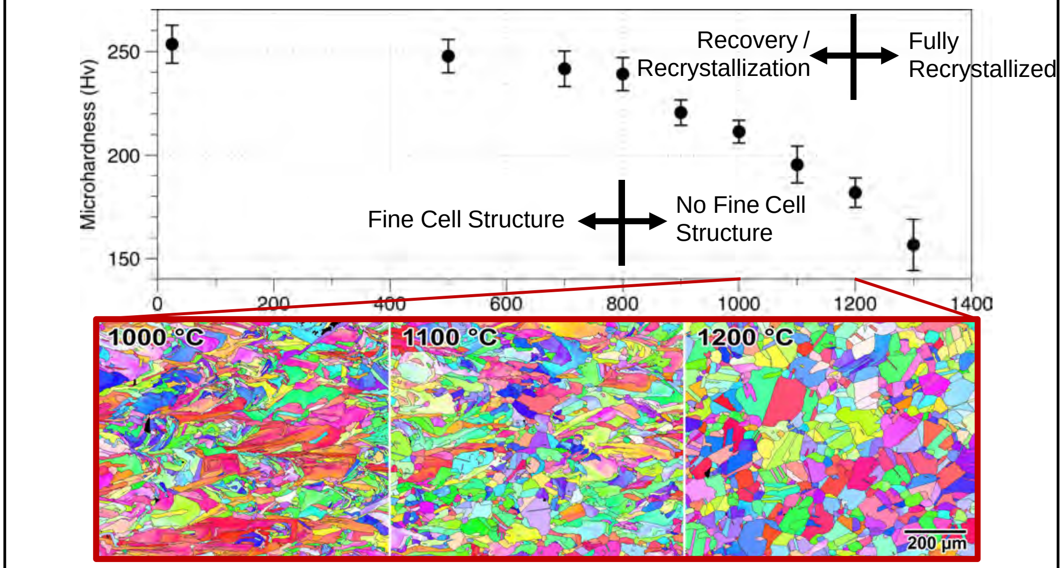
- **Heat treat for 1 hour at various Temps**
- ➢ **Slight decrease up to 800 °C**
- ➢ **Steeper decrease above 800 °C**

## Changes in Cell Structure

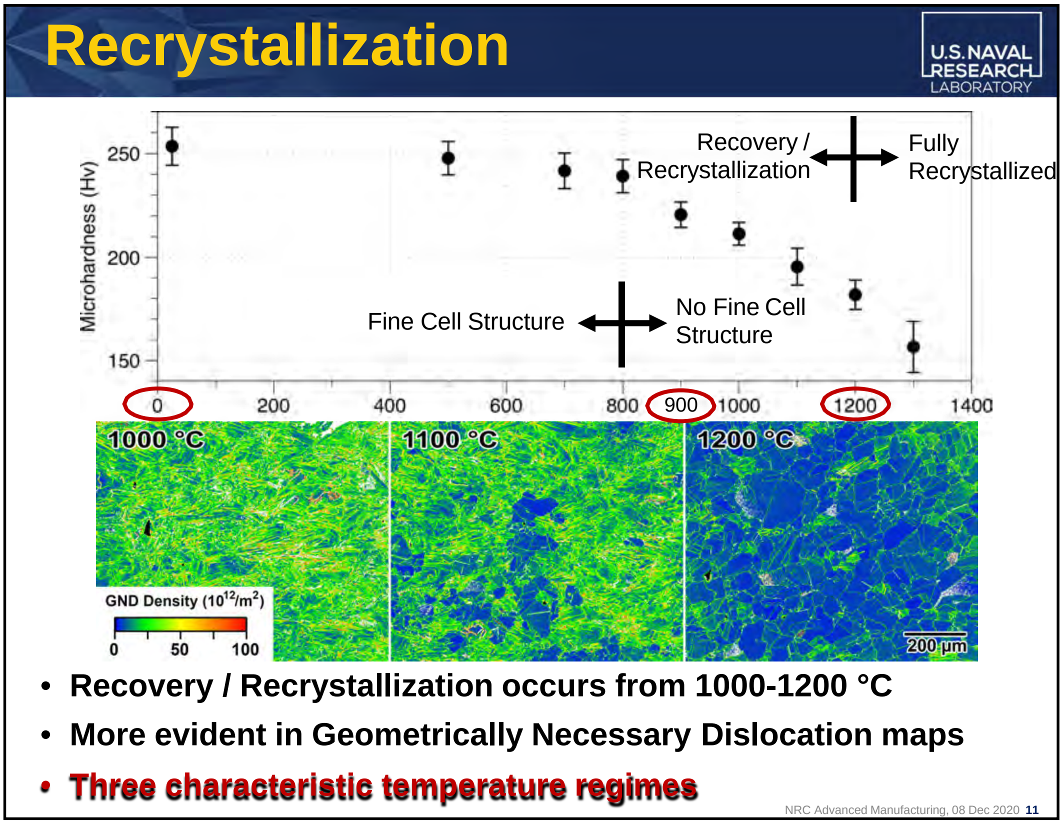


- **Cell structure evident below 800 °C**
- **Associated with higher strength and better corrosion resistance**
- **Completely absent at 900 °C and above**

## Grain Evolution



- **Recovery / Recrystallization occurs from 1000-1200 °C**
- **Difficult to discern from IPF maps**



# Recrystallization

- Recovery / Recrystallization occurs from 1000-1200 °C
- More evident in Geometrically Necessary Dislocation maps
- Three characteristic temperature regimes

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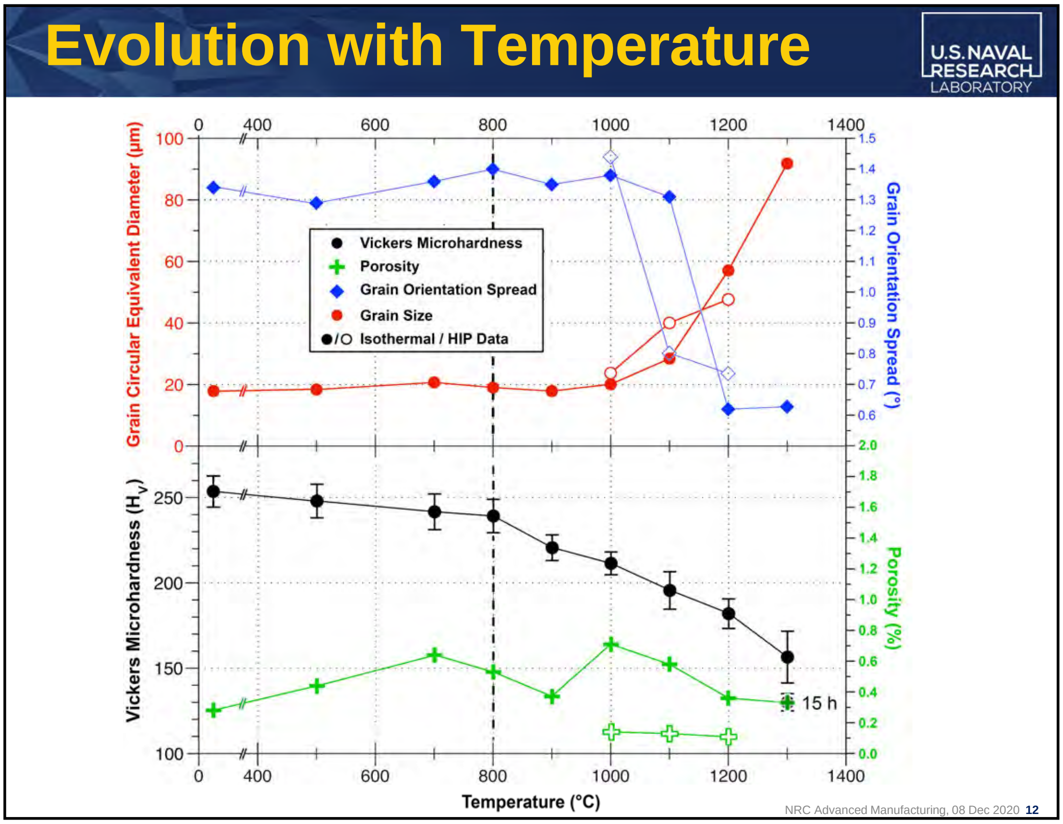

# Evolution with Temperature

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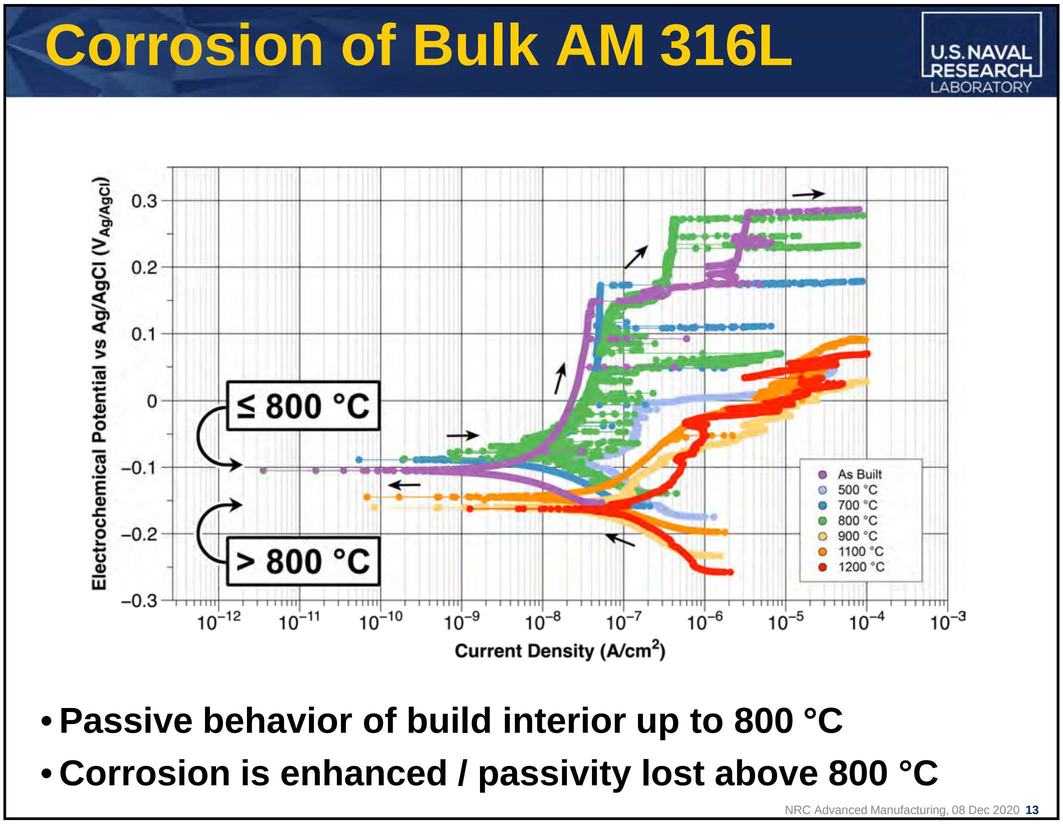
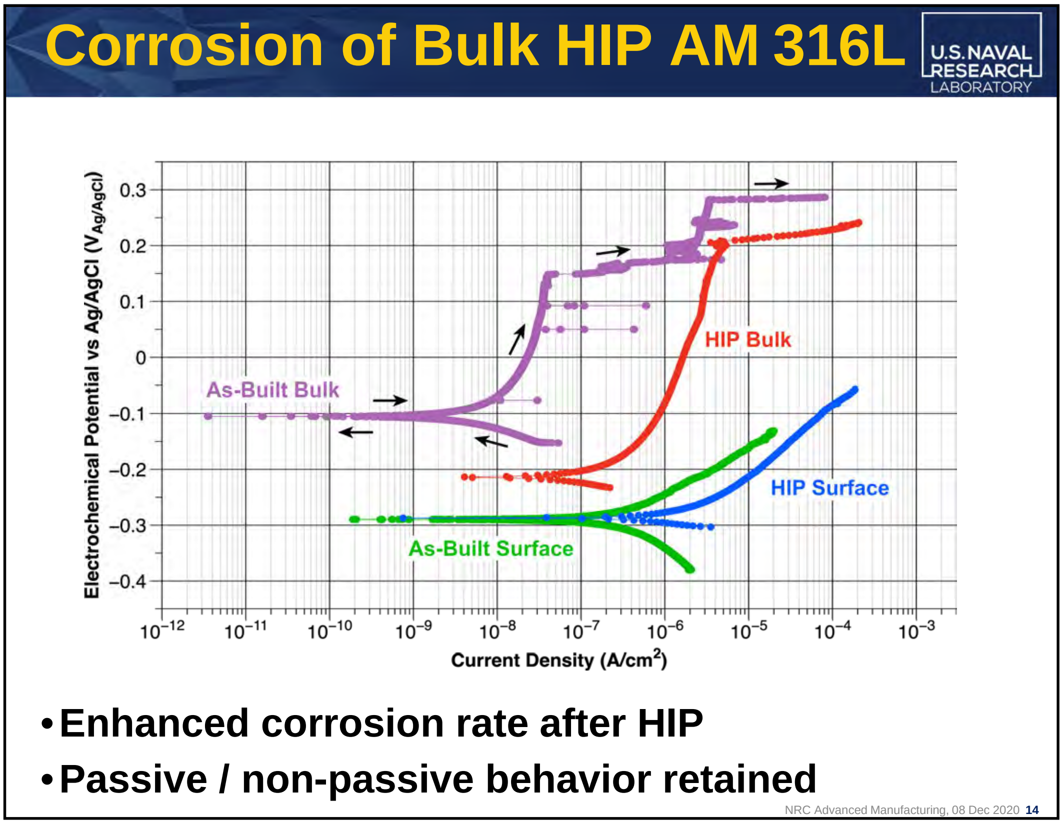


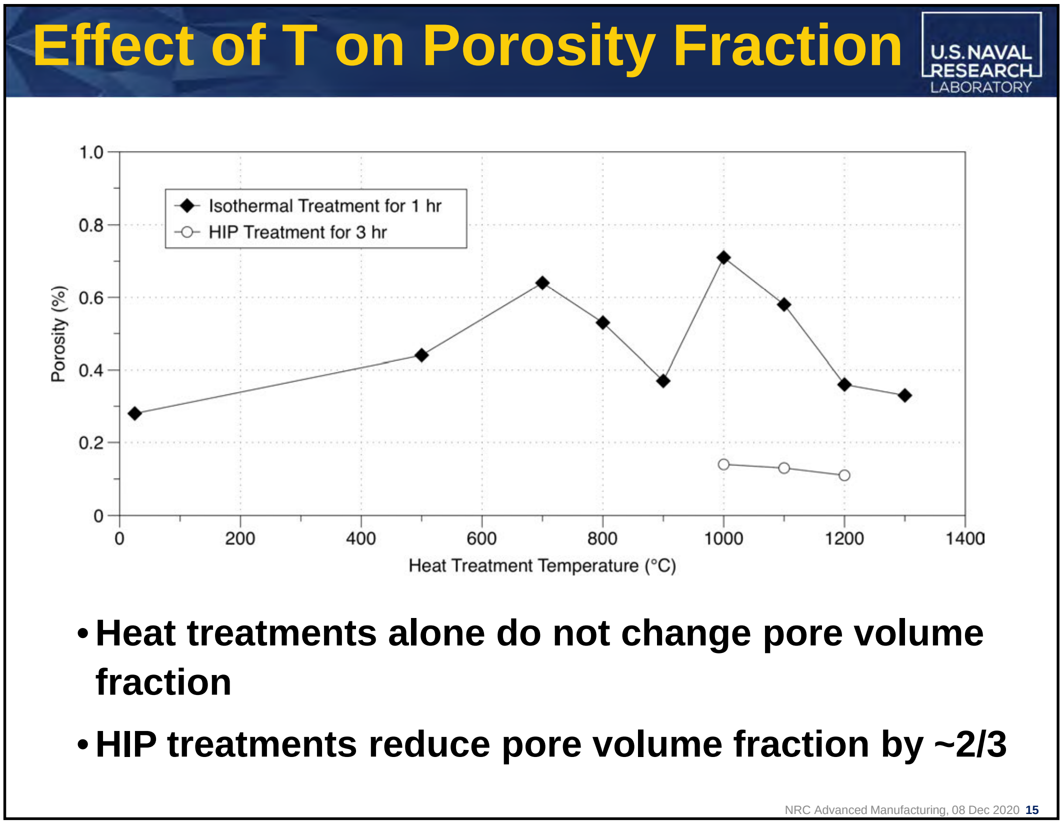
# Corrosion of Bulk AM 316L

- Passive behavior of build interior up to 800 °C
- Corrosion is enhanced / passivity lost above 800 °C



# Corrosion of Bulk HIP AM 316L

- Enhanced corrosion rate after HIP
- Passive / non-passive behavior retained



# Effect of T on Porosity Fraction

- Heat treatments alone do not change pore volume fraction
- HIP treatments reduce pore volume fraction by ~2/3

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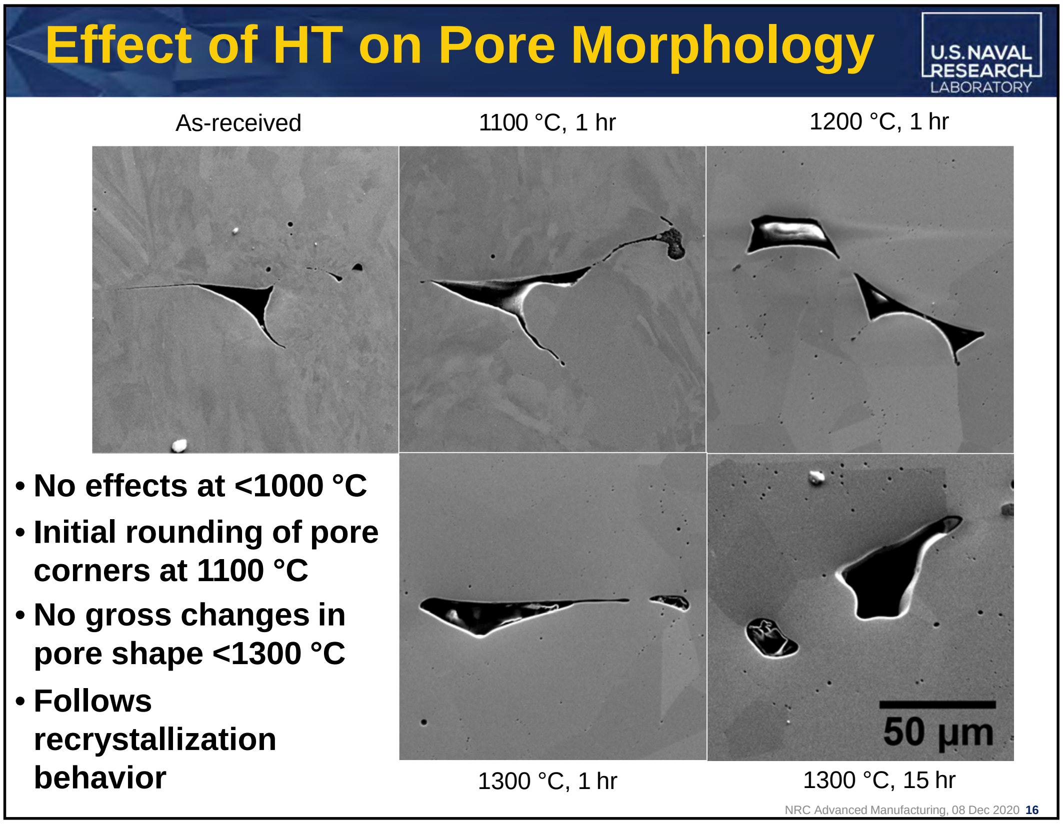

# Effect of HT on Pore Morphology

As-received

1100 °C, 1 hr

1200 °C, 1 hr

1300 °C, 1 hr

1300 °C, 15 hr

- No effects at <1000 °C
- Initial rounding of pore corners at 1100 °C
- No gross changes in pore shape <1300 °C
- Follows recrystallization behavior

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# Effects of HIP on Porosity

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**As-Built** **HIP**

0.75 mm

**LOF pores removed by HIP; small pores remain**

# New Build Parameters

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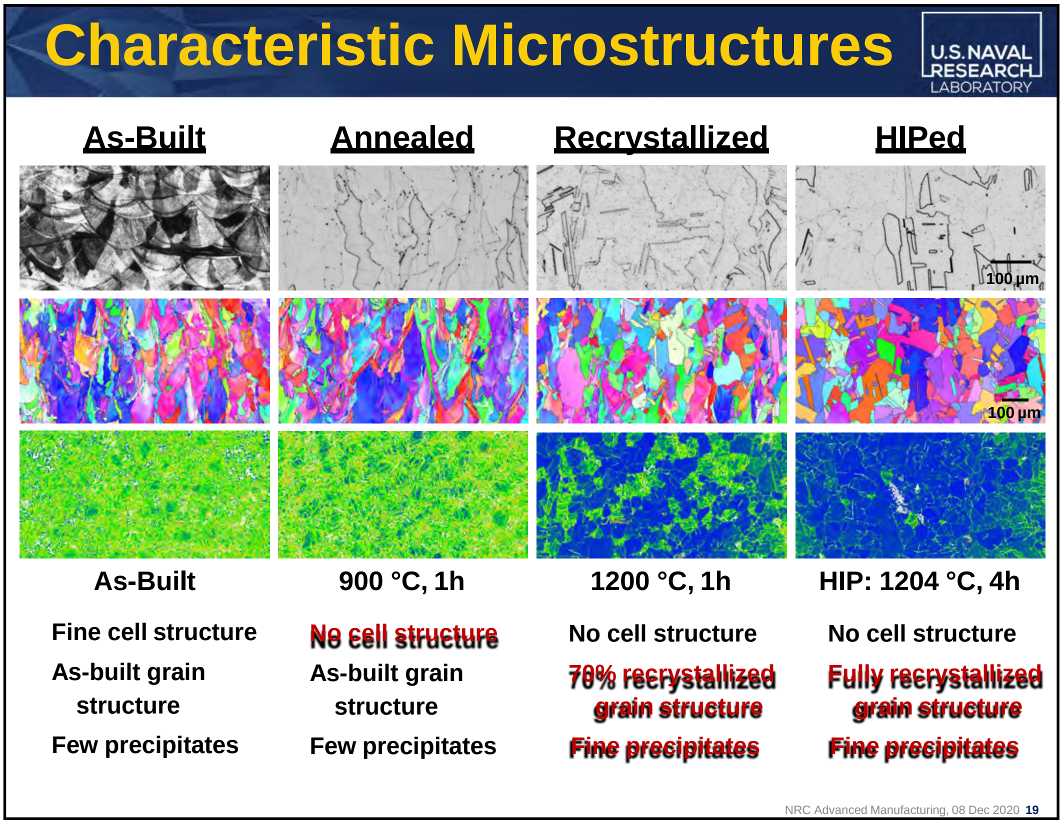
**Further analysis of four characteristic structures**

- **EOS M290 at JHU-APL**
- **EOS StainlessSteel 316L**
- **Porosity <0.1%**

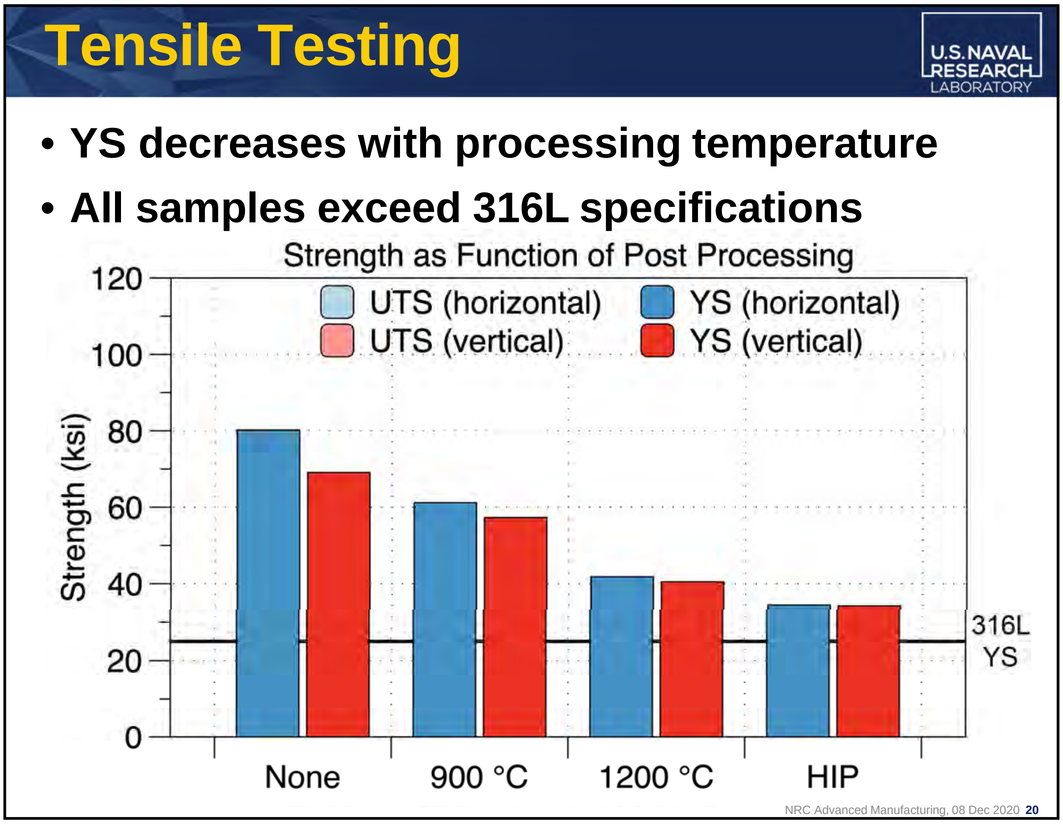
**Parameters**

- **Power: 195 W**
- **Laser Speed: 1083 mm/s**
- **Layer thickness: 0.02 mm**
- **Hatch Distance: 0.09 mm**
- **Stripe width: 5 mm**
- **Stripe overlap: 0.12 mm**



# Characteristic Microstructures

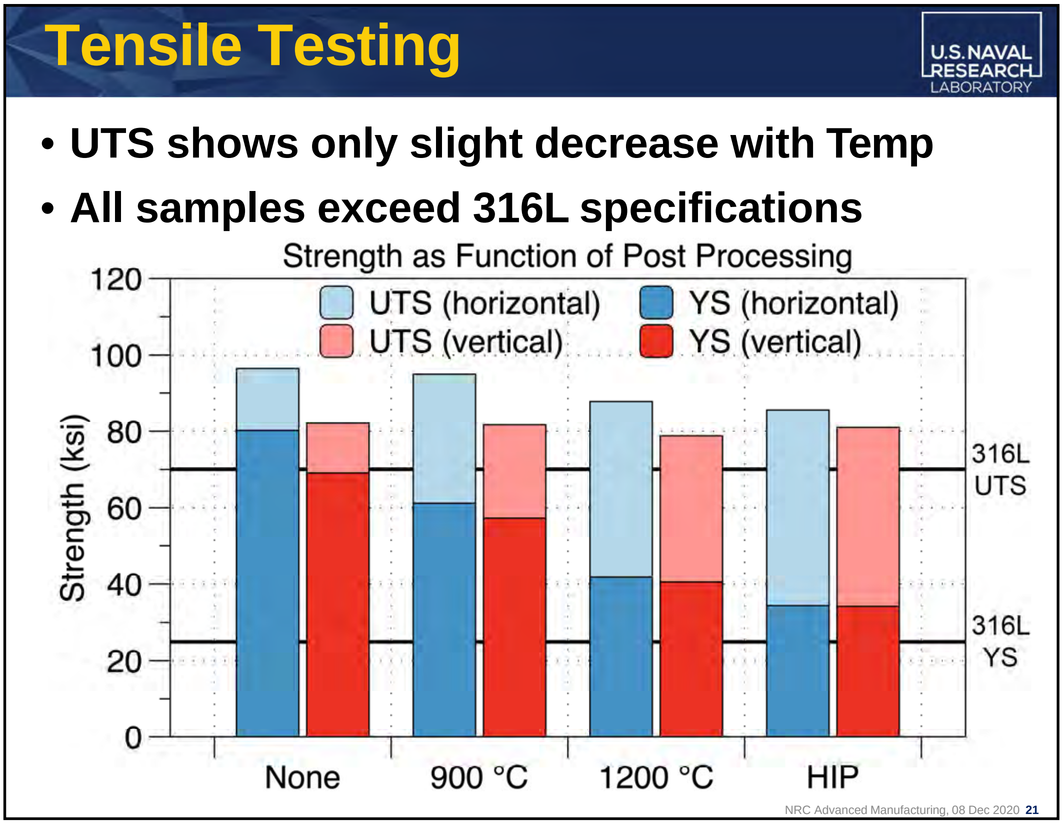
| **As-Built** | **Annealed** | **Recrystallized** | **HIPed** |
|---|---|---|---|
| As-Built | 900 °C, 1h | 1200 °C, 1h | HIP: 1204 °C, 4h |
| Fine cell structure | No cell structure | No cell structure | No cell structure |
| As-built grain structure | As-built grain structure | 70% recrystallized grain structure | Fully recrystallized grain structure |
| Few precipitates | Few precipitates | Fine precipitates | Fine precipitates |



# Tensile Testing

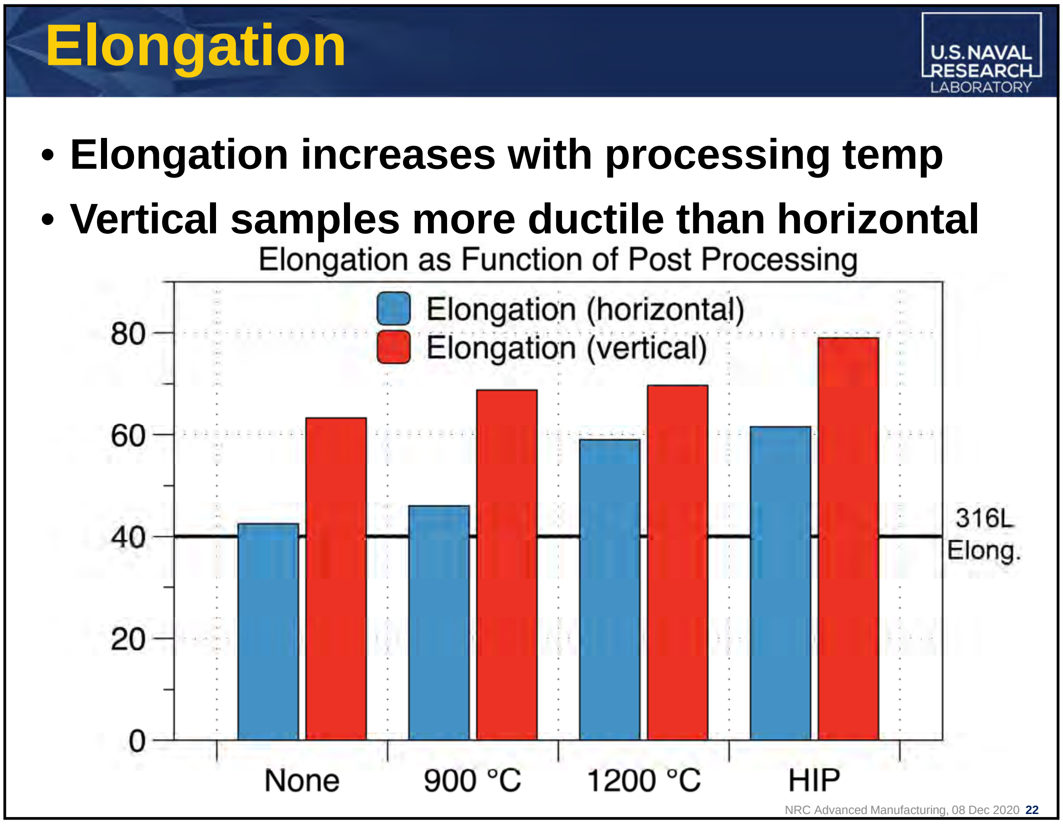
- YS decreases with processing temperature
- All samples exceed 316L specifications

Strength as Function of Post Processing



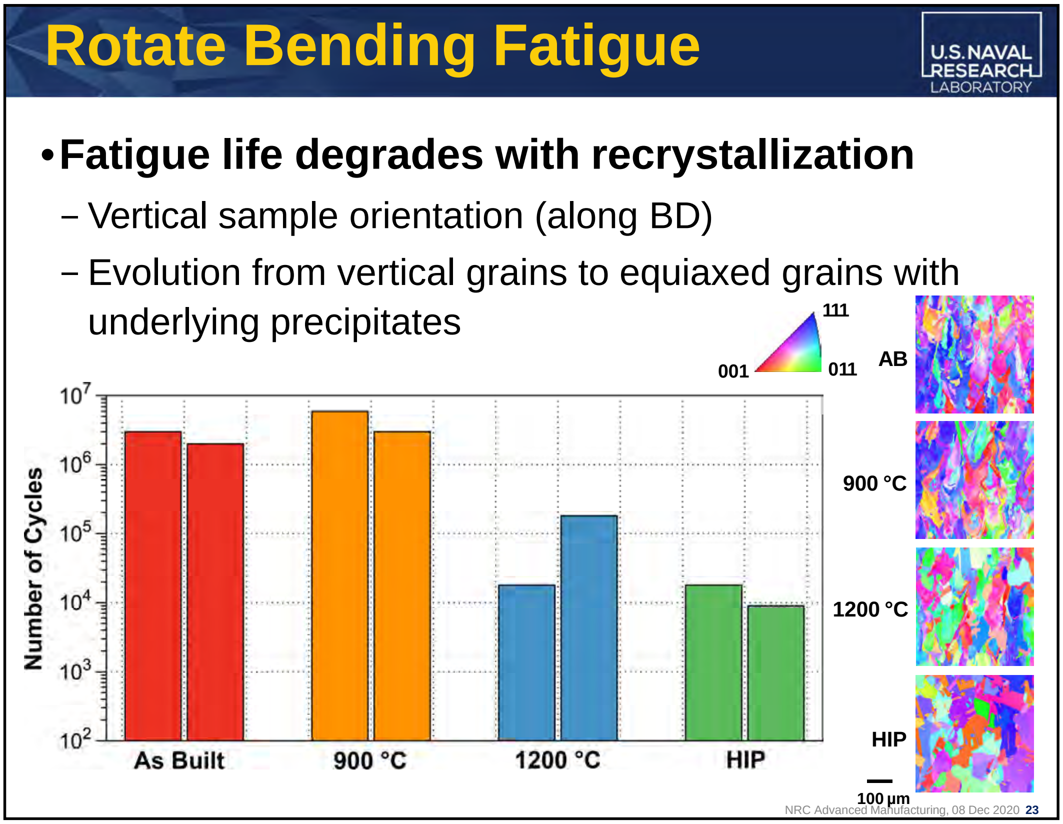
## Tensile Testing

- **UTS shows only slight decrease with Temp**
- **All samples exceed 316L specifications**



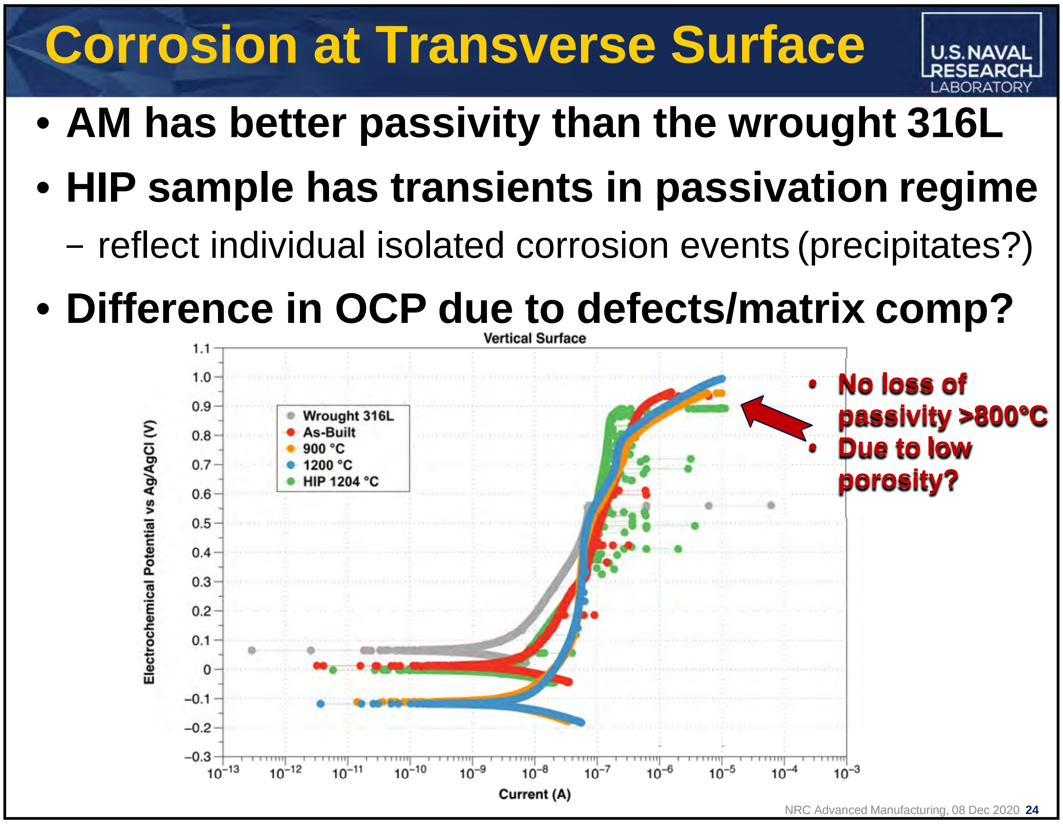
## Elongation

- **Elongation increases with processing temp**
- **Vertical samples more ductile than horizontal**



# Rotate Bending Fatigue

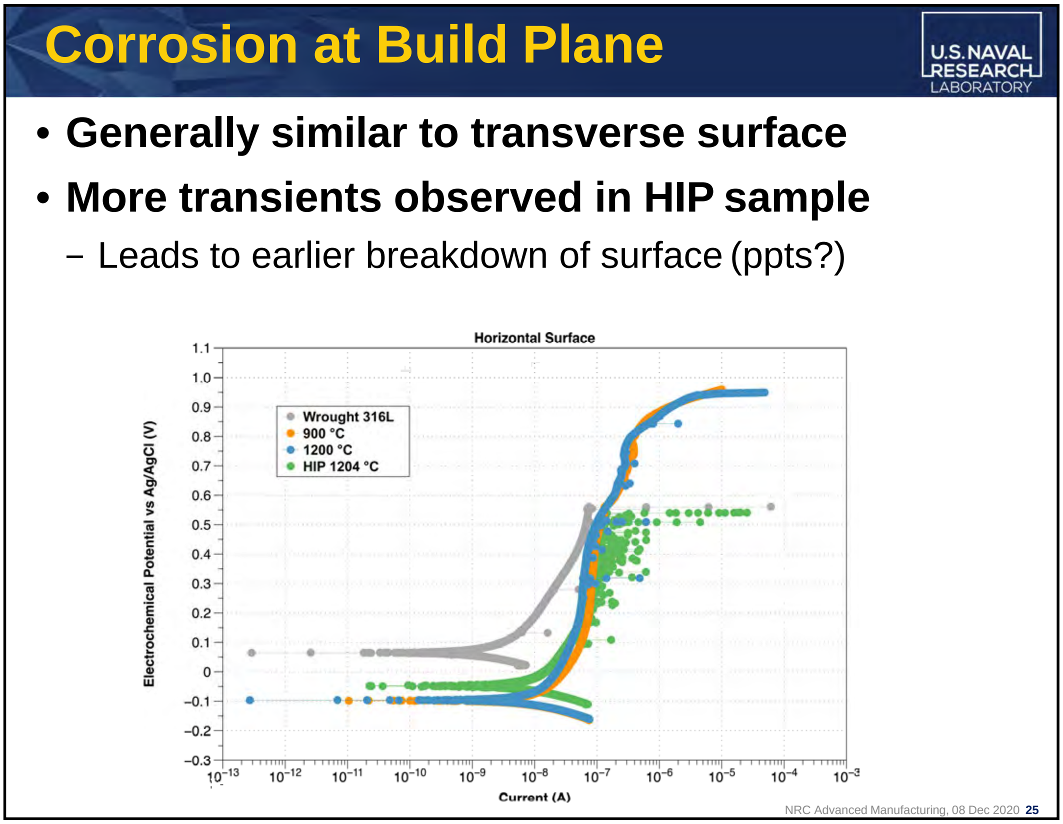
- **Fatigue life degrades with recrystallization**
  - Vertical sample orientation (along BD)
  - Evolution from vertical grains to equiaxed grains with underlying precipitates



# Corrosion at Transverse Surface

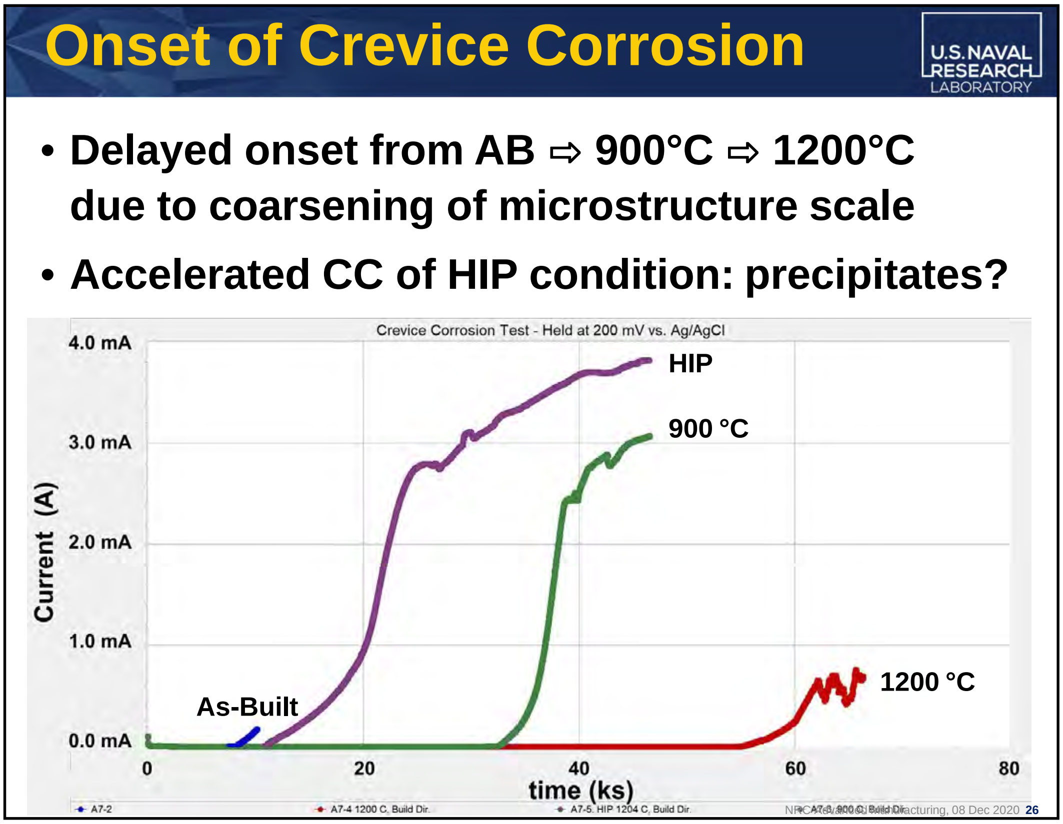
- **AM has better passivity than the wrought 316L**
- **HIP sample has transients in passivation regime**
  - reflect individual isolated corrosion events (precipitates?)
- **Difference in OCP due to defects/matrix comp?**

- No loss of passivity >800°C
- Due to low porosity?



# Corrosion at Build Plane

- **Generally similar to transverse surface**
- **More transients observed in HIP sample**
  - Leads to earlier breakdown of surface (ppts?)



# Onset of Crevice Corrosion

- **Delayed onset from AB ⇨ 900°C ⇨ 1200°C due to coarsening of microstructure scale**
- **Accelerated CC of HIP condition: precipitates?**

# Summary

- **Corrosion** enhanced at surface due to porosity
- **Three distinct microstructural regimes:**

  **As-Built <** 800 °C < **Annealed <** 1200 °C < **Recrystallized**
- **Microhardness** decreases with increasing temperature
- **Porosity fraction** does not evolve with temperature
  - HIP reduces porosity by ~2/3 by closing LOF pores
- **Yield Strength:** ~3x the 316L specification
  - decreases with processing temperature
- **UTS**: slight decrease due to recrystallization/ppt
- **Elongation:** increases with processing temperature
- **RB Fatigue**: ~100x decrease with recrystallization
- **Corrosion:** HIP-induced precipitation causes increased frequency of transients and rapid onset of crevice corr.
- **Crevice corrosion** resistance improves at 900 °C & 1200 °C
- **All AM structures exceed 316L specifications for YS, UTS, and elongation**

# Thank you!

# PROCESS VALIDATION FOR AM

**Daniel Porter, PhD**
Division of Applied Mechanics

Office of Science and Engineering Laboratories
Center for Devices and Radiological Health
U.S. Food and Drug Administration

December 2020

OSEL InfoClear #DAM-6715

## Disclaimer

## Speaker Bio

Dr. Daniel Porter currently is a Regulatory Scientist at the U.S. FDA's Division of Applied Mechanics researching the properties of additively manufactured (AM) lattice structures and AM facemask sealing efficacy. Dr. Porter also has experience as a Lead Reviewer in the Office of Orthopedic Devices (OHT6) within the Center of Devices and Radiological Health at the U.S. FDA. He holds a Bachelor and Master of Science in Mechanical Engineering from the University of Louisville (UofL). He completed nearly two years of internships at Sandia National Laboratories in New Mexico where he researched gas chromatography technologies for national security applications. Dr. Porter received his Ph.D. in Mechanical Engineering from UofL where he studied vibrational energy harvesting, MEMS technology, and AM. He completed his postdoctoral position at Southern Methodist University (SMU) in Dallas, Texas where he studied AM of ultraviolet industrial silicone and thermally curable medical grade silicone.

## Overview of Presentation

- Introduction & Motivations
- Hypothetical Case Study Intro
- Device Design & Draft Labeling
- Process Workflow
- Software Workflow
- Material Control
- Post-Processing
- Monitoring Activities
- Worst-Case AM Selection
- Ending Remarks

## CDRH Snapshot

**1900**
EMPLOYEES

**18k**
Medical Device Manufacturers

**183k**
Medical Devices
On the U.S. Market

**22k/year**
Premarket Submissions
including supplements and amendments

**570k**
Proprietary Brands

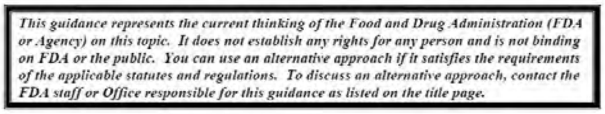
**25k**
Medical Device Facilities Worldwide

**1.4 MILLION/year**
Reports on medical device adverse events and malfunctions

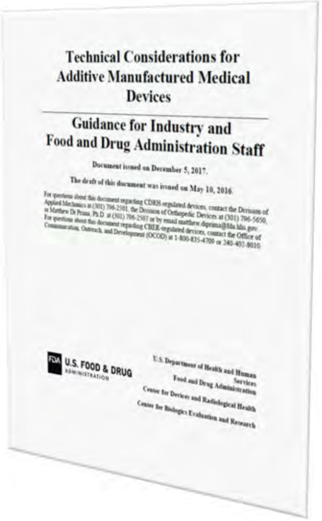
## Introduction

- AM Guidance released December 5th, 2017.
- Intended to help stakeholders address AM aspects in regulatory submissions*.
- Gives a broad overview of considerations for AM.

*Does not include biological, cellular, or tissue-based products in AM.



*This guidance represents the current thinking of the Food and Drug Administration (FDA or Agency) on this topic. It does not establish any rights for any person and is not binding on FDA or the public. You can use an alternative approach if it satisfies the requirements of the applicable statutes and regulations. To discuss an alternative approach, contact the FDA staff or Office responsible for this guidance as listed on the title page.*



Technical Considerations for Additive Manufactured Medical Devices

Guidance for Industry and Food and Drug Administration Staff

Document issued on December 5, 2017.

The draft of this document was issued on May 10, 2016.

For questions about this document regarding CDRH-regulated devices, contact the Division of Applied Mechanics at (301) 796-2501, the Division of Orthopedic Devices at (301) 796-5650, or Matthew Di Prima, Ph.D. at (301) 796-2507 or by email matthew.diprima@fda.hhs.gov. For questions about this document regarding CBER-regulated devices, contact the Office of Communication, Outreach, and Development (OCOD) at 1-800-835-4709 or 240-402-8010.

U.S. FOOD & DRUG ADMINISTRATION

U.S. Department of Health and Human Services
Food and Drug Administration
Center for Devices and Radiological Health
Center for Biologics Evaluation and Research

## FDA Guidance Documents

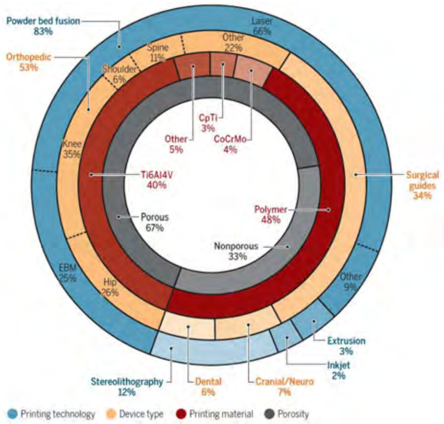
- Represent FDA's current thinking on a topic
- Do not create or confer any rights for or on any person
- Do not bind FDA or the public
- Allow you to use alternative approaches if the approach satisfies the requirements of the applicable statutes and regulations

## Motivation

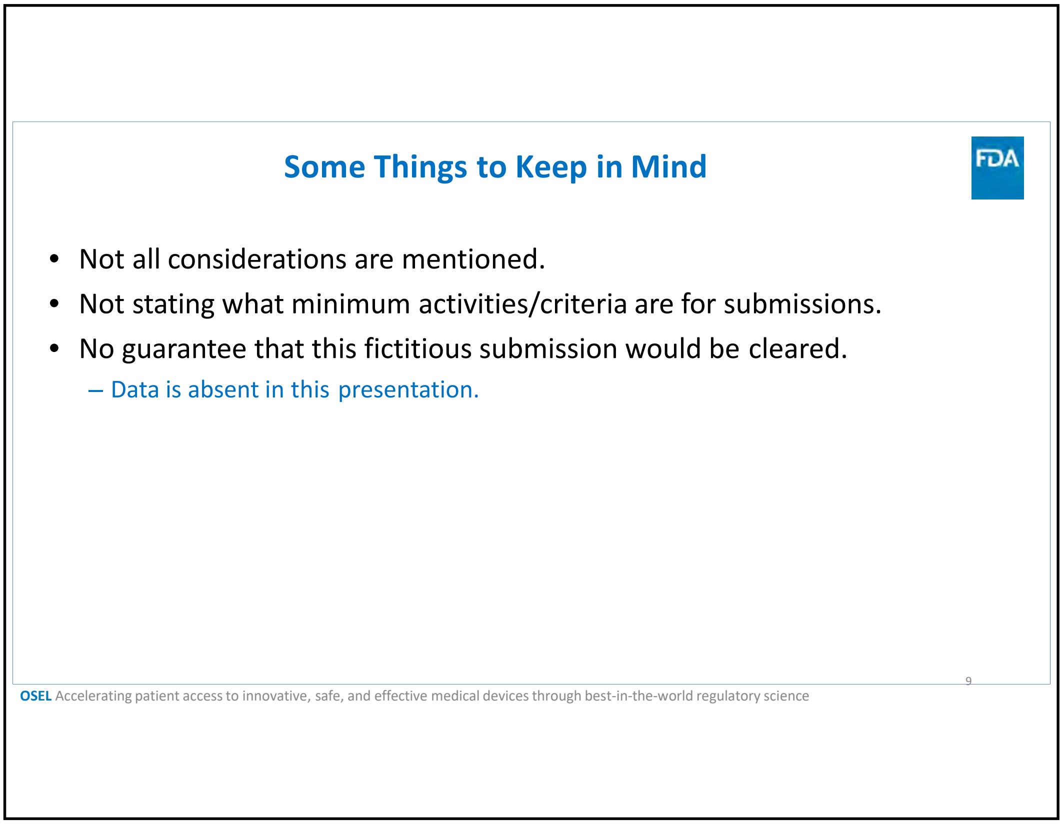
Up to ~2016

U.S. Submissions

- Submissions using AM appear to be increasing.
- More stakeholders new to AM technology.
- Powder Bed Fusion (PBF) appears to be dominant currently.
- <u>Would like to provide a hypothetical case study on one example of how to use the U.S. FDA AM Guidance.</u>

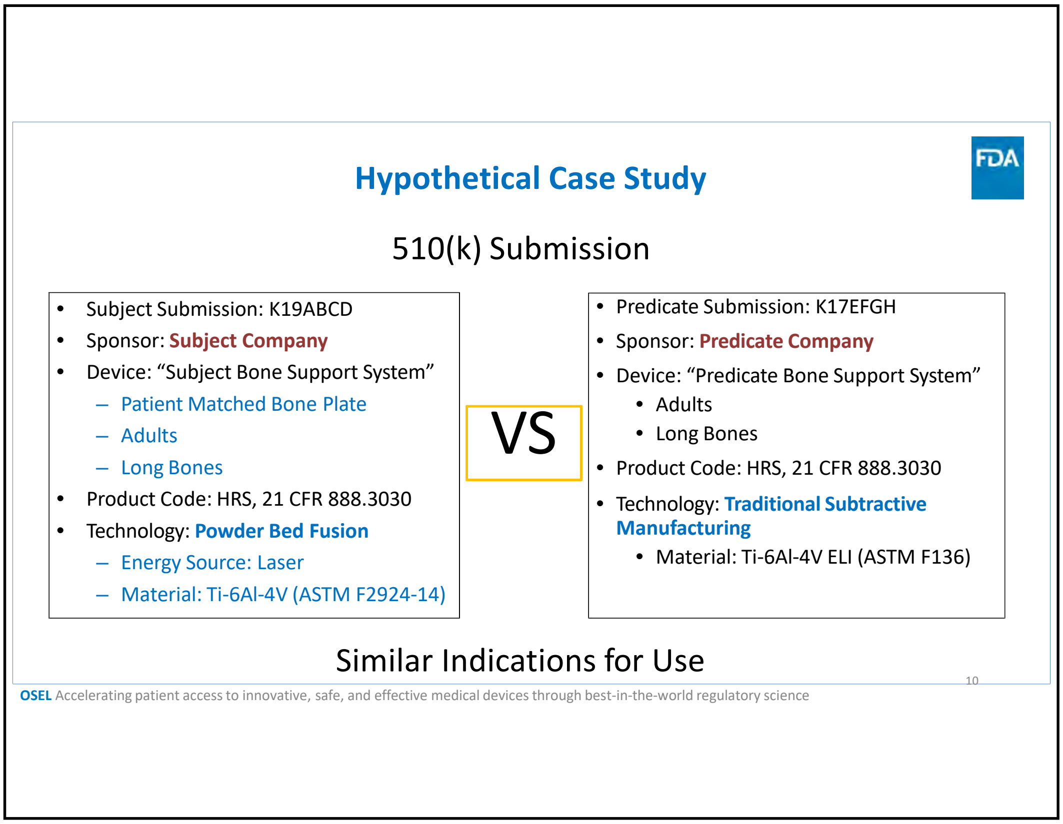


Ricles 2018. Regulating 3D-printed medical products.
https://stm.sciencemag.org/content/10/461/eaan6521



## Some Things to Keep in Mind

- Not all considerations are mentioned.
- Not stating what minimum activities/criteria are for submissions.
- No guarantee that this fictitious submission would be cleared.
  - Data is absent in this presentation.



## Hypothetical Case Study

### 510(k) Submission

- Subject Submission: K19ABCD
- Sponsor: **Subject Company**
- Device: “Subject Bone Support System”
  - Patient Matched Bone Plate
  - Adults
  - Long Bones
- Product Code: HRS, 21 CFR 888.3030
- Technology: **Powder Bed Fusion**
  - Energy Source: Laser
  - Material: Ti-6Al-4V (ASTM F2924-14)

VS

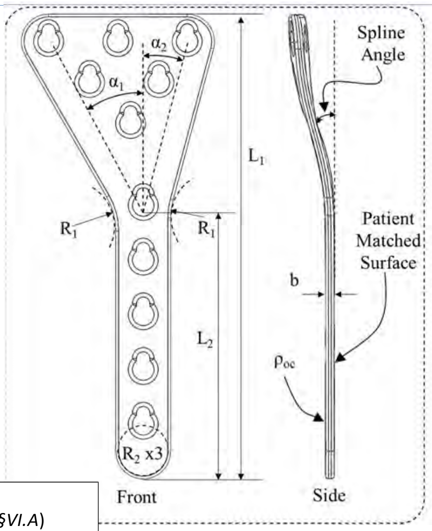
- Predicate Submission: K17EFGH
- Sponsor: **Predicate Company**
- Device: “Predicate Bone Support System”
  - Adults
  - Long Bones
- Product Code: HRS, 21 CFR 888.3030
- Technology: **Traditional Subtractive Manufacturing**
  - Material: Ti-6Al-4V ELI (ASTM F136)

Similar Indications for Use

## Device Design

Patient matched bone plate

- Frontal angle $\alpha_1$
- Anterior angle $\alpha_2$
- Total length $L_1$
- Partial shaft length $L_2$
- Minimum plate thickness b
- Patient matched spline surface
- Radial curvature $\rho_{oc}$

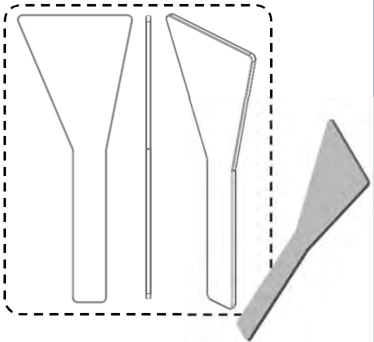


☆ Minimum feature size ~=0.7 mm (*AM Guidance §V.A*)
Understand and describe critical features (*AM Guidance §VI.A*)
All input variables have validated limits (*AM Guidance §V.B*)
Understand allowable dimensional tolerances (*AM Guidance §VI.C*)

Short Configuration

Long Configuration

Representative “Sacrificial” Test Coupon

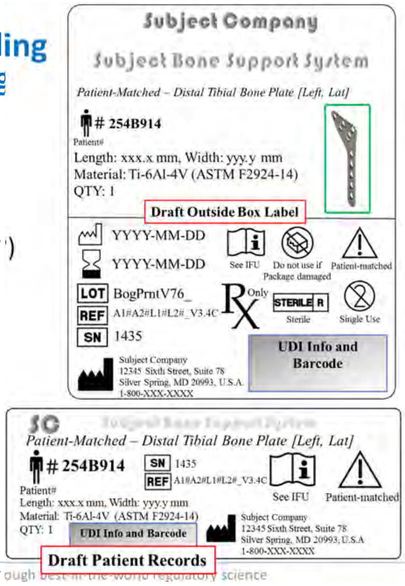


Subject Company presents data showing that Sacrificial coupons are representative of the final, finished device (*AM Guidance §VI.D.2*). ☆

## Draft Labeling

(*AM Guidance §VII*)

- Labeling indicates patient matched
- Patient identification number
- Design iteration number (*AM Guidance §V.B.2*)
- Patient's anatomy location
- Expiration date (*AM Guidance §V.B.1*)
- Other(s)



**Subject Company**

**Subject Bone Support System**

*Patient-Matched – Distal Tibial Bone Plate [Left, Lat]*

**# 254B914**
Patient#
Length: xxx.x mm, Width: yyy.y mm
Material: Ti-6Al-4V (ASTM F2924-14)
QTY: 1

**Draft Outside Box Label**

YYYY-MM-DD
YYYY-MM-DD
LOT BogPrntV76_
REF A1#A2#L1#L2#_V3.4C
SN 1435

**UDI Info and Barcode**

Subject Company
12345 Sixth Street, Suite 78
Silver Spring, MD 20993, U.S.A.
1-800-XXX-XXXX

*Patient-Matched – Distal Tibial Bone Plate [Left, Lat]*

**# 254B914**
Patient#
SN 1435
REF A1#A2#L1#L2#_V3.4C
Length: xxx.x mm, Width: yyy.y mm
Material: Ti-6Al-4V (ASTM F2924-14)
QTY: 1

**UDI Info and Barcode**

Subject Company
12345 Sixth Street, Suite 78
Silver Spring, MD 20993, U.S.A
1-800-XXX-XXXX

**Draft Patient Records**

## Process Workflow

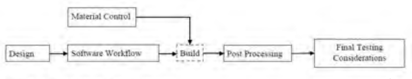
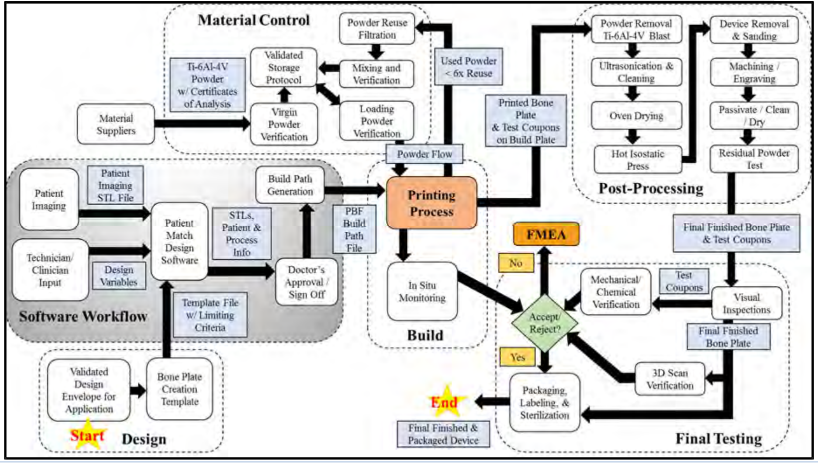
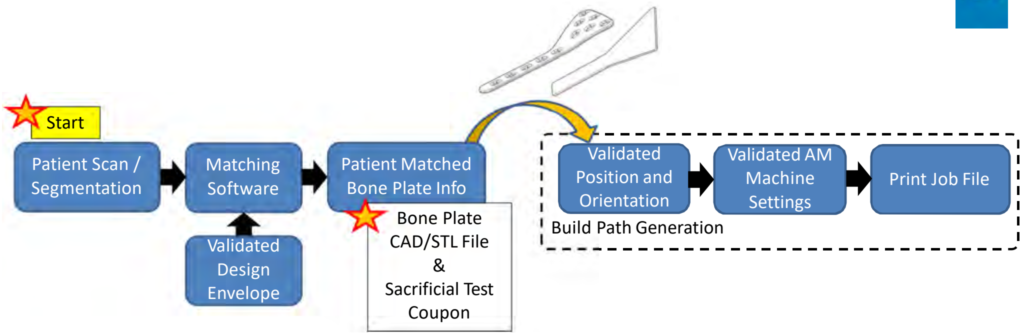


**Figure 1:** Flow chart of the AM process

AM Guidance, pg 8/31

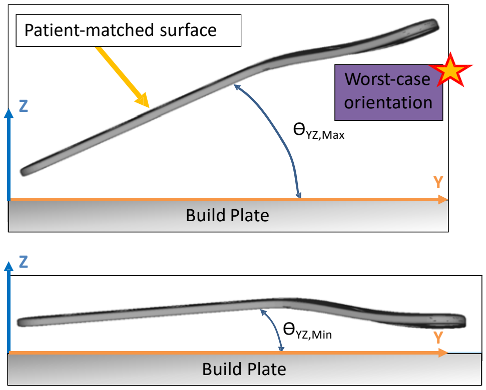


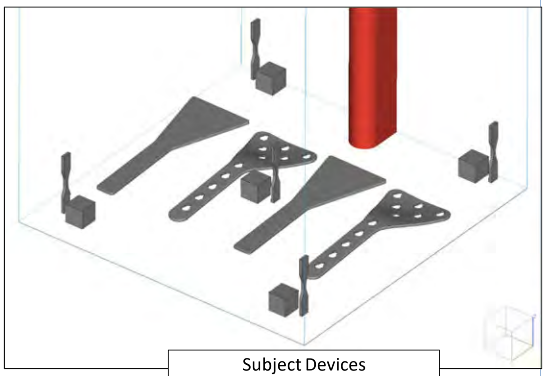
## Software Workflow



- Considers build volume placement, laser power, speed, path, etc. (*AM Guidance §V.C.2*).
- If new software/firmware or changes to software/firmware then the Subject Company understands:
  - Revalidation may be needed (*AM Guidance §V.F.2*) .
  - Consult "*When to Submit a 510(k) for a Change to an Existing Device*".

## Position and Orientation





Subject Devices & Sacrificial Test Coupon

No worst-case position from OQ/PQ

Validated Orientations (*AM Guidance §V.F.4*)

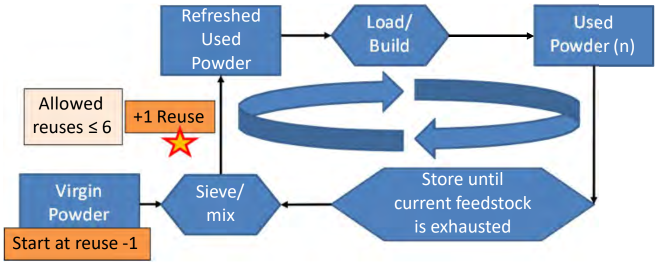
Build supports on non-patient matched face (*AM Guidance §V.C.2.ii*)

## Material Control

- Virgin Ti-6Al-4V powder from supplier, with certificate of analysis.
- Subject Company verifies virgin powder (*AM Guidance §V.D.1*):
  - Particle size distribution.
  - Chemical constituency (ICP-AES, combustion, inert gas fusion).
- Mixes powder in ratio (used:virgin) 1:1.
- Validated storage protocol under inert gas (argon).
- OQ/PQ showed non-conformance to ASTM F2924-14 after **9** reuse/mixes (i.e. sieves).
  - Process is repeatable.
  - Safety factor -> Will only reuse/mix (i.e. sieve) powder up to 6 times.

## Material Control - Powder Reuse

Subject Company's Powder Handling Routine



Refreshed Used Powder

Load/ Build

Used Powder (n)

Allowed reuses ≤ 6

+1 Reuse

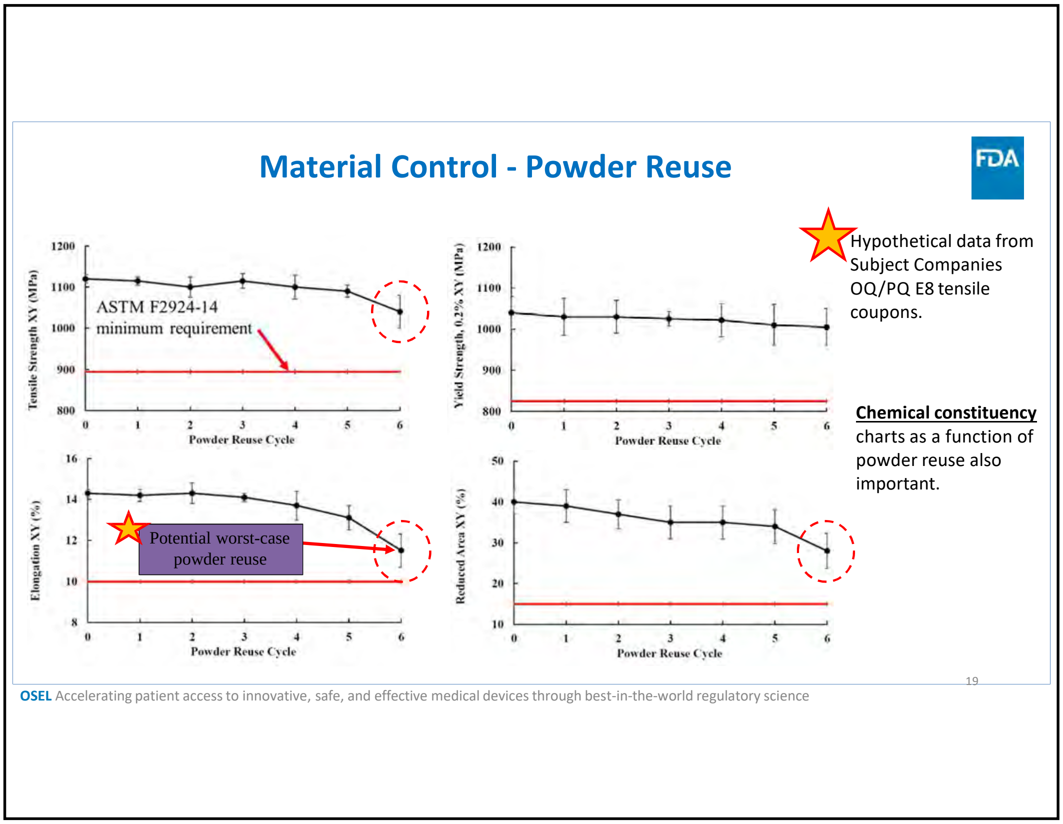
Virgin Powder

Start at reuse -1

Sieve/ mix

Store until current feedstock is exhausted

-Conveying the powder handling routine is important!
-Will not mix powder from differing lots.

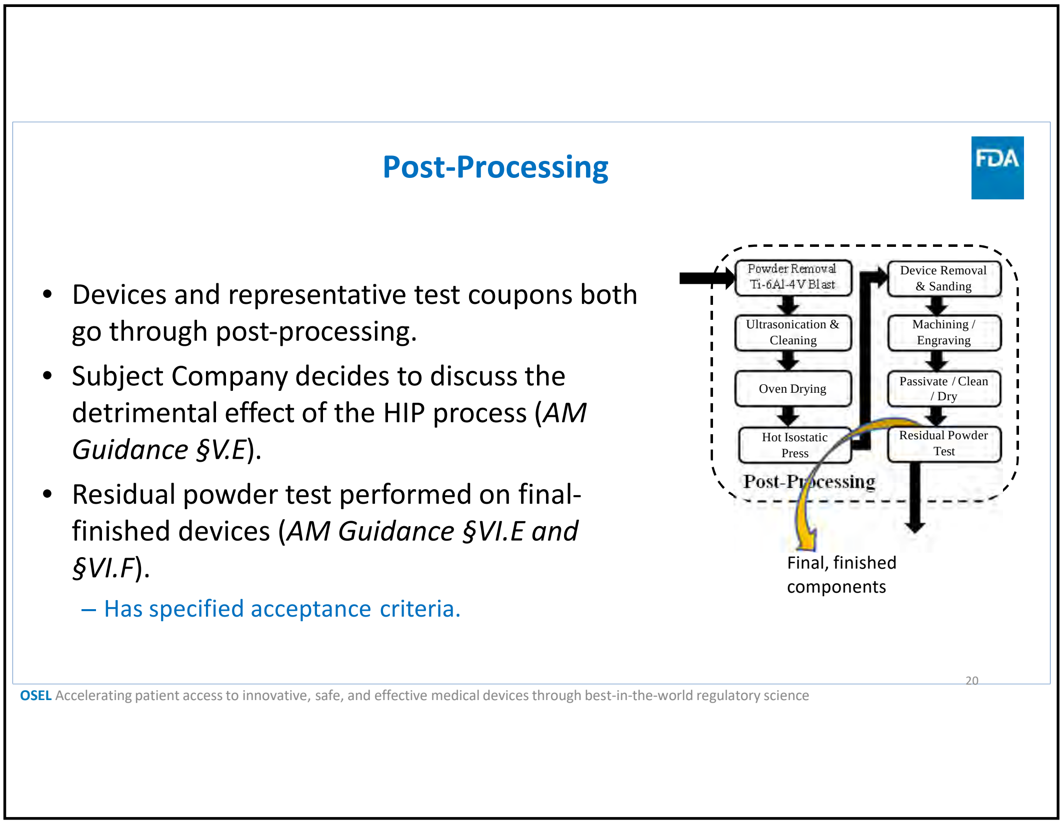


## Material Control - Powder Reuse

Hypothetical data from Subject Companies OQ/PQ E8 tensile coupons.

**Chemical constituency** charts as a function of powder reuse also important.

**OSEL** Accelerating patient access to innovative, safe, and effective medical devices through best-in-the-world regulatory science



## Post-Processing

- Devices and representative test coupons both go through post-processing.
- Subject Company decides to discuss the detrimental effect of the HIP process (*AM Guidance §V.E*).
- Residual powder test performed on final-finished devices (*AM Guidance §VI.E and §VI.F*).
  - Has specified acceptance criteria.

Final, finished components

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## Residual Powder Analysis

- Subject company decides to use USP <788> to evaluate residual powder with 788’s acceptance criteria.
- Uses Method 2, Microscopic Particle Count.
  - – Particle size distribution
    - Size < 10 µm
    - 10 µm ≤ Size ≤ 25 µm
    - 25 µm ≤ Size
  - – Morphology
- Acceptance criteria, assume 1 mL equivalent container volume.
  - – 12 particles ≥ actual count (Size ≥ 10 µm)
  - – 2 particles ≥ actual count (Size ≥ 25 µm)

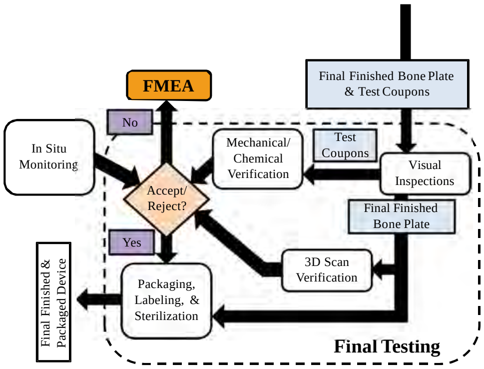
Substitute representative porous volume… if there was one.

-Device is not porous.
-Need better residual powder standards.

## Monitoring (Verification) Activities

The Subject Company also does not want to create a new worst-case

- In situ monitoring (Oxygen sensors, etc.)
- Visual inspections
- 3D metrology scan – subject device
- 2x per build tensile specimens
- 1x density cubes
- Single cycle 4-point bend (ASTM F382-17) – sacrificial coupon
  - – Verify load-displacement curve
- Chemical verification – sacrificial coupons
  - – ICP-AES
  - – Combustion
  - – Inert Gas Fusion



FMEA

Final Finished Bone Plate & Test Coupons

No

In Situ Monitoring

Mechanical/ Chemical Verification

Test Coupons

Visual Inspections

Accept/ Reject?

Final Finished Bone Plate

Yes

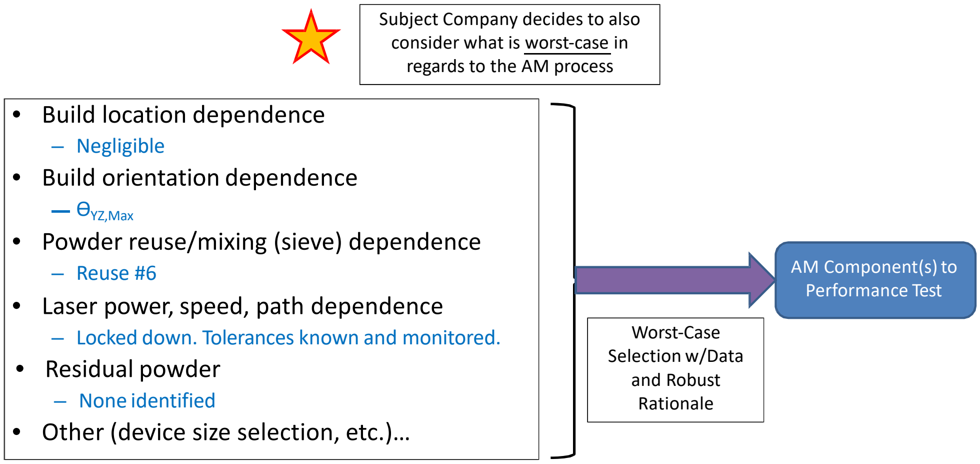
3D Scan Verification

Packaging, Labeling, & Sterilization

Final Finished & Packaged Device

Final Testing

## Worst-Case Selection (AM)



Subject Company decides to also consider what is worst-case in regards to the AM process

- Build location dependence
  - Negligible
- Build orientation dependence
  - $\theta_{YZ,Max}$
- Powder reuse/mixing (sieve) dependence
  - Reuse #6
- Laser power, speed, path dependence
  - Locked down. Tolerances known and monitored.
- Residual powder
  - None identified
- Other (device size selection, etc.)…

Worst-Case Selection w/Data and Robust Rationale

AM Component(s) to Performance Test

## Ending Remarks

- Just **one** example of how to use the AM Guidance.
  - Many ways to address AM considerations for a pre-market submission.
- AM is a broad technology, and we **only look at L-PBF here**.
  - Potentially different considerations with other technologies.
- Should also defer to any device-specific Guidance Document(s) or special controls Guidance Document(s) for pre-market requirements.
- **High-level** overview.
- **No performance data presented** here for the subject or predicate device.

## Thank You For Your Attention

# Questions?

AdditiveManufacturing@fda.hhs.gov

# NRC Technical Assessment of Additive Manufacturing – Laser Powder Bed Fusion

Meg Audrain
Office of Nuclear Regulatory Research
December 8, 2020

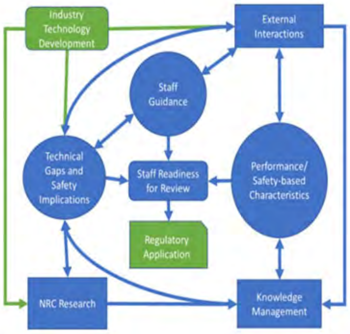
## Outline

- Background on Advanced Manufacturing
- NRC Technical Assessment – Laser Powder Bed Fusion (LPBF)
  - – Background, ranking of significance
  - – LPBF Generic Considerations
  - – Material Specific Considerations
  - – Codes and Standards Gap Assessment
- Conclusions

# Advanced Manufacturing Technologies

- Techniques and material processing methods that have **not** been:
  - Traditionally used in the U.S. nuclear industry
  - Formally standardized/codified by the nuclear industry
- NRC Focus based on industry interest
  - Laser Powder Bed Fusion (LPBF)
  - Direct Energy Deposition (DED)
  - Electron Beam (EB) Welding
  - Powder Metallurgy - Hot Isostatic Pressing (PM-HIP)
  - Cold Spray

# Action Plan – Rev 1 Tasks



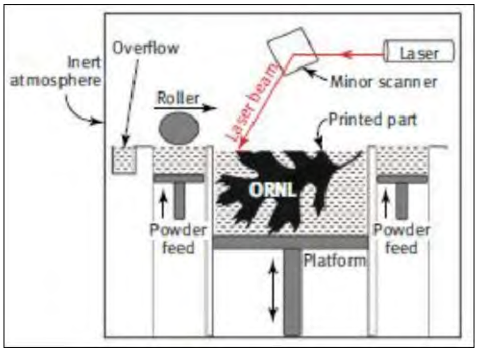
- Task 1 - Technical Preparedness
  - Technical information, knowledge and tools to prepare NRC staff to review AMT applications
- Task 2 - Regulatory Preparedness
  - Regulatory guidance and tools to prepare staff for efficient and effective review of AMT-fabricated components submitted to the NRC for review and approval
- Task 3 - Communications and Knowledge Management
  - Integration of information from external organizations into the NRC staff knowledge base for informed regulatory decision-making
  - External interactions and knowledge sharing, i.e. AMT Workshop

*ML19333B980

# NRC Technical Assessment - LPBF

# Laser Powder Bed Fusion

- Process:
  - Uses laser to melt or fuse powder together in bed of powder
  - Generally most advantageous for more complex geometries
- Potential Applications
  - Smaller Class 1, 2 and 3 components, fuel hardware, small internals



https://www.osti.gov/pages/servlets/purl/1437906

# Background

- Based on a technical information and gap assessment written by ORNL for the NRC
- NRC technical assessment provides regulatory perspective and highlights key technical information
- Fulfills the NRC Action Plan Task 1A deliverable to describe:
  - Differences between AMT/conventional component
  - Safety significance of the differences
  - C&S gaps

# Ranking of Significance

- Importance – impact on final component performance
  - High – significant impact on component performance
  - Medium – moderate impact on component performance
  - Low – minimal impact on component performance
- Knowledge/Manageability – how well understood and manageable is issue?
- The overall impact to plant safety is a function of component performance and the specific component application

# LPBF Generic Differences

# Medium Importance

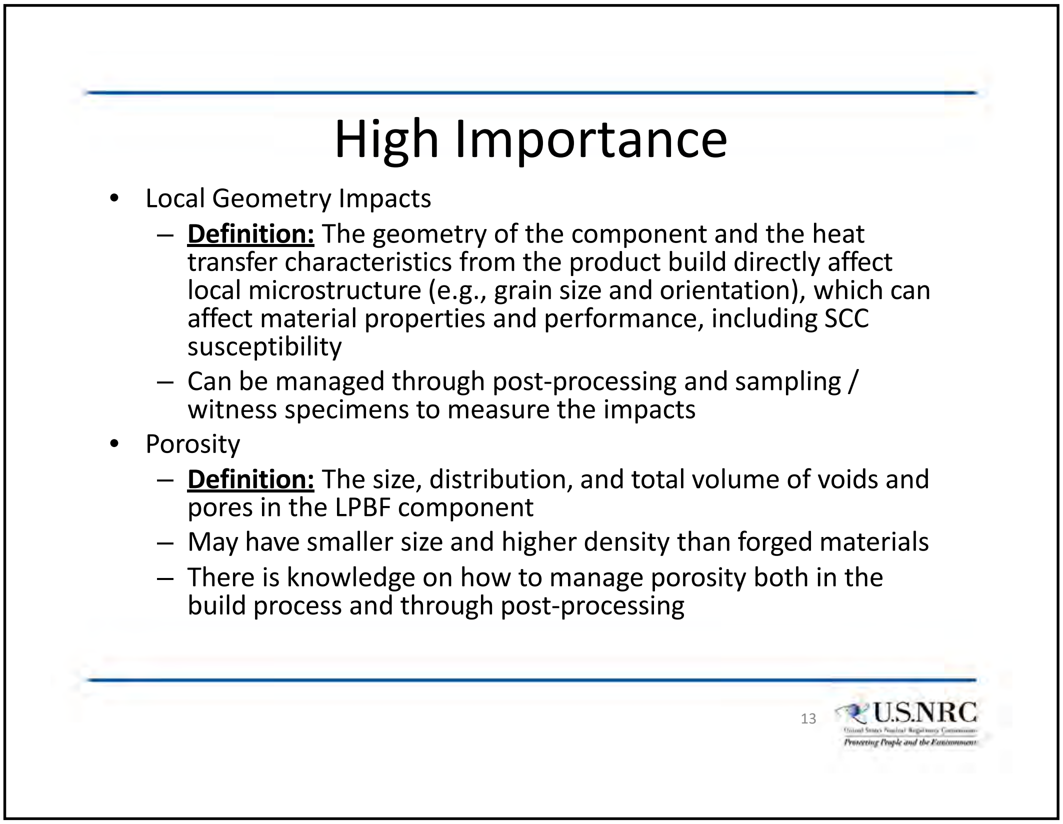
- Machine Process Control
  - **Definition:** Software controlling the scan strategy of the LPBF machine and the machine calibration to reliably fabricate components
  - Manageable with Quality Assurance (QA) including appropriate calibration
- Build Process Management and Control
  - **Definition:** Includes monitoring parameters during fabrication using environmental sensors, in-situ monitoring, and evaluating the effects of build interruptions.
  - Manageable with QA and the use of in situ monitoring and environmental sensor data

# Medium Importance

- Witness Specimens
  - **Definition:** Test specimens that are fabricated concurrently with end-use components and used to provide confirmation of build quality and product performance
  - Well established to detect events that may result in component rejection (e.g., delamination)
- Residual Stress
  - **Definition:** Residual stresses form during the LPBF build process and can lead to warping, cracking, and delamination if not properly managed
  - There is significant knowledge on residual stress, including how to manage it through post-processing or NDE

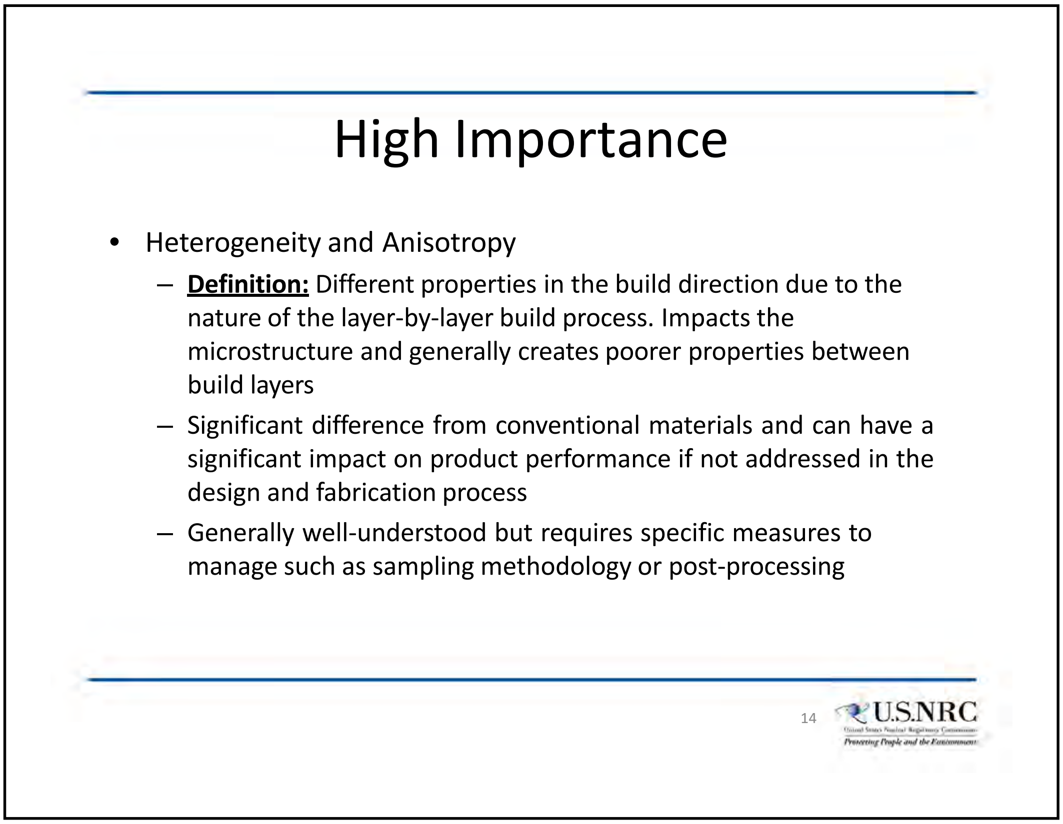
# High Importance

- Powder Quality
  - **Definition:** Important characteristics of the powder, such as composition and size distribution, and how it is managed in the production process prior to the build process (e.g., sieving, reuse, storage, contamination).
  - Can be challenging to manage and the effects on final product performance are material specific
- Post - Processing
  - **Definition:** Includes methods used (e.g., HIP, heat treatments) to improve material properties and performance by increasing density and reducing porosity
  - Should make material properties and performance more homogeneous and similar to conventional forged materials
  - Heat treatments are commonly done for LPBF and conventional materials and are fairly well-understood
  - HIP is well-established method but less commonly used for conventional materials where porosity is not a significant issue



# High Importance

- Local Geometry Impacts
  - **Definition:** The geometry of the component and the heat transfer characteristics from the product build directly affect local microstructure (e.g., grain size and orientation), which can affect material properties and performance, including SCC susceptibility
  - Can be managed through post-processing and sampling / witness specimens to measure the impacts
- Porosity
  - **Definition:** The size, distribution, and total volume of voids and pores in the LPBF component
  - May have smaller size and higher density than forged materials
  - There is knowledge on how to manage porosity both in the build process and through post-processing



# High Importance

- Heterogeneity and Anisotropy
  - **Definition:** Different properties in the build direction due to the nature of the layer-by-layer build process. Impacts the microstructure and generally creates poorer properties between build layers
  - Significant difference from conventional materials and can have a significant impact on product performance if not addressed in the design and fabrication process
  - Generally well-understood but requires specific measures to manage such as sampling methodology or post-processing

# Material Specific Differences
# 316L Stainless Steel

## Low Importance

- Tensile Properties
  - Refers to the ultimate tensile and yield strength of the material
  - Not a common failure mode in nuclear components and no more likely in LPBF materials due to their similar or superior tensile properties

## Medium Importance

- Fatigue
  - Refers to the initiation and propagation of cracks due to cyclic loading with or without environmental effects playing a significant role in the process.
  - Can lead to component failure, however, it's generally addressed conservatively through design standards and has not generally led to many safety-significant failures or flaws
- Weldability/Joining
  - Refers to the ability to successfully weld a material to another component without unacceptable defects
  - Should not impact component performance if welding Code requirements can be developed

## High Importance

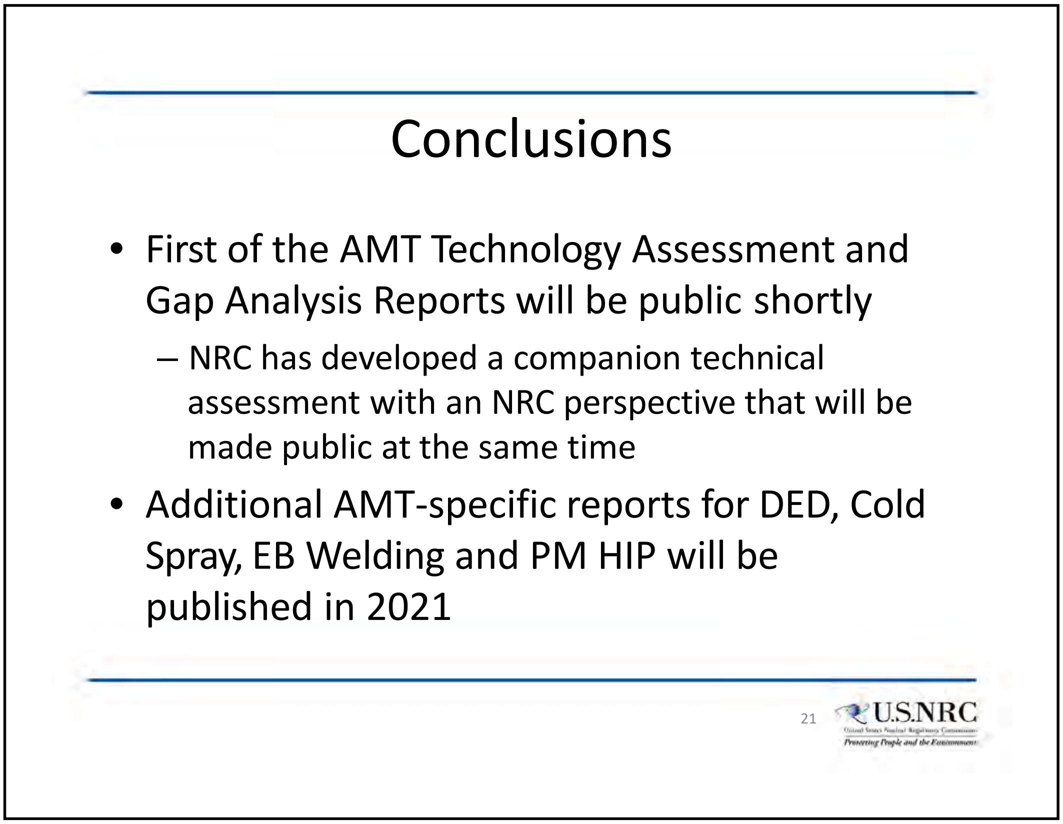
- Initial Fracture Toughness
  - Low fracture toughness can lead to brittle component failure
  - Limited data on 316L have shown significantly lower initial fracture toughness depending on post-processing than similar forged materials
- Thermal Aging, SCC and Irradiation Effects
  - Limited data on 316L
  - Representative data is important to demonstrate material behavior
  - Post processing is expected to make material properties and performance similar to conventional forged materials

## High Importance

- Weld integrity
  - Refers to the properties and performance of the weld and surrounding heat-affected zone
  - Welds can be a location of degradation and may behave significantly differently with LPBF materials
  - Understanding this behavior is important to inspection and aging management

## Codes and Standards Gaps

- Material-specific criteria for powder recycling and sieving
- Assessments of microstructural and material property heterogeneity
  - Should also consider the positive impact of post-processing, such as HIP, on heterogeneity
- Data-driven requirements for number, location and orientations of witness specimens
- Weld integrity and weldability including pre- and post-weld heat treatments



# Conclusions

- First of the AMT Technology Assessment and Gap Analysis Reports will be public shortly
  - NRC has developed a companion technical assessment with an NRC perspective that will be made public at the same time
- Additional AMT-specific reports for DED, Cold Spray, EB Welding and PM HIP will be published in 2021

ELECTRIC POWER RESEARCH INSTITUTE

# PM-HIP and Electron Beam Welding Development for Nuclear Applications

David W. Gandy
Sr. Technical Executive, Nuclear Materials

NRC Advanced Manufacturing Virtual Workshop
December 7-10, 2020

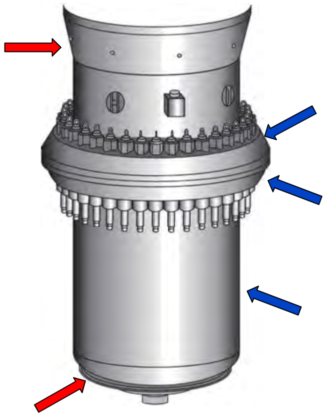
www.epri.com

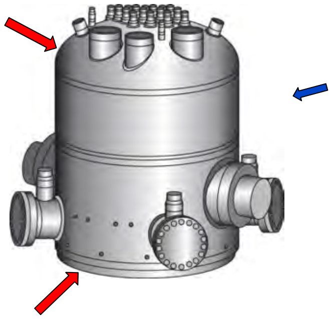
## Overview

- Background
- Advanced Manufacturing/Fabrication Technologies
  - DOE Projects: **DE-NE0008629 and DE-NE0008846**
- Powder Metallurgy-Hot Isostatic Pressing
- Electron Beam Welding Development
- Modular In-Chamber Electron Beam Welding
- Summary

# Objectives – SMR Advanced Manufacturing Project

- Rapidly accelerate the deployment of SMRs
- Develop/Demonstrate new methods for manufacture / fabrication of a RPV in **< 12 months**
- Eliminate 40% from the cost of an SMR RPV, while significantly reducing the schedule
- Primary Advanced Methods:
  - PM-HIP
  - Electron Beam Welding
  - Diode Laser Cladding





*Representative Model of NuScale Power Reactor Pressure Vessel Copyright NuScale Power*

**DOE Project DE-NE0008629**

# Powder Metallurgy-Hot Isostatic Pressing

**Why PM-HIP?**

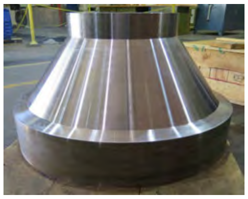
- Near-net shaped components
- Homogenous microstructure
  - Ease of inspection!
- Elimination of welds
- 4-6 months lead times typical
- Ideal for multiple penetration applications (RPV or CNV head) vs expensive forgings

Subsea Manifold. *Courtesy: Sandvik*

40" diameter HIP Vessel *Courtesy: Isostatic Forge International*

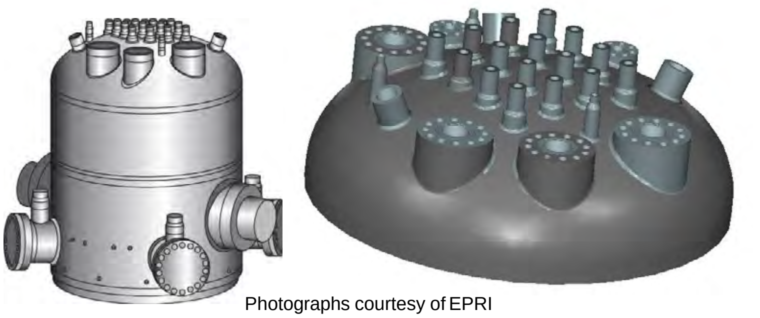
Large Bore Valve (courtesy Roll-Royce)

NNS Reactor Coolant Pump Impeller (courtesy Framatome and Albert & Duval)



3600lb BWR Nozzle

## Small Modular Reactor Upper Head--Example



Photographs courtesy of EPRI and NuScale Power

- ~44% scale
- Single monolithic structure
- A508 Class 1, Grade 3
- 27 penetrations
- 1650kg (3650lbs); 1270mm (50 inches) diameter
- Next, 2/3-scale head
- Need larger HIP Vessel -- ATLAS

**DOE Project: DE-NE0008629**

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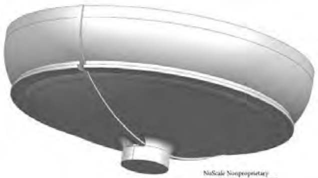
## One-Half Lower Head Capsule in Frame for HIP'ing



NuScale Nonproprietary
© 2017 NuScale Power, LLC

70-inches in diameter, ~6300lbs each

## Capsule & Frame are inserted into HIP; Lower Head after HIP

---

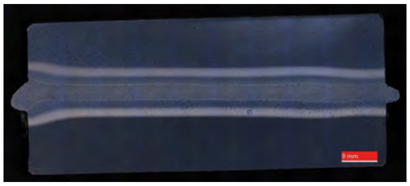
## Electron Beam (EB) Welding

### Why EBW?

- One-pass welding!
- No filler metal required.
- EBW can produce welds w/ minimal HAZ
- Nuclear-AMRC, TWI, Rolls-Royce & EPRI have demonstrated in-chamber and/or local vacuum on thick section alloys
  - Enables field/shop welding!
- RPV girth welds (110mm thick) in <60 min

### Inspection, Costs?

- Huge savings in welding costs (up to 90%)
- Potential to eliminate in-service inspection coupled with heat treatment!

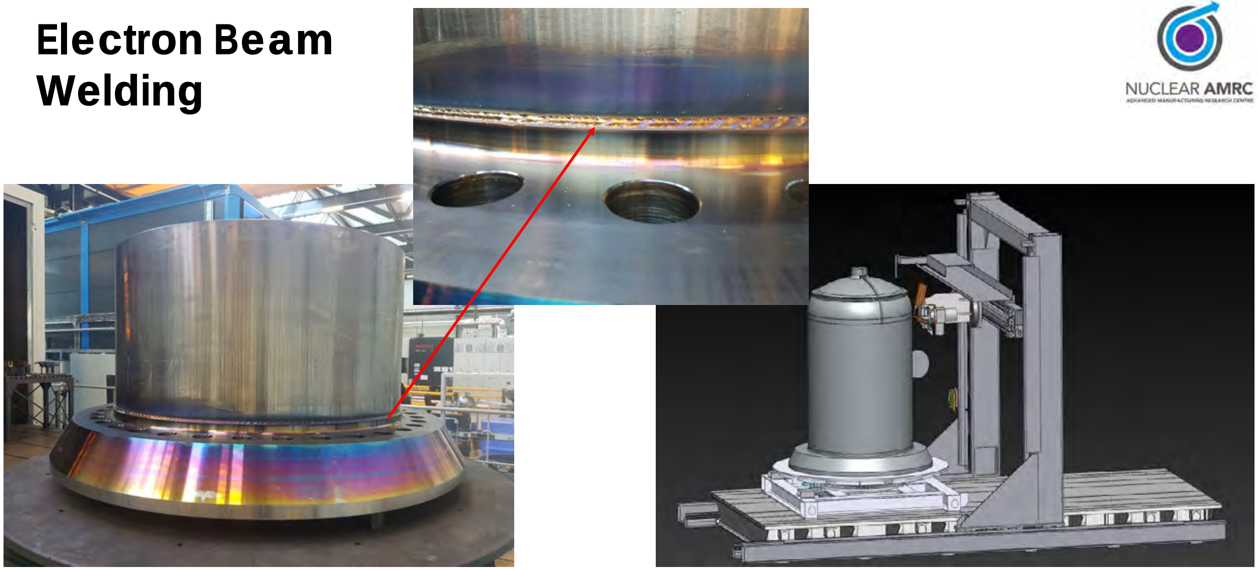


**110mm (thick) EB Weld**

*Photograph provided courtesy: Nuclear AMRC (UK)*

*Photograph provided courtesy: Nuclear AMRC (UK)*

# Electron Beam Welding



Lower Flange Shell Mockup EB Weld -- ~6 ft (1.82m) diameter (Note, mockup is upside down)

**Completed in 47 minutes**

Lower head to Lower Flange Shell (again, upside down)

One-half lower head—Article 4.

Each One-half Lower Reactor Head ~6500lbs (2950 kg) x 70 inches @ 2/3rds scale

# Articles 2 and 3 – EB Welding Complete

# Lower Head Halves – Weld Prep for EBW

NUCLEAR AMRC

# Modular In-Chamber Electron Beam Welding

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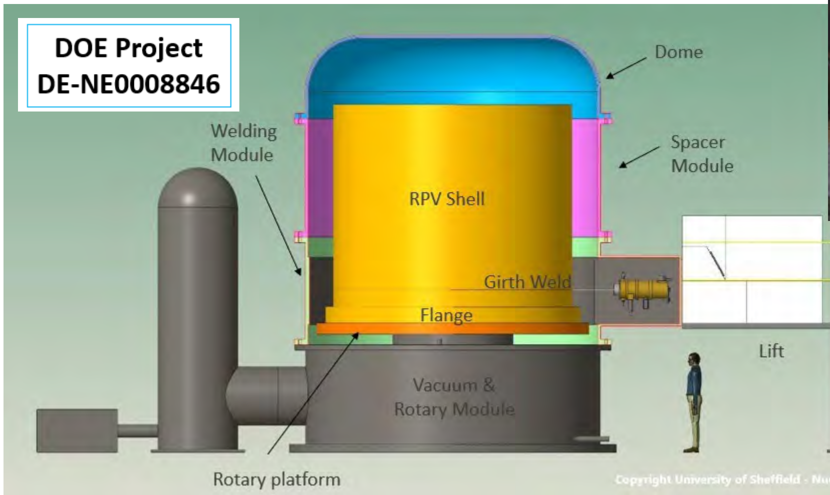
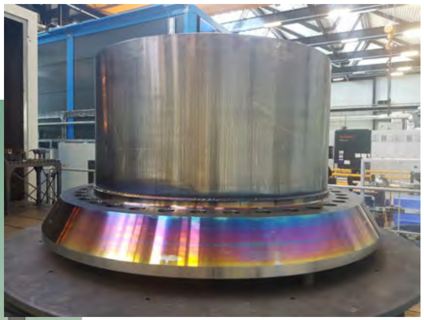
# RPV Shell and Flange Shown Inside of Modular EBW Chamber (in gold)

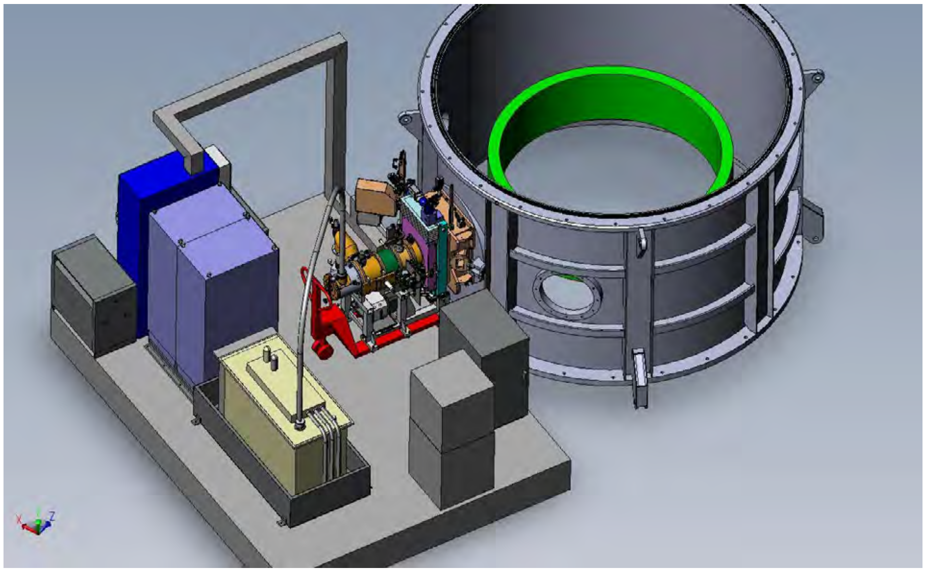




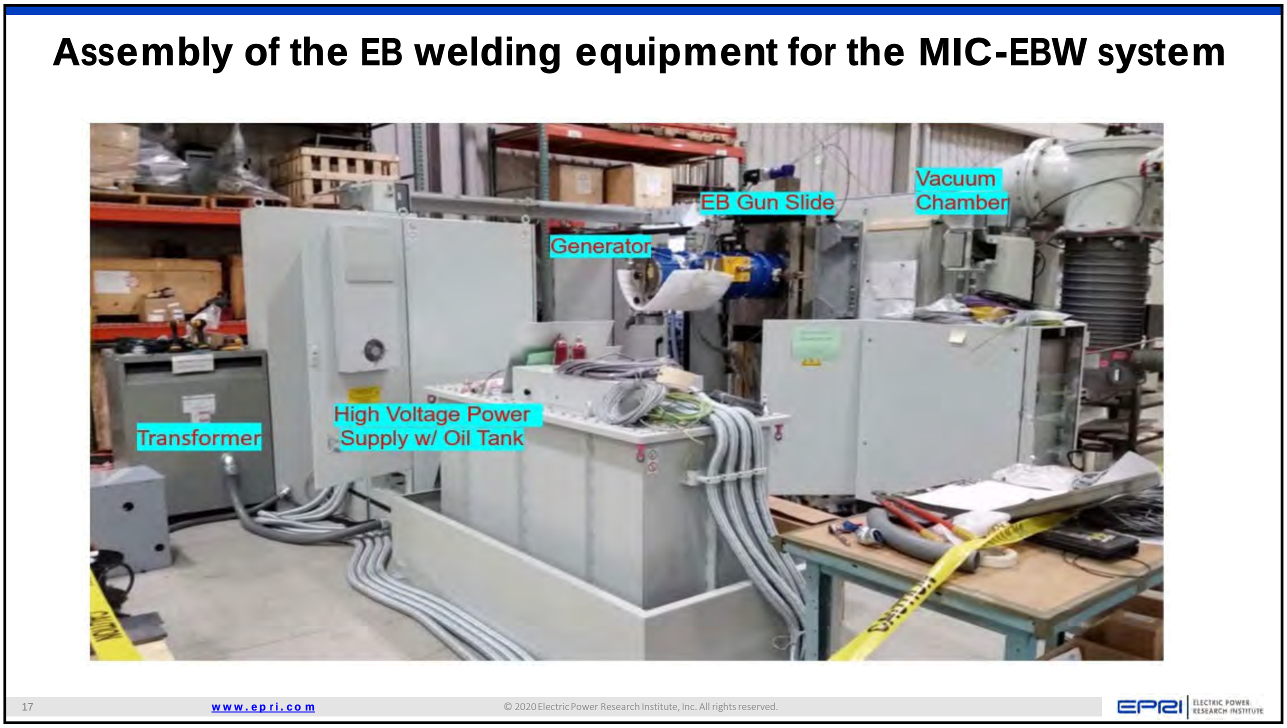
Lower Flange Shell Mockup EB Weld -- ~6 ft (1.82m) diameter (Note, mockup is upside down)

**Completed in 47 minutes**

## Platform & System Layout

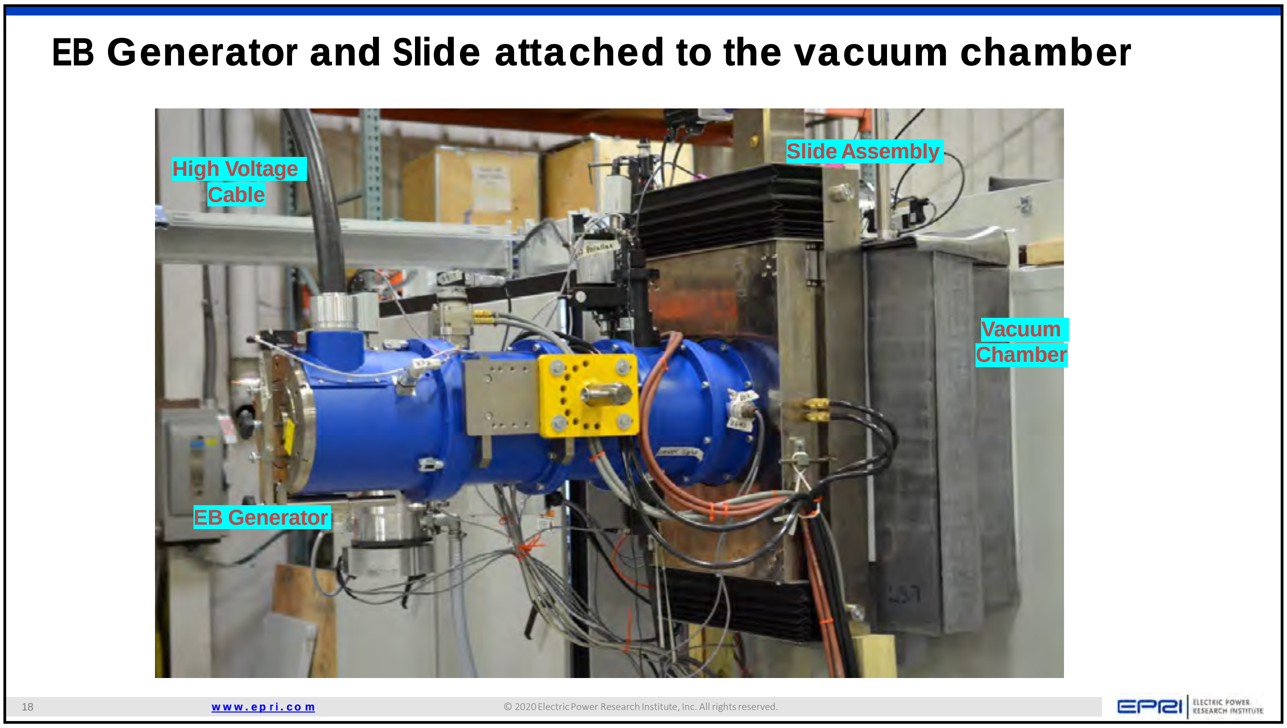


Mechanical pump package



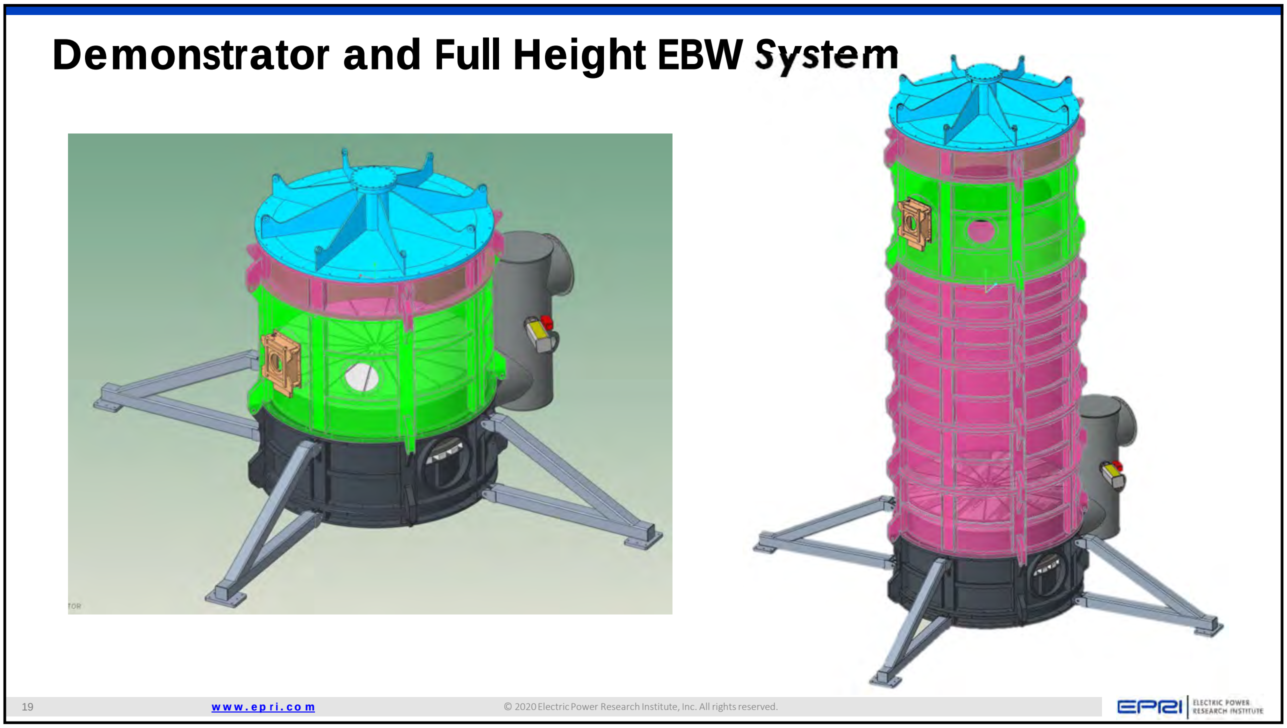
## Assembly of the EB welding equipment for the MIC-EBW system

17

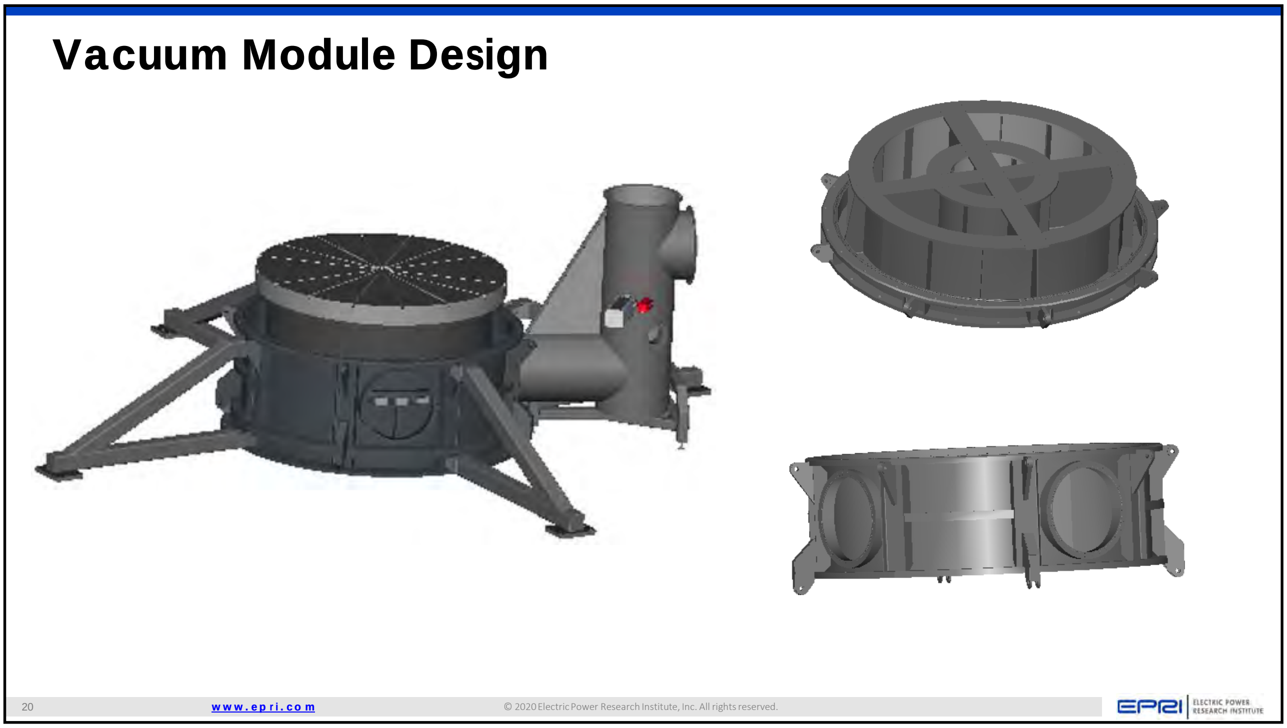


## EB Generator and Slide attached to the vacuum chamber

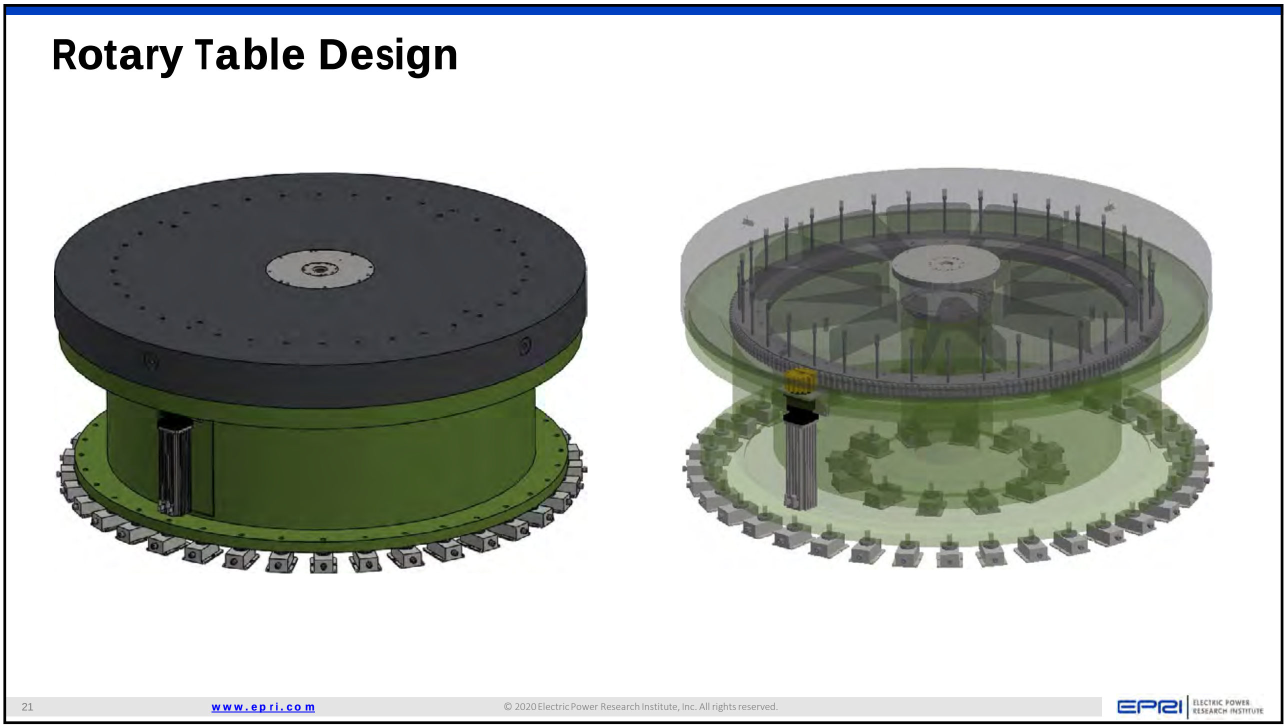
18



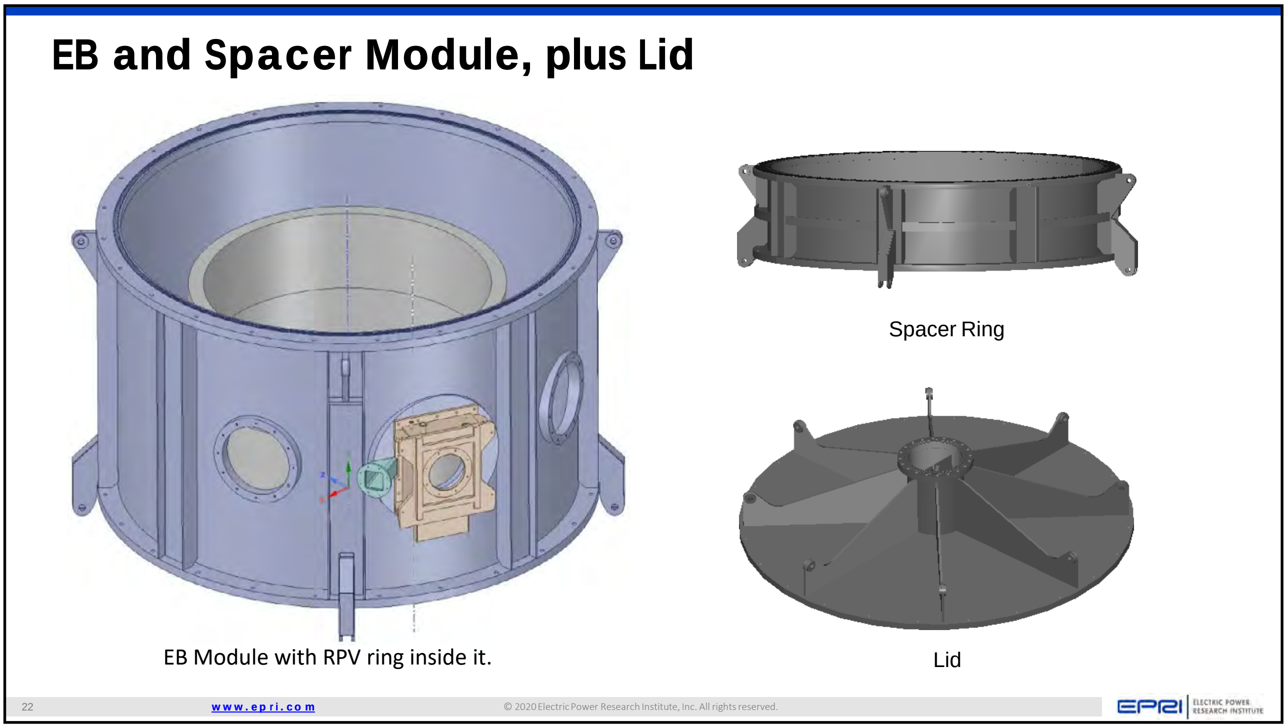
# Demonstrator and Full Height EBW System



# Vacuum Module Design



## Rotary Table Design



## EB and Spacer Module, plus Lid

Spacer Ring

EB Module with RPV ring inside it.

Lid

## 4ft Diameter x 5-inch Thick Weld Performed

## Summary

- Advanced Manufacturing/Fabrication Technologies
  - Reviewed DOE Projects: **DE-NE0008629 and DE-NE0008846**
  - Targets rapid acceleration for deployment of SMRs!
- Powder Metallurgy-Hot Isostatic Pressing
  - Near-net shaped components; ease of inspection; shorter lead times; scale to larger parts
- Electron Beam Welding Development
  - Rapid; single pass; thick section, highly repeatable
- Modular In-Chamber Electron Beam Welding
  - Establishes capability in USA; targets NuScale reactor, but applicable for other major components

## Together...Shaping the Future of Electricity

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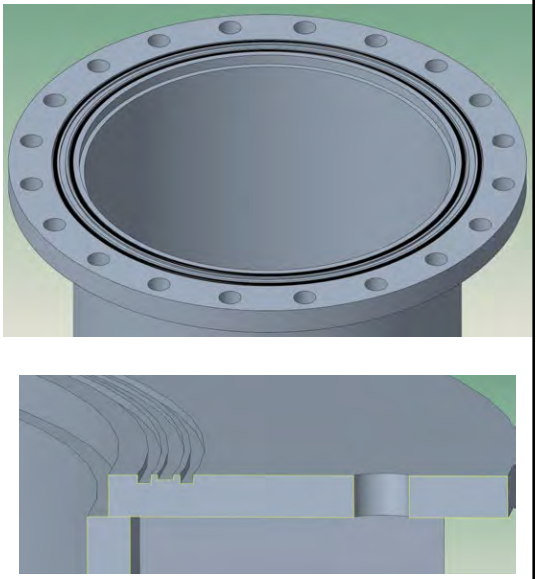
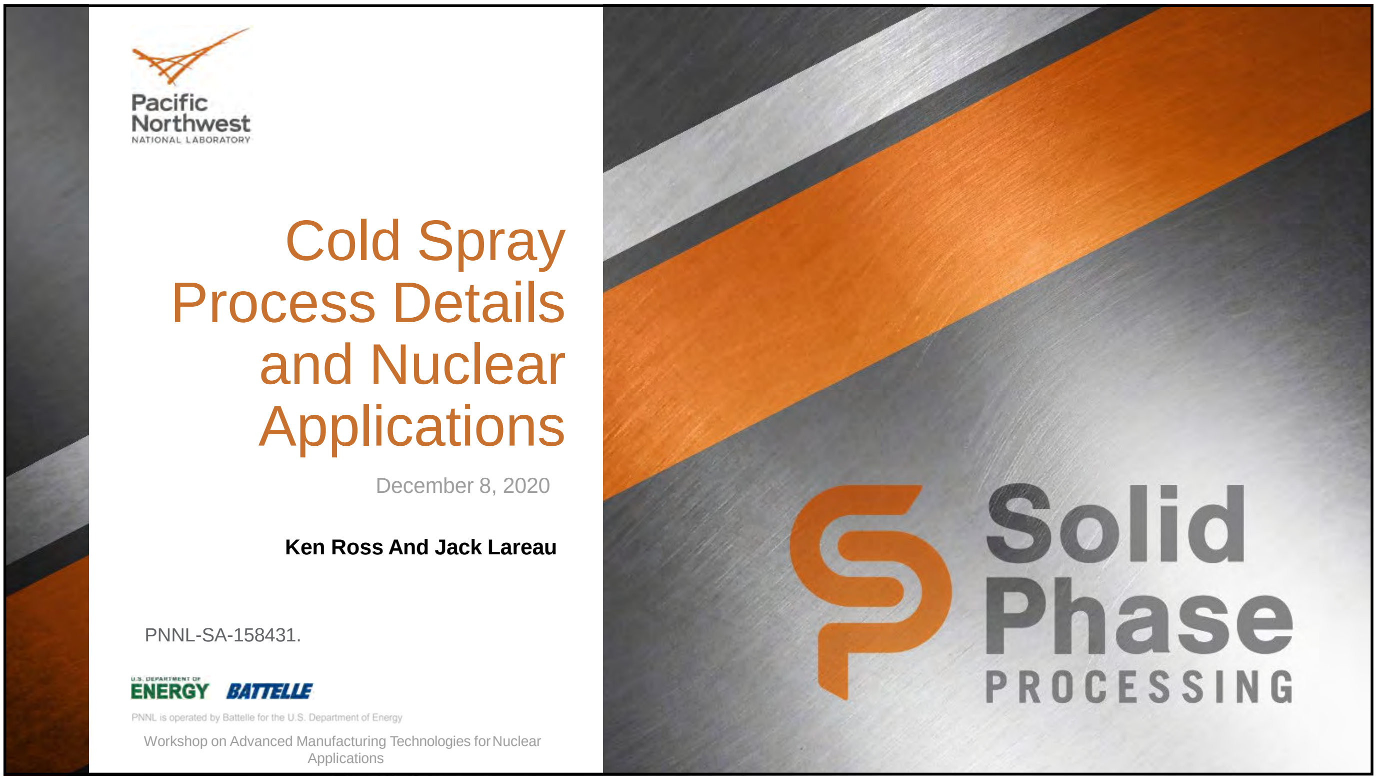
## Task 4--Design Vacuum Seals for Modular Ring Sections --AMRC Lead

- Individual “ring sections” will be produced (Task 6) from >1.5 in. (>38.1 mm) thick carbon steel.
- A flange will be attached to both the upper and lower extremities of the ring section via welding to achieve a good junction between two modules.
- A tight fit is achieved at the junction between the two modules through two engineered vacuum seals.
- A sensor will be positioned between the two vacuum seals to allow vacuum tightness to be checked
  - before pump-down
  - and monitoring during pumping to detect any leaks—extremely important in EBW activities.



Vacuum seals rings--example



# Cold Spray Process Details and Nuclear Applications

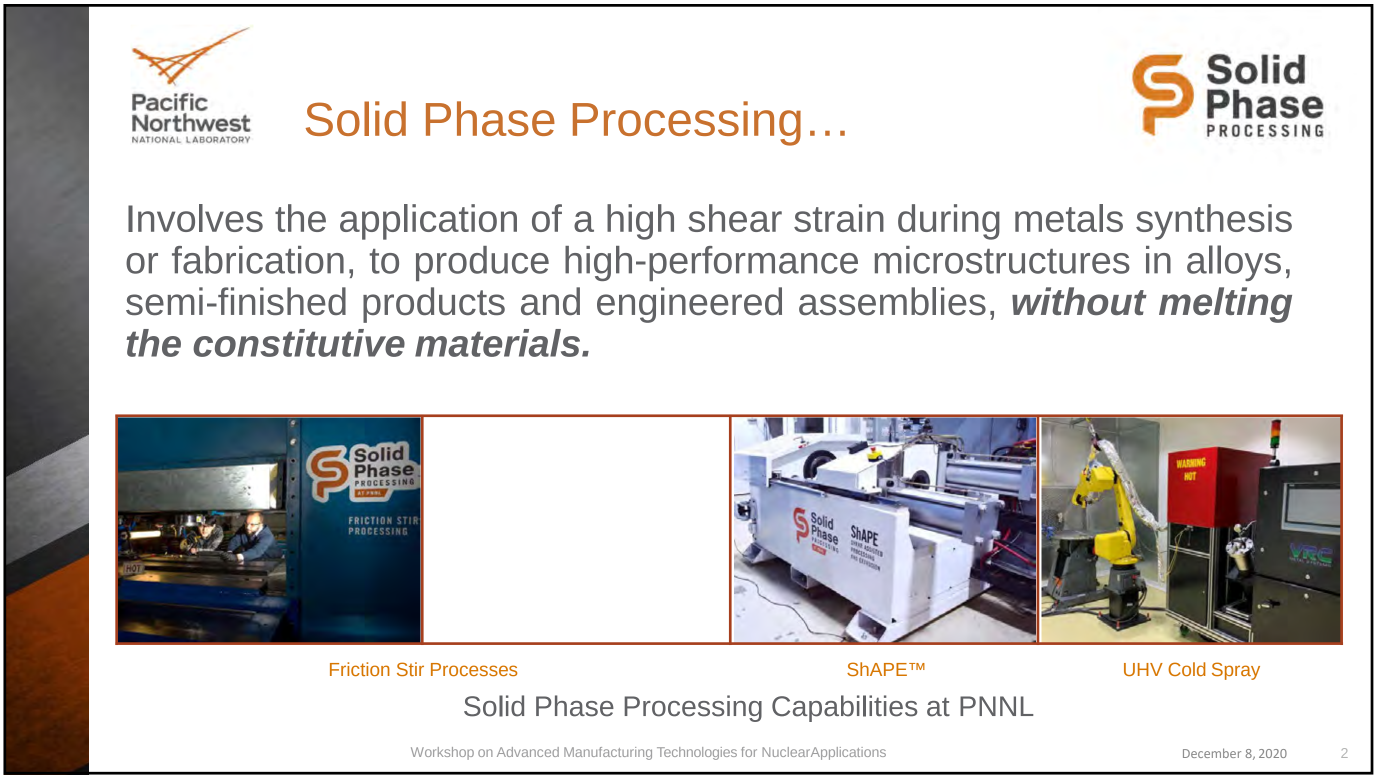
December 8, 2020

**Ken Ross And Jack Lareau**

PNNL-SA-158431.

PNNL is operated by Battelle for the U.S. Department of Energy

Workshop on Advanced Manufacturing Technologies for Nuclear Applications



## Solid Phase Processing…

Involves the application of a high shear strain during metals synthesis or fabrication, to produce high-performance microstructures in alloys, semi-finished products and engineered assemblies, ***without melting the constitutive materials.***

Friction Stir Processes

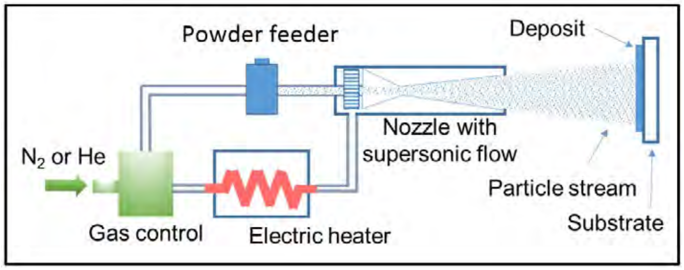
ShAPE™

UHV Cold Spray

Solid Phase Processing Capabilities at PNNL

## Cold Spray: Description

- **High Pressure/velocity** cold spray
- Solid phase deposition process
- Particles are propelled at Mach 1-4
- Typically particle size is 20 - 50µm
- Carrier gas is typically nitrogen or helium
- Impact energy causes extreme plastic deformation creates grain refinement and metallurgical bonds



| | |
|---|---|
| Substrate: | Stainless steel |
| Powder: | Inconel 625 |
| Carrier Gas: | Helium |
| Deposition rate: | 350g/min |

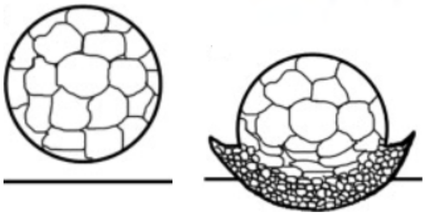
Note:

Arc welding is .25lbs/min =113.4 g/min

Video courtesy of Plasma Giken

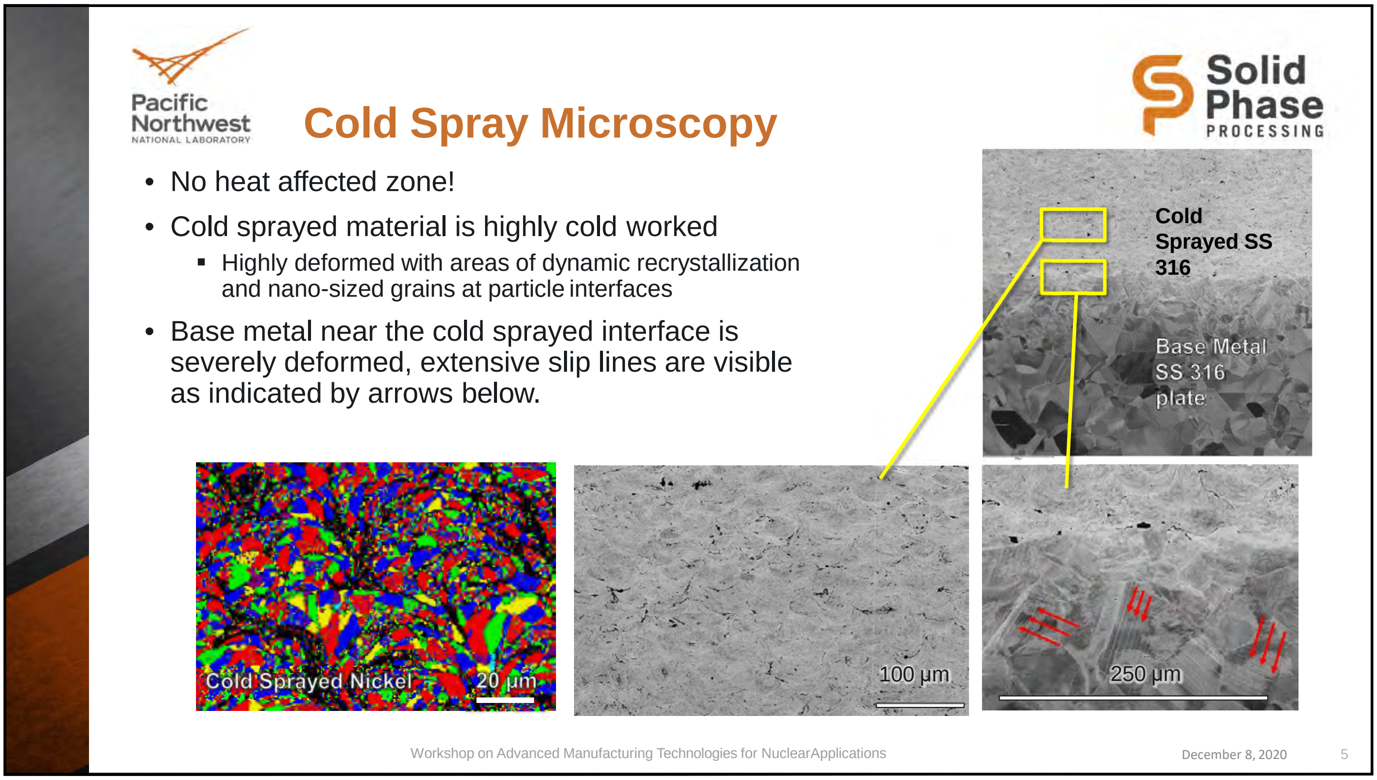
## Cold Spray: Process Details

- Extreme plastic deformation when particle impacts substrate
  - produces a highly refined grain structure
  - Energy of a single particle deformation is so low and happens so quickly that detrimental heat affected zones are avoided.
- As particles are deposited a mixtures areas of extreme to low plastic deformation develop



Grain structure of atomized particles prior to and immediately after impact
-courtesy of VRC Metal Systems

Video: Simulation of particle deformation during high velocity cold spray
-courtesy of VRC Metal Systems



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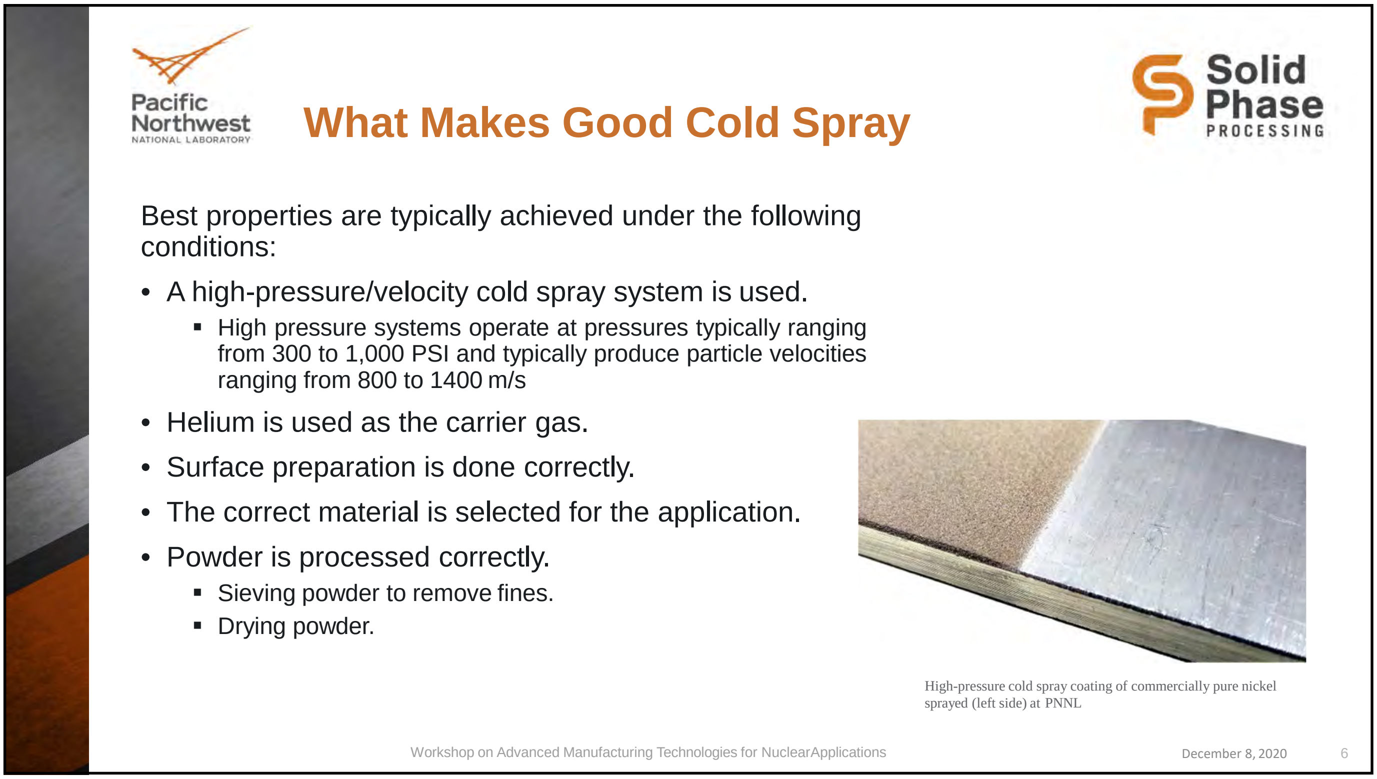
PROCESSING

## Cold Spray Microscopy

- No heat affected zone!
- Cold sprayed material is highly cold worked
  - Highly deformed with areas of dynamic recrystallization and nano-sized grains at particle interfaces
- Base metal near the cold sprayed interface is severely deformed, extensive slip lines are visible as indicated by arrows below.



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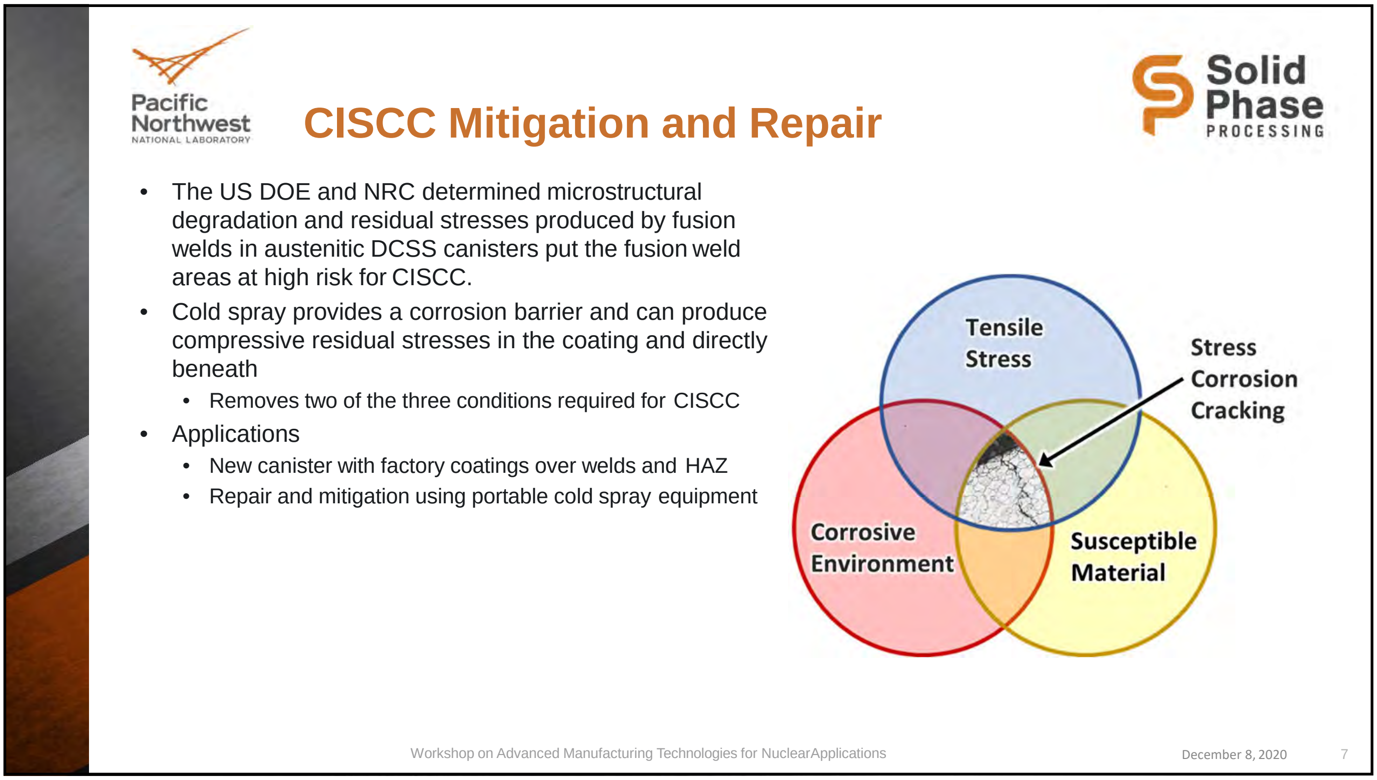
## What Makes Good Cold Spray

Best properties are typically achieved under the following conditions:

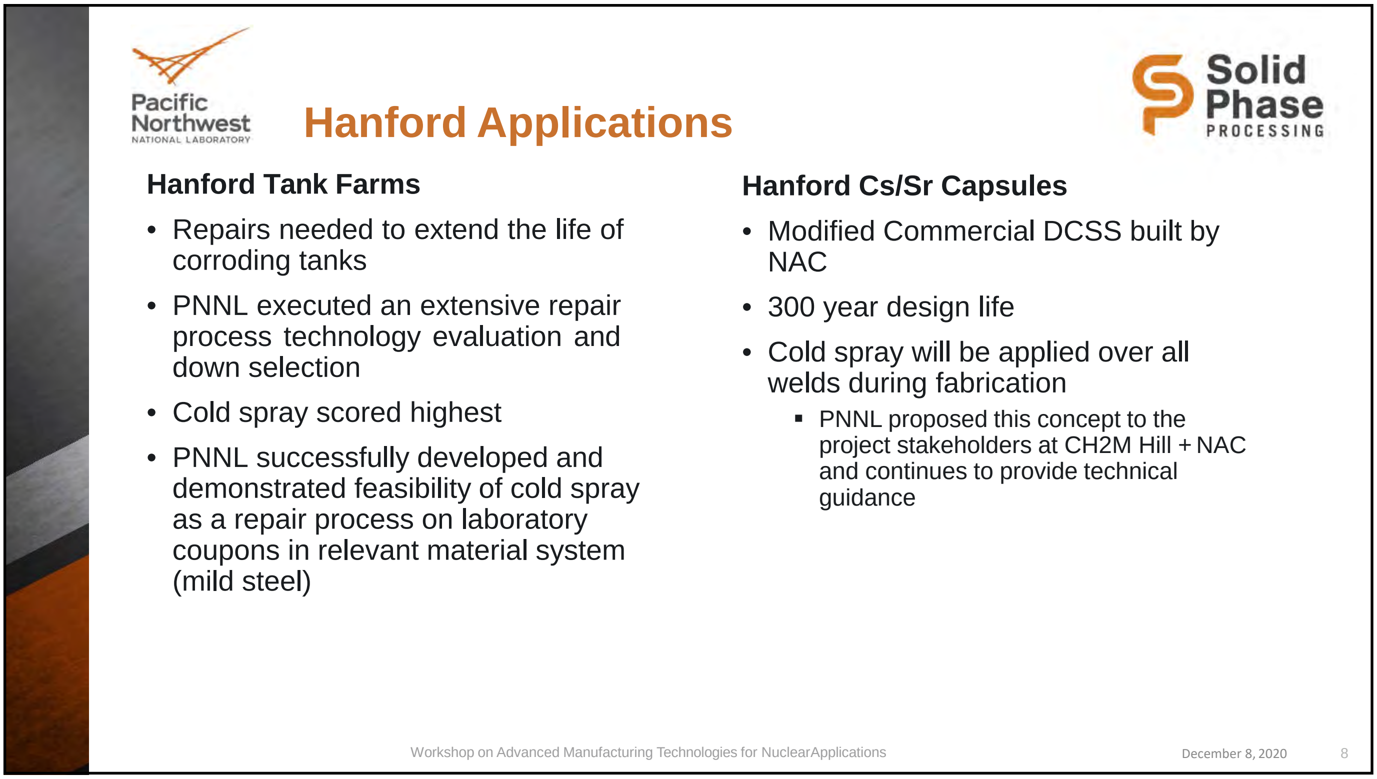
- A high-pressure/velocity cold spray system is used.
  - High pressure systems operate at pressures typically ranging from 300 to 1,000 PSI and typically produce particle velocities ranging from 800 to 1400 m/s
- Helium is used as the carrier gas.
- Surface preparation is done correctly.
- The correct material is selected for the application.
- Powder is processed correctly.
  - Sieving powder to remove fines.
  - Drying powder.

High-pressure cold spray coating of commercially pure nickel sprayed (left side) at PNNL



## CISCC Mitigation and Repair

- The US DOE and NRC determined microstructural degradation and residual stresses produced by fusion welds in austenitic DCSS canisters put the fusion weld areas at high risk for CISCC.
- Cold spray provides a corrosion barrier and can produce compressive residual stresses in the coating and directly beneath
    - Removes two of the three conditions required for CISCC
- Applications
    - New canister with factory coatings over welds and HAZ
    - Repair and mitigation using portable cold spray equipment



## Hanford Applications

**Hanford Tank Farms**

- Repairs needed to extend the life of corroding tanks
- PNNL executed an extensive repair process technology evaluation and down selection
- Cold spray scored highest
- PNNL successfully developed and demonstrated feasibility of cold spray as a repair process on laboratory coupons in relevant material system (mild steel)

**Hanford Cs/Sr Capsules**

- Modified Commercial DCSS built by NAC
- 300 year design life
- Cold spray will be applied over all welds during fabrication
    - PNNL proposed this concept to the project stakeholders at CH2M Hill + NAC and continues to provide technical guidance

## Common Failure Modes in Nuclear Plant Components

- Over the past 50 years, several failure modes for nuclear plant components have been detected
  - Acid and caustic cracking
  - Fatigue (the primary mechanism addressed in ASME Code)
  - Hydriding and oxidizing fuel rods
  - Crevice corrosion
  - Pitting corrosion
  - Flow assisted corrosion (FAC) and cavitation
  - Mechanical wear
- Several base materials have been affected
  - Carbon steel (pressure vessels and piping)
  - Stainless steel (piping and storage tanks)
  - Ni based alloys (inconel welds and base metal)
  - Zirconium based materials (fuel rods and assembly structures)

## Cold Spray Mitigation-Corrosion Resistance

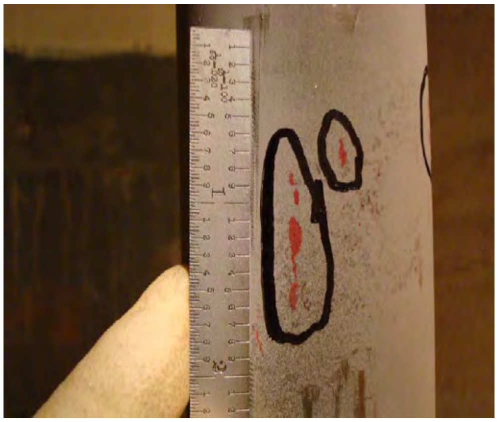
- For corrosion resistance, appropriately selected cold spray coatings provide a barrier between the base metal and corrosive or erosive environment
- Demonstrated powders for corrosion or erosion protection
  - Commercially Pure nickel (CPNi) (corrosion)
  - Stainless steel 316 (corrosion or erosion)
  - Titanium-Titanium Carbide (Crevice corrosion)
  - Inconel 625 (corrosion or erosion)
- Advantages over welding
  - No heat affected zone (HAZ)
  - No tensile residual stresses

## Cold Spray Mitigation: FAC

- FAC in part caused by fracturing oxide layers in two phase flow conditions with carbon steel
- Stainless of inconel coatings would eliminate the oxide layer deterioration
- Welding repairs introduces new problems with heat affected zones
- Cold spray of a high alloy coating could prevent FAC
  - Note: This has not been tried to date, but related work on cavitation and flow erosion has demonstrated high potential for this approach

## Examples of Stainless Steel Corrosion

- Chloride cracking



- Crevice Corrosion

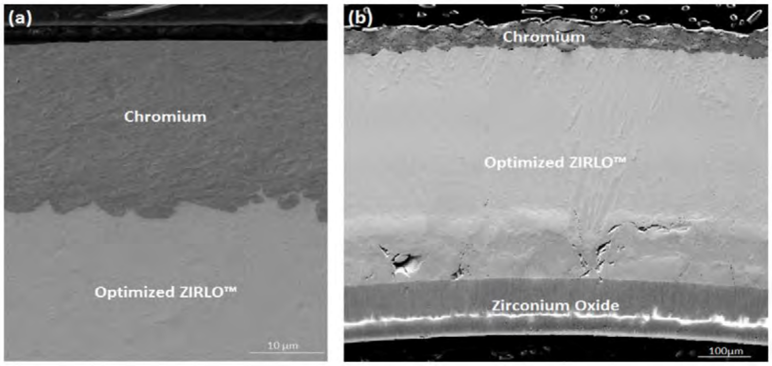
## Examples of Carbon Steel Degradation

- Flow Assisted Corrosion

- Boric Acid Corrosion of Carbon Steel

## Westinghouse LWR Fuel Cladding

- Cold sprayed Chromium on Optimized ZIRLO
- Irradiation testing Byron Unit 2 Cycle 22
- Improved
  - Economics
  - Safety
  - Reliability



As-fabricated microstructure of cold spray chromium coating on Optimized ZIRLO cladding (a). Microstructure of cladding tube following oxidation in steam at 1200°C for 20 minutes https://www.euronuclear.org/archiv/topfuel2018/fullpapers/TopFuel2018-A0145-fullpaper.pdf

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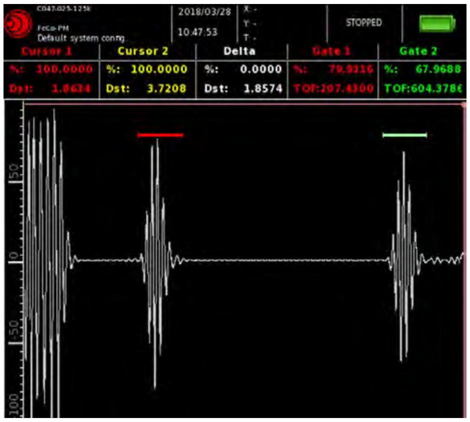
## CP Ni Ultrasonic Transducer

Solid Phase PROCESSING

- Cold Spray for online monitoring

- Ni cold spray coatings are magnetostrictive
- Can be used as a permanently installed electromagnetic acoustic transducer (EMAT)
    - Austenitic stainless steel is not suitable by itself for EMATs
- On-line ultrasonic monitoring of pre-existing cracks is possible

- EMAT reflections form 6 mm reflectors



C047-025-125k
FeCo-PM
Default system config
2018/03/28
10:47:53
X: -
Y: -
T: -
STOPPED

| Cursor 1 | Cursor 2 | Delta | Gate 1 | Gate 2 |
|---|---|---|---|---|
| %: 100.0000 | %: 100.0000 | %: 0.0000 | %: 79.9316 | %: 67.9688 |
| Dst: 1.8634 | Dst: 3.7208 | Dst: 1.8574 | TOF:207.4300 | TOF:604.378 |

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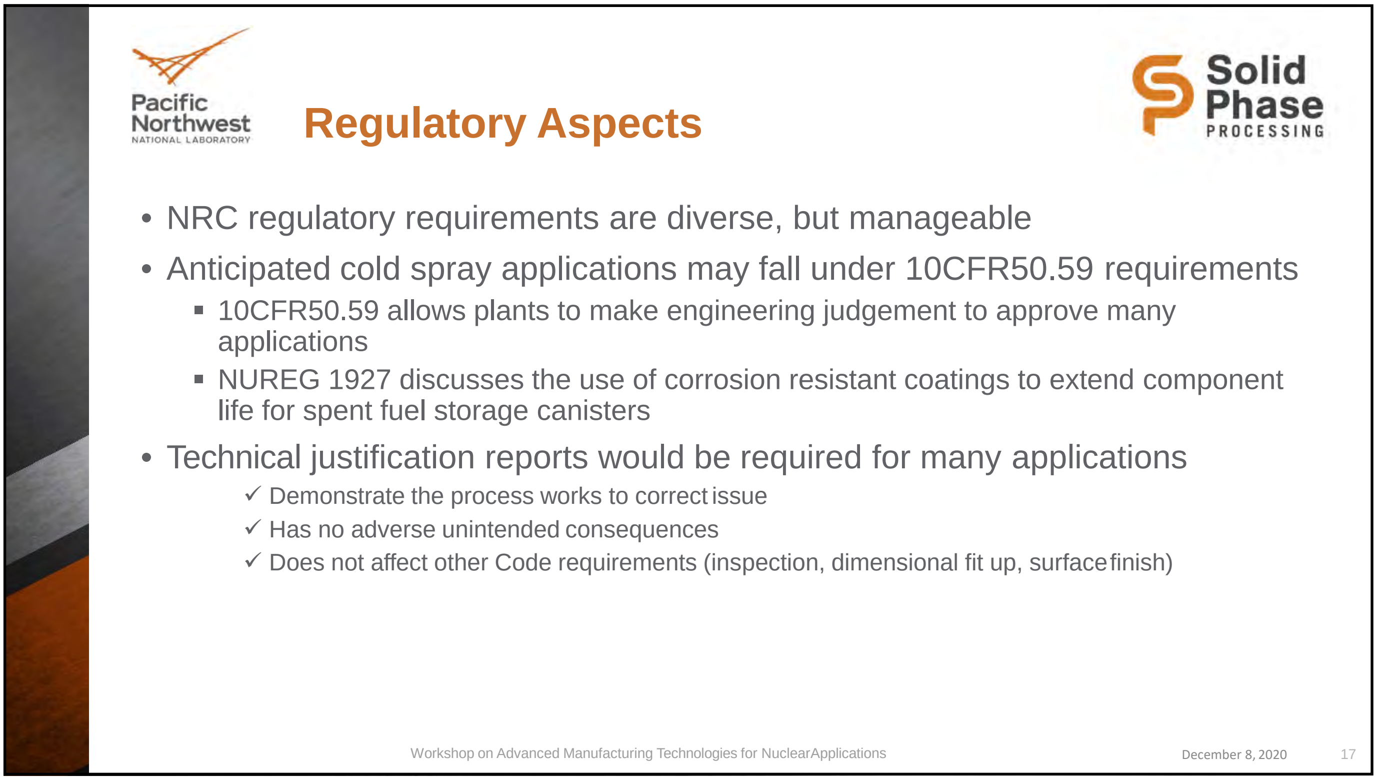
## ASME Code Aspects

Solid Phase PROCESSING

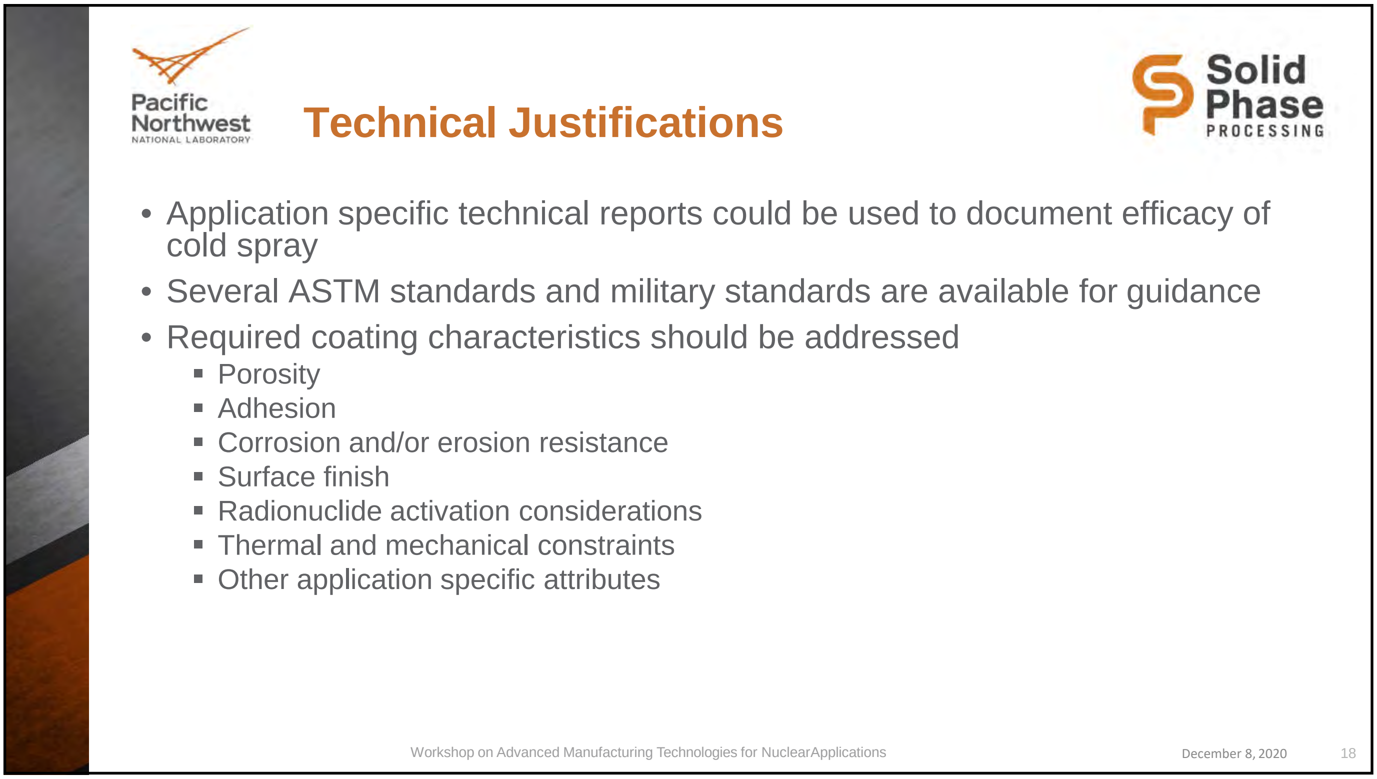
- Anticipated nuclear applications of cold spray are non-structural in nature
    - Anticipated coating thicknesses are on the order of 1-2% of component thickness (no fatigue credit)
    - Corrosion resistant layers and hard-facing are allowed

- This avoids the large hurdles of Code acceptance
    - Section II specifies material properties to be used for structural evaluation
    - Section III specifies design criteria for pressure retaining structures
    - Section XI specifies inspection and repair
        - ✓ Cold spray is a mitigation technique rather than a defect repair
        - ✓ Inspectability must be maintained
        - ✓ Code relief would be required for inspection interval or technique changes
        - ✓ Mitigation techniques have been addressed in Code Cases, as required



## Regulatory Aspects

- NRC regulatory requirements are diverse, but manageable
- Anticipated cold spray applications may fall under 10CFR50.59 requirements
  - 10CFR50.59 allows plants to make engineering judgement to approve many applications
  - NUREG 1927 discusses the use of corrosion resistant coatings to extend component life for spent fuel storage canisters
- Technical justification reports would be required for many applications
  - ✓ Demonstrate the process works to correct issue
  - ✓ Has no adverse unintended consequences
  - ✓ Does not affect other Code requirements (inspection, dimensional fit up, surface finish)



## Technical Justifications

- Application specific technical reports could be used to document efficacy of cold spray
- Several ASTM standards and military standards are available for guidance
- Required coating characteristics should be addressed
  - Porosity
  - Adhesion
  - Corrosion and/or erosion resistance
  - Surface finish
  - Radionuclide activation considerations
  - Thermal and mechanical constraints
  - Other application specific attributes

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Solid Phase PROCESSING

# Acknowledgments

**Sponsors**

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- University of Wisconsin Madison
- Penn State Applied Research Laboratory
- Sandia National Laboratory

Pacific Northwest NATIONAL LABORATORY

# Thank you

Solid Phase PROCESSING

# Cold Spray Mitigation & Repair for Nuclear Applications

*KYLE W. JOHNSON, VRC METAL SYSTEMS*
*NRC AMT WORKSHOP 2020*

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## VRC Metal Systems

- Cold Spray Equipment Manufacturer and Commercialization Partner, specializing in process development for Repair, Additive Manufacturing, Coating, and Joining applications.
- Veteran Owned Small Business Established in 2012 focused primarily on DoD applications.
- Headquartered in Rapid City, South Dakota. 3 US locations.
- 63 Full Time Staff

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## Problem – *Seawater Corrosion*

- Corrosion of structural steels in military and industrial applications is a widespread problem
  - Cost to the US Navy:
    - 20-25% of total maintenance costs Corrosion mitigation and remediation –
    - Estimates as high as $4B Annually
  - Cost to Nuclear Energy:
    - Corrosion-related causes of partial LWR outages - $5M/year
    - Corrosion-related causes of zero power LWR outages - $665M/year
    - Contribution of corrosion to LWR operation and maintenance (O&M) - $2B/year


[1]

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[1] Griesbach, T. J., Gordon, B. M., "Materials aging management programs at nuclear power plants in the United States," Second International Symposium on Nuclear Power Plant Life Management, Shanghai, China, October 15-18, 7007.

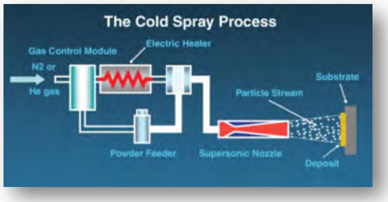
## Stainless Steel Materials for Seawater Service

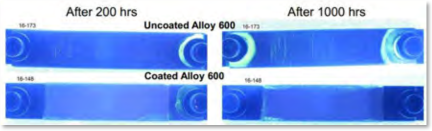
- **Common Austenitic Grades**
  - **304 & 316 most common industrial wrought steels**
  - **CF series most commonly used cast stainless steel**
  - **Cast Austenitic grades can contain up to 40% Ferrite, although higher levels of Ni and C stabilize Austenite in highly alloyed steels**
- **Even the most corrosion resistant grades are susceptible to**
  - **Stress Corrosion Cracking**
  - **Crevice Corrosion**
- **Solution: Cold Spray Corrosion Mitigation**

| Wrought | Cast |
|---|---|
| 304L | CF3 |
| 304 | CF8 |
| 304H | CF10 |
| 316 | CF8M |
| AL-6XN | CN3MN |
| Alloy 20 | CN7M |

# Solution – Cold Spray Corrosion Mitigation

- **Applied at Low Temperatures**
  - **Coatings can be applied as low as 400 °C**
- **Dense and Highly Adherent**
  - **Less than 1% porosity and greater than 10ksi adhesion typical**
- **Can be applied with Nitrogen for cost sensitive applications**
  - **Pure Metals (e.g. CP-Ni), Alloys (e.g. 316L) and Metal Matrix Composites (e.g. Ni / CrC) can be sprayed with high Deposition Efficiency.**
- **Cold Spray contains crack retarding compressive residual stresses**
  - **Resists stress corrosion cracking**
- **Corrosion Control Coatings typically non-structural, allowing quicker implementation.**





[2]

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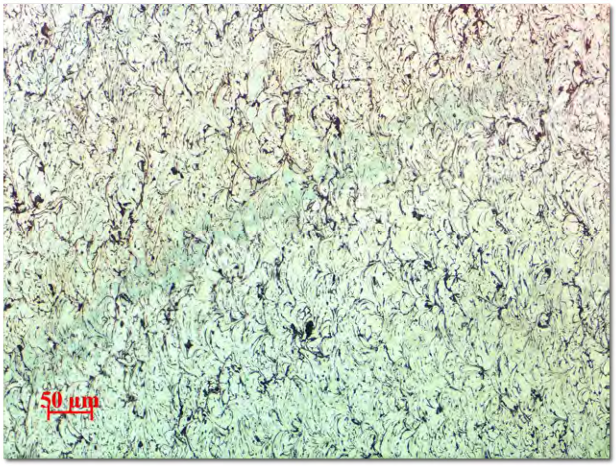
[2] Parsi, A., Lareau, J., Gabriel, B., Champagne, V., "Cold Spray Coatings for Prevention and Mitigation of Stress Corrosion Cracking," 2013 CSAT Workshop, Worcester, MA, 18-19 June 2013.

# Solution – Cold Spray Corrosion Mitigation

- Typical Cold Spray coatings exhibit porosity less than 1%.
- Dependent on material and processing parameters
- Polished cross section – No particles can be seen
- Etched cross section shows particle boundaries
- Significant flattening observed

Cold Sprayed Nickel



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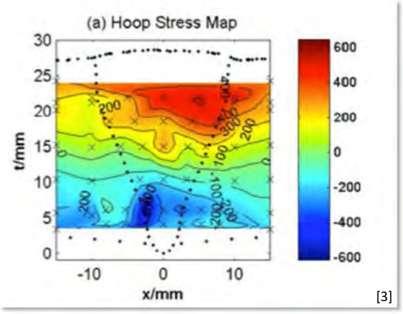
## Case Study – Cold Spray CISCC Mitigation

- Long term on-site is now being considered.
  - Large Existing Fleet Made from welded 304SS - Known for susceptibility to SCC
  - Chlorine-assisted SCC threshold in austenitic stainless steel as low as 80-100 MPa
  - 304 stainless steel girth welds are likely sites for initiation and propagation of SCC
- Dry Canisters not readily maintainable
  - Difficult to inspect and repair
  - Potential for CISCC environment to form, especially near seawater
  - Canister removal and replacement or repair costly
- Cold Spray Corrosion Resistant Coatings with Compressive Residual Stresses Offer an Ideal Solution to CISCC Mitigation.



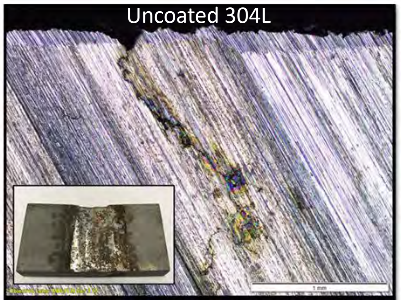
[3]

[3] Haigh, R.D.; Hutchings, M. T.; James, J. A. ; Ganguly, S.; Mizuno, R.; Ogawa, K.; Okido, S.; Paradowska, A.M. and Fitzpatrick, M. E. (2013). Neutron diffraction residual stress measurements on girth-welded 304 stainless steel pipes with weld metal deposited up to half and full pipe wall thickness. International Journal of Pressure Vessels and Piping, 101 pp. 1–11.

## Case Study – Cold Spray CISCC Mitigation

- ASTMG36 Boiling MgCl testing
  - Very effective cracking of 304 and 316 Stainless
  - Boiling point of 140 °C assures cracking efficacy.
    - MgCl Concentration Increased to achieve 140 °C
  - Samples welded to create tensile residual stresses.
  - Uncoated and Cold Spray Coated Samples tested
  - Samples exposed for 24 hours
- Extensive and deep CISCC on Uncoated 304L
- No cracking observed on Coated 304L

Uncoated 304L



Coated 304L

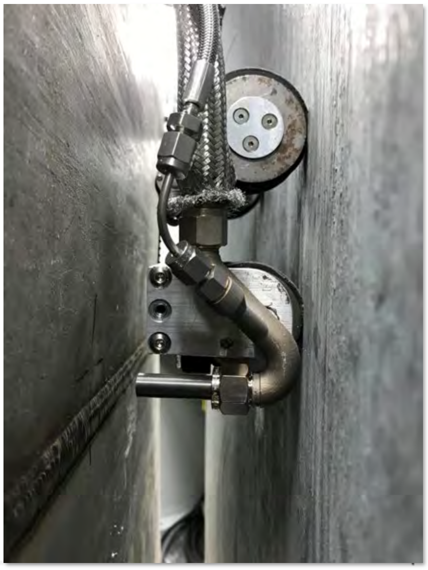
# Case Study – Cold Spray CISCC Mitigation

## - The Challenge -

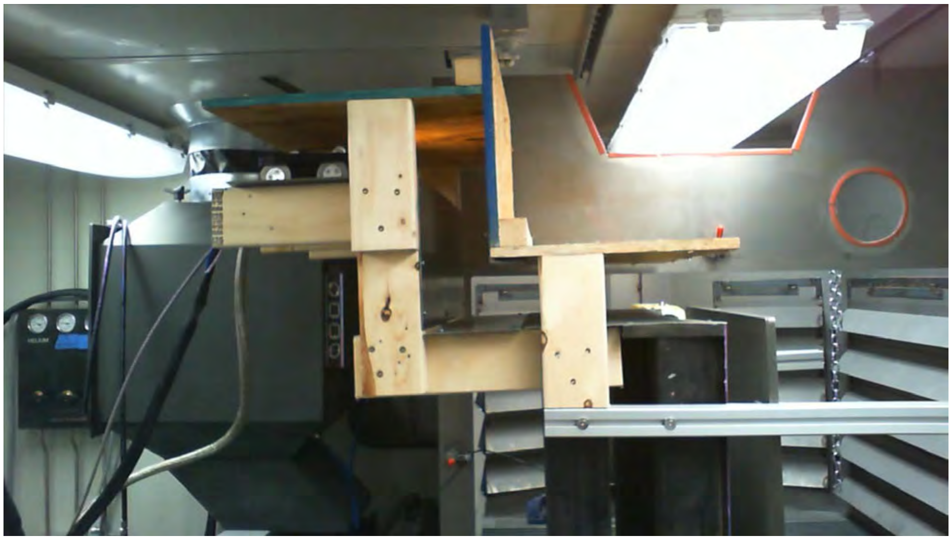
*Can the Cold Spray solution be applied in a difficult-to-access application?*

**YES!**

- Cold Spray Mitigation coatings have been demonstrated in laboratory mock-up canisters and in field conditions.
- Coatings can be applied within Overpack from a modified inspection crawler.
- Demonstrations have been performed in laboratory and field environments for vertical canisters using upper vent access.
  - Mockup demonstrations include straight-vent & stepped vent access and direct overpack placement designs.
  - Field demonstrations have been performed on an ISFISI.

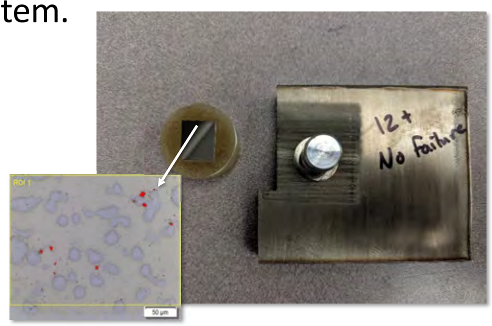


# Case Study – Cold Spray CISCC Mitigation



# Case Study – Cold Spray CISCC Mitigation

- Cold Spray CISCC Mitigation has been successfully deployed on an active ISFSI within a commercial vertical canister system.
  - Developed with and approved by customer.
  - Independently analyzed and verified.
  - Commercial Grade Dedication Process
  - Deployed within a heated test canister
  - Integrated into Long-Term Inspection and Mitigation Plan



| | Stability | Inspect-ability | Adhesion | Porosity | Tensile Strength | Thickness Capability |
|---|---|---|---|---|---|---|
| **Tech. Obj.** | Y | Y | > 10 ksi | < 2 % | > 36 ksi | > 0.100 in. |
| **Result** | Y | Y | > 11.2 ksi | 0.6 % | 40.6 ksi | 0.103 in. |

# Case Study – Seawater Crevice Corrosion Mitigation

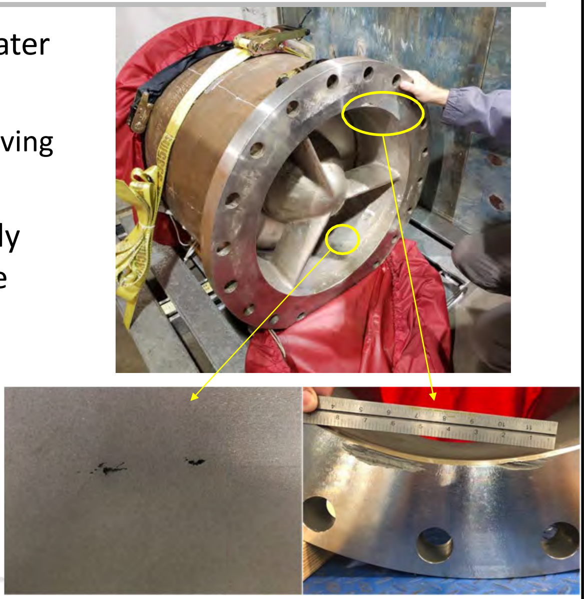
Crevice corrosion plagues even the most seawater corrosion resistant materials

- Especially prevalent in quiescent or slow-moving seawater & brackish water.

Cold Spray offers the ability to apply extremely crevice corrosion resistant materials to isolate structural materials.

Example Seawater Handling Check Valve

- CN3MN – Cast SS, High Mo
- Crevice Corrosion on flange faces
- Casting Defects can lead to pitting and Leakage.

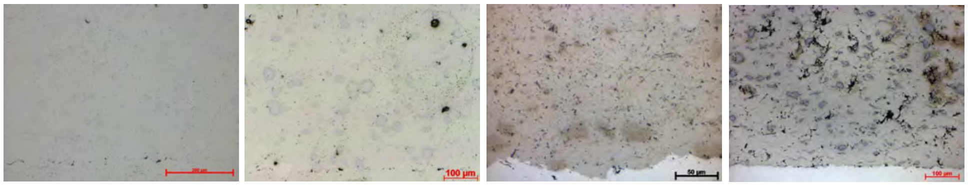


## Case Study – Seawater Crevice Corrosion Mitigation

For this application, Focus on Nitrogen-sprayed coatings on AL-6XN

- High Nickel Materials with hard phase blend
- Titanium-based coatings and hard phase blends

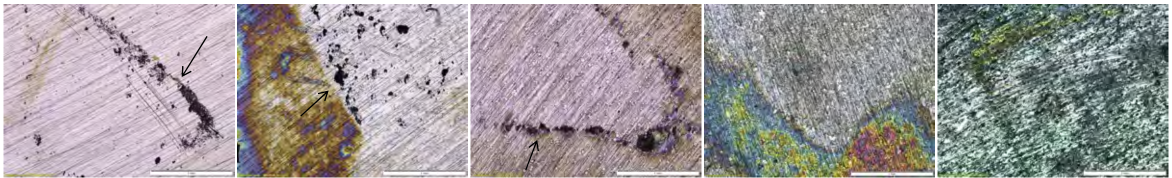
Commercially Pure Titanium (CP-Ti) best performer in ASTM G192 re-passivation crevice corrosion tests.



| A59/CRC on AL-6XN | C276/CRC on AL-6XN | CP-Ti on AL-6XN | CP-Ti/TiC on AL-6XN |
|---|---|---|---|
| 0.05% Porosity | 0.75% Porosity | 1.00% Porosity | ~1.00% Porosity |
| +10 ksi Glue | +10 ksi Glue | 4.61 ksi Adhesion | +10 ksi Glue |

## Case Study – Seawater Crevice Corrosion Mitigation

- Long-Term Seawater Exposure Crevice Corrosion Testing
  - Candidate Materials Tested on AL-6XN Substrates with Crevice Formers
  - Long-Term Exposure to Chesapeake Bay water, silt, and organic matter.
  - 10 May 2019 – 36 cold sprayed sampled + 9 controls installed
  - 10 Sept. 2019 – Half of the sample set pulled for inspection
  - 3 Feb. 2020 – Remainder of sample set pulled for inspection
- No Crevice or Galvanic Corrosion observed in CP-Ti materials



| | | | | |
|---|---|---|---|---|
| AL-6XN | C276 / CrC | Alloy 59 / CrC | CP-Ti | CP-Ti / TiC |

## Case Study – Seawater Crevice Corrosion Mitigation

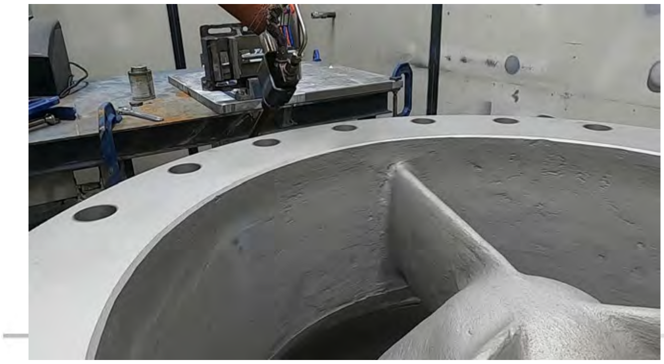
- Application of Ti-based coating for crevice corrosion resistance
  - Excellent adhesion to AL-6XN, low porosity, equivalent or higher hardness, no crevice corrosion
- Qualification Plan developed with and approved by customer
  - Adhesion, Porosity, Hardness, Deposition Efficiency
  - Additional testing for impact resistance, thermal cycling, and salt fog galvanic to ensure no cracking, spallation, or corrosion will occur in the application.

| | Adhesion | Porosity* | Hardness | Deposition Efficiency | Impact Resistance | Thermal Cycling | Salt Fog Galvanic |
|---|---|---|---|---|---|---|---|
| **Tech. Obj.** | > 10 ksi | < 1 % | None | > 50% | No Cracking | No Spallation | No Corrosion |
| **Result** | > 11.3 ksi | 0.73 % | 188 HV | 62% | Pass | Pass | Pass |

*Porosity of Metal Matrix between Carbide Hard Phases

## Case Study – Seawater Crevice Corrosion Mitigation

- Cold Spray Ti-based coating applied to the flange and internal surfaces.
- Coating application performed at VRC Spray Operations Facility, Box Elder, SD.



## Case Study – Seawater Crevice Corrosion Mitigation

- Cold Spray Application Process
  1. Apply targeted cold spray non-structural fill to crevice sites and blended defects.
  2. Apply uniform cold spray coating robotically.
  3. Post-Machine, as necessary.
  4. Repeat for all component sections.
- Applicable to various seawater handling components.
- Process travelers and quality control processes developed and maintained.
- Witness Coupons collected and tested.
  - Results within Acceptance Criteria


Hand Application
+ Targeted Fill
- Less Uniform


Robotic Application
+ Uniform Coating
- Conformally builds defects


Outlet Flange Section

## Conclusions

- High Pressure Cold Spray can be used to generate coatings of extremely corrosion resistant materials at low temperatures.
- Compressive residual stresses present in the coating help prevent stress corrosion cracking.
- Cold Sprayed coatings can be applied in critical applications to protect sensitive materials in corrosive environments, key points:
  - Material Selection is Critical!
  - Process Parameter development, process control, and in-process monitoring are important to achieve desired coating performance and quality assurance.
- Select applications that make sense for cold spray
  - High Value, Temperature Sensitive Components for Critical Applications
  - Applications where In-Situ restoration / mitigation is necessary
- Potential Future Applications
  - High Capacity, High Level Waste Tanks
  - In-Situ Dimensional Restoration of Steam Erosion in Secondary Systems

# Thank You!

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*Pacific Northwest National Lab*
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# Laser Glazing Of Cold Sprayed Coatings For The Mitigation Of Stress Corrosion Cracking In Light Water Reactor (LWR) Applications

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**B. Alexandreanu, Argonne National Laboratory**

**A. K. Rai, R. S. Bhattacharya, UES Inc.**

NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications, Virtual, December 7-10, 2020

Research sponsored by the Office of Science (STTR), THE U.S. DEPARTMENT OF ENERGY Contract No. DE-SC0004356, Program Manager- Sue Lesica

## Background

- Nickel-based Alloy 600 and its associated weldments Alloys 82/182 have commonly been utilized as structural material for the light water reactor (LWR) components
- LWR components operate in harsh environment and may be subject to degradation; a major form of degradation is stress corrosion cracking (SCC)
  - Compromises safety and reliability of reactors
  - Reduces operational life
- Different approaches can be taken to mitigate SCC for improved safety, reliability and enhanced operational life of the reactors
  a. Replace degraded components as the need arises (expensive)
  b. In-situ repair of degraded components and welds

## Objectives and Approach

1. Develop and demonstrate the potential of a hybrid process of cold spray (CS) and laser glazing to mitigate stress corrosion cracking of Alloy 600 and associated weldment Alloy 182 material in a simulated pressurized water reactor (PWR) environment
   - Use alloys known to be SCC susceptible, Alloy 600 and Alloy 182 (a weldment prototypic of those used in nuclear industry was produced for this program)
   - Use SCC-resistant Alloy 690 for coating

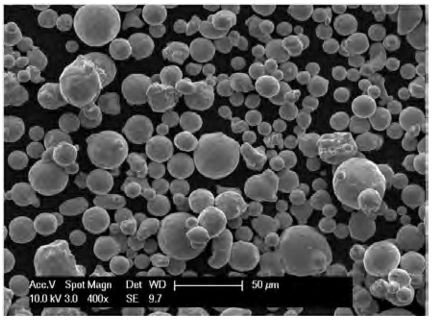
2. Develop a method to quantify the effect of the hybrid process on SCC growth in Alloy 600 or Alloy 182
   - Use interrupted crack growth rate (CGR) testing in simulated reactor environment to measure SCC CGRs prior and after the application of the hybrid process

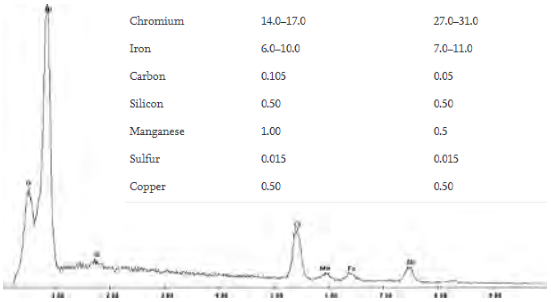
## SCC Mitigation – Test Plan

- Coat SCC-prone materials (A600 and A182) with SCC-resistant material (A690) by CS
- Post-treat coating with laser glazing to further densify and smooth out surface
  - Enhanced corrosion protection
  - Repair un-sealed cracks in the substrate beneath the CS coating
- Analyze fusion zone area (depth, width) as a function of laser glazing parameters (power, traverse speed)
- Evaluate effectiveness of the hybrid treatment
  - SCC crack growth rate (CGR) testing using realistic samples and environments

# Cold Spray

- Alloy 690 powder (10-45µm), Carpenter Powder Products, Bridgeville, Pa
- CS Equipment: Impact Innovations ISS-5/11

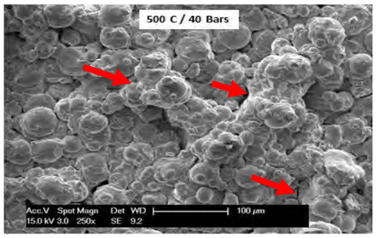


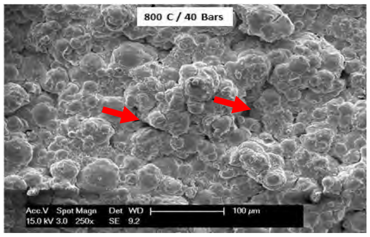


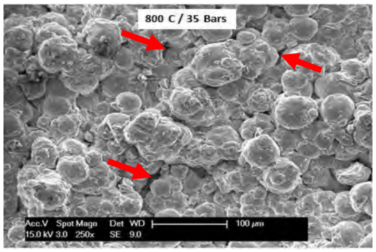
| Element | Alloy 600 (wt%) | Alloy 690 (wt%) |
|---|---|---|
| Nickel | 72.0 | 56.44 |
| Chromium | 14.0–17.0 | 27.0–31.0 |
| Iron | 6.0–10.0 | 7.0–11.0 |
| Carbon | 0.105 | 0.05 |
| Silicon | 0.50 | 0.50 |
| Manganese | 1.00 | 0.5 |
| Sulfur | 0.015 | 0.015 |
| Copper | 0.50 | 0.50 |

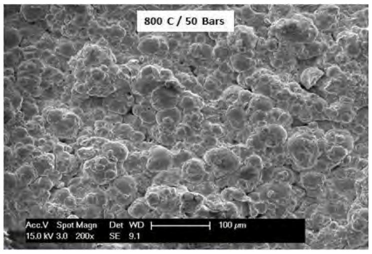
# Cold Spray – Parameter Optimization (Microstructure)

- Resulting microstructure vs. parameters



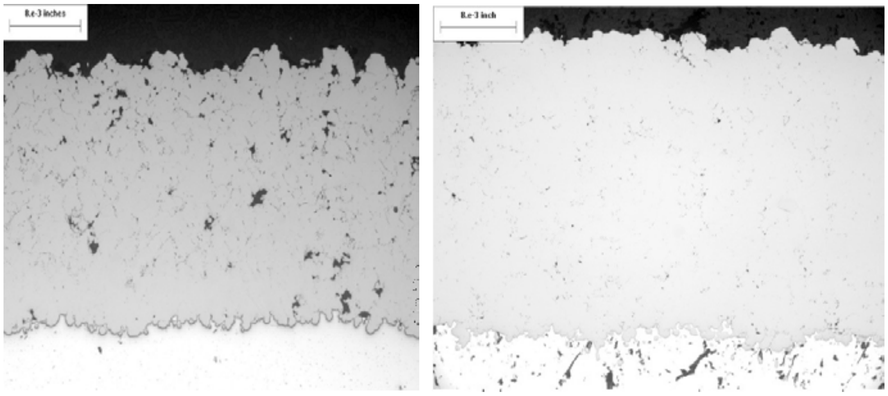






## Cold Spray – Parameter Optimization (Porosity)

- Resulting porosity vs. parameters



500°C/40bars
Avg. Porosity = 2.434±1.404

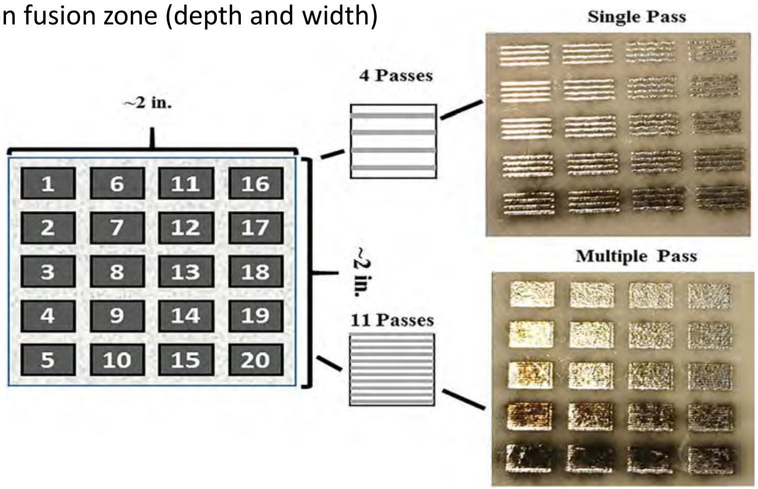
800°C/50bars
Avg. Porosity = 0.116±0.041

## Cold Spray – Optimized Parameters

| Parameter | Value |
|---|---|
| Powder | CPP 690/–325 mesh + 10 µm |
| Gas type and flow rate | Nitrogen/97 m3/Hr |
| **Gas temperature & pressure** | **800C/50 bars** |
| Powder feed rate/vibration | 2.0 and 1.5 RPM/60% |
| carrier gas flow rate | 3.0 m3/Hr |
| Substrate material/dimensions | Alloy 600/2.2” × 12” × 0.25” |
| Spray distance | 25 mm |
| Coating spec | 100, 150 and 200 µm |
| Blast grit/pressure/distance | 46 grit alumina/60 psi/20.0” |
| Spray direction | Along the 12” direction |
| Robot speed | 1000 mm/s |
| Step size | 1.0 mm |

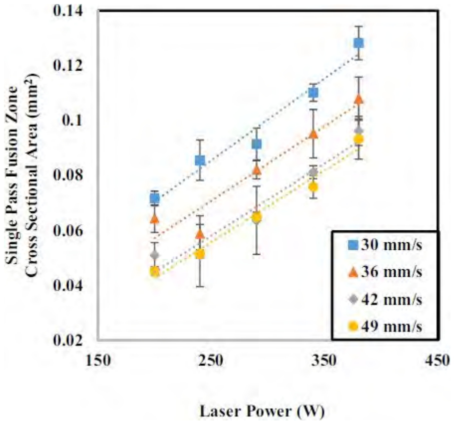
## Laser Glazing of CS Coating of A690 on A600

- Single pass verse multi-pass laser trials were compared to see the impact on fusion zone (depth and width)



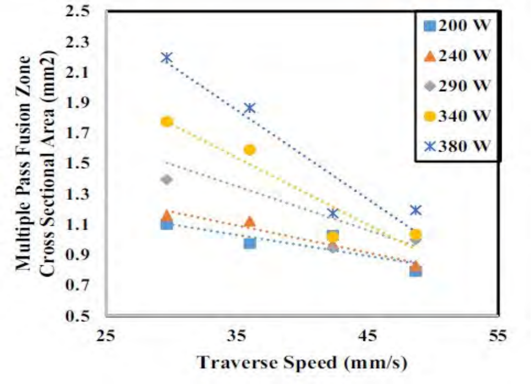
## Single Pass Laser Glazing

- Cross sectional fusion zone area increases with increasing laser power
- Cross sectional fusion zone area increases with decreasing traverse velocity



## Multiple Pass Laser Glazing

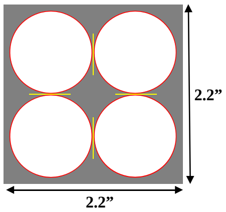
- Cross sectional fusion zone area increases with increasing laser power
- Cross sectional fusion zone area increases with decreasing traverse velocity
- Cross sectional fusion zone area for multiple pass shows on average larger areas relative to single pass



## Adhesion Testing for Selected Cold Sprayed and Laser Glazing Parameters

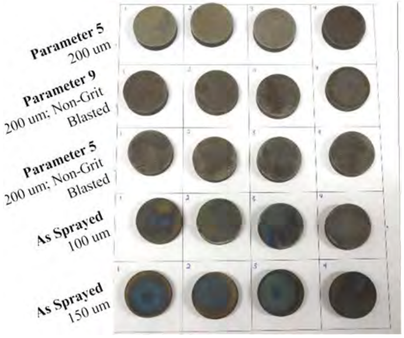
**As Cold Sprayed A690**

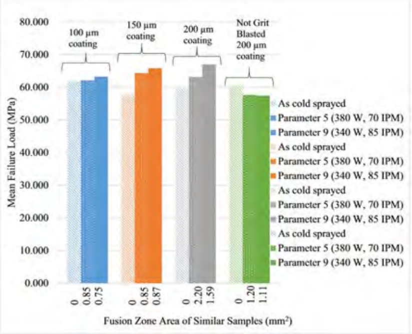
**Adhesion Slugs Schematic**



- 2.2"x2.2"x0.25"
- Wire EDM four (4), 1.0" buttons from 2.2" square

**Example Layout of Adhesion Slugs, Tested in Sets of Four (4)**



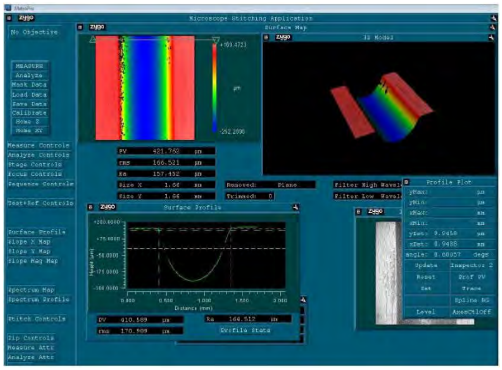


- Adhesion strength was nearly the same regardless of grit blasting the surface prior for non laser glazed samples
- Adhesion did increase in laser glazed samples where the surface was initially grit blasted

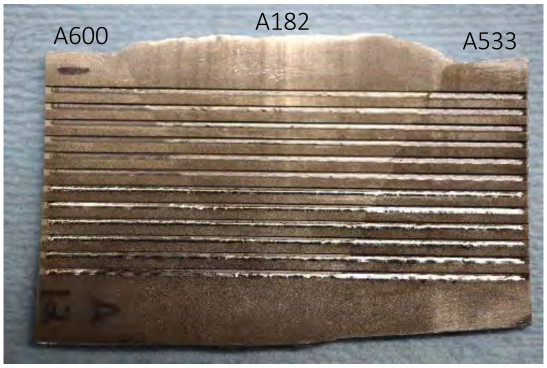
6

## Further Evaluation – CT Specimen Geometry

- Practice laser glazing runs were made on machined grooves on a piece spanning three materials: without A690 powder (grooves 1-6) and with A690 (grooves 7-12)
- The machined grooves were matched in terms of depth and width of the CT specimen

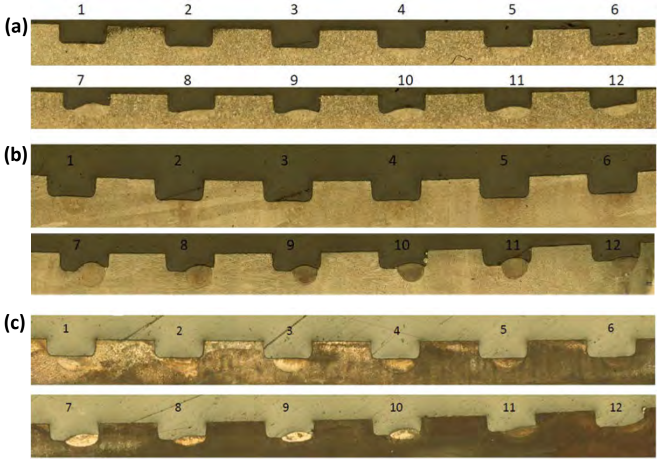


PV 421.762 µm
rms 166.521 µm
Ra 157.452 µm
Size X 1.66 mm
Size Y 1.66 mm
Removed: Plane
Trimmed: 0
Filter High Wavel
Filter Low Wavel
yMax: µm
yMin: µm
xMax: mm
xMin: mm
yDst: 9.9458 µm
xDst: 0.9488 mm
angle: 0.60057 degs
PV 410.589 µm
rms 170.989 µm
Ra 164.512 µm



## Further Evaluation – CT Specimen Geometry

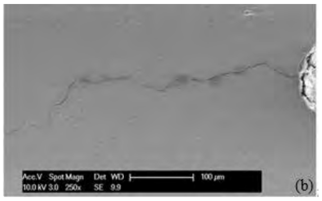
- Treated (a) A600, (b) A182 and (c) A533 to determine depth and width of the fusion zone with and without Alloy 690 powder

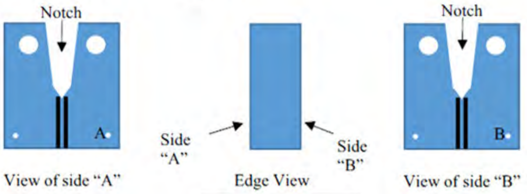


## Evaluation of Effectiveness of Hybrid Treatment

### SCC CGR Testing Sequence

1) SCC growth was first induced in a compact tension (CT) test specimen of Alloy 600 or Alloy 182 exposed to a high temperature water environment, and an initial SCC CGR is measured. Target crack depth was 0.5 mm.
2) Then, the CT specimen is removed from the test to allow for the hybrid treatment to be applied. Due to the notch geometry, we were not able to CS the crack. To demonstrate repair feasibility (fill and seal the crack), powder was laid and laser glazed





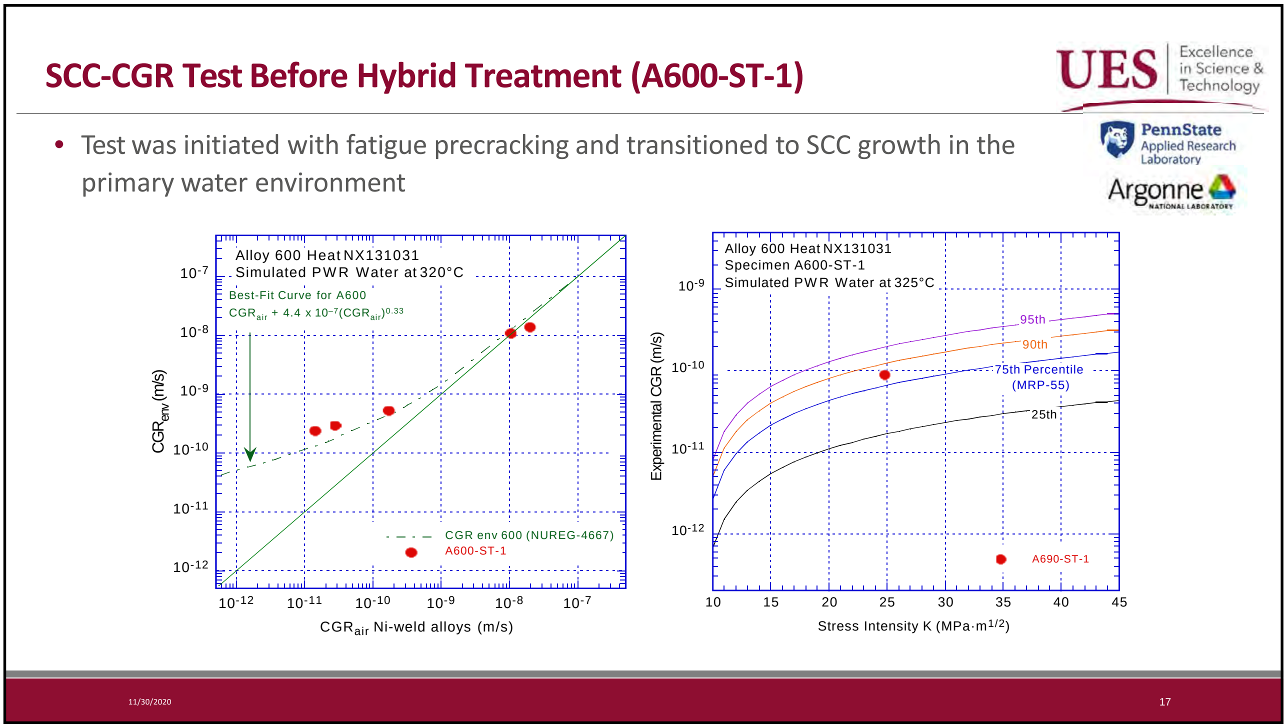
## Evaluation of Effectiveness of Hybrid Treatment

### SCC CGR Testing Sequence

3) The groove on both sides (A and B) and the notch were treated with the hybrid treatment.
4) The specimen is reintroduced into the same environment, and under the same loading, and a new SCC CGR is measured

If the hybrid treatment is effective at mitigating SCC, the SCC crack is sealed, and the SCC CGR measured after the application of the treatment is reduced vs. the CGR measured prior to the treatment

One specimen (A600-ST-1) was destructively examined post-test, whereas two specimens (A600-ST-2 and A182-ST-2) were not destructively examined post-test; the intent is to conduct fatigue CGR testing to determine whether the response is consistent with Alloy 600, 690, 182 or not – further substantiating the effectiveness of the repair



## SCC-CGR Test Before Hybrid Treatment (A600-ST-1)

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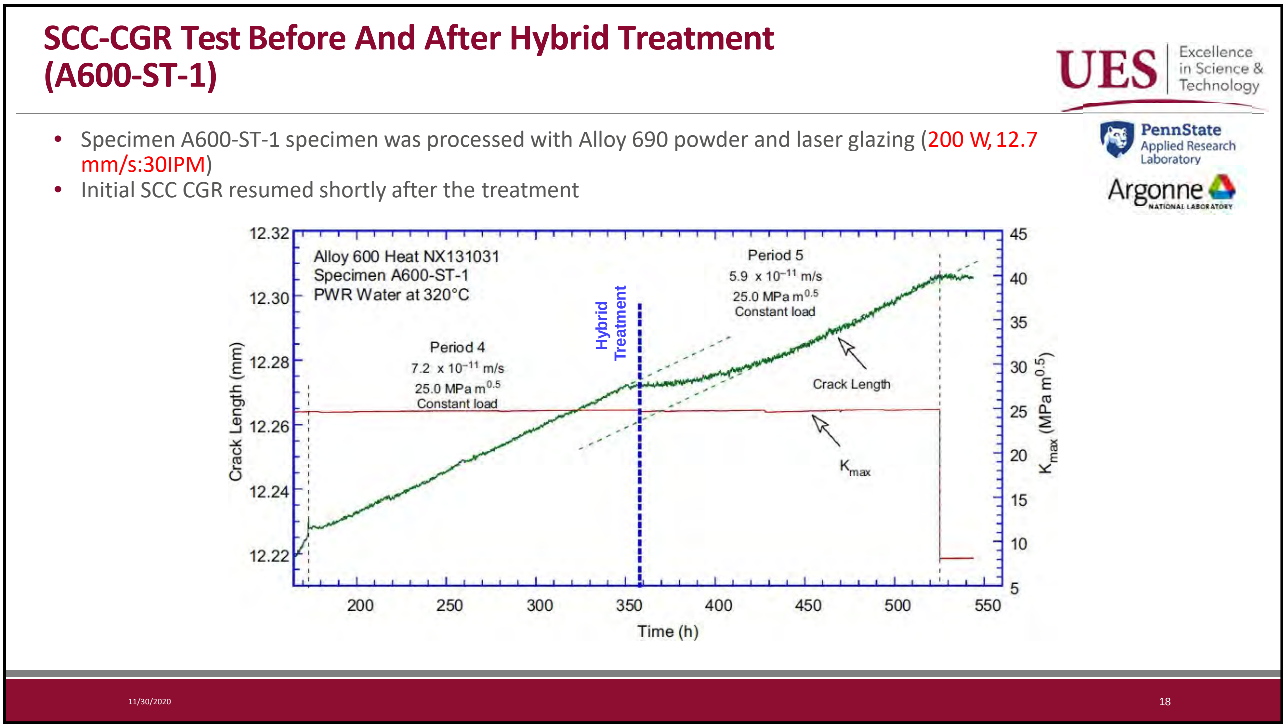
- Test was initiated with fatigue precracking and transitioned to SCC growth in the primary water environment



## SCC-CGR Test Before And After Hybrid Treatment (A600-ST-1)

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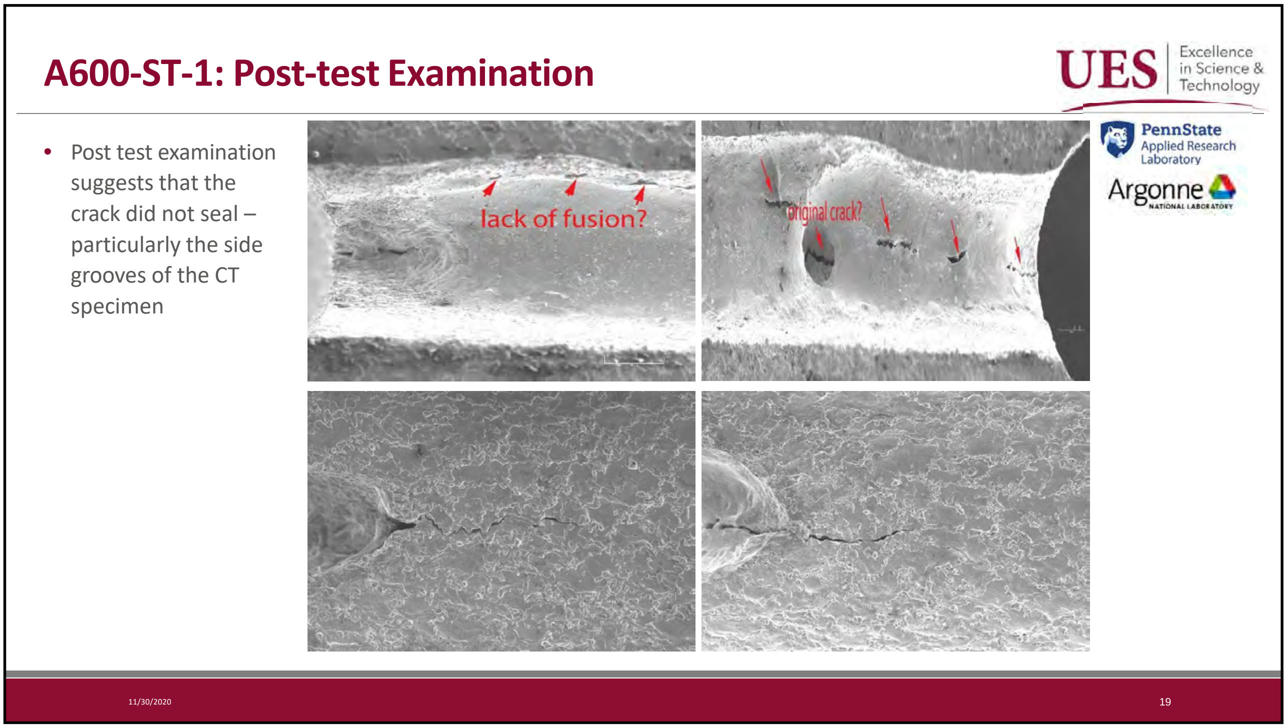
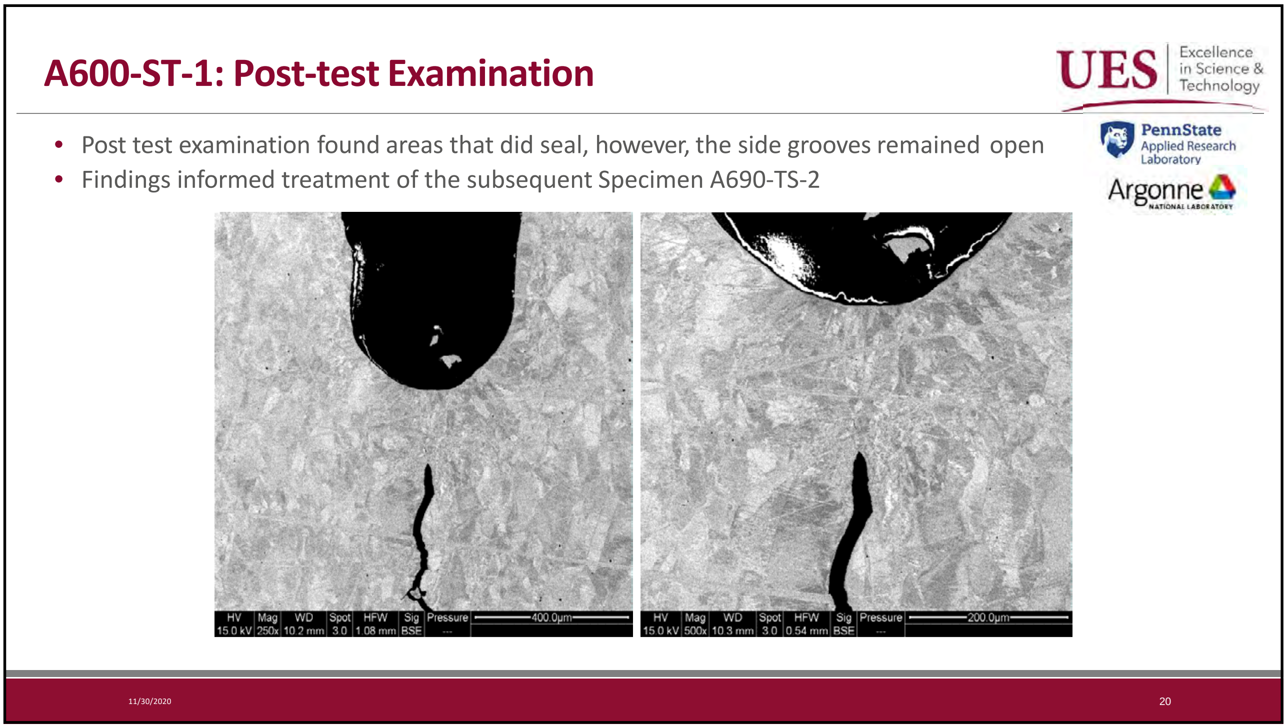
- Specimen A600-ST-1 specimen was processed with Alloy 690 powder and laser glazing (200 W, 12.7 mm/s:30IPM)
- Initial SCC CGR resumed shortly after the treatment



## A600-ST-1: Post-test Examination

- Post test examination suggests that the crack did not seal – particularly the side grooves of the CT specimen

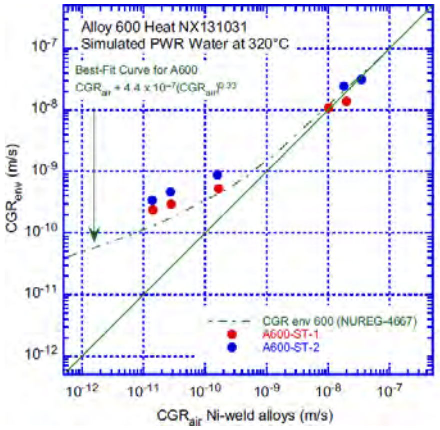


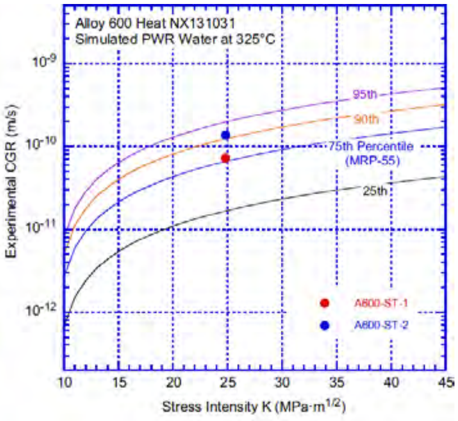
## A600-ST-1: Post-test Examination

- Post test examination found areas that did seal, however, the side grooves remained open
- Findings informed treatment of the subsequent Specimen A690-TS-2

## CGR Test Before Hybrid Treatment (A600-ST-2)

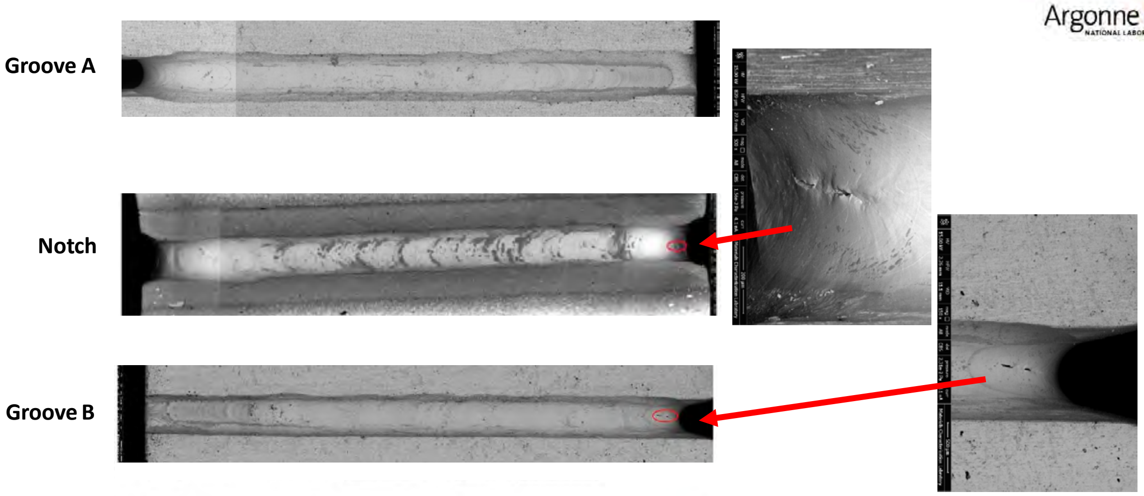
- As before, test was initiated with fatigue pre-cracking and transitioned to SCC growth in the primary water environment.
- Identical cyclic and SCC CGR response





## A600-ST-2 – Pre-reinsertion Examination

- Pre-reinsertion examination suggests that the crack did seal



## A600-ST-2: SCC CGR Response Before and After the Hybrid Process

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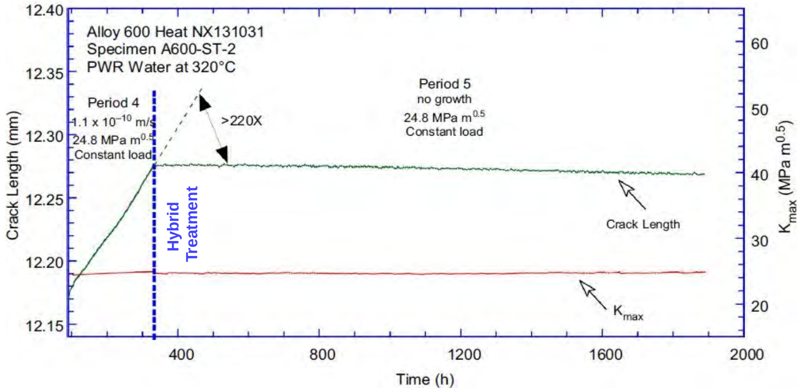
- Specimen A600-ST-2 was processed using two laser glazing steps:
  - 500 W at 25.4 mm/s followed by 300 W at 25.4 mm/s
- Growth did not re-initiate cracking in 1200 h (FOI > 220 assuming detection limit 5 x $10^{-13}$ m/s)



## Alloy 182 SCC CGR Testing

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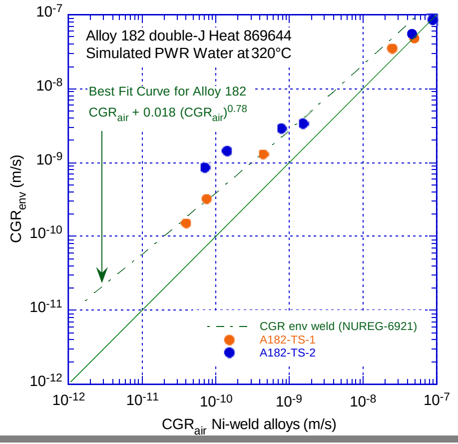
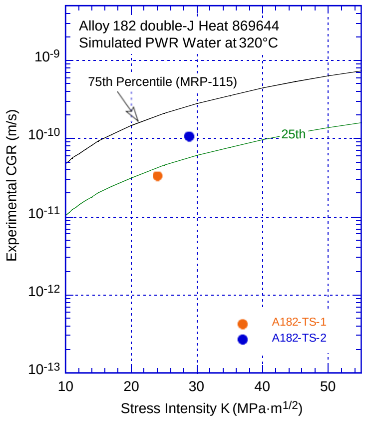
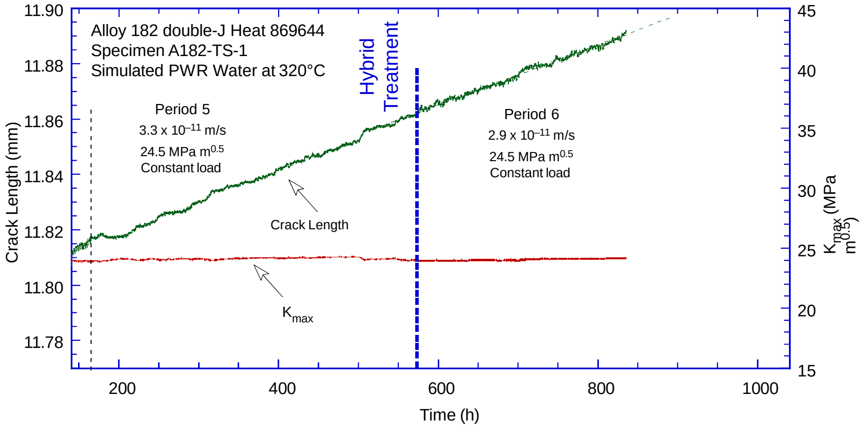
- Two SCC CGR tests were conducted on Alloy 182 (Specimens A182-TS-1 and A600-TS-2)
- Both tests were initiated with fatigue pre-cracking and transitioned to SCC growth in the primary water environment.





## SCC-CGR Test Before And After Hybrid Process (A182-TS-1)

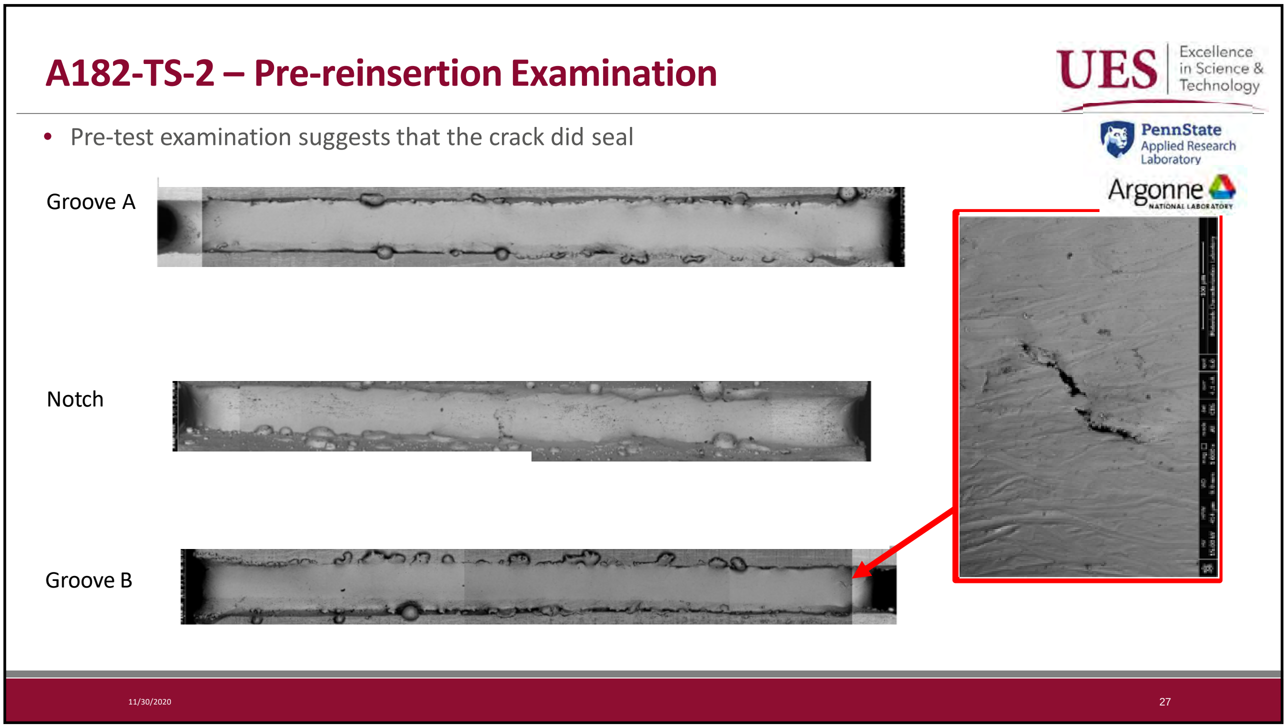
- Initial test on Alloy 182 (Specimen A182-TS-1). Processed with 2 laser glazing steps that were successful for Alloy 690 (500 W at 25.4 mm/s followed by 300 W at 25.4 mm/s)
- As with A690-TS-2 previously, decision was made to further adjust laser parameters



## Optimized Laser Glazing Parameters in Alloy 182 Weld (A182-TS-2)

- As before, optimized laser glazing parameters for Alloy 182 (Specimen A182-TS-2), notch and both side grooves were included
- Three laser glazing steps were used (IG interdendritic morphology in the weld may not be as uniform as that of the base metal)

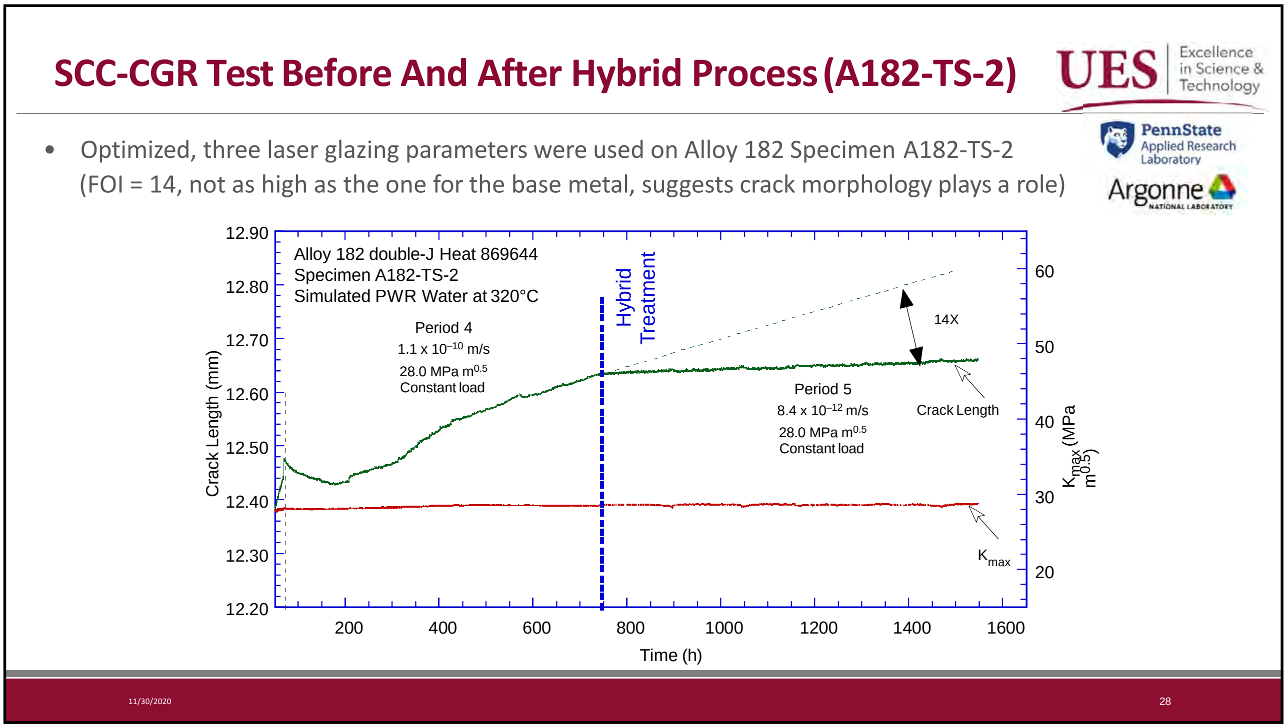
| Laser Power Setting (watts) | Travel Speed (IPM) | Shielding Gas (L/min) | Focus Head Standoff (mm) | Spot Size (mm) | Comments |
|---|---|---|---|---|---|
| 500 | 60 | 25 | 18.62 | 1 | preheat to 400 C side A, A690 powder added |
| 500 | 60 | 25 | 18.62 | 1 | preheat to 400 C side B, A690 powder added |
| 500 | 60 | 25 | 18.87 | 1 | preheat to 400 C side Notch, A690 powder added |



# A182-TS-2 – Pre-reinsertion Examination

- Pre-test examination suggests that the crack did seal

27



# SCC-CGR Test Before And After Hybrid Process (A182-TS-2)

- Optimized, three laser glazing parameters were used on Alloy 182 Specimen A182-TS-2 (FOI = 14, not as high as the one for the base metal, suggests crack morphology plays a role)

28

14

## Summary

1. Alloys 600 and 182 weld were selected as the SCC-prone substrate materials. Alloy 690, an alloy with superior resistance to SCC was selected as the repair material.
2. CS processing parameters were optimized to fabricate denser and highly adherent coatings of Alloy 690 powders. The adhesion strength of the coating with the substrate was determined and found to be very high (>8140PSI).
3. Several laser processing tests were conducted on uncoated and CS-coated alloy substrates to determine optimal conditions for the repair (sealing) of underlying cracks at a given depth/dimension.
4. Using the optimized laser and CS parameters, hybrid treatments were further adapted and optimized for the compact tension (CT) specimen geometry used in SCC CGR testing and sharp cracks
5. A method to quantify the effectiveness of the hybrid process to seal the cracks, thus mitigating SCC growth in Alloys 600/182 was developed: interrupted crack growth rate (CGR) testing to measure SCC CGRs prior and after the application of the treatment
6. SCC CGR testing have shown that under optimal conditions, the hybrid treatment sealed the crack, and substantial reductions in CGR of **220x** in Alloy 600 and **14x** in Alloy 182 were achieved for test durations of ~1000 hours demonstrating the feasibility of the laser-cold spray hybrid process to mitigate SCC.

## Future Work

1. Utilize repaired A600-ST-2 and A182-TS-2 specimens to conduct fatigue CGR testing to determine whether the response is consistent with Alloy 600, 690, 182 or not – further substantiating the effectiveness of the repair.
2. Utilize cold spray and/or hybrid treatment to develop coatings for corrosion resistance and/or tritium permeation in molten salt environment of advanced high temperature reactors (AHTRs)

# US NRC Workshop on Advanced Manufacturing

## Westinghouse AM Thimble Plugging Device / Advanced Debris Filtering Bottom Nozzle Implementation Process

David Huegel, Fuel Product Technical Lead

Westinghouse

## Agenda

- Westinghouse AM Objectives
- Advanced AM Components
- Reactor Ready Component
- Licensing of AM TPD
- Advanced AM Debris Filter Bottom Nozzle

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# Westinghouse AM Objective

- Westinghouse is using the AM process to produce high quality / high performance fuel products for use in commercial nuclear reactors.
- Westinghouse has performed significant testing, designing, prototype building, verifying design characteristics, validating material properties, etc. to ensure that the AM process is fully understood and thus can be safely used for producing fuel components for use in commercial reactors.

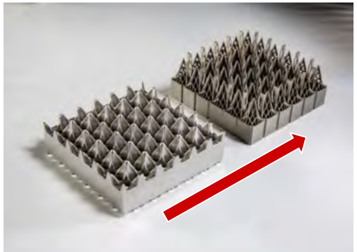
**AM Provides Significant Benefits Relative to Existing Manufacturing Methods**

Westinghouse

# Advanced AM Components - Bottom Nozzles

**Numerous Advanced AM Component designs have been developed and tested by Westinghouse and are close to being implemented via Lead Test Assembly Programs**

- Advanced AM debris filtering bottom nozzle created
  - Low Pressure drop
  - Improved filtering performance
  - Improved structural support via use of Alloy 718



**AM Optimizes performance**

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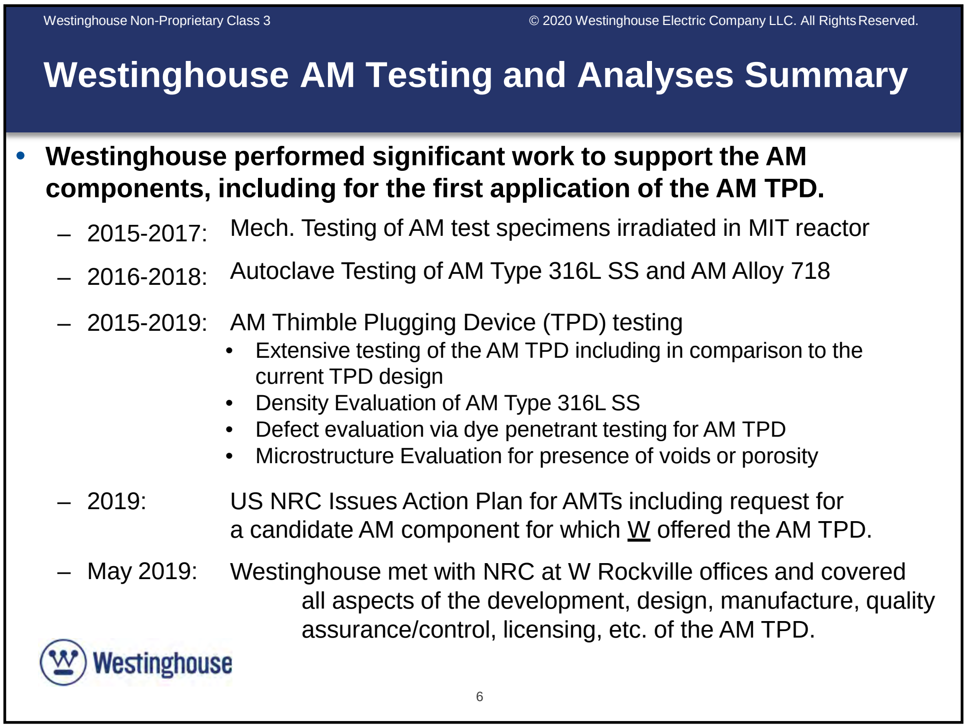
Westinghouse Non-Proprietary Class 3

## Reactor Ready Component Project

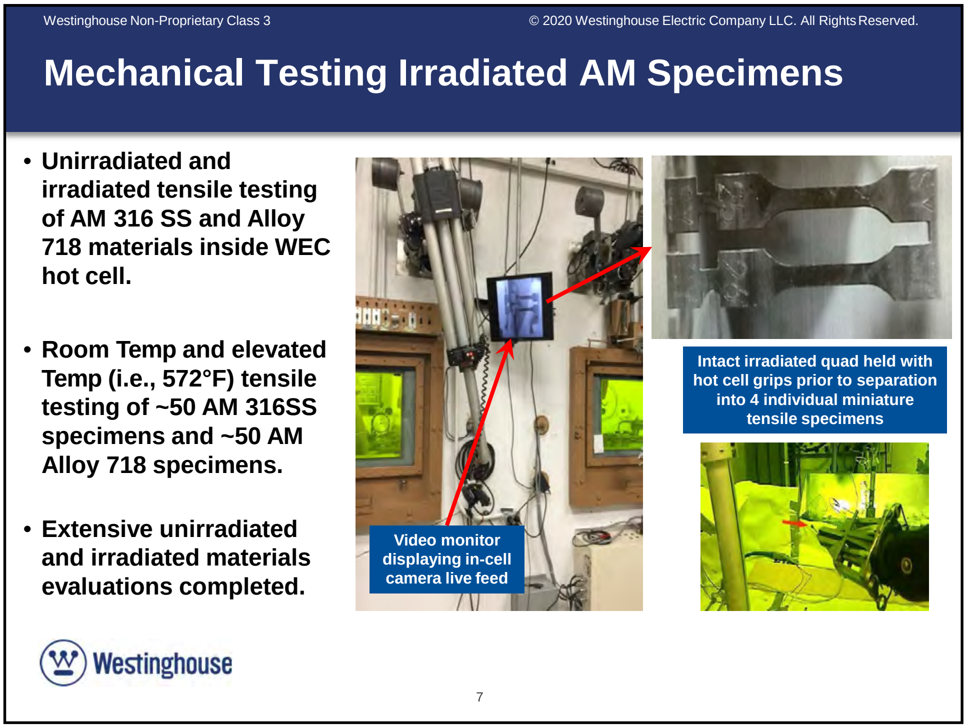
- **Kaizen Event Held to Select Demonstration Component – Dec 2014**
  - Thimble Plugging Device (TPD) selected as the first AM Fuels component to be placed in a commercial reactor as a demonstration component
  - Low risk component, moderate complexity, fully contained in guide thimble tubes.
  - AM TPD is equivalent in Form, Fit and Function as existing TPD.
- **Completed testing, analysis, quality assurance, manufacturing qualification, licensing, etc. to support one production AM TPD**
- **Working with Exelon, the AM TPD was delivered for the Byron Unit 1 Spring 2020 Outage via 10CFR50.59**



Westinghouse Non-Proprietary Class 3

## Westinghouse AM Testing and Analyses Summary

- **Westinghouse performed significant work to support the AM components, including for the first application of the AM TPD.**
  - 2015-2017: Mech. Testing of AM test specimens irradiated in MIT reactor
  - 2016-2018: Autoclave Testing of AM Type 316L SS and AM Alloy 718
  - 2015-2019: AM Thimble Plugging Device (TPD) testing
    - Extensive testing of the AM TPD including in comparison to the current TPD design
    - Density Evaluation of AM Type 316L SS
    - Defect evaluation via dye penetrant testing for AM TPD
    - Microstructure Evaluation for presence of voids or porosity
  - 2019: US NRC Issues Action Plan for AMTs including request for a candidate AM component for which W offered the AM TPD.
  - May 2019: Westinghouse met with NRC at W Rockville offices and covered all aspects of the development, design, manufacture, quality assurance/control, licensing, etc. of the AM TPD.



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## Mechanical Testing Irradiated AM Specimens

- Unirradiated and irradiated tensile testing of AM 316 SS and Alloy 718 materials inside WEC hot cell.
- Room Temp and elevated Temp (i.e., 572°F) tensile testing of ~50 AM 316SS specimens and ~50 AM Alloy 718 specimens.
- Extensive unirradiated and irradiated materials evaluations completed.

Video monitor displaying in-cell camera live feed

Intact irradiated quad held with hot cell grips prior to separation into 4 individual miniature tensile specimens

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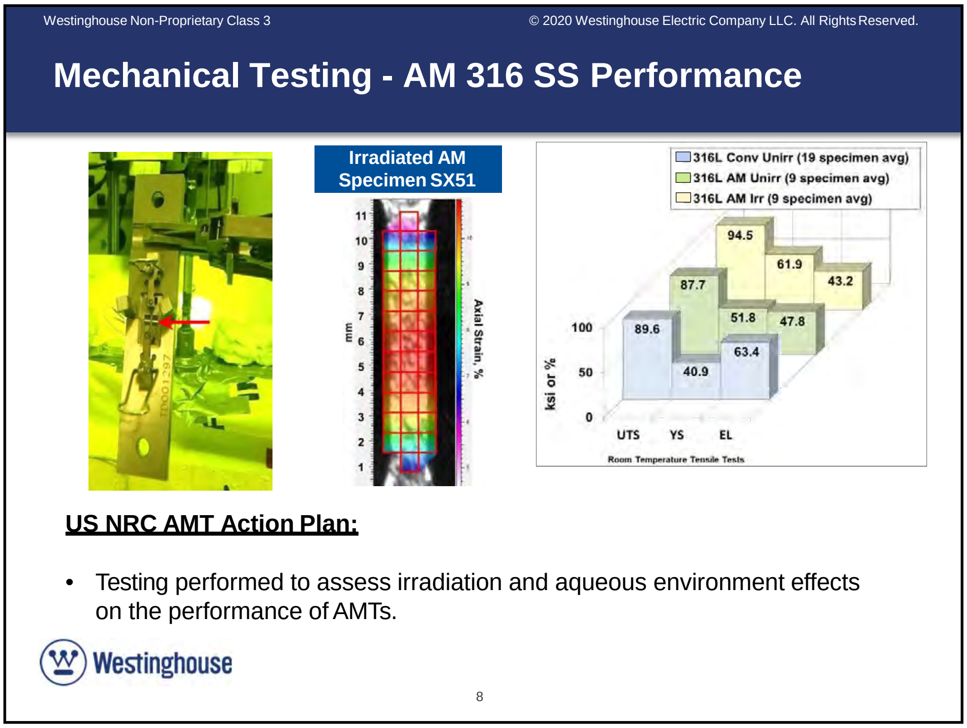
7



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## Mechanical Testing - AM 316 SS Performance

Irradiated AM Specimen SX51

**US NRC AMT Action Plan:**

- Testing performed to assess irradiation and aqueous environment effects on the performance of AMTs.

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8

## Manufacturing Validation Process

- Three confirmatory AM TPD builds were created utilizing the same AM machine, same lot of material and same process parameters. Each of these builds included witness specimens and tensile bars.
- Two builds were destructively tested along with the witness specimens to establish consistency of the witness specimen results.

**US NRC AMT Action Plan:**

- Discusses the need to investigate state-of-the-art modeling and simulation tools being developed to predict AM microstructure and properties of AMT materials, to provide a path for validating the acceptability of AMT components similar to the use of witness specimens and lot testing.

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## Westinghouse AM TPD Testing

### Mechanical Testing of AM TPDs:

- Mechanical testing was performed for the existing and the AM TPDs. Testing included axial pull tests, lateral bending tests and baseplate weld integrity tests.
- Performance of the AM TPD was consistent with the existing TPD.
- All TPD mechanical design criteria satisfied.

**NRC AMT Action Plan:**

– Testing should address differences between AMTs and traditional manufacturing processes from a performance-based perspective. Focus should be on those performance characteristics pertinent to safety that deviate from traditional manufacturing requirements.

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# ASTM E-8 Tensile Specimen Testing

- ASTM E-8 Tensile specimens cut from AM TPD
- Tensile testing performed on resulting ASTM E-8 Tensile specimens.

**ASTM specimens from X and Y cylinders**

**Z Specimens from Z cylinder and from select AM rodlets**

**US NRC AMT Action Plan:**

- Performance criteria for the AMT component may include physical properties, mechanical properties, dimensionality, functionality, and reliability.

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# Westinghouse AM TPD Testing

## Additional Testing and Evaluation:

**Dye Penetration Testing:**

- Dye penetrant testing was performed on the complete AM TPD and there were no observed defects.

**Microstructure Evaluation:**

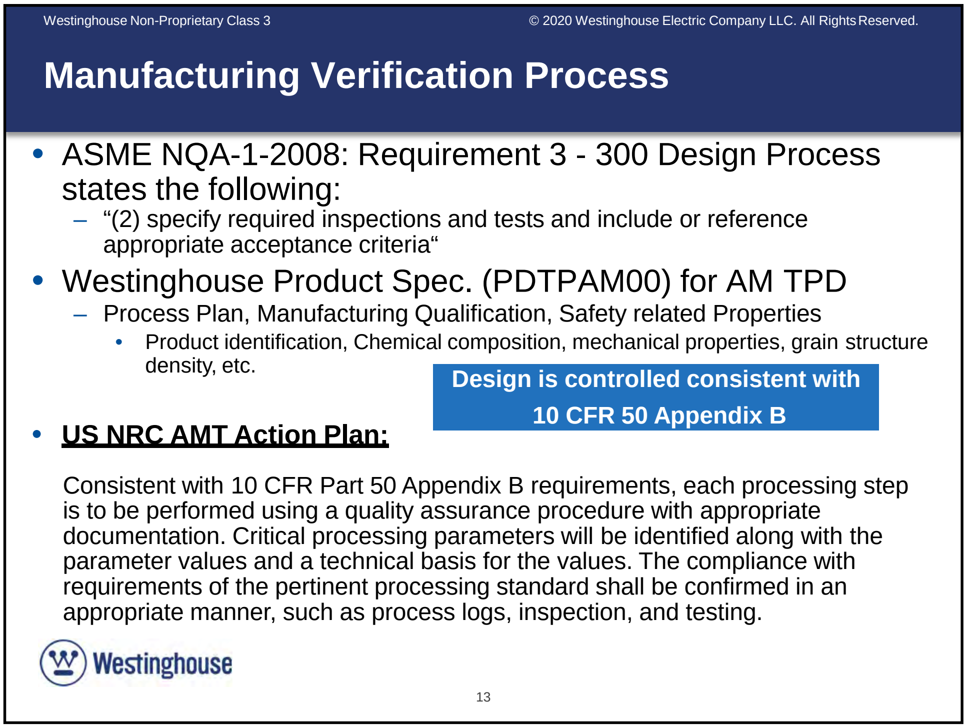
- Cylinders were created from the AM Rodlets and were cut in half and polished and examined at 50x magnification and found to be free of voids or porosity.

**Density Evaluation:**

- Cylinders were created from the AM Rodlets and were evaluated for density and were determined to be consistent with wrought 316L Stainless Steel material.

- **US NRC AMT Action Plan:**

  Adequate information to demonstrate whether inspection and non-destructive examination (NDE) techniques are sufficient to assess the condition of AMT-fabricated components, and in particular for the types of defects that can compromise the safe performance of the component and can accelerate degradation of the component during service.



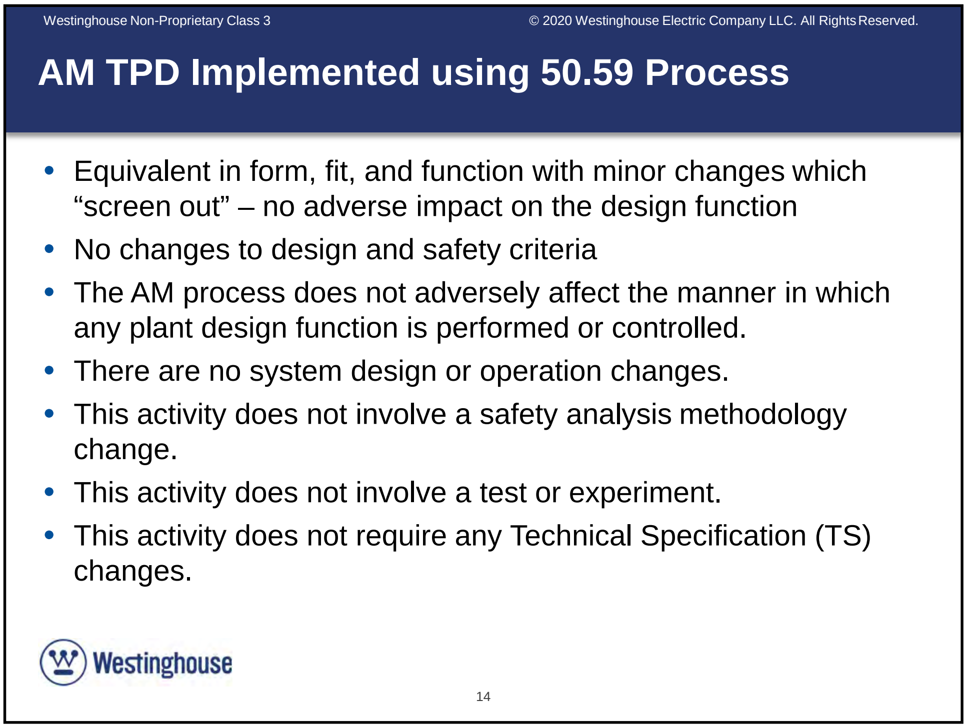
## Manufacturing Verification Process

- ASME NQA-1-2008: Requirement 3 - 300 Design Process states the following:
  - "(2) specify required inspections and tests and include or reference appropriate acceptance criteria"
- Westinghouse Product Spec. (PDTPAM00) for AM TPD
  - Process Plan, Manufacturing Qualification, Safety related Properties
    - Product identification, Chemical composition, mechanical properties, grain structure density, etc.

**Design is controlled consistent with 10 CFR 50 Appendix B**

- **US NRC AMT Action Plan:**

Consistent with 10 CFR Part 50 Appendix B requirements, each processing step is to be performed using a quality assurance procedure with appropriate documentation. Critical processing parameters will be identified along with the parameter values and a technical basis for the values. The compliance with requirements of the pertinent processing standard shall be confirmed in an appropriate manner, such as process logs, inspection, and testing.



## AM TPD Implemented using 50.59 Process

- Equivalent in form, fit, and function with minor changes which "screen out" – no adverse impact on the design function
- No changes to design and safety criteria
- The AM process does not adversely affect the manner in which any plant design function is performed or controlled.
- There are no system design or operation changes.
- This activity does not involve a safety analysis methodology change.
- This activity does not involve a test or experiment.
- This activity does not require any Technical Specification (TS) changes.

## Post Irradiation Evaluation of AM TPD

- **Post Irradiation Examination (PIE)**
  - Westinghouse currently plans on performing inspections of the AM TPD which will include detailed visual inspections with a high-resolution camera system as well as performing drag tests.
- **US NRC AMT Action Plan:**

Although there is nothing specific regarding PIEs, Subtask 2C: AMT Guidance Document mentions that a report will be created to be used as a resource for staff reviews of AMTs and includes the topic of "In-Service Inspection"

Westinghouse

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## AM Advanced Debris Filter Bottom Nozzle

- Full size AM Advanced Debris Filter Bottom Nozzle
  - Reduced pressure drop
  - Improved Filtering capability
- Pursuing the licensing of Lead Test Assembly AM Bottom Nozzles (4 to 8) using the 50.59 process.
- Coordinating with the NRC to ensure licensing approach is acceptable.
- Licensing support will include GSI-191 testing to demonstrate acceptability of design

Westinghouse

# Summary

- Westinghouse has invested significant time and effort thoroughly evaluating the Additively Manufactured process for application to fuel components for a commercial reactor.
- Material and Mechanical Property Testing concluded that AM Properties are consistent with conventional wrought material.
- First reactor ready component (AM TPD) installed in Byron Unit 1 in the spring of 2020.
- Westinghouse continues to pursue through testing and development of advanced AM components following guidance provided in the US NRC Action Plan on AMTs.

# Questions

?

# 316L Stainless Steel Manufactured via Laser Powder Bed Fusion Additive Manufacturing

## Data Package & Code Case

D. Gandy, S. Tate, M. Albert (EPRI)
C. Armstrong (Westinghouse)

U.S. NRC Workshop on Advanced Manufacturing
Technologies for Nuclear Applications
December 9, 2020

**DOE Project:**
**DE-NE0008521**

www.epri.com

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

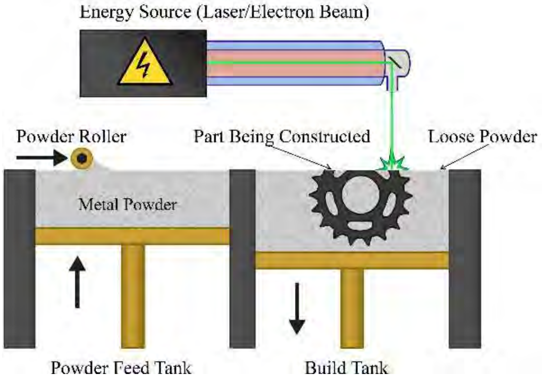
Westinghouse

## A Few Attributes of LPBF-AM

- Attractive for pressure retaining applications across the power-, chemical-, process-, and pulp & paper industries, etc. including:
  1. Speed to produce a final part/component
  2. Capability to produce multiple parts using identical parameters with little or no variance between the parts
  3. Ability to monitor/capture build conditions throughout the build process
  4. Ability to produce structural parts with optimized support / features, enabling lighter and/or stronger components
  5. The ability to produce obsolete components in a relatively short timeframe

# AM Qualification for Nuclear Applications
## --ASME Data Package Development

- DOE Project: **DE-NE0008521**
- EPRI lead
- Five organizations involved
  - Rolls-Royce
  - Westinghouse
  - ORNL MDF
  - Auburn University
  - Oerlikon
- Laser Powder Bed-AM
- 316L SS



Laser Powder Bed-AM (*courtesy of 3DEO*)

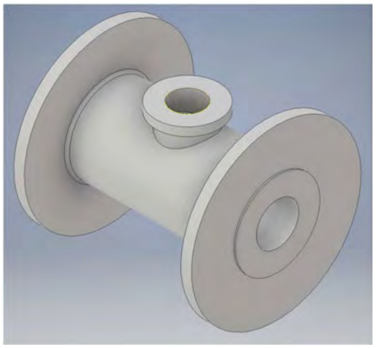
# AM Qualification for Nuclear Applications
## --ASME Data Package Development

- 2 Types of machines
  - EOS, Renishaw
- 4 sets of processing parameters
- 4 different 316L powder heats
- 3 different components (next slide)
- Components are >8-inches in diameter and ~0.5-inch thick
- Different build environments --argon and nitrogen
- Two conditions: HIP and SA; SA only
- Vertical control/witness samples included
- Parameter data sheet recorded for each build

EOS M290 System

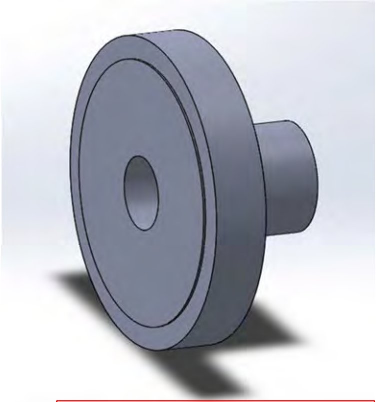
*Courtesy: Westinghouse / Penn United Technologies*

# AM Qualification for Nuclear Applications
## --ASME Data Package Development



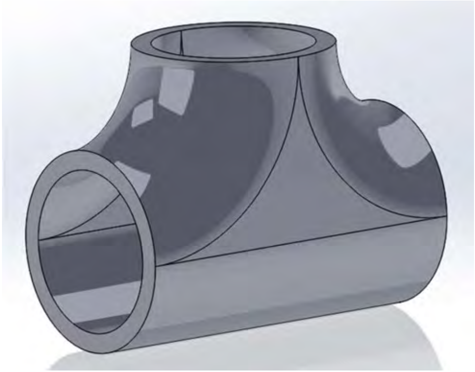
Class 300 Forged Gate Valve Body

8”Ø x 2”bore x 4”OD x ½”T



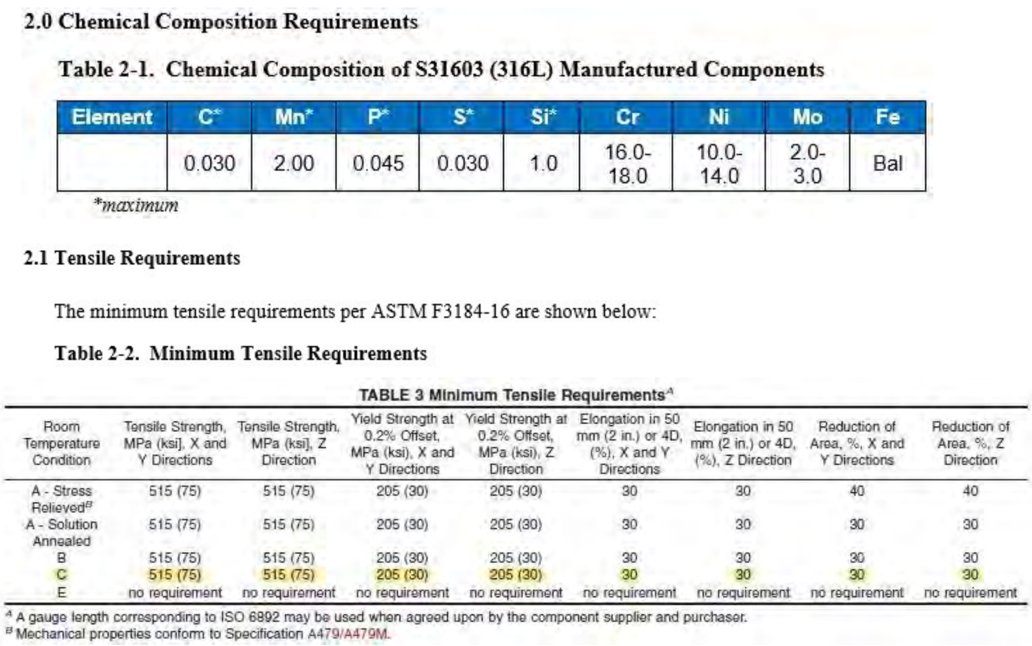
Ring Flange End Connection

8.5”Ø x 1.5”T x 2” bore



Straight Pipe Tee

8-1/4”W x 4-1/8”T



### 2.0 Chemical Composition Requirements

**Table 2-1. Chemical Composition of S31603 (316L) Manufactured Components**

| Element | C* | Mn* | P* | S* | Si* | Cr | Ni | Mo | Fe |
|---|---|---|---|---|---|---|---|---|---|
| | 0.030 | 2.00 | 0.045 | 0.030 | 1.0 | 16.0-18.0 | 10.0-14.0 | 2.0-3.0 | Bal |

**maximum*

### 2.1 Tensile Requirements

The minimum tensile requirements per ASTM F3184-16 are shown below:

**Table 2-2. Minimum Tensile Requirements**

**TABLE 3 Minimum Tensile Requirements**[A]

| Room Temperature Condition | Tensile Strength, MPa (ksi), X and Y Directions | Tensile Strength, MPa (ksi), Z Direction | Yield Strength at 0.2% Offset, MPa (ksi), X and Y Directions | Yield Strength at 0.2% Offset, MPa (ksi), Z Direction | Elongation in 50 mm (2 in.) or 4D, (%), X and Y Directions | Elongation in 50 mm (2 in.) or 4D, (%), Z Direction | Reduction of Area, %, X and Y Directions | Reduction of Area, %, Z Direction |
|---|---|---|---|---|---|---|---|---|
| A - Stress Relieved[B] | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 40 | 40 |
| A - Solution Annealed | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 30 | 30 |
| B | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 30 | 30 |
| C | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 30 | 30 |
| E | no requirement | no requirement | no requirement | no requirement | no requirement | no requirement | no requirement | no requirement |

[A] A gauge length corresponding to ISO 6892 may be used when agreed upon by the component supplier and purchaser.

[B] Mechanical properties conform to Specification A479/A479M.

## 2.2 Heat Treatment Requirements

The minimum heat treatment requirements per ASTM F3184-16 are shown below:

Process components under inert atmosphere at not less than 100MPa (14.5ksi) within the range of 1120 to 1163°C (2050 to 2125°F); hold at the selected temperature within ± 14°C (± 25°F) for 240 ± 60 min and cool under inert atmosphere to below 427°C (800°F), or to parameters agreed upon by the component supplier and purchaser.

*NOTE 10—Proper heat treatment of Condition C components may be necessary to enhance corrosion and environmental cracking resistance. When specified by the purchaser, the component supplier shall test the material in its final condition in accordance with Supplementary Requirement S16.*

Components shall be solution annealed in accordance with AMS 2759 or Specification A484/A484M.

## 2.3 Hardness Requirement

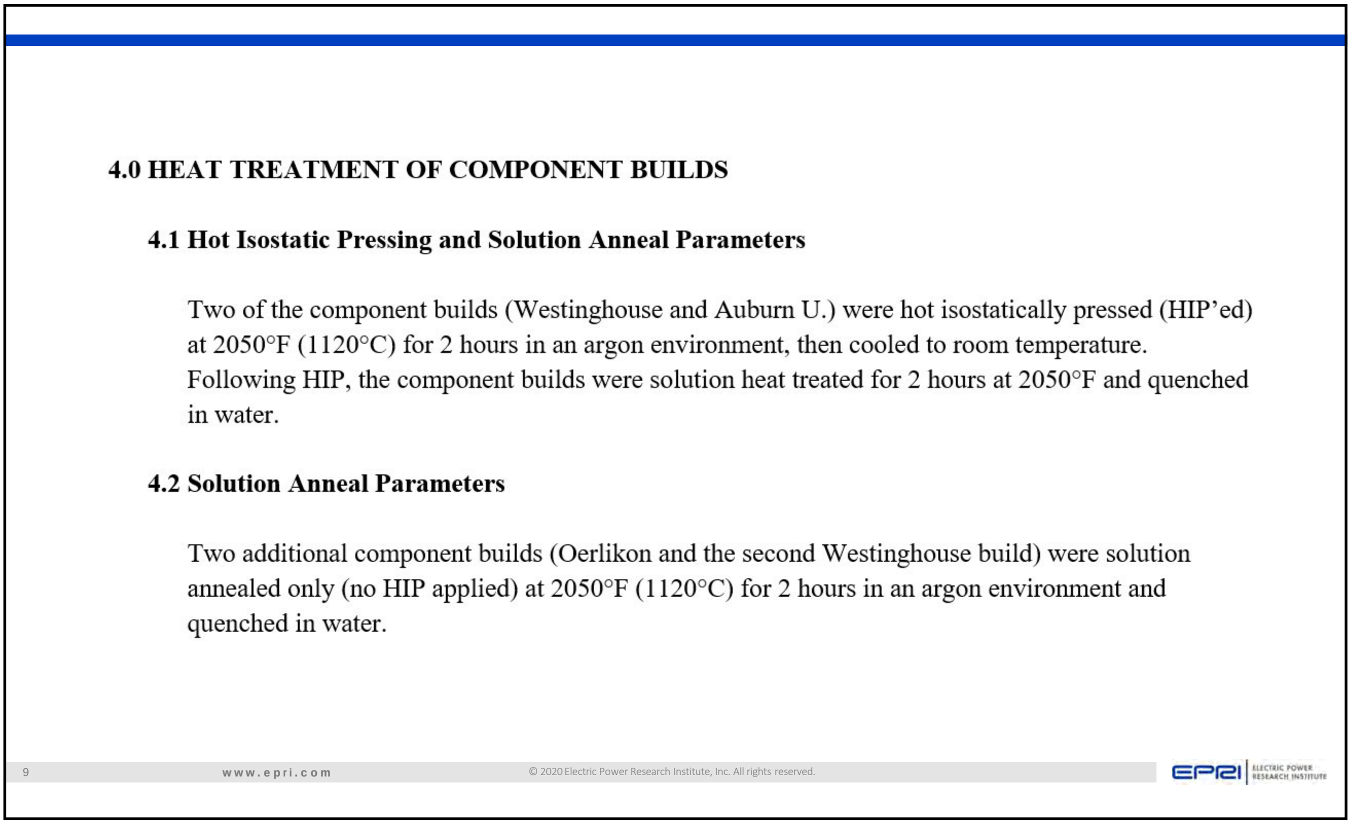
Not applicable under ASTM F3184-16.

## 3.0 COMPONENT BUILD AM PARAMETERS

Table 3-1. Component Build Parameters Used by Each Manufacturer

| Parameter | Westinghouse Build | Auburn University Build | Rolls-Royce Build | Oerlikon Build |
|---|---|---|---|---|
| Laser Power: | 214W | 200W | 195W | 265 |
| Layer Thickness: | 40 microns | 50 microns | 20microns | 40 |
| Melting Method: | Stripe, (12mm) | Stripe, (8mm) | Stripe, (5mm) | Stripe (7mm) |
| Rotation: | 47 degrees | 67 degrees | 67 degrees | 67 degrees |
| Exposure Time: | N/A | 80 us | N/A | N/A |
| Point Distance: | N/A | 60 microns | N/A | N/A |
| Effective Velocity: | 0.928 m/s | 0.75 m/s | 1.083 m/s | 1.15 m/s |
| Hatch Spacing: | 100 microns | 100 microns | 90 microns | 100 microns |
| Energy Density (J/mm3) | 57.65 | 53.33 | 100.03 | 57.61 |
| Recoater Blade Type | Hard (Steel) | Silicon Rubber | High speed steel | Silicone Rubber |
| Atomized Powder Gas Type | Argon | Argon | Nitrogen | Argon |
| Build Chamber Gas Type | Argon | Argon | Nitrogen | Argon |
| Equipment Type | **EOS M290** | **Renishaw AM250** | **EOS M280** | **EOS M290** |

The actual components are shown in Section 5.5 of this Data Package.



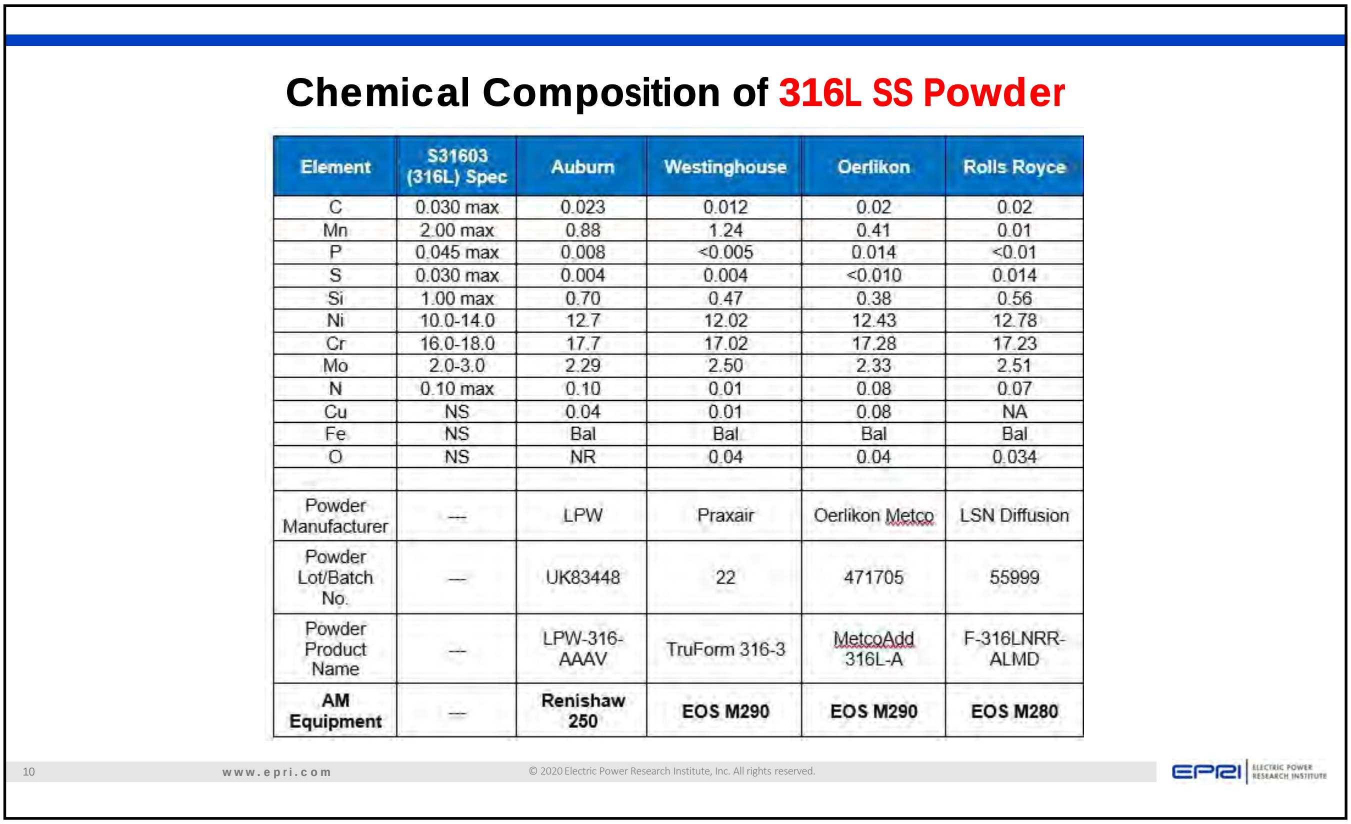
## 4.0 HEAT TREATMENT OF COMPONENT BUILDS

### 4.1 Hot Isostatic Pressing and Solution Anneal Parameters

Two of the component builds (Westinghouse and Auburn U.) were hot isostatically pressed (HIP'ed) at 2050°F (1120°C) for 2 hours in an argon environment, then cooled to room temperature. Following HIP, the component builds were solution heat treated for 2 hours at 2050°F and quenched in water.

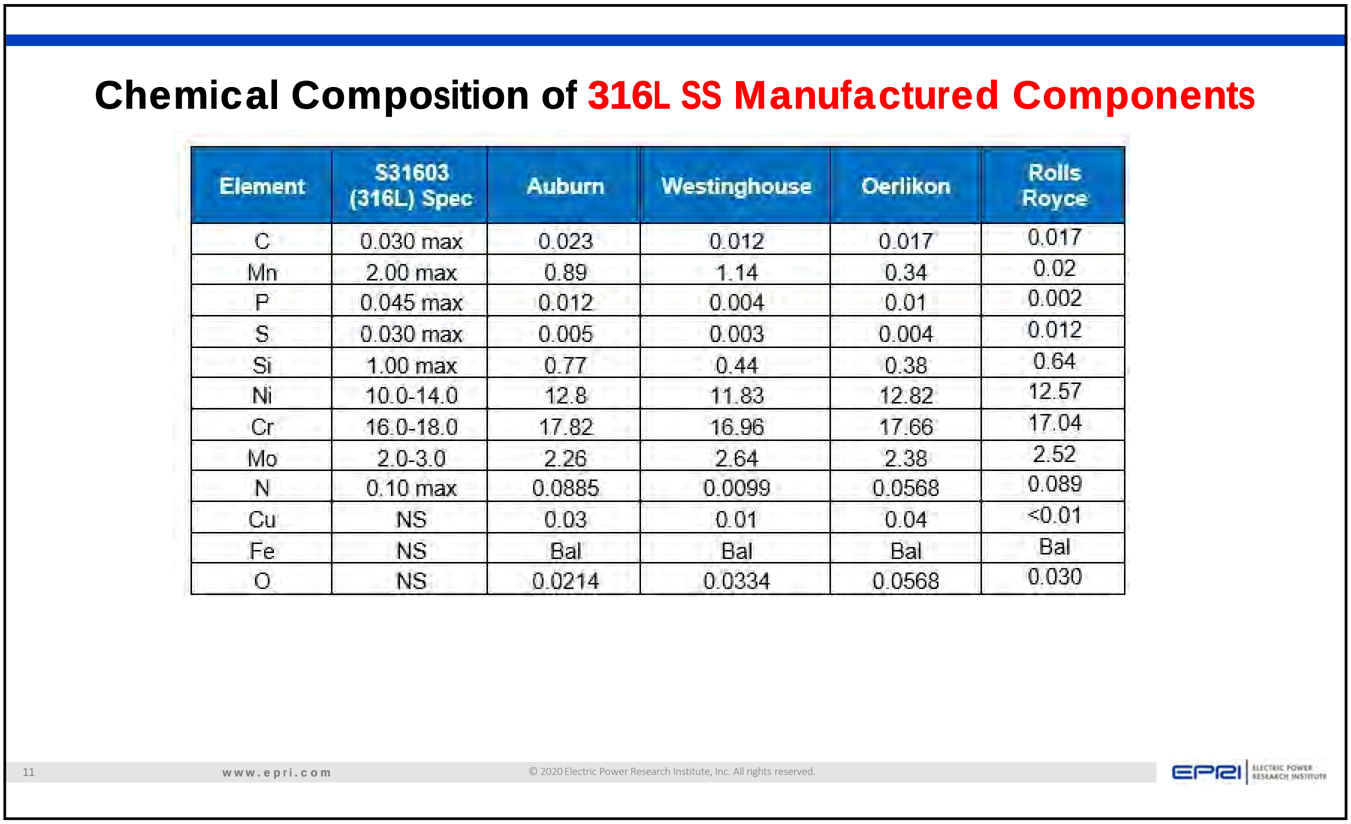
### 4.2 Solution Anneal Parameters

Two additional component builds (Oerlikon and the second Westinghouse build) were solution annealed only (no HIP applied) at 2050°F (1120°C) for 2 hours in an argon environment and quenched in water.



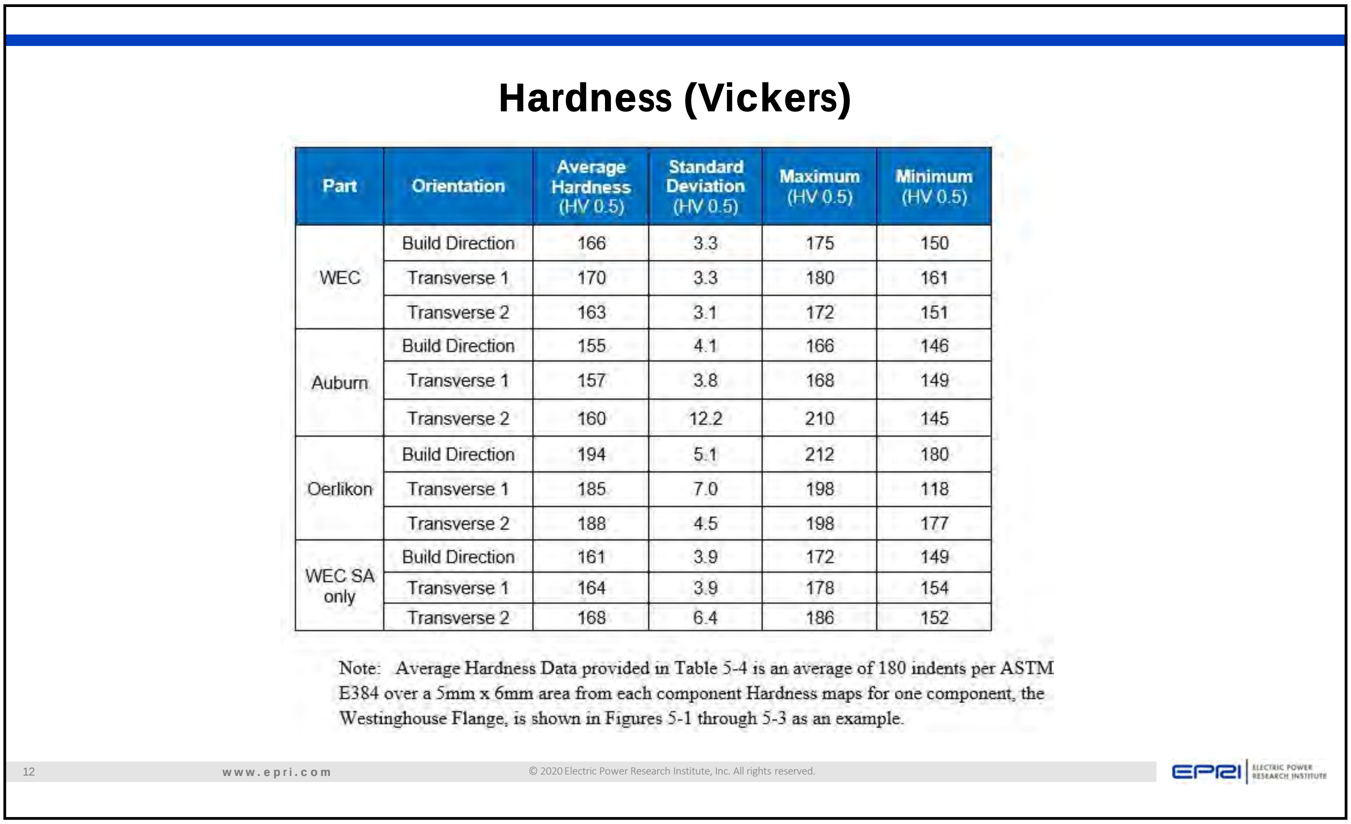
## Chemical Composition of 316L SS Powder

| Element | S31603 (316L) Spec | Auburn | Westinghouse | Oerlikon | Rolls Royce |
|---|---|---|---|---|---|
| C | 0.030 max | 0.023 | 0.012 | 0.02 | 0.02 |
| Mn | 2.00 max | 0.88 | 1.24 | 0.41 | 0.01 |
| P | 0.045 max | 0.008 | <0.005 | 0.014 | <0.01 |
| S | 0.030 max | 0.004 | 0.004 | <0.010 | 0.014 |
| Si | 1.00 max | 0.70 | 0.47 | 0.38 | 0.56 |
| Ni | 10.0-14.0 | 12.7 | 12.02 | 12.43 | 12.78 |
| Cr | 16.0-18.0 | 17.7 | 17.02 | 17.28 | 17.23 |
| Mo | 2.0-3.0 | 2.29 | 2.50 | 2.33 | 2.51 |
| N | 0.10 max | 0.10 | 0.01 | 0.08 | 0.07 |
| Cu | NS | 0.04 | 0.01 | 0.08 | NA |
| Fe | NS | Bal | Bal | Bal | Bal |
| O | NS | NR | 0.04 | 0.04 | 0.034 |
| | | | | | |
| Powder Manufacturer | --- | LPW | Praxair | Oerlikon Metco | LSN Diffusion |
| Powder Lot/Batch No. | --- | UK83448 | 22 | 471705 | 55999 |
| Powder Product Name | --- | LPW-316-AAAV | TruForm 316-3 | MetcoAdd 316L-A | F-316LNRR-ALMD |
| **AM Equipment** | --- | **Renishaw 250** | **EOS M290** | **EOS M290** | **EOS M280** |



## Chemical Composition of 316L SS Manufactured Components

| Element | S31603 (316L) Spec | Auburn | Westinghouse | Oerlikon | Rolls Royce |
|---|---|---|---|---|---|
| C | 0.030 max | 0.023 | 0.012 | 0.017 | 0.017 |
| Mn | 2.00 max | 0.89 | 1.14 | 0.34 | 0.02 |
| P | 0.045 max | 0.012 | 0.004 | 0.01 | 0.002 |
| S | 0.030 max | 0.005 | 0.003 | 0.004 | 0.012 |
| Si | 1.00 max | 0.77 | 0.44 | 0.38 | 0.64 |
| Ni | 10.0-14.0 | 12.8 | 11.83 | 12.82 | 12.57 |
| Cr | 16.0-18.0 | 17.82 | 16.96 | 17.66 | 17.04 |
| Mo | 2.0-3.0 | 2.26 | 2.64 | 2.38 | 2.52 |
| N | 0.10 max | 0.0885 | 0.0099 | 0.0568 | 0.089 |
| Cu | NS | 0.03 | 0.01 | 0.04 | <0.01 |
| Fe | NS | Bal | Bal | Bal | Bal |
| O | NS | 0.0214 | 0.0334 | 0.0568 | 0.030 |

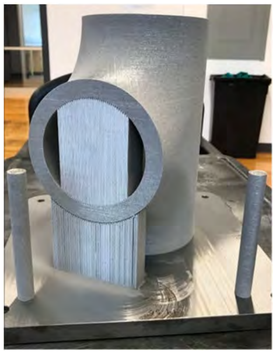


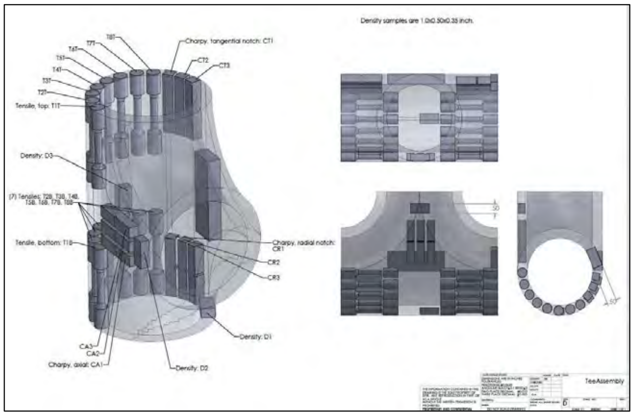
## Hardness (Vickers)

| Part | Orientation | Average Hardness (HV 0.5) | Standard Deviation (HV 0.5) | Maximum (HV 0.5) | Minimum (HV 0.5) |
|---|---|---|---|---|---|
| WEC | Build Direction | 166 | 3.3 | 175 | 150 |
| | Transverse 1 | 170 | 3.3 | 180 | 161 |
| | Transverse 2 | 163 | 3.1 | 172 | 151 |
| Auburn | Build Direction | 155 | 4.1 | 166 | 146 |
| | Transverse 1 | 157 | 3.8 | 168 | 149 |
| | Transverse 2 | 160 | 12.2 | 210 | 145 |
| Oerlikon | Build Direction | 194 | 5.1 | 212 | 180 |
| | Transverse 1 | 185 | 7.0 | 198 | 118 |
| | Transverse 2 | 188 | 4.5 | 198 | 177 |
| WEC SA only | Build Direction | 161 | 3.9 | 172 | 149 |
| | Transverse 1 | 164 | 3.9 | 178 | 154 |
| | Transverse 2 | 168 | 6.4 | 186 | 152 |

Note: Average Hardness Data provided in Table 5-4 is an average of 180 indents per ASTM E384 over a 5mm x 6mm area from each component Hardness maps for one component, the Westinghouse Flange, is shown in Figures 5-1 through 5-3 as an example.

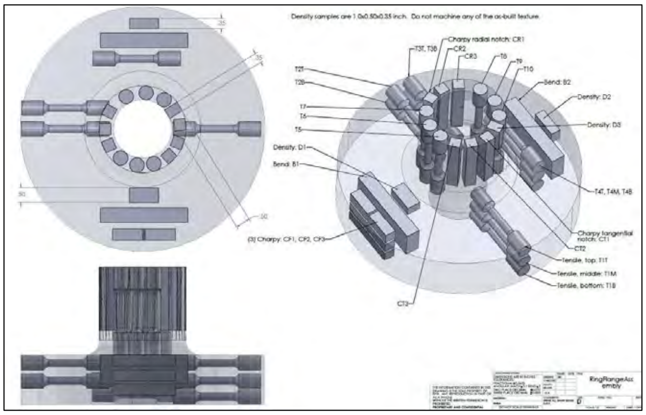
## Pipe Tee Section - Auburn U.





8-1/4”W x 4-1/8”T

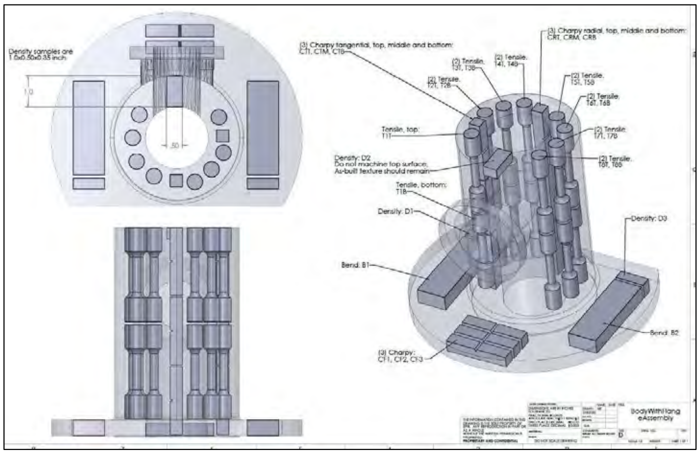
## Ring Flange End Connection - Westinghouse



8.5”Ø x 1.5”T x 2” bore

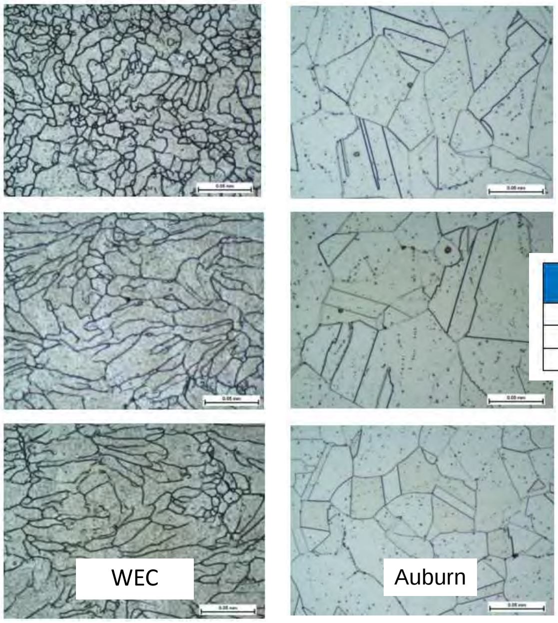
# Gate Valve Body - Oerlikon

8"Ø x 2"bore x 4"OD x ½"T



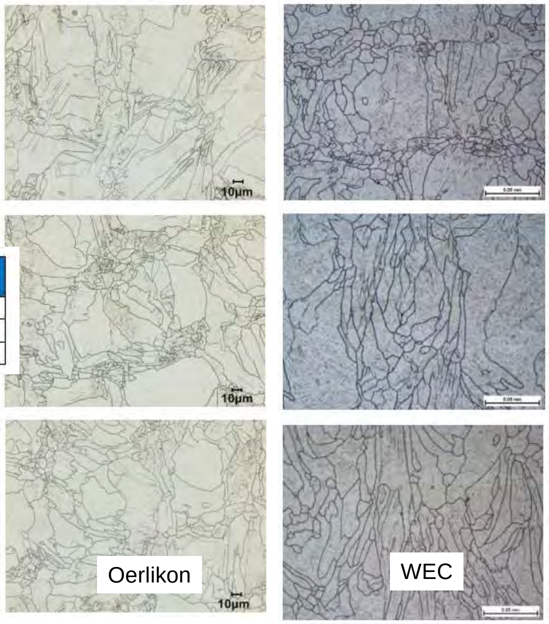
# HIP & Solution Annealed

# Solution Annealed only



| Part | Grain Size |
|---|---|
| WEC | 8 |
| Auburn | 4 |
| Oerlikon | 6.5 |

500X



# Charpy Impact Results – HIP & Solution Anneal

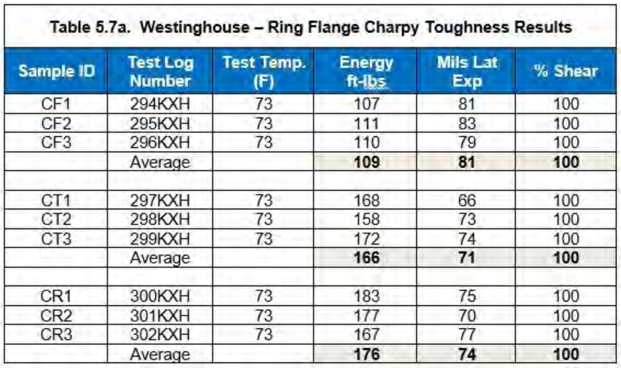


Table 5.7a. Westinghouse – Ring Flange Charpy Toughness Results

| Sample ID | Test Log Number | Test Temp. (F) | Energy ft-lbs | Mils Lat Exp | % Shear |
|---|---|---|---|---|---|
| CF1 | 294KXH | 73 | 107 | 81 | 100 |
| CF2 | 295KXH | 73 | 111 | 83 | 100 |
| CF3 | 296KXH | 73 | 110 | 79 | 100 |
| | Average | | **109** | **81** | **100** |
| | | | | | |
| CT1 | 297KXH | 73 | 168 | 66 | 100 |
| CT2 | 298KXH | 73 | 158 | 73 | 100 |
| CT3 | 299KXH | 73 | 172 | 74 | 100 |
| | Average | | **166** | **71** | **100** |
| | | | | | |
| CR1 | 300KXH | 73 | 183 | 75 | 100 |
| CR2 | 301KXH | 73 | 177 | 70 | 100 |
| CR3 | 302KXH | 73 | 167 | 77 | 100 |
| | Average | | **176** | **74** | **100** |

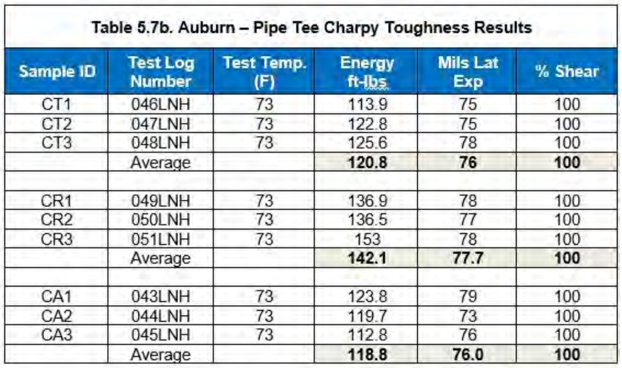


Table 5.7b. Auburn – Pipe Tee Charpy Toughness Results

| Sample ID | Test Log Number | Test Temp. (F) | Energy ft-lbs | Mils Lat Exp | % Shear |
|---|---|---|---|---|---|
| CT1 | 046LNH | 73 | 113.9 | 75 | 100 |
| CT2 | 047LNH | 73 | 122.8 | 75 | 100 |
| CT3 | 048LNH | 73 | 125.6 | 78 | 100 |
| | Average | | **120.8** | **76** | **100** |
| | | | | | |
| CR1 | 049LNH | 73 | 136.9 | 78 | 100 |
| CR2 | 050LNH | 73 | 136.5 | 77 | 100 |
| CR3 | 051LNH | 73 | 153 | 78 | 100 |
| | Average | | **142.1** | **77.7** | **100** |
| | | | | | |
| CA1 | 043LNH | 73 | 123.8 | 79 | 100 |
| CA2 | 044LNH | 73 | 119.7 | 73 | 100 |
| CA3 | 045LNH | 73 | 112.8 | 76 | 100 |
| | Average | | **118.8** | **76.0** | **100** |

# Charpy Impact Results – Solution Anneal only

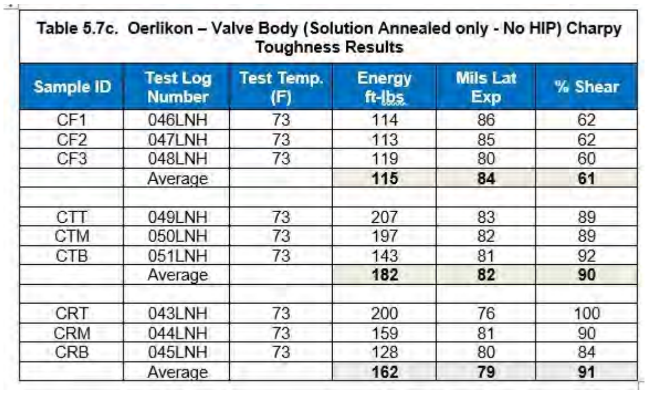


Table 5.7c. Oerlikon – Valve Body (Solution Annealed only - No HIP) Charpy Toughness Results

| Sample ID | Test Log Number | Test Temp. (F) | Energy ft-lbs | Mils Lat Exp | % Shear |
|---|---|---|---|---|---|
| CF1 | 046LNH | 73 | 114 | 86 | 62 |
| CF2 | 047LNH | 73 | 113 | 85 | 62 |
| CF3 | 048LNH | 73 | 119 | 80 | 60 |
| | Average | | **115** | **84** | **61** |
| | | | | | |
| CTT | 049LNH | 73 | 207 | 83 | 89 |
| CTM | 050LNH | 73 | 197 | 82 | 89 |
| CTB | 051LNH | 73 | 143 | 81 | 92 |
| | Average | | **182** | **82** | **90** |
| | | | | | |
| CRT | 043LNH | 73 | 200 | 76 | 100 |
| CRM | 044LNH | 73 | 159 | 81 | 90 |
| CRB | 045LNH | 73 | 128 | 80 | 84 |
| | Average | | **162** | **79** | **91** |

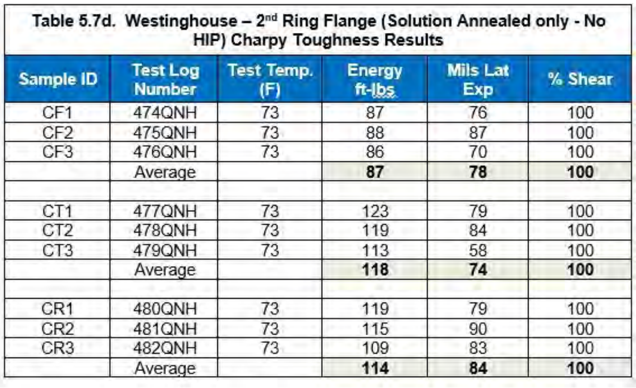


Table 5.7d. Westinghouse – 2nd Ring Flange (Solution Annealed only - No HIP) Charpy Toughness Results

| Sample ID | Test Log Number | Test Temp. (F) | Energy ft-lbs | Mils Lat Exp | % Shear |
|---|---|---|---|---|---|
| CF1 | 474QNH | 73 | 87 | 76 | 100 |
| CF2 | 475QNH | 73 | 88 | 87 | 100 |
| CF3 | 476QNH | 73 | 86 | 70 | 100 |
| | Average | | **87** | **78** | **100** |
| | | | | | |
| CT1 | 477QNH | 73 | 123 | 79 | 100 |
| CT2 | 478QNH | 73 | 119 | 84 | 100 |
| CT3 | 479QNH | 73 | 113 | 58 | 100 |
| | Average | | **118** | **74** | **100** |
| | | | | | |
| CR1 | 480QNH | 73 | 119 | 79 | 100 |
| CR2 | 481QNH | 73 | 115 | 90 | 100 |
| CR3 | 482QNH | 73 | 109 | 83 | 100 |
| | Average | | **114** | **84** | **100** |

## Tensile Properties - HIP & Solution Anneal - Westinghouse

| Sample ID | Temp. (°F) | Temp. (°C) | UTS (ksi) | UTS (MPa) | YS (ksi) | YS (MPa) | Elong. in 4D (%) | ROA (%) |
|---|---|---|---|---|---|---|---|---|
| T1T | 70 | 21.1 | 87.8 | 605.4 | 45.8 | 315.8 | 72.7 | 78 |
| T1M | 100 | 37.8 | 83.8 | 577.8 | 46.5 | 320.6 | 69.9 | 76.5 |
| T1B | 150 | 65.6 | 78.7 | 542.6 | 44.1 | 304.1 | 61.7 | 78.5 |
| T2T | 200 | 93.3 | 73.1 | 504.0 | 41.7 | 287.5 | 48.7 | 77 |
| T2M | 250 | 121.1 | 71.7 | 494.4 | 42.3 | 291.6 | 47.0 | 74.5 |
| T2B | 300 | 148.9 | 69.5 | 479.2 | 40.0 | 275.8 | 44.7 | 76.5 |
| T3T | 350 | 176.7 | 68.1 | 469.5 | 37.9 | 261.3 | 43.2 | 76.5 |
| T3B | 400 | 204.4 | 66.6 | 459.2 | 38.9 | 268.2 | 40.6 | 73 |
| T4T | 450 | 232.2 | 65.5 | 451.6 | 37.2 | 256.5 | 39.1 | 73 |
| T4B | 500 | 260.0 | 65.1 | 448.8 | 37.3 | 257.2 | 37.2 | 73.5 |
| T5 | 550 | 287.8 | 61.0 | 420.6 | 34.1 | 235.1 | 44.1 | 76 |
| T6 | 600 | 315.6 | 61.1 | 421.3 | 33.7 | 232.4 | 44.9 | 73 |
| T7 | 650 | 343.3 | 61.4 | 423.3 | 32.9 | 226.8 | 47.9 | 72 |
| T8 | 700 | 371.1 | 60.7 | 418.5 | 32.6 | 224.8 | 44.6 | 72.5 |
| T9 | 750 | 398.9 | 61.0 | 420.6 | 31.7 | 218.6 | 47.2 | 74.5 |
| T10 | 800 | 426.7 | 61.3 | 422.6 | 31.4 | 216.5 | 48.5 | 69.5 |
| **Witness Samples** | | | | | | | | |
| T11 (HIP) | 70 | 21.1 | 84.2 | 580.5 | 43.7 | 301.3 | 86.1 | 73 |
| T12 (HIP) | 70 | 21.1 | 84.1 | 579.8 | 44.7 | 308.2 | 87.3 | 79 |
| T13 (AB) | 70 | 21.1 | 87.3 | 601.9 | 63.0 | 434.4 | 76.0 | 78 |
| T14 (AB) | 70 | 21.1 | 87.3 | 601.9 | 62.9 | 433.7 | 76.5 | 78 |

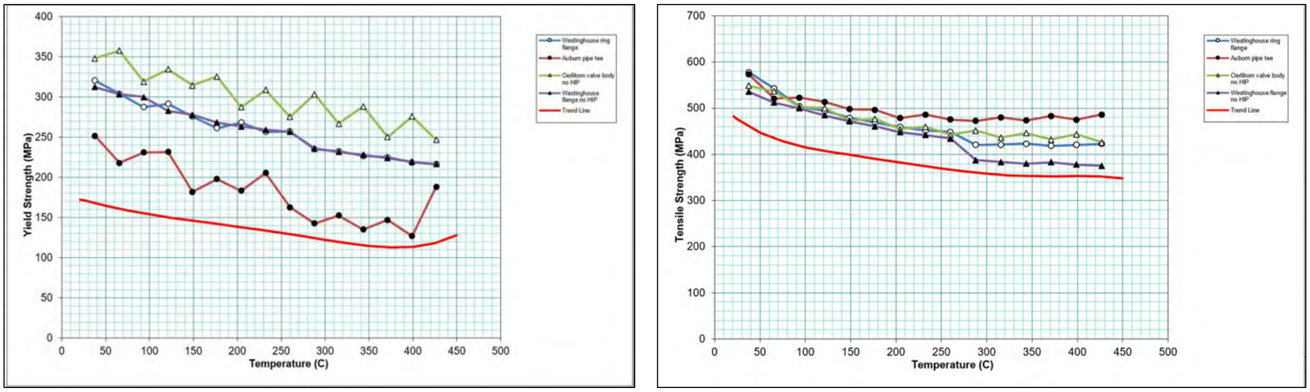
*Note: 0.252 diameter coupons per ASTM E21-17*

## Tensile Properties – Solution Anneal only - Westinghouse

| Sample ID | Temp. (°F) | Temp. (°C) | UTS (ksi) | UTS (MPa) | YS (ksi) | YS (MPa) | Elong. in 4D (%) | ROA (%) |
|---|---|---|---|---|---|---|---|---|
| T1T | 70 | 21.1 | 81.6 | 562.6 | 46.7 | 322.0 | 58 | 67 |
| T1M | 100 | 37.8 | 77.7 | 535.7 | 45.3 | 312.3 | 53 | 67.5 |
| T1B | 150 | 65.6 | 74.3 | 512.3 | 44 | 303.4 | 46 | 70.5 |
| T2T | 200 | 93.3 | 72.5 | 499.9 | 43.5 | 299.9 | 43 | 68 |
| T2M | 250 | 121.1 | 70.3 | 484.7 | 41 | 282.7 | 40 | 72 |
| T2B | 300 | 148.9 | 68.4 | 471.6 | 40.3 | 277.9 | 40 | 71 |
| T3T | 350 | 176.7 | 66.8 | 460.6 | 38.9 | 268.2 | 38 | 71.5 |
| T3B | 400 | 204.4 | 65 | 448.2 | 38.2 | 263.4 | 36 | 73 |
| T4T | 450 | 232.2 | 64.1 | 442.0 | 37.6 | 259.2 | 35 | 68 |
| T4B | 500 | 260.0 | 63 | 434.4 | 37.2 | 256.5 | 35 | 70.5 |
| T5 | 550 | 287.8 | 56.2 | 387.5 | 34.2 | 235.8 | 41 | 71 |
| T6 | 600 | 315.6 | 55.6 | 383.3 | 33.6 | 231.7 | 41 | 72.5 |
| T7 | 650 | 343.3 | 55.1 | 379.9 | 33.1 | 228.2 | 41 | 70.5 |
| T8 | 700 | 371.1 | 55.5 | 382.7 | 32.5 | 224.1 | 45 | 68.5 |
| T9 | 750 | 398.9 | 54.8 | 377.8 | 31.8 | 219.3 | 43 | 65 |
| T10 | 800 | 426.7 | 54.4 | 375.1 | 31.4 | 216.5 | 43 | 69 |
| **Witness Samples** | | | | | | | | |
| T11 (HIP) | 70 | 21.1 | 74.7 | 515.0 | 44.5 | 306.8 | 45 | 37 |
| T12 (HIP) | 70 | 21.1 | 75.5 | 520.6 | 44.3 | 305.4 | 72 | 69 |

*Note: 0.252 diameter coupons per ASTM E21-17*

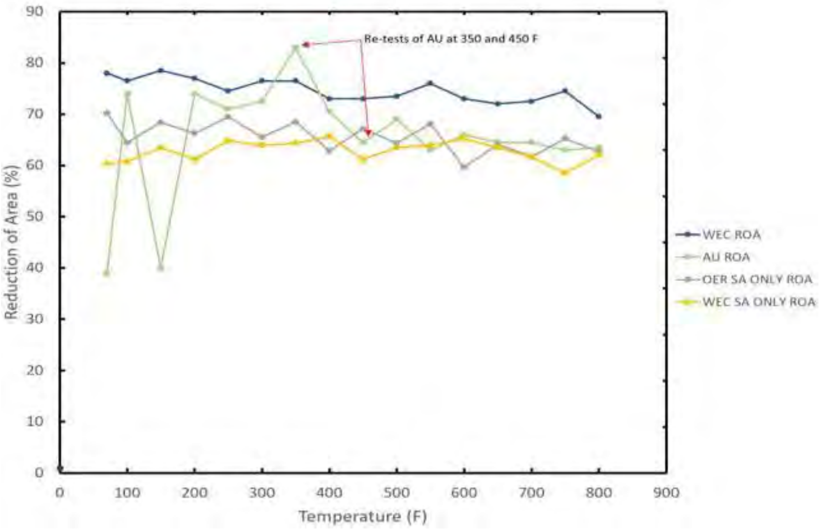
## Yield and Tensile Strength as a Function of Temperature



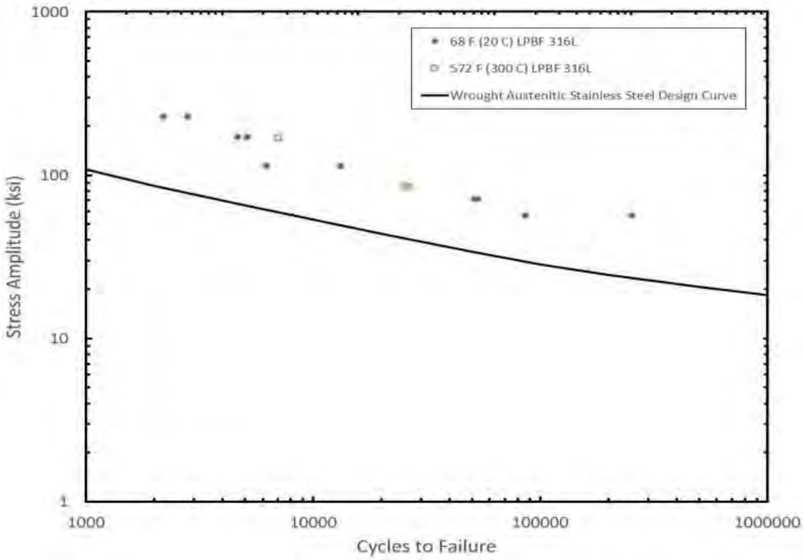
Note: Shift (lower) in Westinghouse Yield and Ultimate Strength between 260°C (500°F) and 287.8°C (550°F), is due to the transition from Z to XY direction specimens

- See slide 14 for specimen layout and slides 19 and 20 for associated tensile results

## Reduction of Area as a Function of Temperature



## Fatigue Data - HIP and Solution Anneal - Rolls Royce component build



## Summary

- Three components, 5 builds performed
- >0.50-inch thick components (for testing)
- All builds provide acceptable microstructural and mechanical properties
  - HIP and Solution annealed
  - Solution annealed only
- Good fatigue properties
- Stress allowables developed
- Weldment data to be provided shortly

## Draft ASME Section III Code Case for LPBF AM 316L

- Submitted to Section III MF&E sub-committee for August 2020 Code Week
  - Record # 20-254
  - Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components
- Standard ASME approach of calling out ASTM material / process spec and adding clarifications and additional requirements
  - ASTM F3184-16 is base spec for LPBF 316L
  - Significant clarification required due many requirements are left open to be agreed upon by the component supplier and purchaser
- Proposes use of HIP (per ASTM F3184-16 section 13, Condition C) plus Solution Anneal (per ASTM F3184-16 section 12.2, Condition B)
- For welding procedure and performance qualification, material considered P-number 8

## Draft ASME Section III Code Case for LPBF AM 316L (Cond)

- Design stress intensity values and the maximum allowable stress values are included in the code case Tables 1(1M) and 2(2M)
- Feedstock powder: Re-cert after 10 uses and max powder size of 100um
- Manufacturing plan: requiring documentation of essential process parameters
- Witness specimens, in 2 limiting locations: tensile (4x), hardnes (1x), microstructure (Z & XY, 100X & 500X), chemistry (1x, 1st and last build only)
- UT and RT per the sub-article of NB/NC/ND-2500 applicable to the product form being produced
- Components shall be pressure tested per NB-6000
- Neutron dose <7x10$^{20}$ n/cm$^{2}$ (E > 1 MeV) for design life

## Next Steps

- AM 316L Code Case Routing
  - David Gandy has been appointed project manager for the code case
  - EPRI is completing weld testing & weldment data will be added to the data package
  - The code case will go through ASME commenting, editing and balloting
  - It will likely be routed to Section II (Materials) and potentially Section IX (welding) for review
- Additional Code Cases
  - Directed energy deposition (DED) for valve production (Korean WG)
  - Westinghouse is looking to collaborate on material testing, analysis, data package consolidation and code case submittals
    - Currently producing 718 Ni Alloy, 304 SST, 17-4 PH, MS1, Haynes 230 and select high temperature alloys with LPBF
- ASME Interactions
  - AM Special Committee and Div 5 Advanced Manufacturing Task Group

## Together…Shaping the Future of Electricity

## Acknowledgements

**US Department of Energy**

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- Caitlin Hensley, UTK-ORNL
- Kevin Sisco, UTK-ORNL
- Amy Godfrey, UTK-ORNL
- Serena Beauchamp, UTK-ORNL
- Xiao Lou, Auburn University

**Industry**

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- Dane Buller, Rolls-Royce
- Thomas Jones, Rolls-Royce
- Thomas Pomorski, Penn United Technologies
- Brian Bishop, Oerlikon

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## Backup Materials:

Full Draft LPBF AM 316L Code Case Verbiage,

Fatigue Data

# DRAFT Code Case – XXXX (p.1/4)

Westinghouse

Record 20-254

**DRAFT Code Case XXXX**
**Austenitic Stainless Steel (UNS S31603)**
**Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components**

*Inquiry:* May UNS S31603 that meets the specification requirements of ASTM F3184-16 for additively manufactured stainless steel products produced using the laser powder bed fusion process, then hot isostatic pressed and solution annealed, be used for Section III, Division 1--Subsection NB/NC/ND, Class 1, 2 and 3 components construction?

*Reply:* It is the opinion of the Committee that UNS S31603 conforming to ASTM F3184-16 for additively manufactured stainless steel products produced using laser powder bed fusion, then hot isostatic pressed and solution annealed, may be used for Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 components construction provided the following additional requirements are met:

# DRAFT Code Case – XXXX, (p. 2/4)

Westinghouse

Record 20-254

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-number 8.
(b) The design stress intensity values and the maximum allowable stress values for the material shall be those given in Tables 1(1M) and 2(2M).
(c) Feedstock powder cert(s) associated to individual lots and/or powder blends will be provided for each production build. In addition to the Feedstock requirements in ASTM F3184-16 Section 7, the following requirements apply:
   a. Complete or partially used powder lots will be re-analyzed after 10 uses maximum, to ensure it conforms to the specified chemical composition, size distribution, shape, density and flow rate.
   b. The maximum allowable powder size is 100 microns or less.

# DRAFT Code Case – XXXX, (p. 3/4)

Westinghouse

Record 20-254

(d) Essential laser powder bed fusion build variables, captured within the manufacturing plan, shall include, at a minimum:
   a. Layer thickness
   b. Laser power
   c. Pulse Characteristics
   d. Pulsing
   e. Focus Settings
   f. Beam Diameter
   g. Position of Beam Diameter Relative to Feedstock Layer
   h. Energy density
   i. Effective velocity
   j. Scan strategy
   k. Stripe width
   l. Offset
   m. Hatch spacing
   n. Shielding gas composition and flow rate
   o. Recoater blade type / material

(e) All production components and witness specimens produced by the laser powder bed fusion process shall be hot isostatic pressed per the requirements of ASTM F3184-16 section 13 (Condition C), and then solution annealed per the requirements of ASTM F3184-16 Section 12.2 (Condition B).

# DRAFT Code Case – XXXX, (p. 4/4)

Westinghouse

Record 20-254

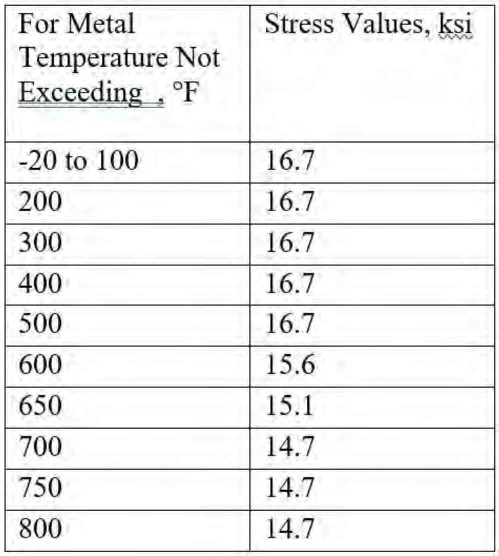
(f) Witness specimens shall be constructed with each production build and tested after all thermal post-processing.
   a. One witness specimen from the first and final production builds, for each production run, shall be analyzed for chemical composition per the requirements of ASTM F3184-16 Section 9.
   b. A minimum of 4 tensile specimens (2 built in the Z orientation, 2 built in the X-Y orientation) will be built in the 2 locations of limiting material conditions, and tested per the requirements of ASTM F3184-16 Section 11.
      i. Locations of limiting material conditions shall be identified during machine and/or process qualification builds (supplemental requirement to ASTM F3184-16 Section 6.1.1 and Note 3)
   c. Hardness testing shall be completed on one witness specimen per the requirements of ASTM F3184-16 Supplemental Requirement S4.
   d. Microstructure examination shall be completed on one witness specimen.
      i. 100X and 500X micrographs will be supplied for the Z and X-Y build orientations.
      ii. Per ASTM F3184-16 Section 10, Specimen preparation shall be in accordance with ASTM Guide E3 and Practice E407.

(g) The material shall be examined using either the ultrasonic method or radiographic method per the Sub-article of NB/NC/ND-2500 applicable to the product form being produced.

(h) All production components shall be pressure tested per NB-6000 requirements.

(i) The material shall not be used for components where neutron dose will exceed $7x10^{20}$ n/cm$^2$ (E > 1 Mev) within the design life of the component.

High values (Sect III)

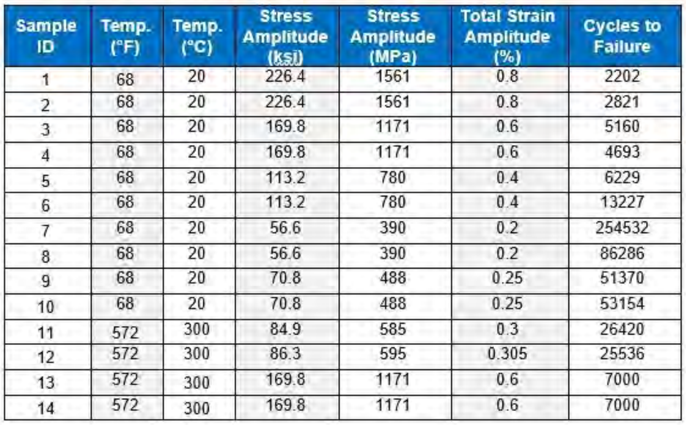


| For Metal Temperature Not Exceeding , °F | Stress Values, ksi |
|---|---|
| -20 to 100 | 16.7 |
| 200 | 16.7 |
| 300 | 16.7 |
| 400 | 16.7 |
| 500 | 16.7 |
| 600 | 15.6 |
| 650 | 15.1 |
| 700 | 14.7 |
| 750 | 14.7 |
| 800 | 14.7 |

---

# Extra -- Fatigue Data

**Table 7-1. Fatigue Data for Rolls Royce Tee**



| Sample ID | Temp. (°F) | Temp. (°C) | Stress Amplitude (ksi) | Stress Amplitude (MPa) | Total Strain Amplitude (%) | Cycles to Failure |
|---|---|---|---|---|---|---|
| 1 | 68 | 20 | 226.4 | 1561 | 0.8 | 2202 |
| 2 | 68 | 20 | 226.4 | 1561 | 0.8 | 2821 |
| 3 | 68 | 20 | 169.8 | 1171 | 0.6 | 5160 |
| 4 | 68 | 20 | 169.8 | 1171 | 0.6 | 4693 |
| 5 | 68 | 20 | 113.2 | 780 | 0.4 | 6229 |
| 6 | 68 | 20 | 113.2 | 780 | 0.4 | 13227 |
| 7 | 68 | 20 | 56.6 | 390 | 0.2 | 254532 |
| 8 | 68 | 20 | 56.6 | 390 | 0.2 | 86286 |
| 9 | 68 | 20 | 70.8 | 488 | 0.25 | 51370 |
| 10 | 68 | 20 | 70.8 | 488 | 0.25 | 53154 |
| 11 | 572 | 300 | 84.9 | 585 | 0.3 | 26420 |
| 12 | 572 | 300 | 86.3 | 595 | 0.305 | 25536 |
| 13 | 572 | 300 | 169.8 | 1171 | 0.6 | 7000 |
| 14 | 572 | 300 | 169.8 | 1171 | 0.6 | 7000 |

*Note: Per ASTM E606—19e1*

# Certification of the First Powder Bed Fusion Component in the US Naval Nuclear Propulsion Plant

**Tressa White, James Carter[1], Steven Attanasio,**
**Chelsea Snyder, William DePoppe, James Eliou**
Naval Nuclear Laboratory
[1]Huntington Ingalls Industries, Standard Navy Valve Yard

Tressa.White@unnpp.gov
(518) 395-7925

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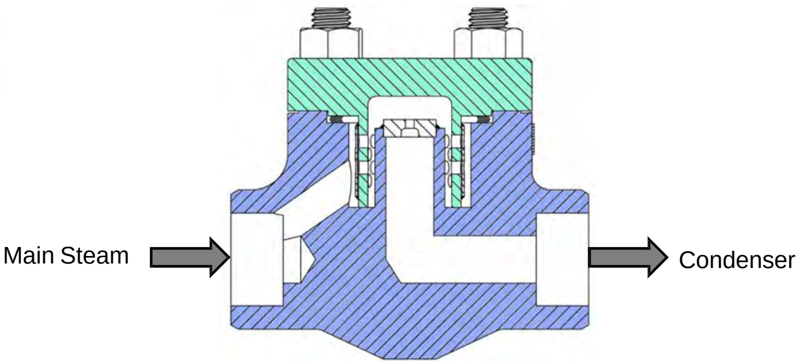
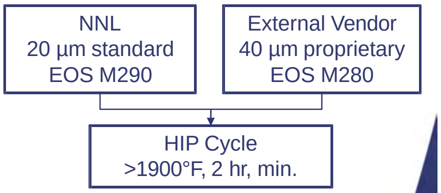
# Purpose

- First attempt to make AM hardware suitable as a pressure boundary component for submarine propulsion plant operation.
- Step through manufacturing and inspections to identify administrative or technical roadblocks.
- Familiarize designers, pressure equipment safety, and quality groups with new material form.



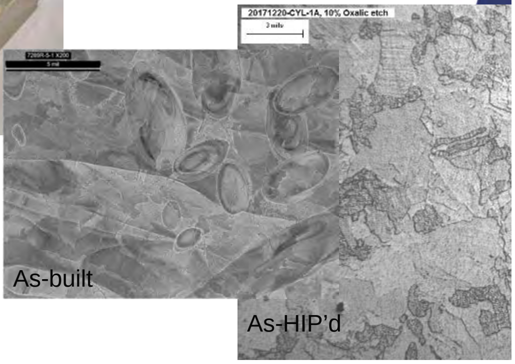
## 316L Material Processing



NNL
20 µm standard
EOS M290

External Vendor
40 µm proprietary
EOS M280

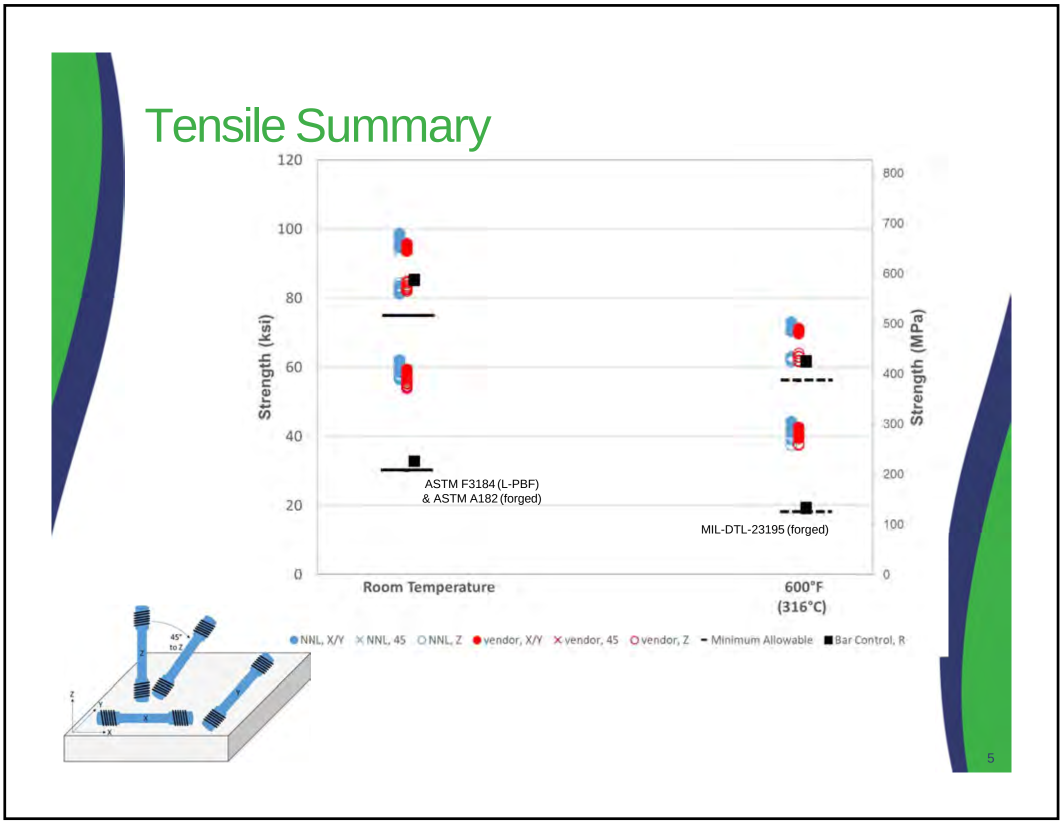
HIP Cycle
>1900°F, 2 hr, min.



## Acceptance Testing

- Geometric equivalence
- ASTM A182 strength, ductility, composition, and intergranular attack resistance
- Density
- Fatigue Crack Growth Rate Screening
- Charpy & Fracture Toughness Screening
- Weldability
- Hydrostatic Test
- Shock & Vibration Test
- Prototypic Steam Test

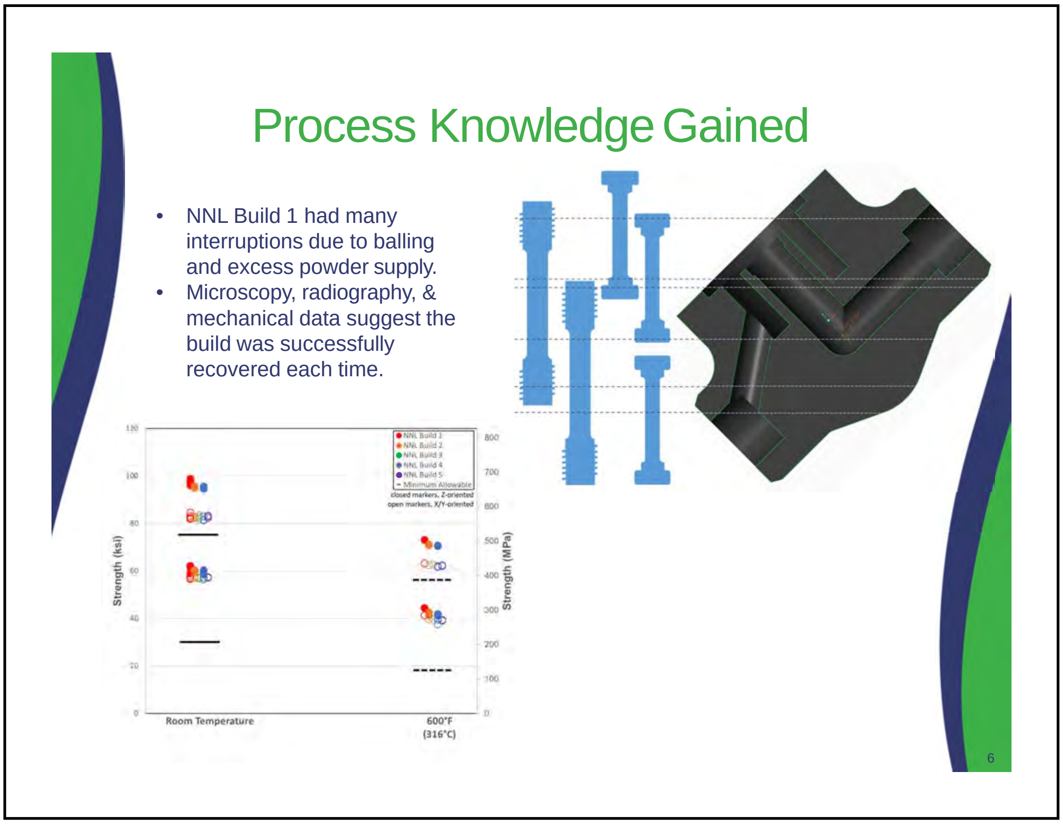
Certification testing happened in parallel with a large materials development program.



## Tensile Summary

ASTM F3184 (L-PBF)
& ASTM A182 (forged)

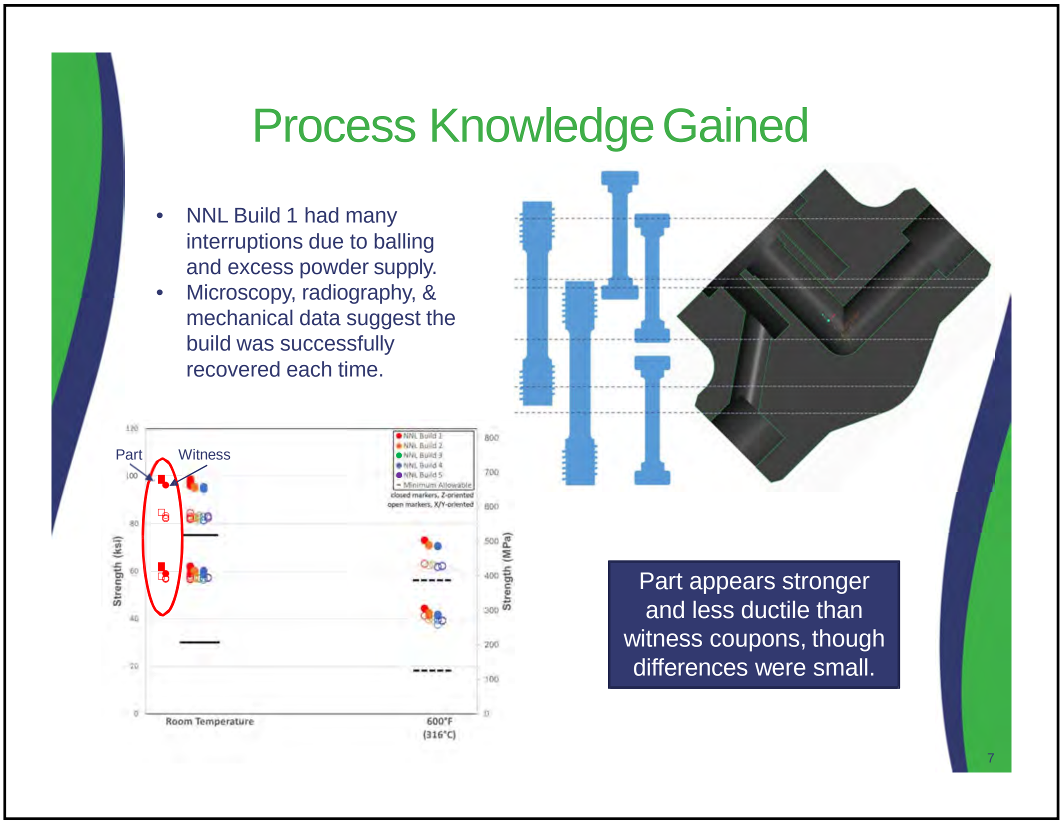
MIL-DTL-23195 (forged)



## Process Knowledge Gained

- NNL Build 1 had many interruptions due to balling and excess powder supply.
- Microscopy, radiography, & mechanical data suggest the build was successfully recovered each time.

closed markers, Z-oriented
open markers, X/Y-oriented

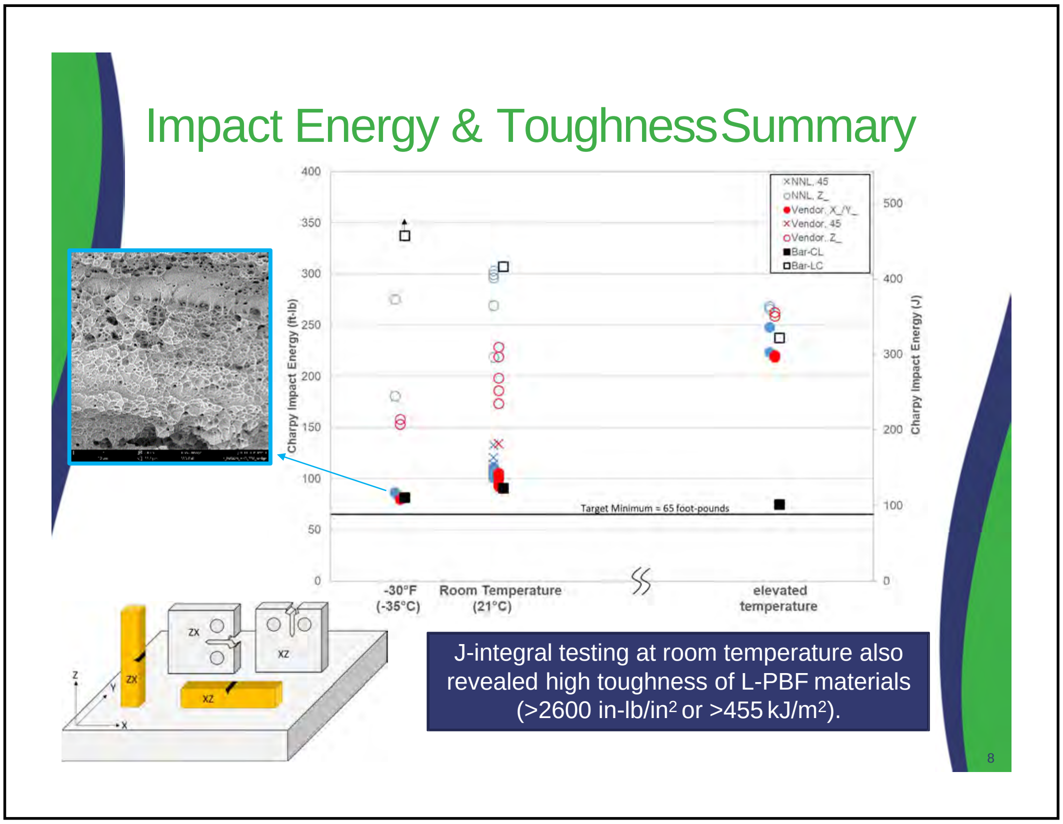


# Process Knowledge Gained

- NNL Build 1 had many interruptions due to balling and excess powder supply.
- Microscopy, radiography, & mechanical data suggest the build was successfully recovered each time.

Part appears stronger and less ductile than witness coupons, though differences were small.

7

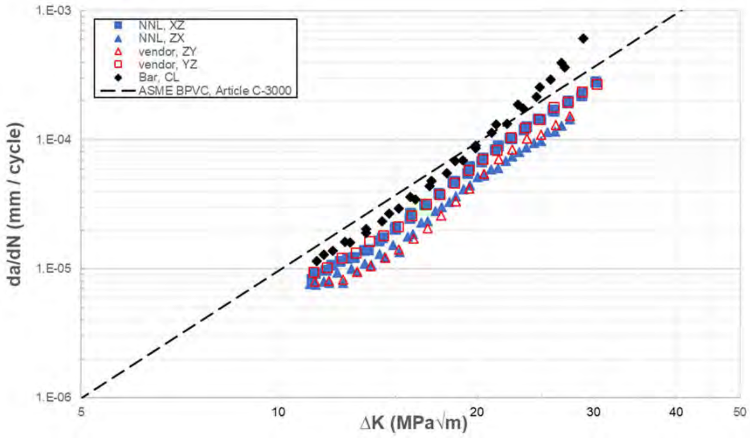


# Impact Energy & Toughness Summary

J-integral testing at room temperature also revealed high toughness of L-PBF materials (>2600 in-lb/in² or >455 kJ/m²).

8

## Fatigue Crack Growth at elevated temp.

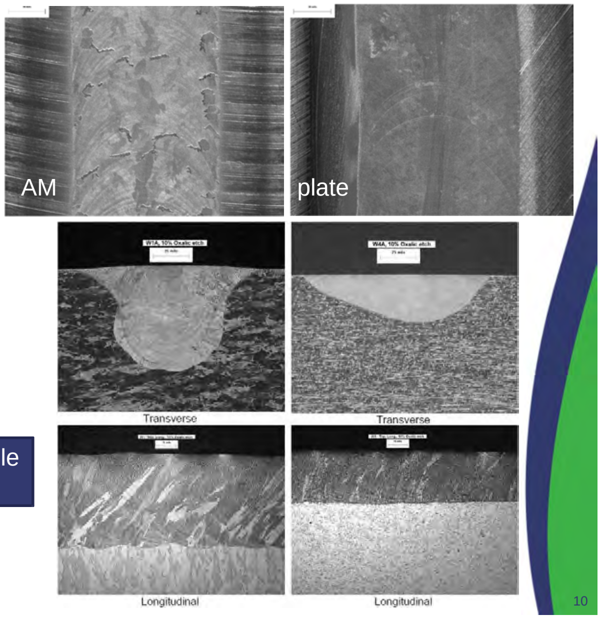


## AM Weldability Trial: autogenous GTA

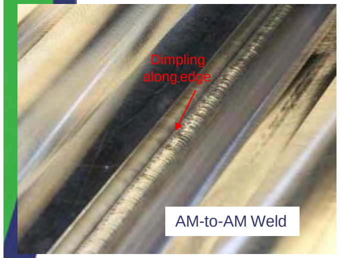
Bead on plate at same conditions

Increased penetration in AM material, likely due to increased O content (540ppm vs. <10ppm)

Autogenous welding acceptable for strainer assembly.

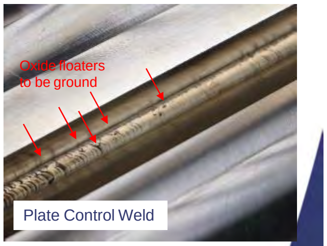


# AM Weldability Trial: wire-fed GTA

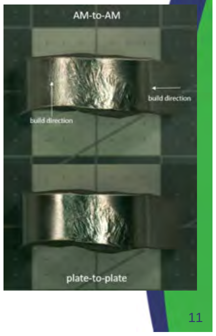


8” long butt joints using AWS-ER316L wire

Welded in accordance with NAVSEA procedure



| | AM (vert) to AM (horiz) | AM (horiz) to plate | AM (vert) to plate | Plate to plate |
|---|---|---|---|---|
| Weldable? | none | | | |
| Radiography & Penetrant Indications? | none | | | |
| Tensile Strength<br>--failure location | 81 & 81 ksi<br>(558 MPa)<br>AM (vert) | 90 & 92 ksi<br>(621 & 634 MPa)<br>Weld | 83 & 83 ksi<br>(573 MPa)<br>AM (vert) | 92 & 93 ksi<br>(634 & 641 MPa)<br>Weld |
| 20% Bend | no defects | | | |
| Charpy HAZ | > 100 ft-lbs (>136 J) propagation along epitaxy<br>>150 ft-lbs (>203 J) propagation across epitaxy | | | > 150 ft-lbs |



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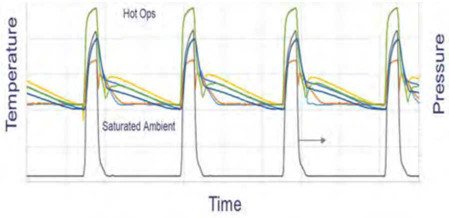
# Component Testing

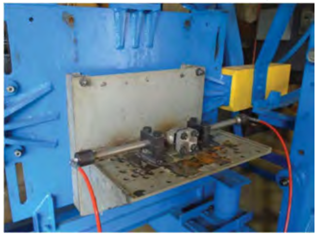
## Prototypic Steam

Simulate 1000’s of start-up / shutdown cycles and 100’s of hot operational hours. Parts did not exhibit cracking or erosion.



## Shock & Vibration

Expose DSOs to typical fleet shock loads and worst case vibration frequencies while pressurized. Parts did not leak and were not damaged.



## Proof Test

Pressurized to >4.5 times the ASME Group 2.2 maximum allowable working pressure (2160 psig) before leaking at gasket.

# Summary

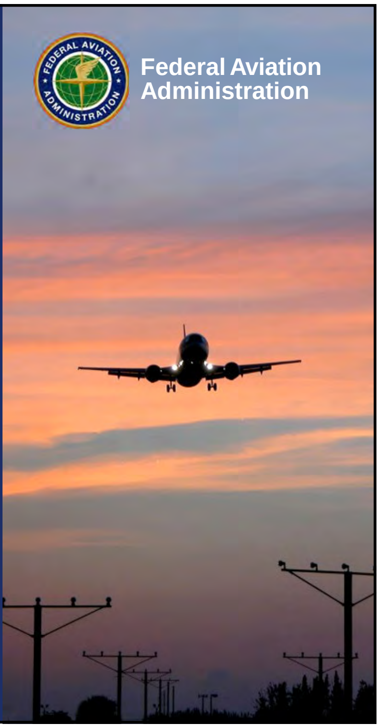
- A focused, case-basis certification plan and final data package was approved by NAVSEA.

Approved in August.
Installed in September.
Steaming in October.

- Subsequently ran a multi-site Design Challenge to encourage adoption by design engineers.

# On the Development of Fatigue and Damage Tolerance Framework for *Metal* AM Parts

Federal Aviation Administration



***Presented at:***

**NRC Workshop on Advanced Manufacturing Technologies – *Session 4***

*December 9, 2020*

**Presented by:**

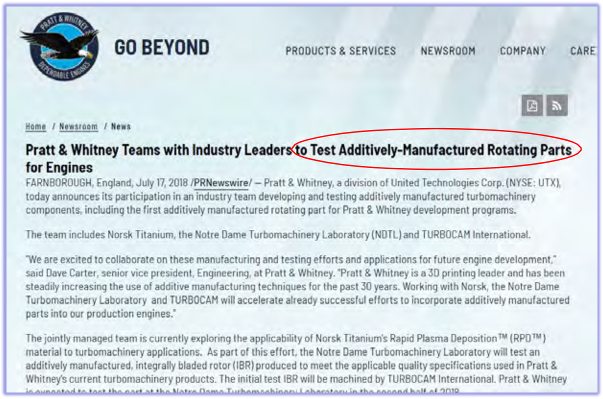
***Dr. Michael Gorelik***

FAA Chief Scientist and Technical Advisor
*for Fatigue and Damage Tolerance*

## BLUF *(bottom line upfront)*

- **All the existing rules apply to AM**
- **Need to consider unique / AM-specific attributes, especially for high-criticality components**
- **Leverage industry and regulatory experience with other relevant material systems**
  - ***More on this topic in Dec. 10th presentation***
- **Leverage public standards**

# ***Example***: Moving Towards Safety-critical AM Parts



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**Pratt & Whitney Teams with Industry Leaders to Test Additively-Manufactured Rotating Parts for Engines**

FARNBOROUGH, England, July 17, 2018 /PRNewswire/ -- Pratt & Whitney, a division of United Technologies Corp. (NYSE: UTX), today announces its participation in an industry team developing and testing additively manufactured turbomachinery components, including the first additively manufactured rotating part for Pratt & Whitney development programs.

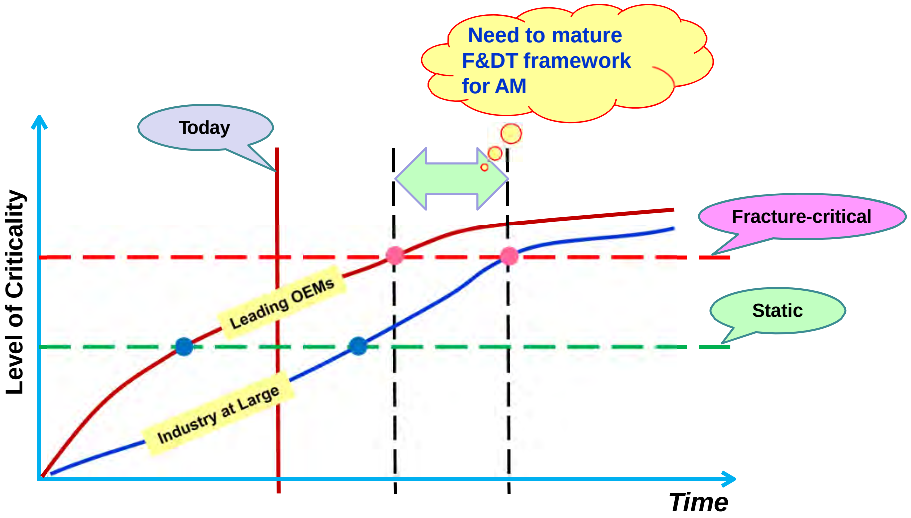
The team includes Norsk Titanium, the Notre Dame Turbomachinery Laboratory (NDTL) and TURBOCAM International.

"We are excited to collaborate on these manufacturing and testing efforts and applications for future engine development," said Dave Carter, senior vice president, Engineering, at Pratt & Whitney. "Pratt & Whitney is a 3D printing leader and has been steadily increasing the use of additive manufacturing techniques for the past 30 years. Working with Norsk, the Notre Dame Turbomachinery Laboratory and TURBOCAM will accelerate already successful efforts to incorporate additively manufactured parts into our production engines."

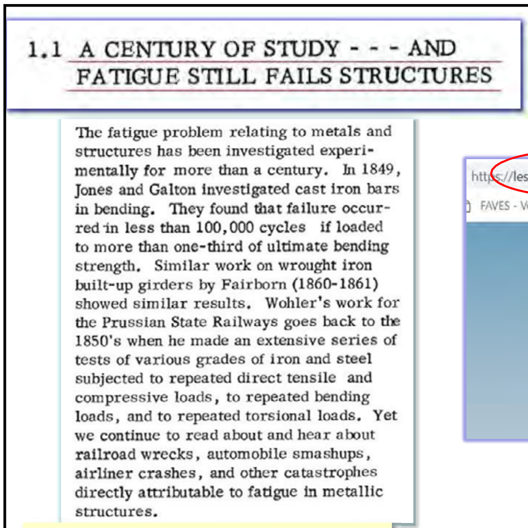
The jointly managed team is currently exploring the applicability of Norsk Titanium's Rapid Plasma Deposition™ (RPD™) material to turbomachinery applications. As part of this effort, the Notre Dame Turbomachinery Laboratory will test an additively manufactured, integrally bladed rotor (IBR) produced to meet the applicable quality specifications used in Pratt & Whitney's current turbomachinery products. The initial test IBR will be machined by TURBOCAM International. Pratt & Whitney

Federal Aviation Administration

# State of Industry



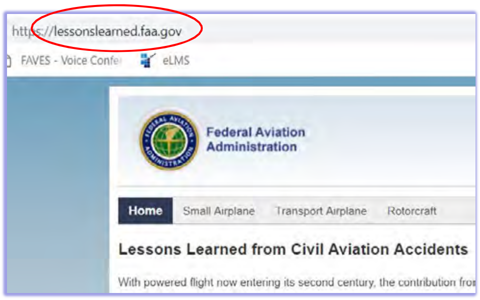
Federal Aviation Administration



### 1.1 A CENTURY OF STUDY - - - AND FATIGUE STILL FAILS STRUCTURES

The fatigue problem relating to metals and structures has been investigated experimentally for more than a century. In 1849, Jones and Galton investigated cast iron bars in bending. They found that failure occurred in less than 100,000 cycles if loaded to more than one-third of ultimate bending strength. Similar work on wrought iron built-up girders by Fairborn (1860-1861) showed similar results. Wohler's work for the Prussian State Railways goes back to the 1850's when he made an extensive series of tests of various grades of iron and steel subjected to repeated direct tensile and compressive loads, to repeated bending loads, and to repeated torsional loads. Yet we continue to read about and hear about railroad wrecks, automobile smashups, airliner crashes, and other catastrophes directly attributable to fatigue in metallic structures.

*C. R. Smith, "Tips on Fatigue", Dept. of the Navy,* **1963**



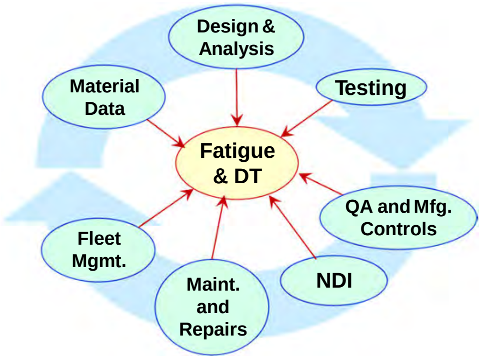
https://lessonslearned.faa.gov

Lessons Learned from Civil Aviation Accidents

With powered flight now entering its second century, the contribution fro

**How can we leverage this experience for AM?**

# System-Level View of F&DT Discipline



**All elements of the system are essential to ensure safety …**

## Two Types of Anomalies

*that may result in life debit*

**Rogue (rare) Anomalies**

*Examples:*

- Melt-related defects (hard alpha) in Ti
- Machining induced

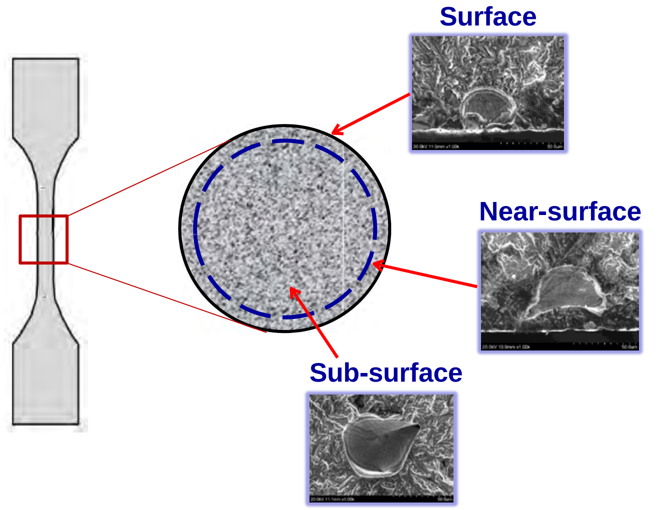
**Inherent Anomalies**

*Examples:*

- Porosity in castings
- NMEs (non-metallic inclusions) in PM alloys

*Surface vs. Volume*

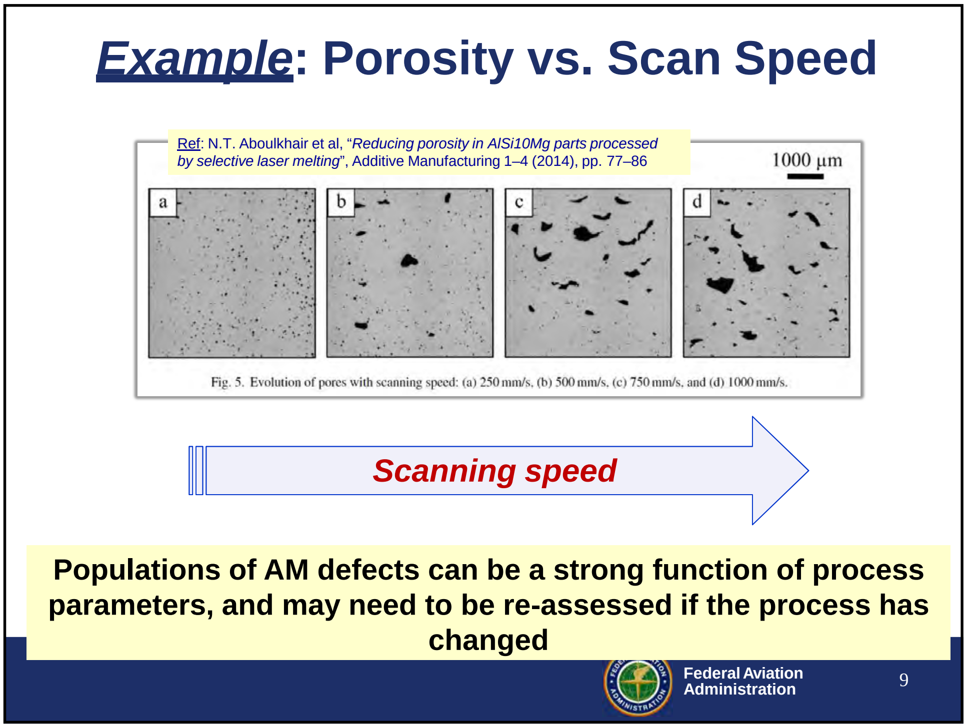
## Categories of Anomalies by Location



**Considerations**

- Crack initiation vs. propagation
- Defect types
- NDI detectability
- Size distribution
- Frequency of occurrence
- Effect of post-processing
- *Near-surface scan pattern (for PBF)*

Photo credits: S. Jha et al, "*Fatigue Life Prediction OF Additively Manufactured Ti-6Al-4V*", MS&T 2019, Portland, OR.



# *Example*: Porosity vs. Scan Speed

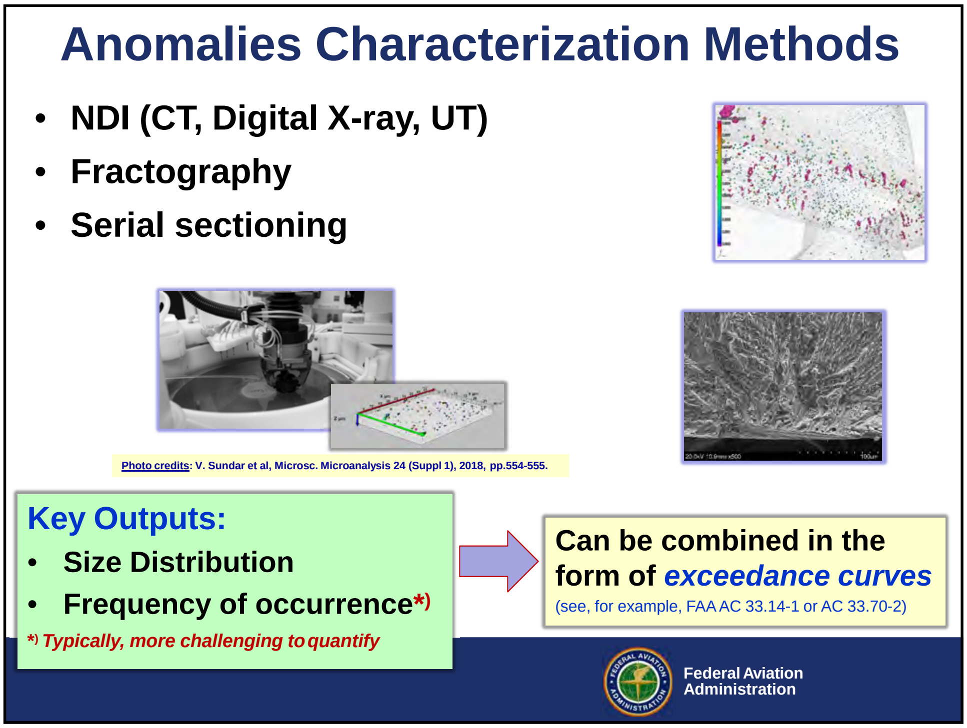
Ref: N.T. Aboulkhair et al, "*Reducing porosity in AlSi10Mg parts processed by selective laser melting*", Additive Manufacturing 1–4 (2014), pp. 77–86

Fig. 5. Evolution of pores with scanning speed: (a) 250 mm/s, (b) 500 mm/s, (c) 750 mm/s, and (d) 1000 mm/s.

***Scanning speed***

**Populations of AM defects can be a strong function of process parameters, and may need to be re-assessed if the process has changed**

Federal Aviation Administration



# Anomalies Characterization Methods

- **NDI (CT, Digital X-ray, UT)**
- **Fractography**
- **Serial sectioning**

Photo credits: V. Sundar et al, Microsc. Microanalysis 24 (Suppl 1), 2018, pp.554-555.

**Key Outputs:**

- **Size Distribution**
- **Frequency of occurrence*)**

*) *Typically, more challenging to quantify*

**Can be combined in the form of *exceedance curves***

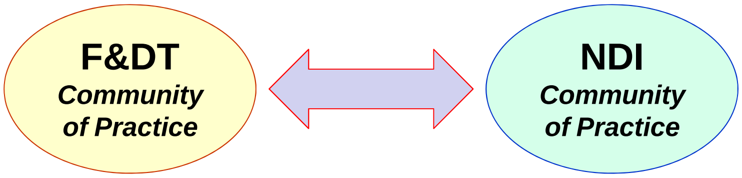
(see, for example, FAA AC 33.14-1 or AC 33.70-2)

Federal Aviation Administration

# NDI Considerations for AM

- **Current lack of validated and quantified NDI capabilities for flaw detection in metal AM parts**
- **Effective two-way dialogue is needed between the NDI and F&DT (fatigue and damage tolerance) communities of practice**

➢ **Focus on the largest flaw that can be missed, not the smallest flaw that can be found…**



**F&DT**
***Community of Practice***

**NDI**
***Community of Practice***

- **What types of defects need to be detected?**
- **What is the range of defect sizes that need to be *reliably* detected?**

- **What are the *quantifiable* detection capabilities for a given class of defects (QNDI)?**

---

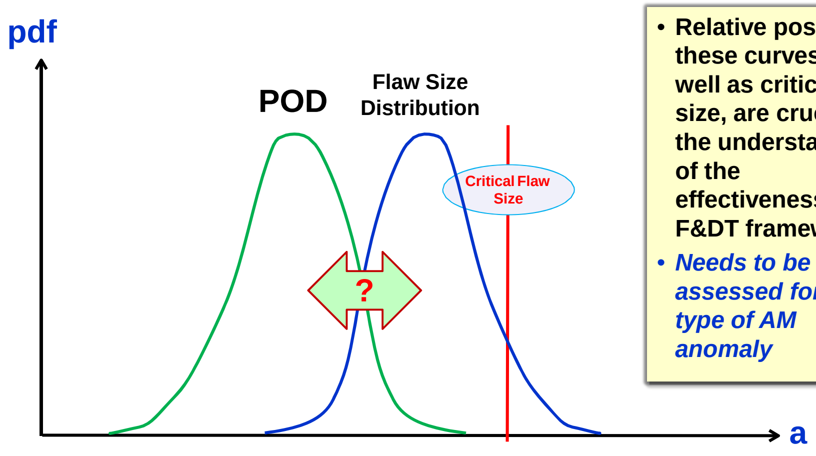
# Example: Cross-Committee Collaboration *(SDO-level)*

Committee E08 on Fatigue and Fracture

Committee E07 on Nondestructive Testing

Committee F42 on Additive Manufacturing Technologies

# Detection Capability vs. Flaw Size Distribution



- Relative position of these curves, as well as critical flaw size, are crucial to the understanding of the effectiveness of F&DT framework
- ***Needs to be assessed for each type of AM anomaly***

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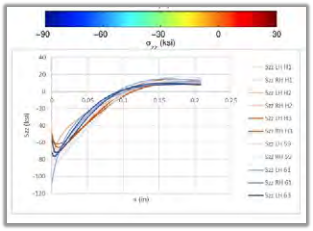
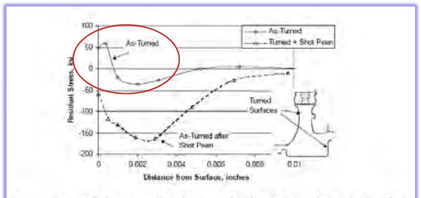
# Residual Stress (RS) Considerations

**Measurement / modeling capabilities for beneficial *engineered residual stresses* continue to advance**



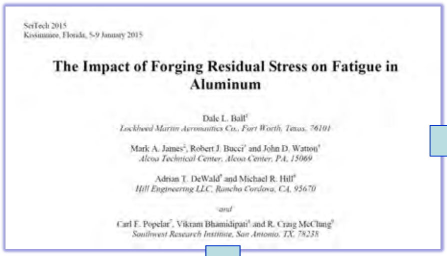
**Unfavorable residual stresses *resulting from manufacturing process* may significantly reduce component's safe life (by 10x or more), as well as DT capabilities**



Near surface residual stress gradient for a turned surface before and after shot peening.

**Existing F&DT assessment tools can largely account for the presence of residual stresses**

# *Example*: RS in Aluminum Forgings



SciTech 2015
Kissimmee, Florida, 5-9 January 2015

**The Impact of Forging Residual Stress on Fatigue in Aluminum**

Dale L. Ball[1]
*Lockheed Martin Aeronautics Co., Fort Worth, Texas, 76101*

Mark A. James[2], Robert J. Bucci[3] and John D. Watton[4]
*Alcoa Technical Center, Alcoa Center, PA, 15069*

Adrian T. DeWald[5] and Michael R. Hill[6]
*Hill Engineering LLC, Rancho Cordova, CA, 95670*

*and*

Carl F. Popelar[7], Vikram Bhamidipati[8] and R. Craig McClung[9]
*Southwest Research Institute, San Antonio, TX, 78238*

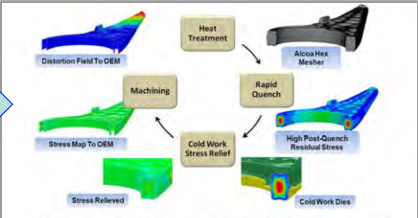
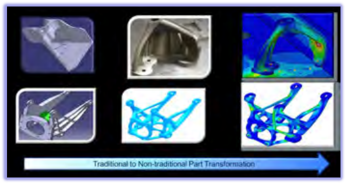


**Figure 1. Alcoa's forging process model: 1) solution heat treatment, 2) quench, 3) cold work stress relief, and 4) machining. The capability includes material models for 7050 and 7085, Watton[11].**

**"…the detrimental effects of tensile RS can be mitigated and/or managed during design by establishing and imposing appropriate requirements for their location, spatial distribution and magnitude, and for the inclusion of their effects during design structural analyses."**

# *Example* - "Smarter Testing" (BCA)

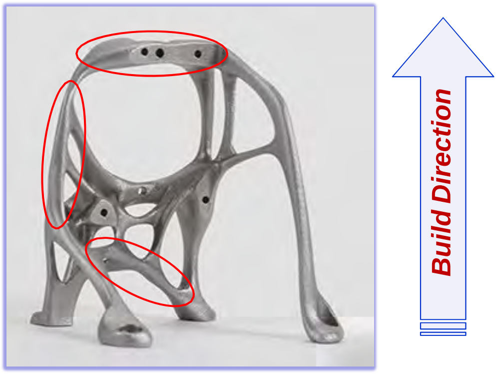
**"Use of advanced analysis techniques using fundamental (coupon-derived) inputs can lead to reduced quantities of program-led mid-level structural tests, reducing airplane development costs and risks".**



**"…AM presents new challenges for certification in that there are no traditional validated analysis methods suited to the arbitrary and organic nature of many AM parts…"**

**Credits**: S. Chisholm et al, "*Smarter Testing Through Simulation for Efficient Design and Attainment of Regulatory Compliance*", Boeing, Presented at 30th ICAF Symposium – Kraków, 5 – 7 June 2019.

## ***Example***: Location-Specific Properties



**Each area encircled in red has a different orientation with respect to the build direction, and thus *may* have different local properties**

## Part Zoning Considerations for AM

- **Many Interpretations exist…**
- **Zones can be defined based on:**
  - **Criticality of failure mode, inspectability, population of defect species, design "margin", microstructure, residual stress, etc.**
  - ***Somewhat similar to zoning of structural castings***
- **Level of analysis for each zone may vary from simplified / conservative (e.g. safety factors) approach to more accurate / less conservative (e.g. probabilistic DT) assessment for higher criticality parts / zones**
- **Two main attributes of the proposed approach:**
  - ➢ **Flexibility (only use necessary level of complexity)**
  - ➢ **Ability of perform *quantitative assessment* (when needed)**

## *Example*: “Smarter Testing” (BCA) – *cont.*

- **“…Fatigue and damage tolerance considerations currently pose significant challenges to the use of AM parts on airplane structures”.**
- **“The presence of *inherent material defects* randomly distributed throughout the volume, which may be *below the threshold of detectability*, means that due consideration has to be given to size effects and the *possibility of cracks not always nucleating where they would ordinarily be expected*…”**
- **“The solution to these challenges for AM structural applications may lie in the *application of probabilistic fatigue analysis methods*…”**

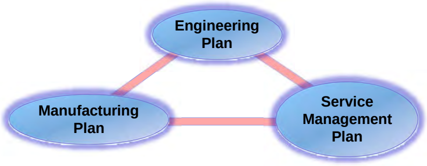
**Credits**: S. Chisholm et al, “*Smarter Testing Through Simulation for Efficient Design and Attainment of Regulatory Compliance*”, Boeing, Presented at 30th ICAF Symposium – Kraków, 5 – 7 June 2019.

## Excerpts from 14 CFR 33.70

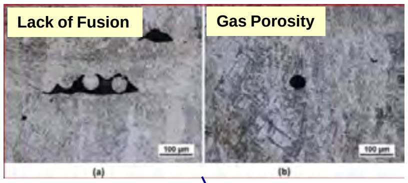
- **WHY: Industry data has shown that manufacturing-induced anomalies have caused about 40% of rotor cracking and failure events**
- **WHAT: 33.70 rule requires applicants to develop coordinated engineering, manufacturing, and service management plans for each life-limited part**
  - This will ensure the attributes of a part that determine its life are identified and controlled so that the part will be consistently manufactured and properly maintained during service operation

**“The *probabilistic approach to damage tolerance* assessment is one of two elements necessary to appropriately assess damage tolerance”.**

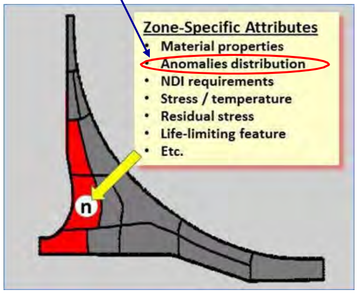
***AC 33.70-1, GUIDANCE MATERIAL FOR AIRCRAFT ENGINE LIFE-LIMITED PARTS REQUIREMENTS, 7/31/2009.***



# AM Part Zoning and Probabilistic DT



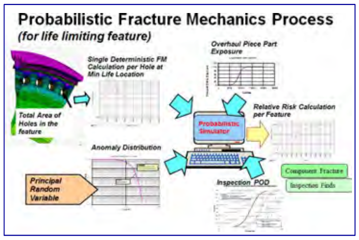
- AM parts are uniquely suited for *zone-based evaluation*
- Concept is similar to zoning considerations for castings…
- … however, modeling represents a viable *alternative to empirical* "casting factors"



**Zone-Specific Attributes**

- Material properties
- Anomalies distribution
- NDI requirements
- Stress / temperature
- Residual stress
- Life-limiting feature
- Etc.

### *One Assessment Option – PFM *)*



*) PFM - Probabilistic Fracture Mechanics

**Reference**: M. Gorelik, "Additive Manufacturing in the Context of Structural Integrity", International Journal of Fatigue 94 (2017), pp. 168–177.

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# Increasing Recognition of the Probabilistic DT for AM…

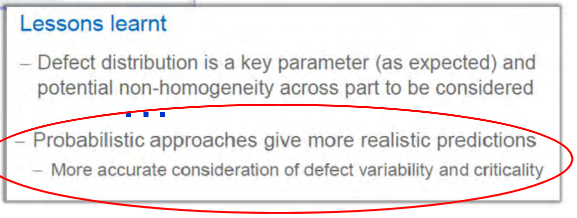
ASTM INTERNATIONAL
Helping our world work better

Effect of defects on Additive Manufacturing fatigue
Application of probabilistic approaches

J. Mardaras, P. Caracciolo, A. Santgerma, J. Van-Doeselaar
October 7-10, 2019
Gaylord National Resort and Convention Center

AIRBUS

www.amcoe.org



Lessons learnt

- Defect distribution is a key parameter (as expected) and potential non-homogeneity across part to be considered

…

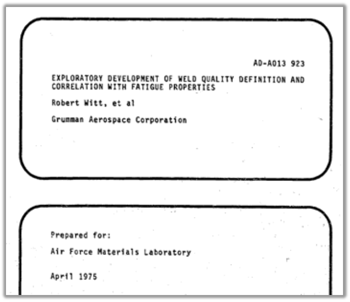
- Probabilistic approaches give more realistic predictions
  - More accurate consideration of defect variability and criticality

# “Special Topics”

- Seeded defects studies
- Bi-modal fatigue distributions in AM

---

# ***Example***: “Seeded” Defects Study in Weldments *(circa 1975)*



AD-A013 923

EXPLORATORY DEVELOPMENT OF WELD QUALITY DEFINITION AND CORRELATION WITH FATIGUE PROPERTIES

Robert Witt, et al

Grumman Aerospace Corporation

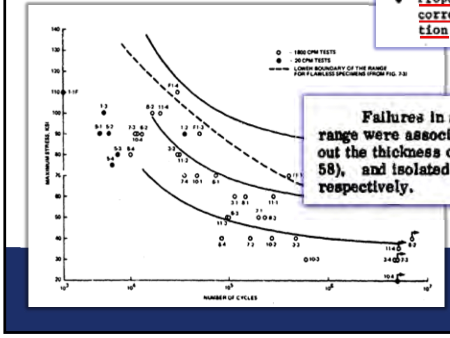
Prepared for:

Air Force Materials Laboratory

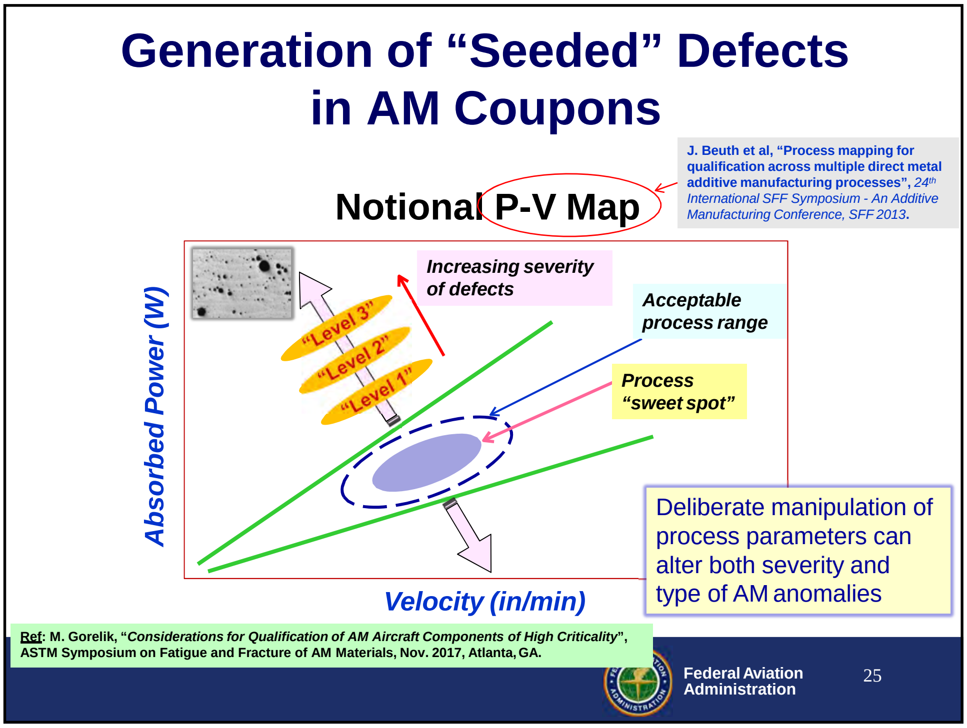
April 1975

The program objectives were as follows:

- Determine the feasibility of producing typical defects in Ti-6Al-4V titanium alloy weldments by intentional variation of processing parameters. Ti-6Al-4V (STOA) plates were utilized as base materials.
- Evaluate the effect of flaws produced intentionally in experimental welds by electron-beam (EB), plasma-arc (PA), gas-tungsten-arc (GTA), and gas-metal-arc (GMA) welding on fatigue endurance.
- Propose acceptance criteria for titanium fusion weldments based on correlation of fatigue test results with both nondestructive inspection and fractographic findings.



Failures in specimens with fatigue endurance values in the $K_t = 2$ to $K_t = 3$ range were associated typically with 0.010 to 0.035 inch porosity scattered throughout the thickness of the specimens which caused multiple failure initiations (Figure 58), and isolated surface or subsurface porosity, as shown in Figures 59 and 60, respectively.



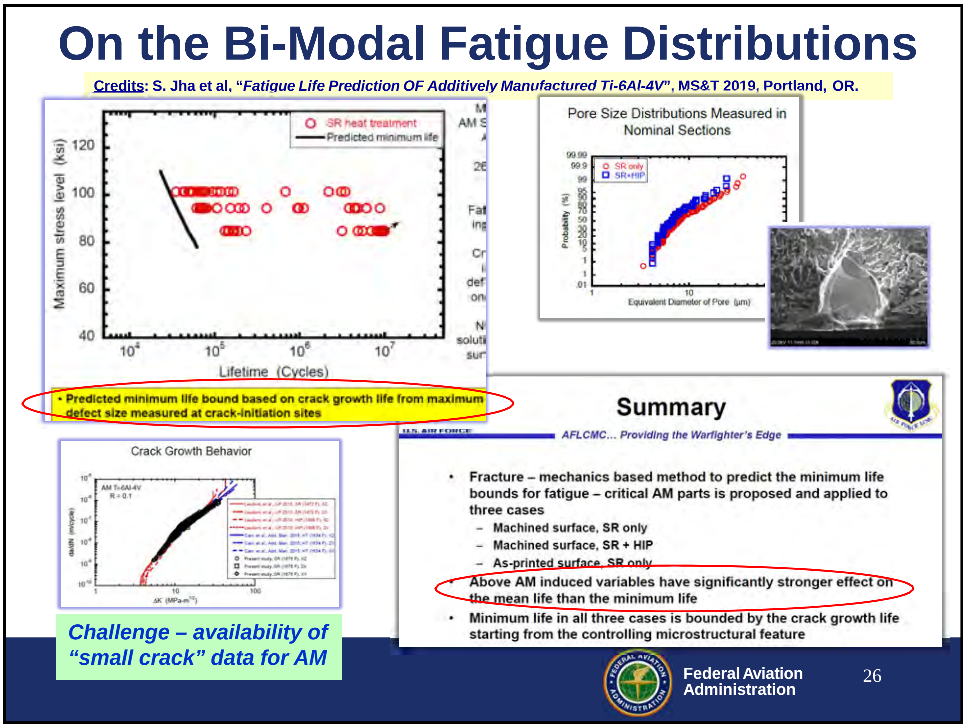
# Generation of "Seeded" Defects in AM Coupons

J. Beuth et al, "Process mapping for qualification across multiple direct metal additive manufacturing processes", *24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013*.

Deliberate manipulation of process parameters can alter both severity and type of AM anomalies

Ref: M. Gorelik, "*Considerations for Qualification of AM Aircraft Components of High Criticality*", ASTM Symposium on Fatigue and Fracture of AM Materials, Nov. 2017, Atlanta, GA.

Federal Aviation Administration



# On the Bi-Modal Fatigue Distributions

Credits: S. Jha et al, "*Fatigue Life Prediction OF Additively Manufactured Ti-6Al-4V*", MS&T 2019, Portland, OR.

- Predicted minimum life bound based on crack growth life from maximum defect size measured at crack-initiation sites

## Summary

U.S. AIR FORCE AFLCMC… Providing the Warfighter's Edge

- Fracture – mechanics based method to predict the minimum life bounds for fatigue – critical AM parts is proposed and applied to three cases
  - Machined surface, SR only
  - Machined surface, SR + HIP
  - As-printed surface, SR only
- Above AM induced variables have significantly stronger effect on the mean life than the minimum life
- Minimum life in all three cases is bounded by the crack growth life starting from the controlling microstructural feature

*Challenge – availability of "small crack" data for AM*

Federal Aviation Administration

# Summary

- **Expect rapid expansion of AM in Aviation and increase in the levels of AM parts criticality**
- **Good progress is being made by the F&DT community of practice in application to metal AM**
  - ➢ ***However, most areas are still "work in progress"***
- **Continued focus is important, through a combination of funded R&D, standardization, technical interchange meetings, and collaborative efforts**
- ***Potential areas*** **for collaborative efforts:**
  - **Development of public standards for F&DT and NDI of AM**
  - **Seeded defects studies → "*effect of defects*"**
    - *Reference: M. Gorelik's ASTM 2017 AM Symposium presentation*
  - **Development of "Lessons Learned" best practice documents and databases (longer-term)**

# Discussion

***Dr. Michael Gorelik***

Chief Scientist, *Fatigue and Damage Tolerance*
Aviation Safety
Federal Aviation Administration
michael.gorelik@faa.gov
(480) 284-7968

Oak Ridge National Laboratory

# Accelerating Quality Certification of Critical Components with Additive Manufacturing

Vincent Paquit, PhD
Lead – Energy Systems Analytics group
TCR Lead – Digital/Manufacturing/Testing

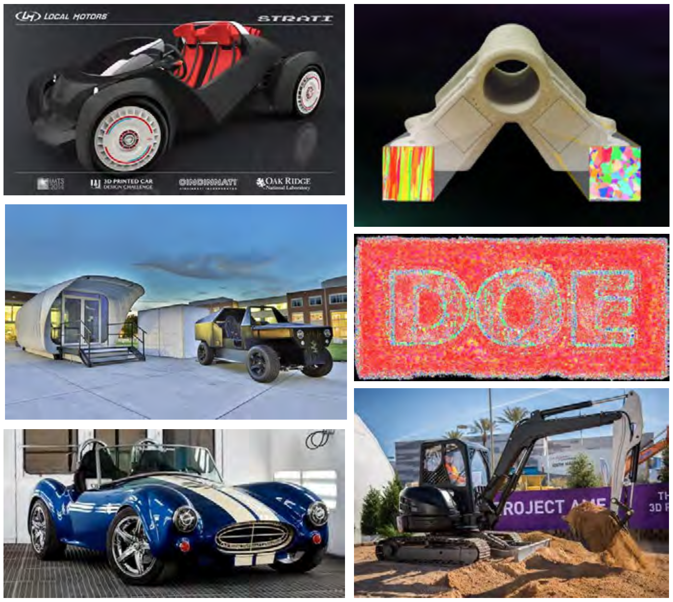
Workshop on Advanced Manufacturing Technologies for Nuclear Applications
Session 4 – Approaches to Component Qualification and Aging Management

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

This work has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy

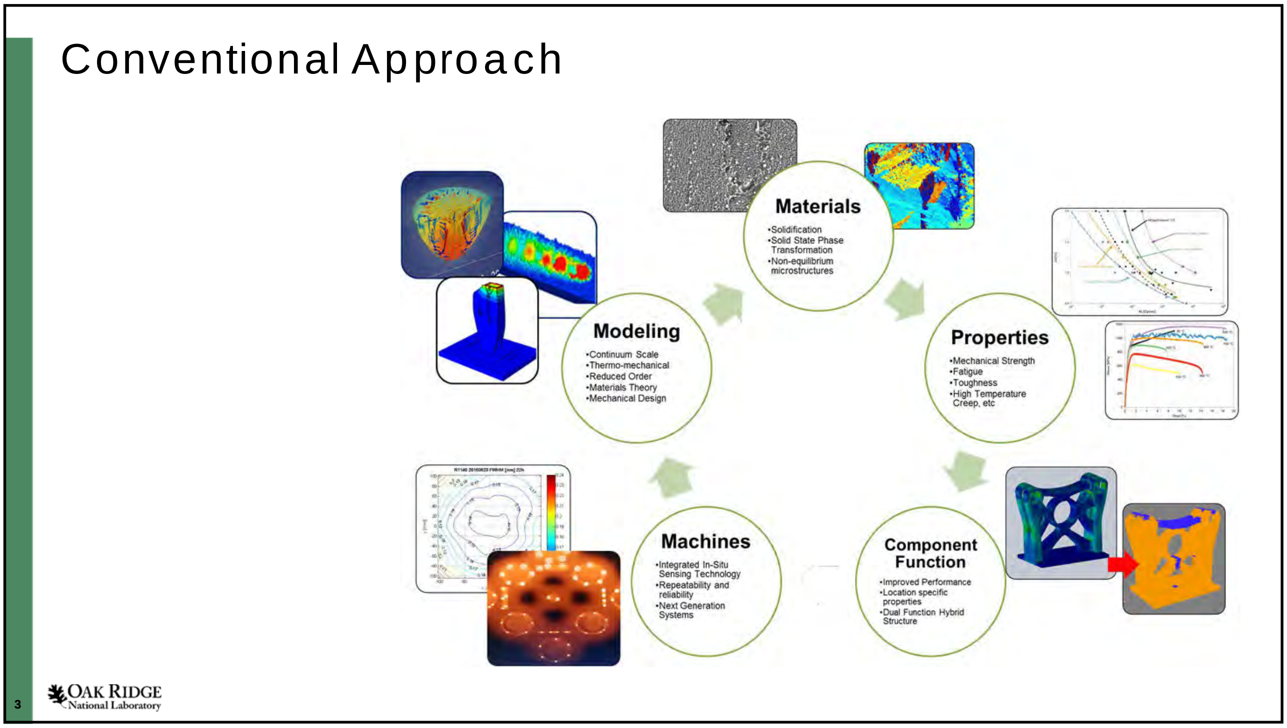
U.S. Department of Energy

## Scientific drivers



- Certification of AM components by conventional methods eliminates the business case for AM components
- Limited understanding of local and global processing state for additive manufacturing

**Develop new certification methodologies for manufacturing technologies**



# Conventional Approach

**Materials**
- Solidification
- Solid State Phase Transformation
- Non-equilibrium microstructures

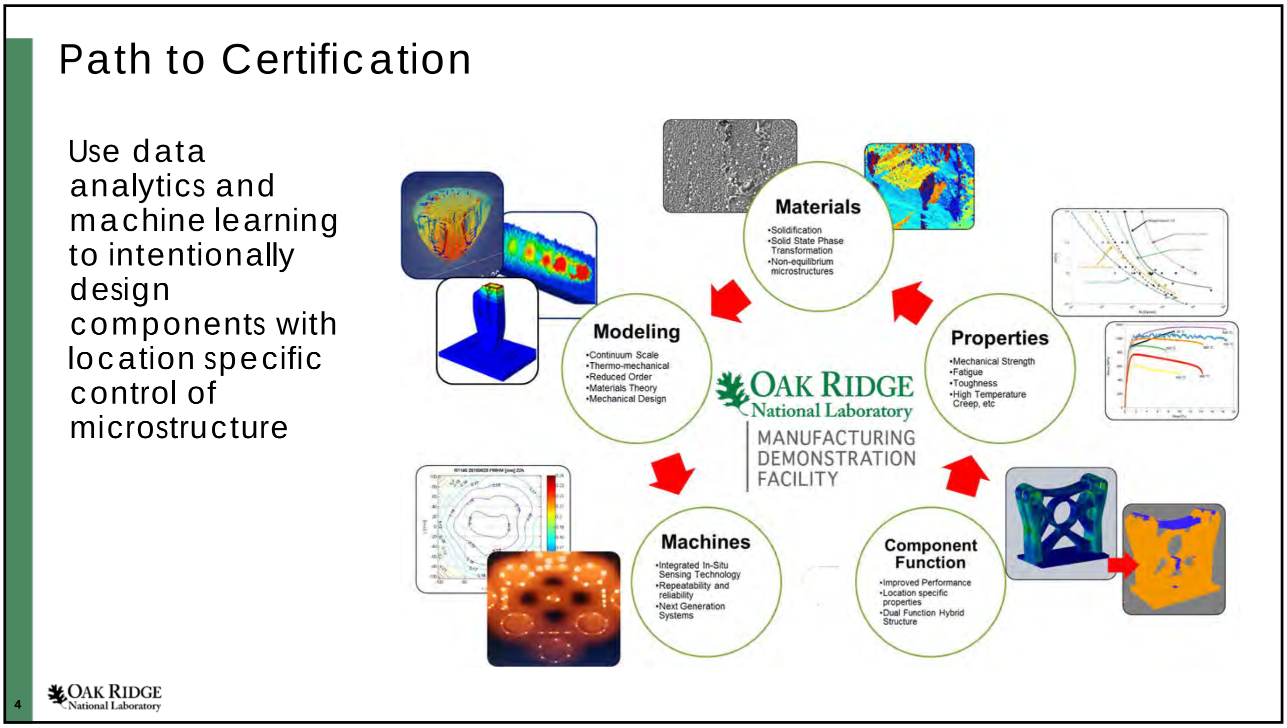
**Properties**
- Mechanical Strength
- Fatigue
- Toughness
- High Temperature Creep, etc

**Component Function**
- Improved Performance
- Location specific properties
- Dual Function Hybrid Structure

**Machines**
- Integrated In-Situ Sensing Technology
- Repeatability and reliability
- Next Generation Systems

**Modeling**
- Continuum Scale
- Thermo-mechanical
- Reduced Order
- Materials Theory
- Mechanical Design

OAK RIDGE National Laboratory



# Path to Certification

Use data analytics and machine learning to intentionally design components with location specific control of microstructure

**Materials**
- Solidification
- Solid State Phase Transformation
- Non-equilibrium microstructures

**Properties**
- Mechanical Strength
- Fatigue
- Toughness
- High Temperature Creep, etc

**Component Function**
- Improved Performance
- Location specific properties
- Dual Function Hybrid Structure

**Machines**
- Integrated In-Situ Sensing Technology
- Repeatability and reliability
- Next Generation Systems

**Modeling**
- Continuum Scale
- Thermo-mechanical
- Reduced Order
- Materials Theory
- Mechanical Design

OAK RIDGE National Laboratory
MANUFACTURING DEMONSTRATION FACILITY

OAK RIDGE National Laboratory

# Smart Manufacturing Approach

ORNL has developed a technology agnostic data analytics framework for manufacturing.

A four-steps data driven approach toward processes optimization, and qualification, and certification of manufactured parts

**Step 1: Understanding the process**

**Step 2: Optimizing the process**

**Step 3: Feedback loop for self-optimization/correction**

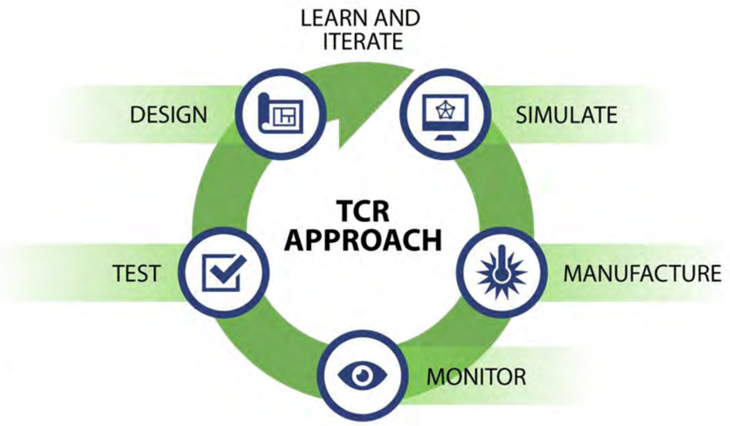
**Step 4: Certifying and qualifying components**

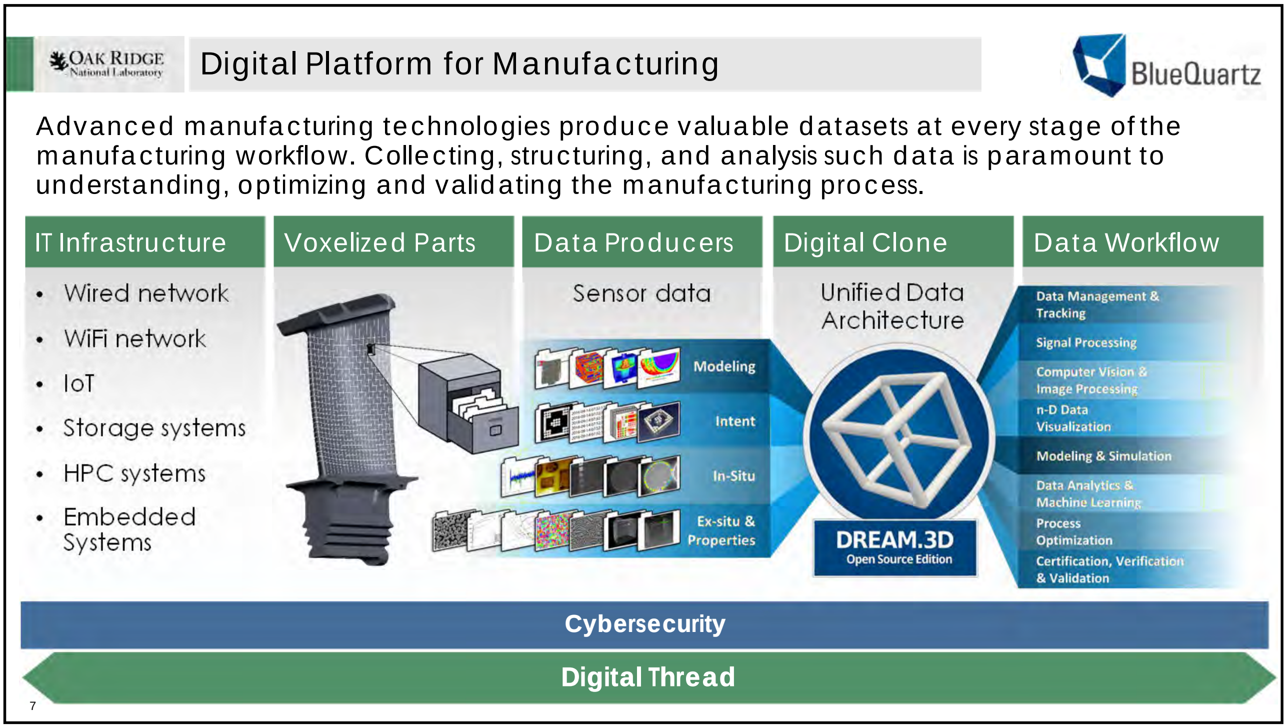
---

# TCR will demonstrate that an agile development approach can be applied to accelerate deployment.

- An agile approach breaks with traditional linear development models to exercise an iterative, dynamic development process.

- The approach lends itself to complex projects in which a large, multidisciplinary team works together closely to complete a product.





## Digital Platform for Manufacturing

Advanced manufacturing technologies produce valuable datasets at every stage of the manufacturing workflow. Collecting, structuring, and analysis such data is paramount to understanding, optimizing and validating the manufacturing process.

**IT Infrastructure**
- Wired network
- WiFi network
- IoT
- Storage systems
- HPC systems
- Embedded Systems

**Voxelized Parts**

**Data Producers**

Sensor data

Modeling

Intent

In-Situ

Ex-situ & Properties

**Digital Clone**

Unified Data Architecture

DREAM.3D
Open Source Edition

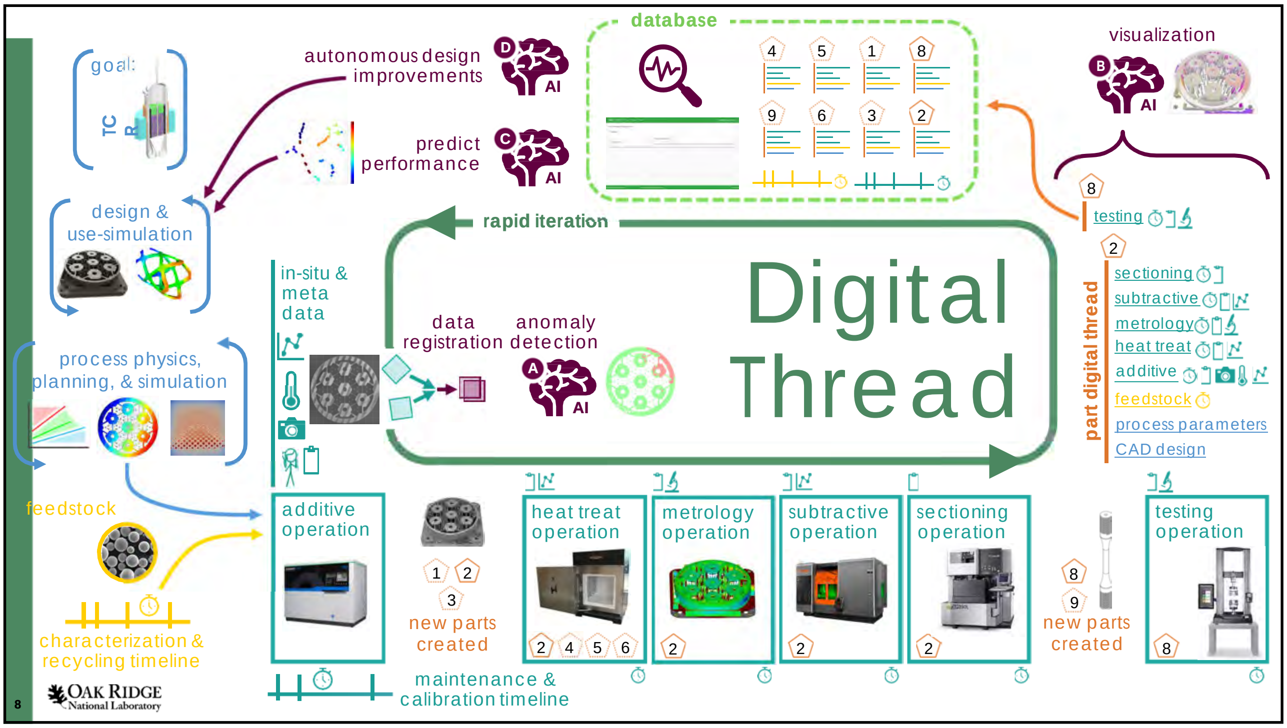
**Data Workflow**
- Data Management & Tracking
- Signal Processing
- Computer Vision & Image Processing
- n-D Data Visualization
- Modeling & Simulation
- Data Analytics & Machine Learning
- Process Optimization
- Certification, Verification & Validation

**Cybersecurity**

**Digital Thread**

7

7



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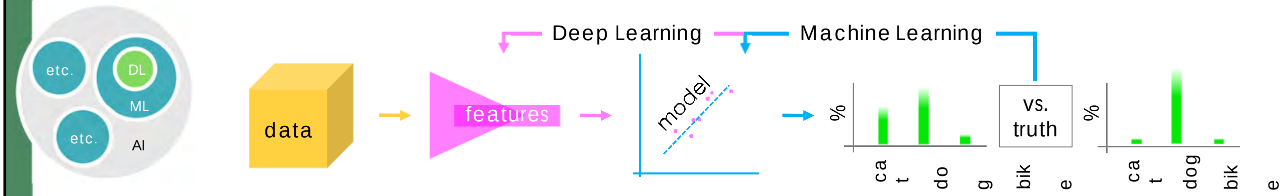
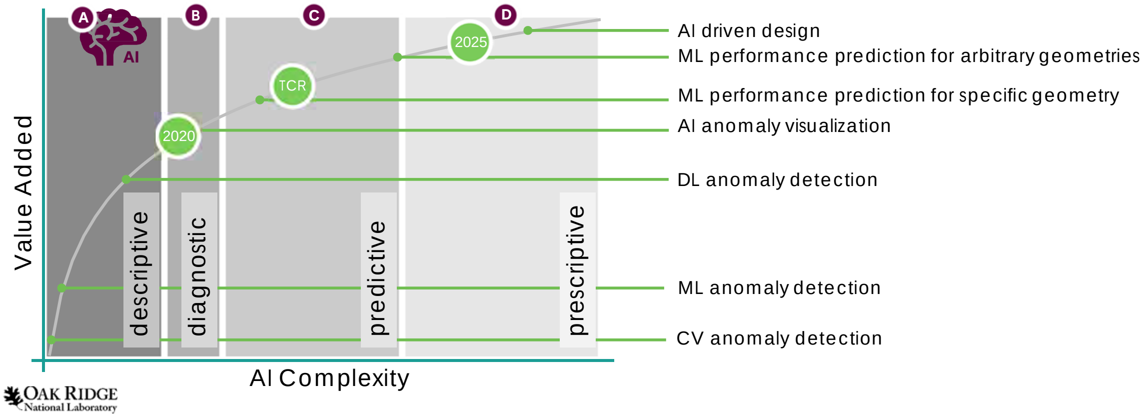
# Augmented Intelligence for Advanced Manufacturing





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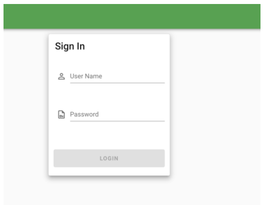
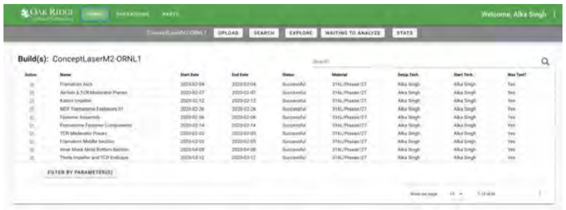
# Web-Based Interface and API Makes Data Accessible

## LDAP authentication

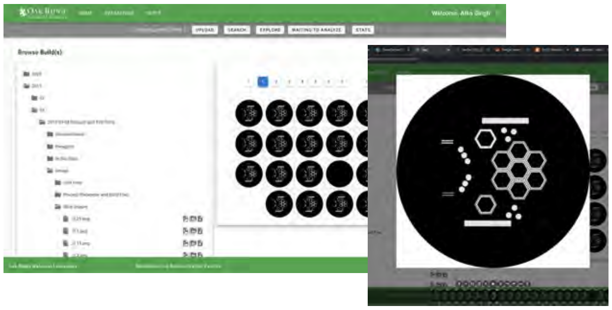


## Metadata search



## Upload form

## Data viewer



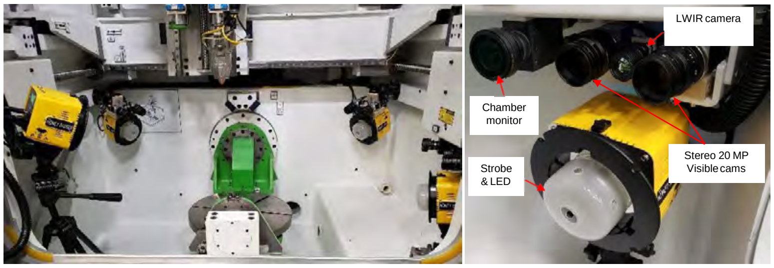
## Additive Technologies & Parts

### Laser Powder Bed

### Blown Powder

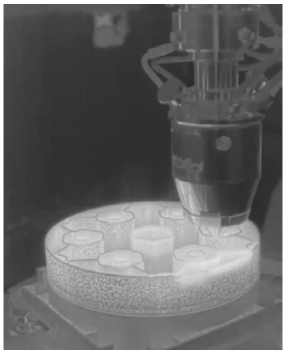
### Binder Jet

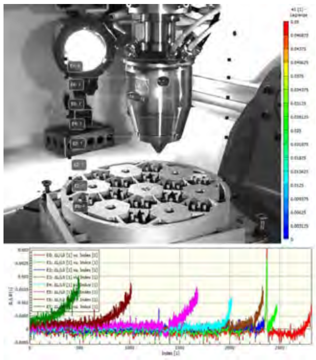
## BeAM – Blown Powder

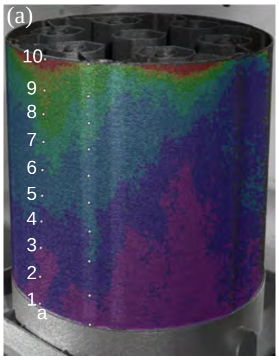


Imaging system provides:

- real time 360 measurement
- 3D geometry dimensions
- 3D strain measurement,
- thermal measurement







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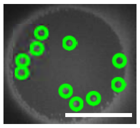
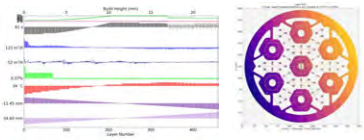
# Anomaly Detection

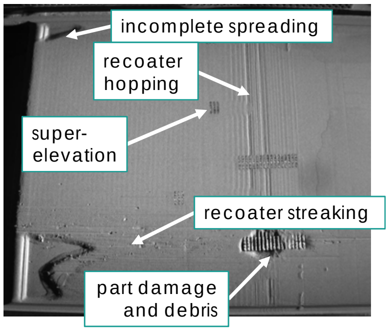
1. Detect and **classify** any anomalies
2. **Localize** anomaly detections



3. **Register** sensing modalities



4. Perform **process interventions**
5. Fully **machine agnostic** solution

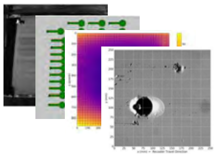


"Critical layer"
"Attempt to re-spread the powder"

---

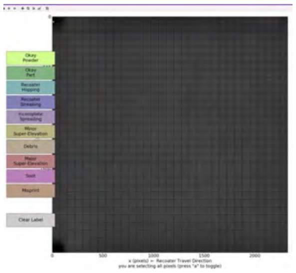
# AI workflow and transfer learning

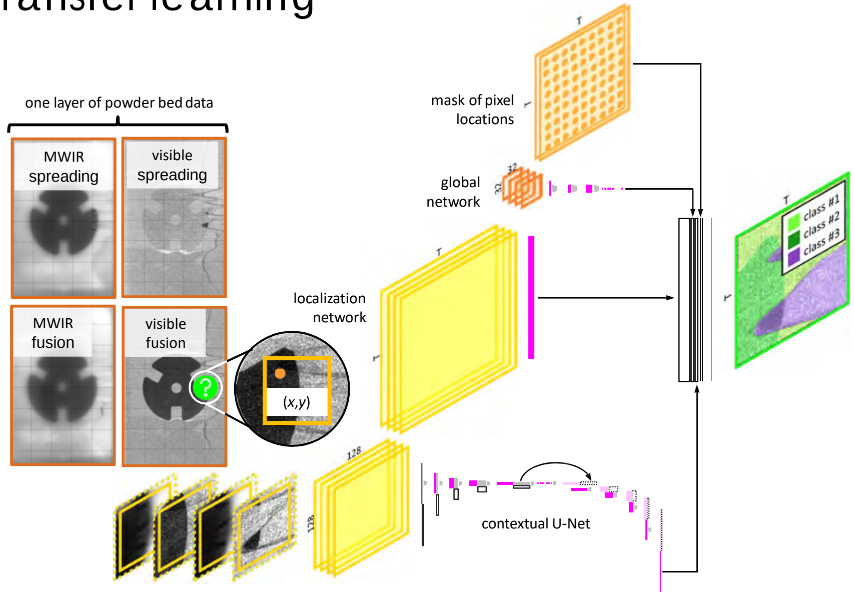
data curation



Manual data annotation

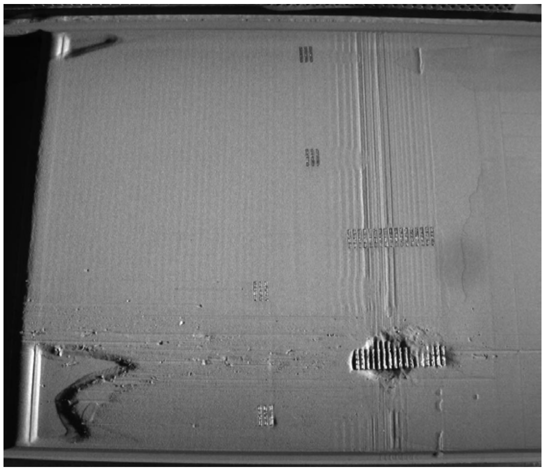
- Training the machine learning algorithm from scratch
  - 100,000,000+ labeled pixels



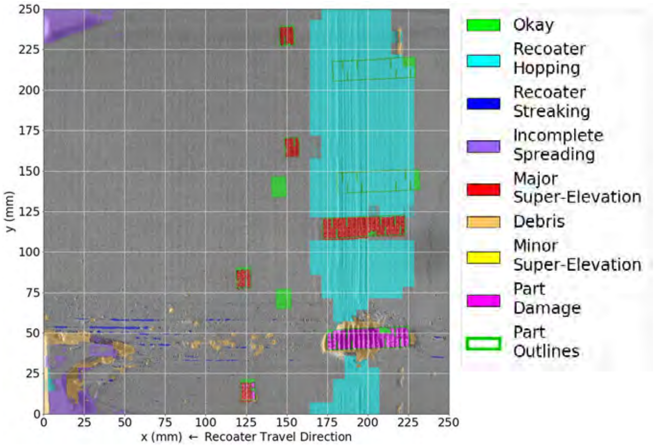


Dynamic Segmentation Convolutional Neural Network

# Approach: classification results



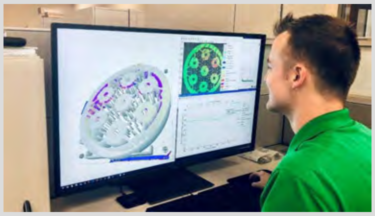
Input image



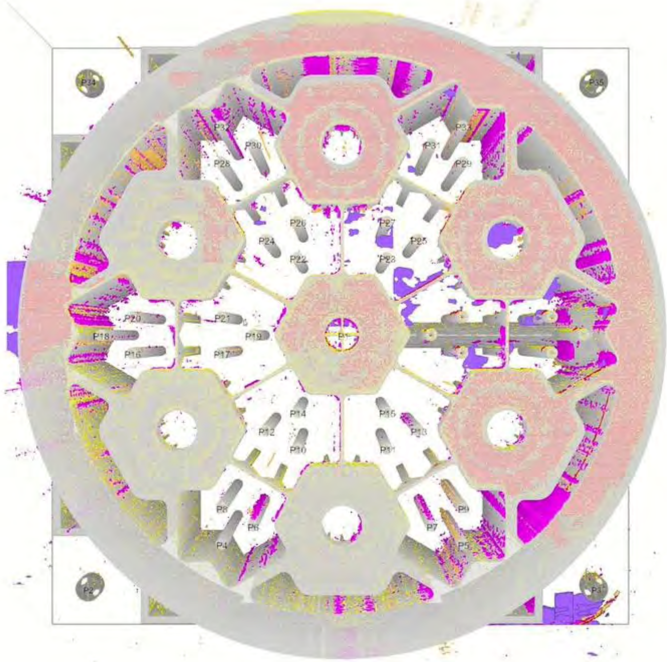
Classification results

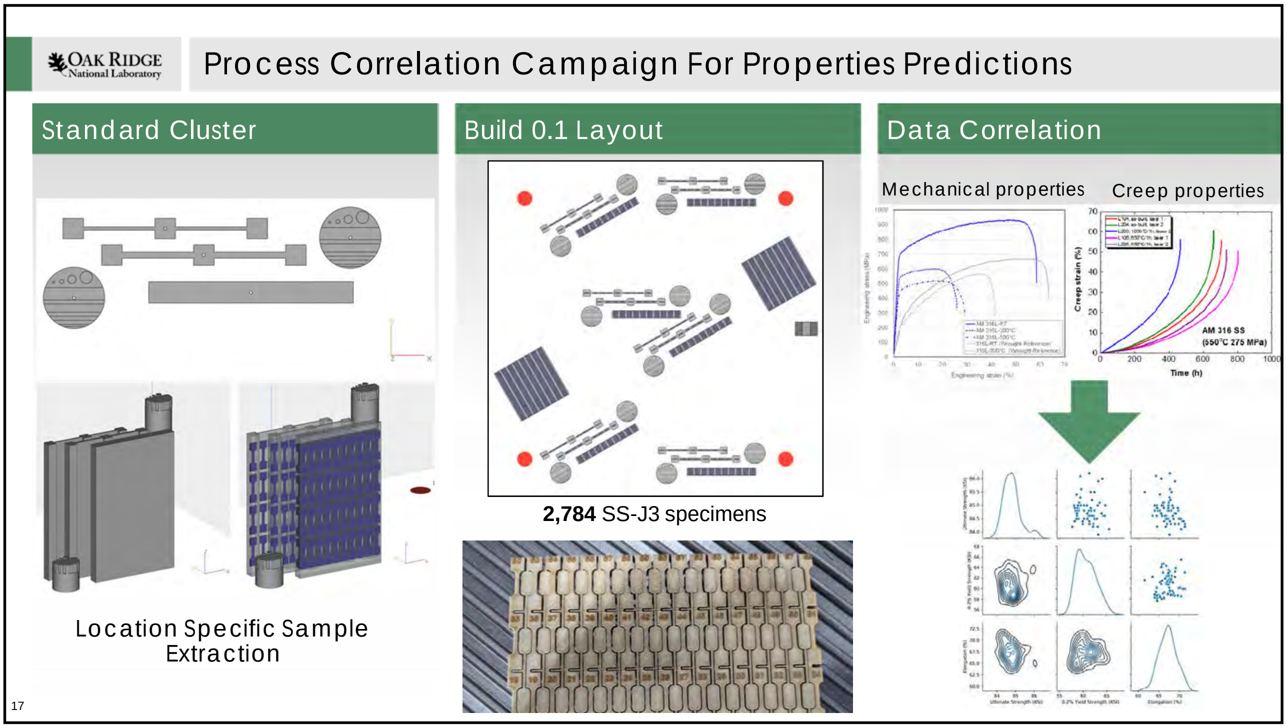
---

# Peregrine



- AI software for real-time 3D print monitoring
- Main platform for most of the TCR data analytics activities
- Commercial copyright license available
- Publication DOI: 10.1016/j.addma.2020.101453





## Process Correlation Campaign For Properties Predictions

**Standard Cluster**

Location Specific Sample Extraction

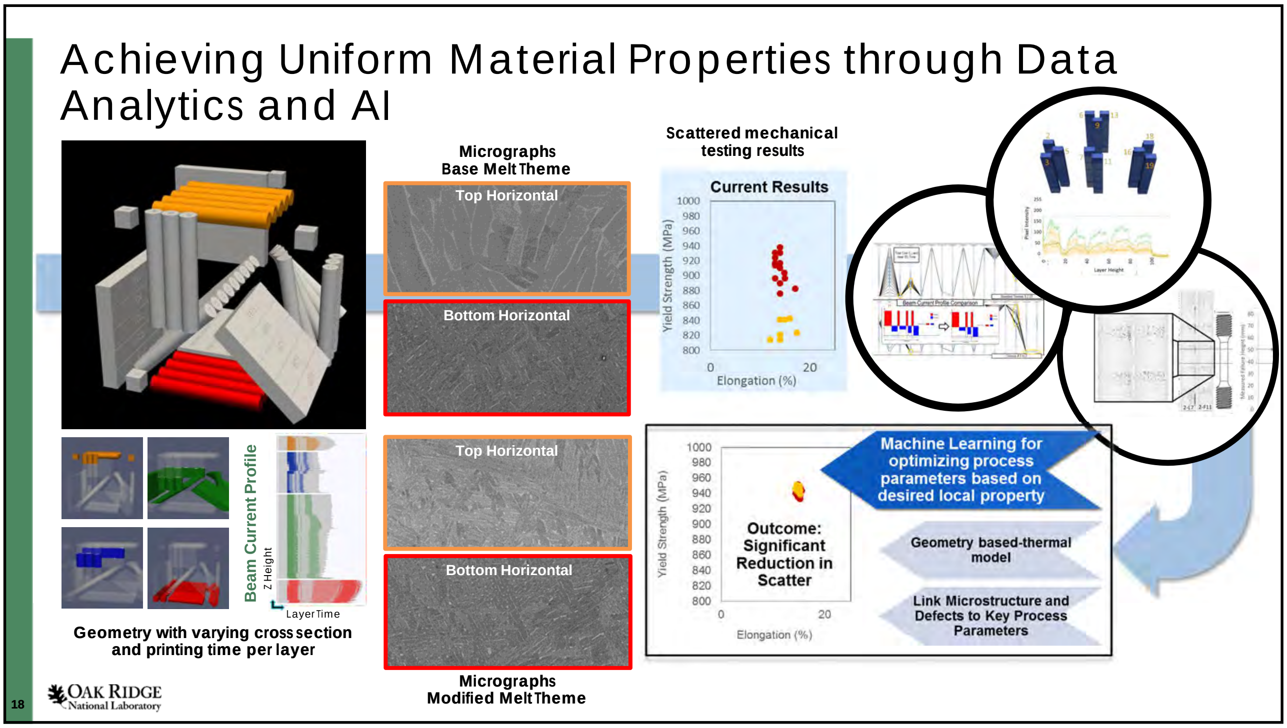
**Build 0.1 Layout**

**2,784** SS-J3 specimens

**Data Correlation**

Mechanical properties

Creep properties



## Achieving Uniform Material Properties through Data Analytics and AI

Geometry with varying cross section and printing time per layer

**Micrographs Base Melt Theme**

**Micrographs Modified Melt Theme**

**Scattered mechanical testing results**

**Current Results**

**Outcome: Significant Reduction in Scatter**

**Machine Learning for optimizing process parameters based on desired local property**

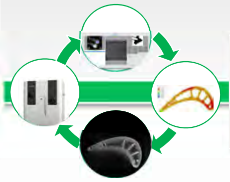
**Geometry based-thermal model**

**Link Microstructure and Defects to Key Process Parameters**

## Relevance and impact

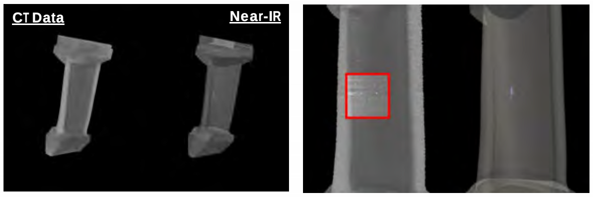
### Solar Turbines

- **Objective:** Fabricate near net-shaped SGT5-400F airfoil with no surface breaking cracks from a high gamma prime Ni-base superalloy
- **Successfully tested on August 25th 2020**



Manufactured component

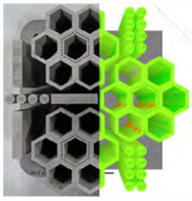

Mercury 50 Gas Turbine Engine

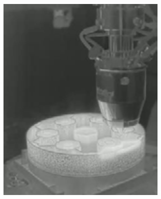


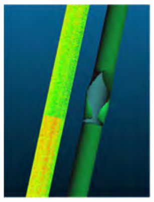
AI for CT reconstruction and defect detection

### TCR

- **Objective:** Develop a digital platform and associated processes to couple data analytics with design and manufacturing data for use in rapid prototyping and quality evaluations of manufactured products.


In-situ & AI


Sensor development

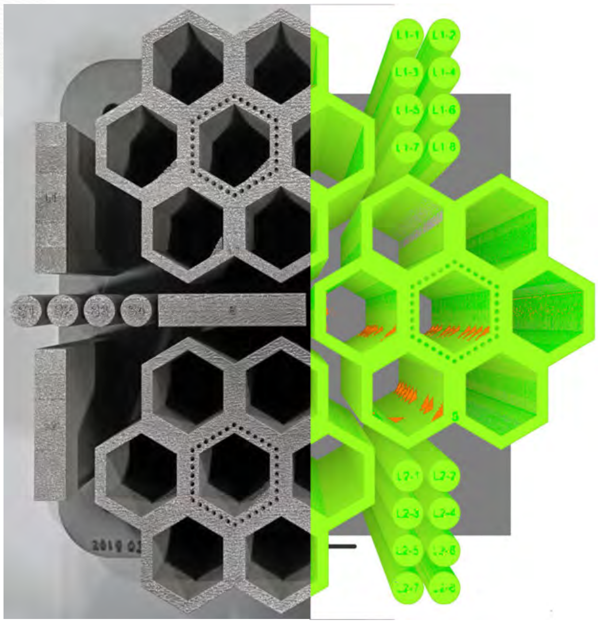

In-situ and Ex-situ correlation

---

# Framatome, TVA, Oak Ridge National Laboratory to load first 3D-printed component in commercial reactor

*"The fuel assembly channel fasteners were printed at ORNL using additive-manufacturing techniques, also known as 3D printing, as part of the lab's Transformational Challenge Reactor Program and installed on ATRIUM 10XM fuel assemblies at Framatome's nuclear fuel manufacturing facility in Richland, Washington."*

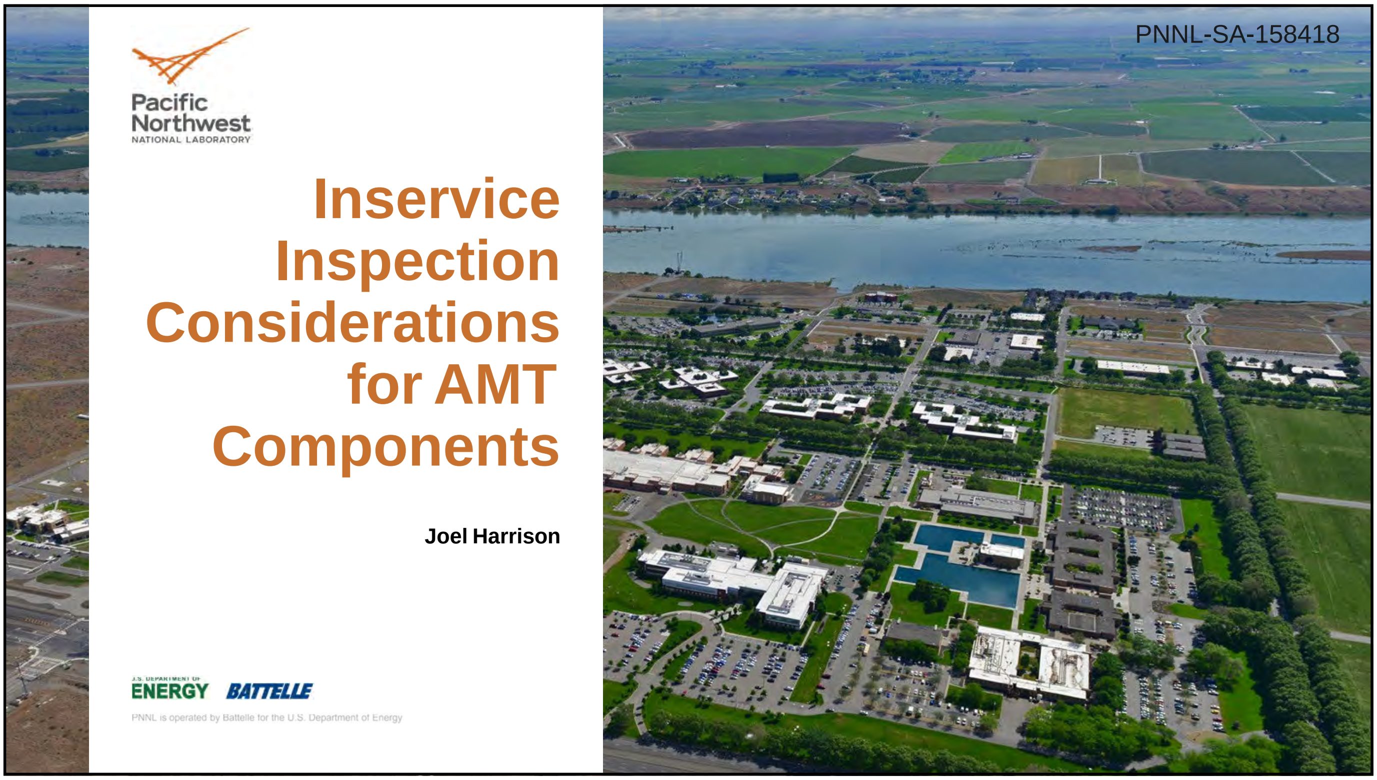
Framatome website (Dec 2020)



# Questions?

Contact: paquitvc@ornl.gov

OAK RIDGE National Laboratory | MANUFACTURING DEMONSTRATION FACILITY



PNNL-SA-158418

Pacific Northwest
NATIONAL LABORATORY

# Inservice Inspection Considerations for AMT Components

**Joel Harrison**

ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Pacific Northwest
NATIONAL LABORATORY

## Advanced Manufacturing Techniques

- **AMT has gained significant attention and success in several industries**
  - Aerospace, automotive, medical, consumer products, and energy
- **ASME Code and the nuclear power industry is yet to fully embrace AMT**
  - The nuclear industry could benefit from precision replacement components that are difficult to obtain due to a reduction or loss of supply chain capabilities
  - AMT components must meet quality and regulatory requirements
  - The NDE methods employed during ISI of the existing nuclear fleet have evolved over more than 40 years into an established practice with strong technical and regulator backing
  - There are several papers and reports on NDE of AMT components but none related to ISI

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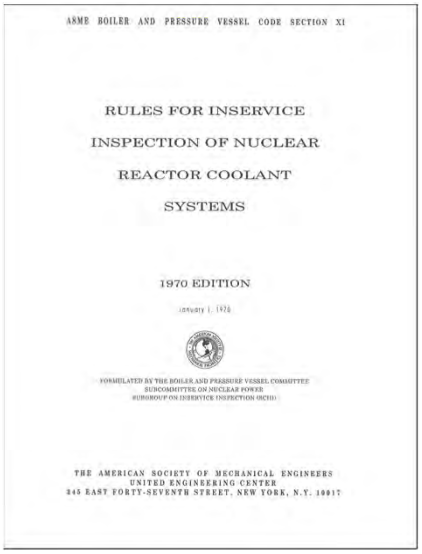
## ASME Section XI

- **Draft published in 1968**
- **First Edition published on January 1, 1970**
  - Entire document was 42 pages with only 24 devoted to ISI requirements
- **Compared to 2019 Edition – 676 pages**
- **Rules for Inservice Inspection of Nuclear Power Plant Components**
  - Does not cover component fabrication NDE or plant construction/Repair Replacement NDE
  - These issues are addressed in ASME Section III



ASME BOILER AND PRESSURE VESSEL CODE SECTION XI

RULES FOR INSERVICE
INSPECTION OF NUCLEAR
REACTOR COOLANT
SYSTEMS

1970 EDITION
January 1, 1970

FORMULATED BY THE BOILER AND PRESSURE VESSEL COMMITTEE
SUBCOMMITTEE ON NUCLEAR POWER
SUBGROUP ON INSERVICE INSPECTION (SCIII)

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
UNITED ENGINEERING CENTER
345 EAST FORTY-SEVENTH STREET, NEW YORK, N.Y. 10017

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## ASME Section XI

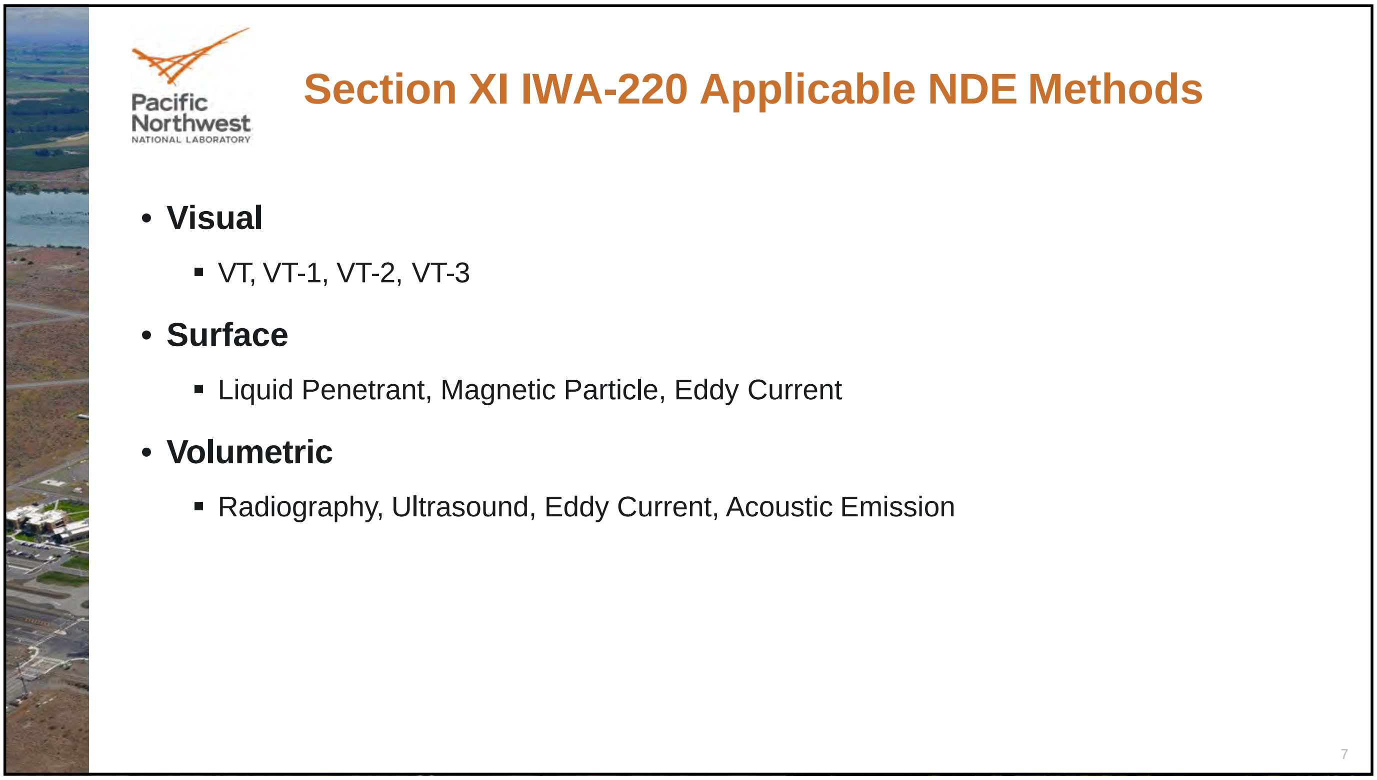
- **Currently no discussion regarding ISI of AMT fabricated components within Section XI NDE Committees**
- **Only one Code Case, N-834, has been adopted in ASME Section III, Division 1**
  - PM-HIP of 316L Stainless Steel
  - EPRI Report 1025491, May 2012
- **ASME's Board on Pressure Technology Codes and Standards (BPTCS) and Board on Nuclear Codes and Standards (BNCS)**
  - Convened Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment
  - Scheduled to meet quarterly during ASME Code Week

## Thoughts Regarding ISI of AMT Components

- **Are AMT fabricated components comparable to conventionally fabricated methods?**
  - Without investigation, how can we know for sure?
  - Such information will help define inspection volumes and intervals and provide the basis for the development of aging management programs
- **How will proprietary AMT processes and manufacturing methods be standardized?**
- **Can it be anticipated that considerations for most ISI of AMT components would overlap with those of conventional components?**

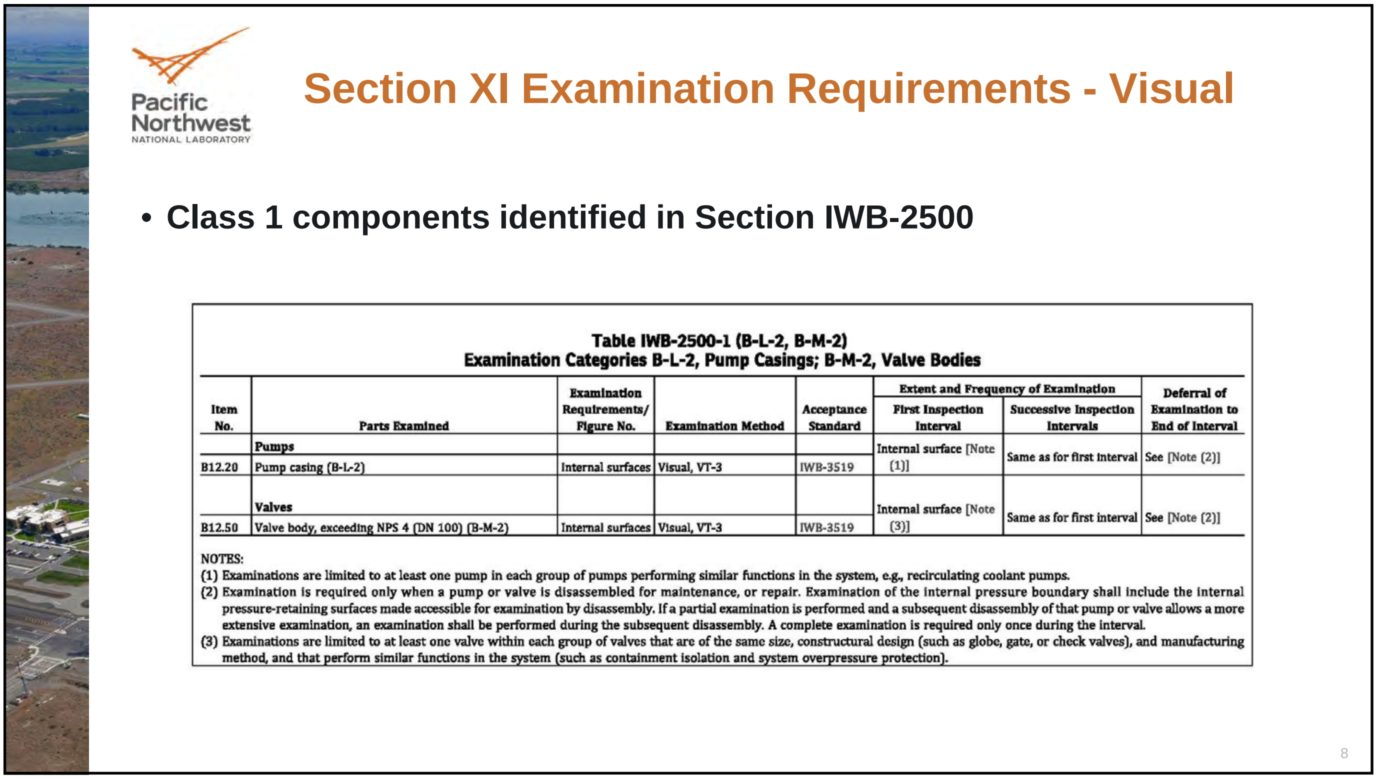
## Thoughts Regarding ISI of AMT Components

- **An AMT component may contain no welds, so the inspection volume cannot be defined in terms of weld regions.**
  - What is the relevant inspection volume?
  - How is a piping component welded to a valve body or piping elbow fabricated by an AMT process defined?
- **Can critical defects, once defined, be detected with current NDE technology?**
- **What will be the NDE resolution requirements?**
  - Can NDE techniques be validated without destructive testing?
- **Will the grain structure of the AMT components interfere with UT detection?**



## Section XI IWA-220 Applicable NDE Methods

- **Visual**
  - VT, VT-1, VT-2, VT-3
- **Surface**
  - Liquid Penetrant, Magnetic Particle, Eddy Current
- **Volumetric**
  - Radiography, Ultrasound, Eddy Current, Acoustic Emission



## Section XI Examination Requirements - Visual

- **Class 1 components identified in Section IWB-2500**

**Table IWB-2500-1 (B-L-2, B-M-2)**
**Examination Categories B-L-2, Pump Casings; B-M-2, Valve Bodies**

| Item No. | Parts Examined | Examination Requirements/ Figure No. | Examination Method | Acceptance Standard | Extent and Frequency of Examination | | Deferral of Examination to End of Interval |
|---|---|---|---|---|---|---|---|
| | | | | | First Inspection Interval | Successive Inspection Intervals | |
| | **Pumps** | | | | | | |
| B12.20 | Pump casing (B-L-2) | Internal surfaces | Visual, VT-3 | IWB-3519 | Internal surface [Note (1)] | Same as for first interval | See [Note (2)] |
| | **Valves** | | | | | | |
| B12.50 | Valve body, exceeding NPS 4 (DN 100) (B-M-2) | Internal surfaces | Visual, VT-3 | IWB-3519 | Internal surface [Note (3)] | Same as for first interval | See [Note (2)] |

NOTES:
(1) Examinations are limited to at least one pump in each group of pumps performing similar functions in the system, e.g., recirculating coolant pumps.
(2) Examination is required only when a pump or valve is disassembled for maintenance, or repair. Examination of the internal pressure boundary shall include the internal pressure-retaining surfaces made accessible for examination by disassembly. If a partial examination is performed and a subsequent disassembly of that pump or valve allows a more extensive examination, an examination shall be performed during the subsequent disassembly. A complete examination is required only once during the interval.
(3) Examinations are limited to at least one valve within each group of valves that are of the same size, constructural design (such as globe, gate, or check valves), and manufacturing method, and that perform similar functions in the system (such as containment isolation and system overpressure protection).

## Visual Examination

- **Early AMT fabrication attention in the nuclear power industry has been on pump and valve housings.**
- **Visual examinations should be relatively straight forward provided:**
  - Anticipated flaw types have been determined
  - Critical flaw size & acceptance standards have been defined

## Section XI Examination Requirements – Surface & Volumetric

- **Class 1 components identified in Section IWB-2500**

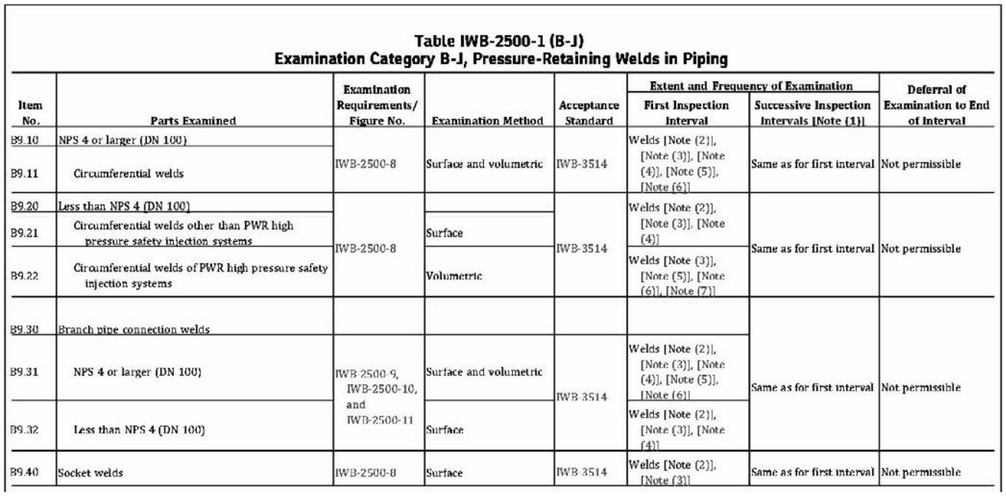


**Table IWB-2500-1 (B-J)**
**Examination Category B-J, Pressure-Retaining Welds in Piping**

| Item No. | Parts Examined | Examination Requirements/ Figure No. | Examination Method | Acceptance Standard | Extent and Frequency of Examination |  | Deferral of Examination to End of Interval |
|---|---|---|---|---|---|---|---|
|  |  |  |  |  | First Inspection Interval | Successive Inspection Intervals [Note (1)] |  |
| B9.10 | NPS 4 or larger (DN 100) | IWB-2500-8 | Surface and volumetric | IWB-3514 | Welds [Note (2)], [Note (3)], [Note (4)], [Note (5)], [Note (6)] | Same as for first interval | Not permissible |
| B9.11 | Circumferential welds |  |  |  |  |  |  |
| B9.20 | Less than NPS 4 (DN 100) | IWB-2500-8 |  | IWB-3514 | Welds [Note (2)], [Note (3)], [Note (4)] | Same as for first interval | Not permissible |
| B9.21 | Circumferential welds other than PWR high pressure safety injection systems |  | Surface |  |  |  |  |
| B9.22 | Circumferential welds of PWR high pressure safety injection systems |  | Volumetric |  | Welds [Note (3)], [Note (5)], [Note (6)], [Note (7)] |  |  |
| B9.30 | Branch pipe connection welds |  |  |  |  | Same as for first interval | Not permissible |
| B9.31 | NPS 4 or larger (DN 100) | IWB-2500-9, IWB-2500-10, and IWB-2500-11 | Surface and volumetric | IWB-3514 | Welds [Note (2)], [Note (3)], [Note (4)], [Note (5)], [Note (6)] |  |  |
| B9.32 | Less than NPS 4 (DN 100) |  | Surface |  | Welds [Note (2)], [Note (3)], [Note (4)] |  |  |
| B9.40 | Socket welds | IWB-2500-8 | Surface | IWB-3514 | Welds [Note (2)], [Note (3)] | Same as for first interval | Not permissible |

# Section XI Examination Requirements – Surface & Volumetric

- **Class 1 components identified in Section IWB-2500**
- **Examination volumed defined in reference to a weld**

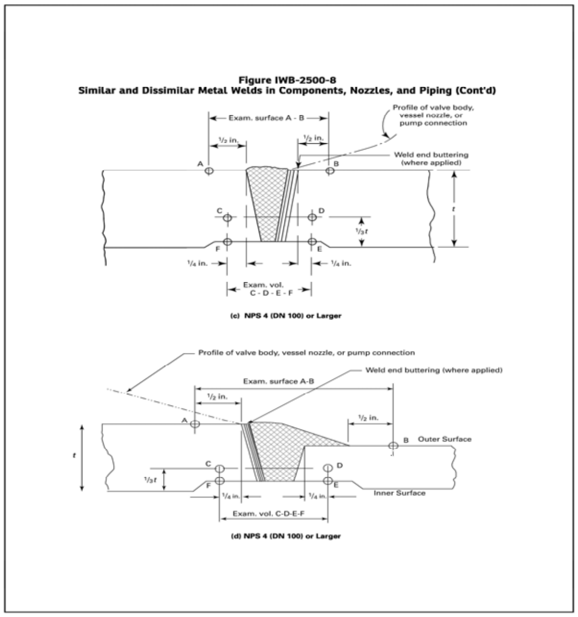


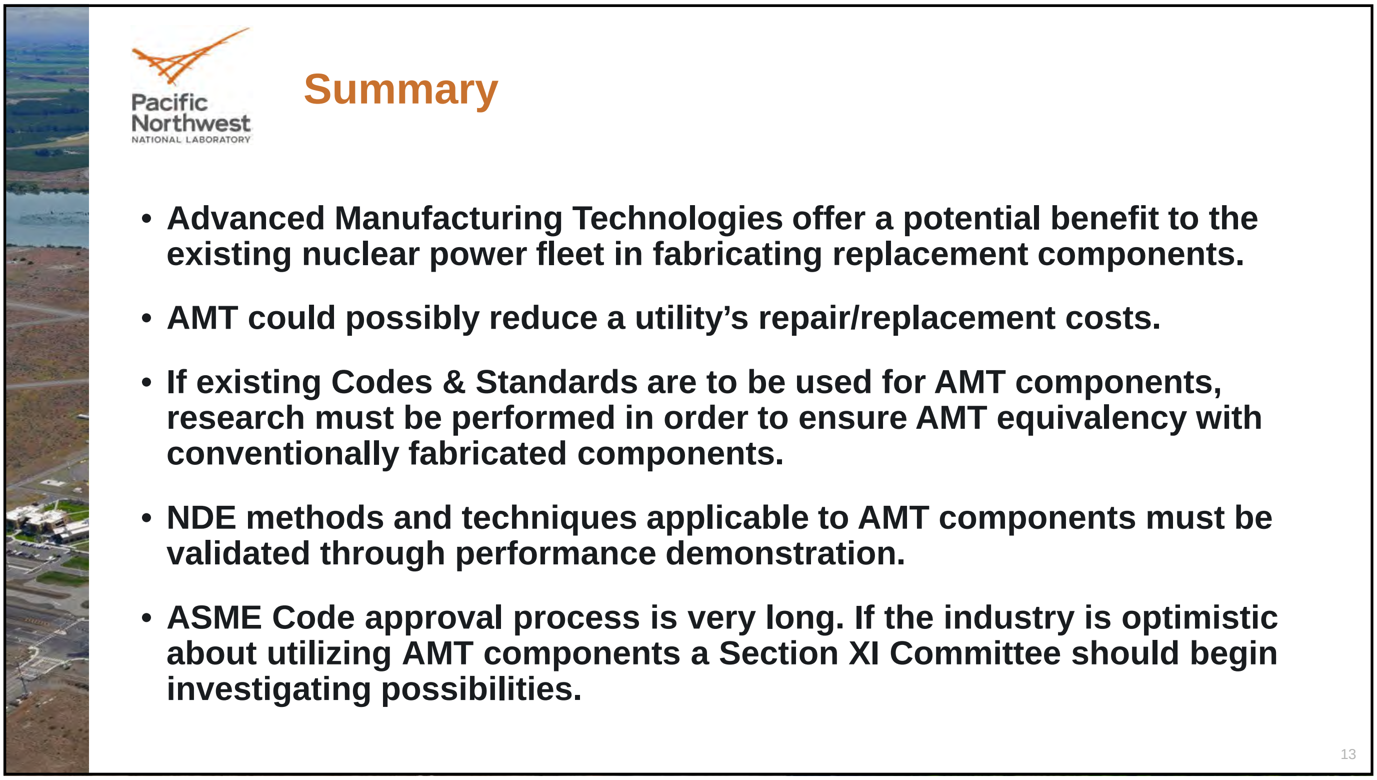
Figure IWB-2500-8
Similar and Dissimilar Metal Welds in Components, Nozzles, and Piping (Cont'd)

(c) NPS 4 (DN 100) or Larger

(d) NPS 4 (DN 100) or Larger

# Surface & Volumetric Examination

- **Surface**
  - A important factor for surface examinations is surface finish. Will AMT components' surface finish be conducive to surface examinations?
- **Volumetric**
  - Volumetric examinations for inservice inspection are predominantly performed with ultrasound
  - Single sided exams – pipe to AMT valve or pump
    - ✓ Pump & Valve components are typically a casting
  - Pipe to AMT fabricated elbow in place of a CASS elbow
  - Appendix VIII Considerations



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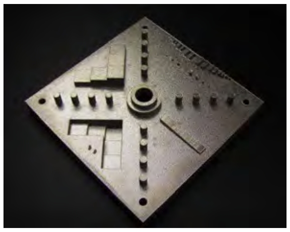
## Summary

- Advanced Manufacturing Technologies offer a potential benefit to the existing nuclear power fleet in fabricating replacement components.
- AMT could possibly reduce a utility’s repair/replacement costs.
- If existing Codes & Standards are to be used for AMT components, research must be performed in order to ensure AMT equivalency with conventionally fabricated components.
- NDE methods and techniques applicable to AMT components must be validated through performance demonstration.
- ASME Code approval process is very long. If the industry is optimistic about utilizing AMT components a Section XI Committee should begin investigating possibilities.

# NIST Perspectives on Additive Manufacturing Standards Landscape



Shawn Moylan
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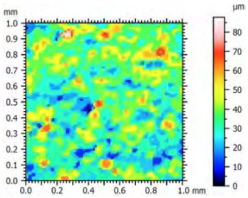
Intelligent Systems Division
Engineering Laboratory
National Institute of Standards and Technology (NIST)

National Institute of Standards and Technology
U.S. Department of Commerce

December 9, 2020



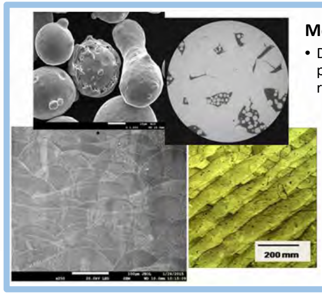
## Role of Additive Manufacturing Standards

- Standards can be used for (among others):
  - specifying requirements
  - communicating guidance and best practices
  - defining test methods and protocols
  - documenting technical data
  - accelerating adoption of new technologies
  - enabling trade in global markets
  - ensuring human health and safety
- Government regulatory agencies and certifying bodies may reference publicly available standards in their regulations and procedures
- Standards development in the U.S. is conducted through voluntary participation and consensus

# NIST Influence on Additive Manufacturing Standards

- Identify consensus <u>needs and priorities</u> for standards
  - Workshops, industry meetings, outreach events, etc.
- Conduct measurement science research to develop <u>technical basis</u> for standards
  - Draft content / starting point for development of documentary standards
- Serve on standards committees
  - Leadership roles
  - Technical standards development
  - Strategic planning / big picture view
- Support the <u>coordination, facilitation, and communication</u> among standards groups

# Example NIST Measurement Science Research in Support of AM Standards



**Methods to characterize metal powder**

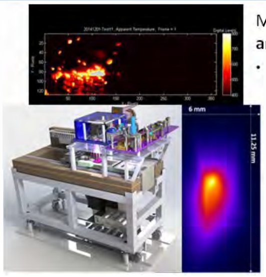
- Dimensional – mechanical – thermal – powder bed density – powder condition for recyclability

**Methods to characterize built materials**

- Mechanical – microstructure – porosity – density – post processing

**Exemplar data**

- Round robin studies – variability analyses – powder/process/material relationships



Methods enabling **in-situ process monitoring and control** to robustly predict part quality

- Process metrology – signature analysis – uncertainty quantification – AM G-Code for machine control

**Reference data** identifying correlations to enable intelligent controller design

- Process parameters ← ❼ Process signatures ← ❼ Part quality

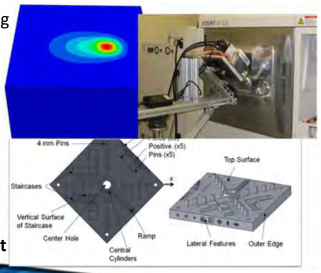
**Additive Manufacturing Metrology Testbed (AMMT)**

**Reference data** to be used by modeling community to improve model inputs and validate model outputs

- Temperature – Microstructure – Residual Stress

**Pre-process and post-process test methods** to characterize performance and assess part quality

- Machine performance characterization – XCT of AM parts



**NIST AM Test Artifact**

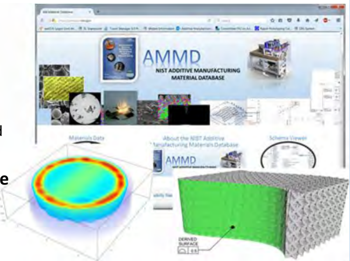
**AM information systems architecture,** including metrics, information models, and validation methods

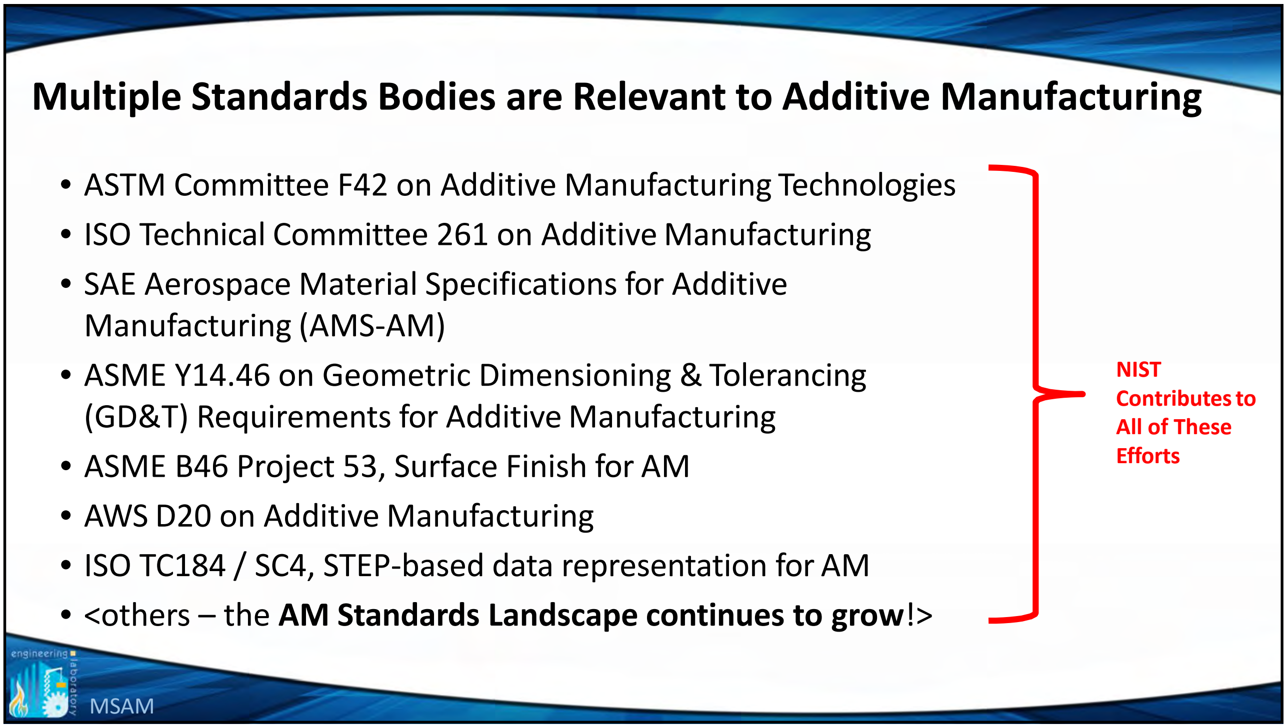
**Public AM Material Database**

- AM schema/ database –- populated with round robin data

**Product definition and tolerance representation** (GD&T) for AM

**AM design rules** and their fundamental principles





## Multiple Standards Bodies are Relevant to Additive Manufacturing

- ASTM Committee F42 on Additive Manufacturing Technologies
- ISO Technical Committee 261 on Additive Manufacturing
- SAE Aerospace Material Specifications for Additive Manufacturing (AMS-AM)
- ASME Y14.46 on Geometric Dimensioning & Tolerancing (GD&T) Requirements for Additive Manufacturing
- ASME B46 Project 53, Surface Finish for AM
- AWS D20 on Additive Manufacturing
- ISO TC184 / SC4, STEP-based data representation for AM
- <others – the **AM Standards Landscape continues to grow**!>

**NIST Contributes to All of These Efforts**

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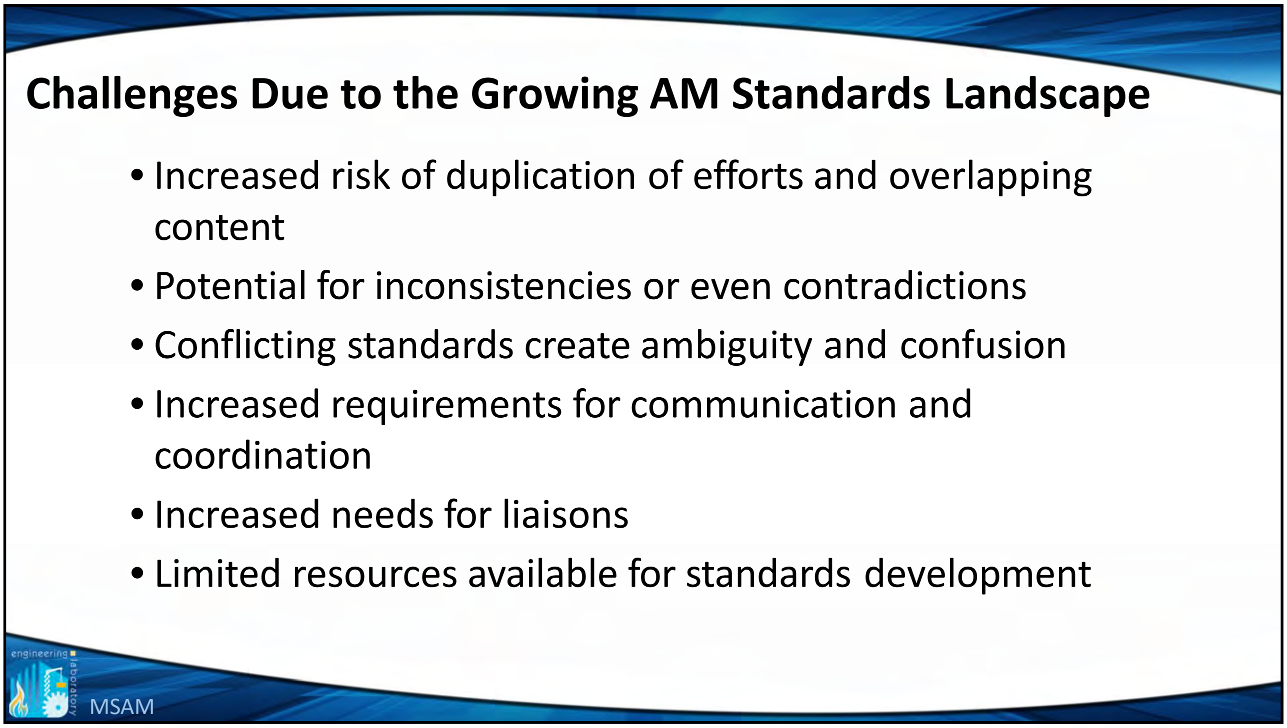


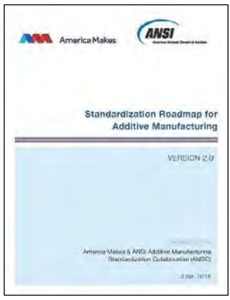
## Challenges Due to the Growing AM Standards Landscape

- Increased 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
- Increased needs for liaisons
- Limited resources available for standards development

MSAM

# 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; experts from many industry sectors identified AM standards gaps and priorities
- Standardization Roadmap for Additive Manufacturing / AMSC Standards Landscape, Version 2.0 (June 2018)
  - Identifies published and in-development standards and specifications, assesses gaps, makes recommendations for priority areas where there is a perceived need for additional standardization



America Makes

ANSI

Standardization Roadmap for Additive Manufacturing

VERSION 2.0

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

JUNE 2018

www.ansi.org/amsc

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ANSI American National Standards Institute

# Additive Manufacturing Standards Collaborative (AMSC)

- Open Gaps in Standards Landscape

| Section | High (0-2 years) | Medium (2-5 years) | Low (5+ years) | Total |
|---|---|---|---|---|
| Design | 4 | 15 | 6 | 25 |
| Precursor Materials | 1 | 4 | 4 | 10 |
| Process Control | 4 | 8 | 4 | 16 |
| Post-processing | 0 | 4 | 3 | 7 |
| Finished Material Properties | 3 | 1 | 0 | 4 |
| Qualification & Certification | 4 | 8 | 3 | 15 |
| Nondestructive Evaluation | 2 | 4 | 2 | 8 |
| Maintenance & Repair | 0 | 7 | 1 | 8 |
| Total | 18 | 51 | 24 | 93 |

- 65 gaps need Research & Development

MSAM

ANSI American National Standards Institute

# ASTM Committee F42 on Additive Manufacturing Technologies

ASTM INTERNATIONAL

## Quick facts

- **Formed:** 2009
- **Current Membership:** 1000+ members (Over 30% outside the US)
- **Standards:** 30+ approved, 45+ in development (Jointly with ISO)
- **Meet twice a year, next meeting:** March 2021, Colorado School of Mines
- **Global Representation, including:**

**Argentina**
**Australia**
**Austria**
**Belgium**
**Canada**
**China**
**Czech Republic**
**France**
**Germany**
**India**
**Italy**
**Japan**
**Korea**
**Mexico**
**Netherlands**
**Nigeria**
**Norway**
**Puerto Rico**
**Russian Federation**
**Singapore**
**South Africa**
**South Korea**
**Spain**
**Sweden**
**Switzerland**
**Taiwan**
**United Kingdom**
**United States**

http://www.astm.org/COMMITTEE/F42.htm

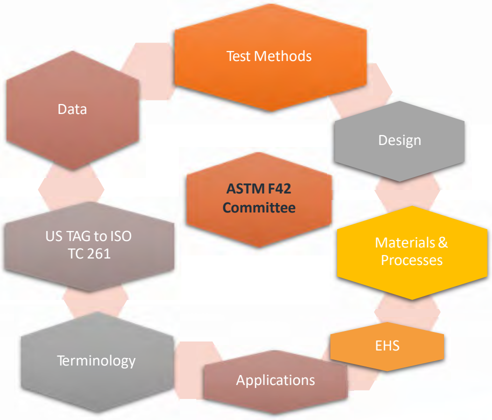
# ASTM Committee F42 Structure

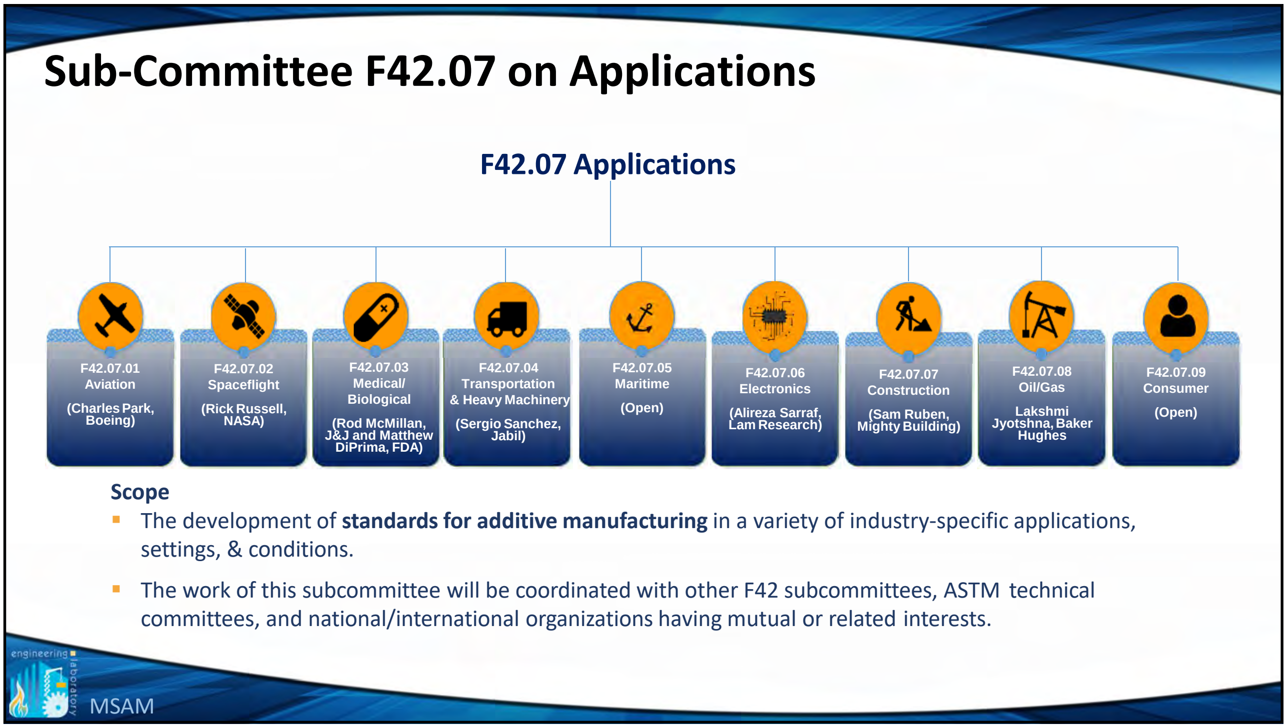
**Standards under the jurisdiction of F42** (https://www.astm.org/COMMIT/SUBCOMMIT/F42.htm )

***Subcommittees*** *address specific segments within the general subject area covered by the technical committee.*

- F42.01 **Test Methods** – Jesse Boyer, Pratt & Whitney
- F42.04 **Design** – David Rosen, GA Tech
- F42.05 **Materials and Processes** – Frank Medina, UTEP/Tim Shinbara, AMT
- F42.06 **Environment, Health, and Safety** – Francoise Richard, P&W Canada
- F42.07 **Applications** – Shane Collins, Additive Industries
- F42.08 **Data –** Alex Kitt, EWI
- F42.90 **Executive** – John Slotwinski, JHU/APL
- F42.90.05 **Research and Innovation** – Matt Donovan, Jabil
- F42.91 **Terminology** – Klas Boivie, Sintef
- F42.95 **US TAG to ISO TC 261** – Stacey Clark, US Army

*8 Subcommittees and Focus*





# Sub-Committee F42.07 on Applications

## F42.07 Applications

- **F42.07.01** Aviation (Charles Park, Boeing)
- **F42.07.02** Spaceflight (Rick Russell, NASA)
- **F42.07.03** Medical/ Biological (Rod McMillan, J&J and Matthew DiPrima, FDA)
- **F42.07.04** Transportation & Heavy Machinery (Sergio Sanchez, Jabil)
- **F42.07.05** Maritime (Open)
- **F42.07.06** Electronics (Alireza Sarraf, Lam Research)
- **F42.07.07** Construction (Sam Ruben, Mighty Building)
- **F42.07.08** Oil/Gas Lakshmi Jyotshna, Baker Hughes
- **F42.07.09** Consumer (Open)

**Scope**

- The development of **standards for additive manufacturing** in a variety of industry-specific applications, settings, & conditions.
- The work of this subcommittee will be coordinated with other F42 subcommittees, ASTM technical committees, and national/international organizations having mutual or related interests.

# ASTM: AM Footprint Across Committees

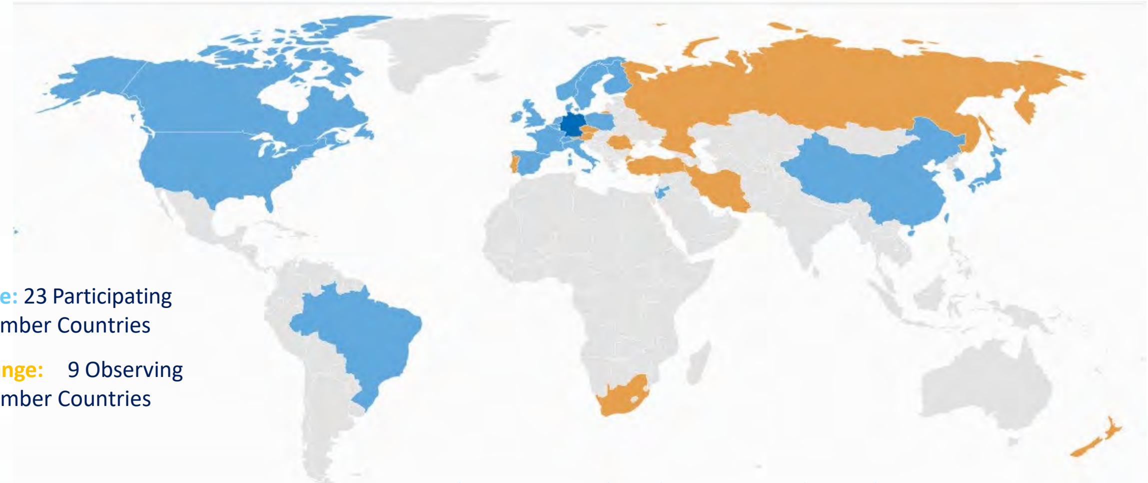
- **Breadth**
  - More than 20 AM relevant Committees
  - 1000+ standards applicable to AM
  - 2000+ technical experts
- **Collaboration**
  - PSDO – ISO TC261 (CEN TC438)
  - MOU & Membership – America Makes
  - MOU – SME
  - Liaison Agreement – 3MF
  - Strategic Relationships – NIST, NASA, FAA, FDA, DOD, ….

# ISO Technical Committee 261 on Additive Manufacturing

- TC261 Working Groups established for:
  - WG1 – Terminology
  - WG2 – Processes, Systems, and Materials
  - WG3 – Test Methods and Quality Specifications
  - WG4 – Data and Design
  - WG6 – Environment, Health, and Safety
  - JWG10 (with ISO TC44) – AM in Aerospace Applications
  - JWG11 (with ISO TC61) – AM for Plastics

https://www.iso.org/committee/629086.html

# ISO TC 261: Participating (P) and Observing (O) Members



- **Blue:** 23 Participating Member Countries
- **Orange:** 9 Observing Member Countries

**+ 26 liaisons with other ISO technical committees for cooperation**

## 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 dual-logo 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"

## Some Details of the F42 / TC261 Collaboration

- New Work Items offered to the partner body
- If accepted, draft standards developed by Joint Groups and reviewed by both organizations
- Parallel ASTM and ISO ballots
  - ISO/TC 261: "Draft International Standard" (DIS) ballot; 3-month balloting cycle, an FDIS ballot may be needed…
  - ASTM F42: Final balloting; 30-days balloting cycle
- Editorial changes are allowed; comments resulting from ASTM balloting can be submitted into the ISO balloting process
- Separate (new) fast-tracking process allowed within ISO
- Publication, copyright, and commercial arrangements

# ISO TC261 / ASTM F42 – Guiding Principles for Standards Development

01 ***Trusted***

One set of AM standards to be used all over the world

02 ***Similarity***

Common roadmap and organizational structure for AM standards

03 ***Don't reinvent the wheel***

Use and build upon existing standards, modified for AM when necessary

04 ***Partnerships***

Emphasis on joint standards development, co-located meetings, etc.

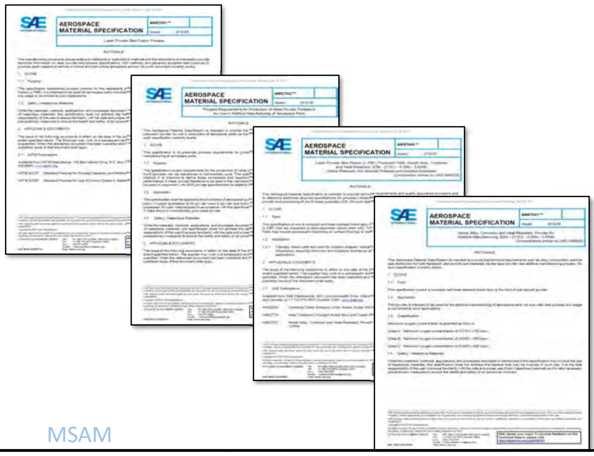
engineering laboratory MSAM

17

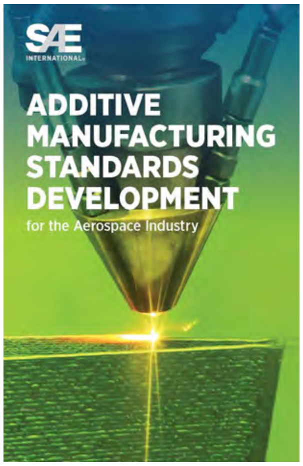
# SAE International: Aerospace Material Specifications for Additive Manufacturing (AMS-AM)

## Committee Scope

*To develop and maintain aerospace material and process specifications for additive manufacturing…*



SAE AEROSPACE MATERIAL SPECIFICATION



MSAM

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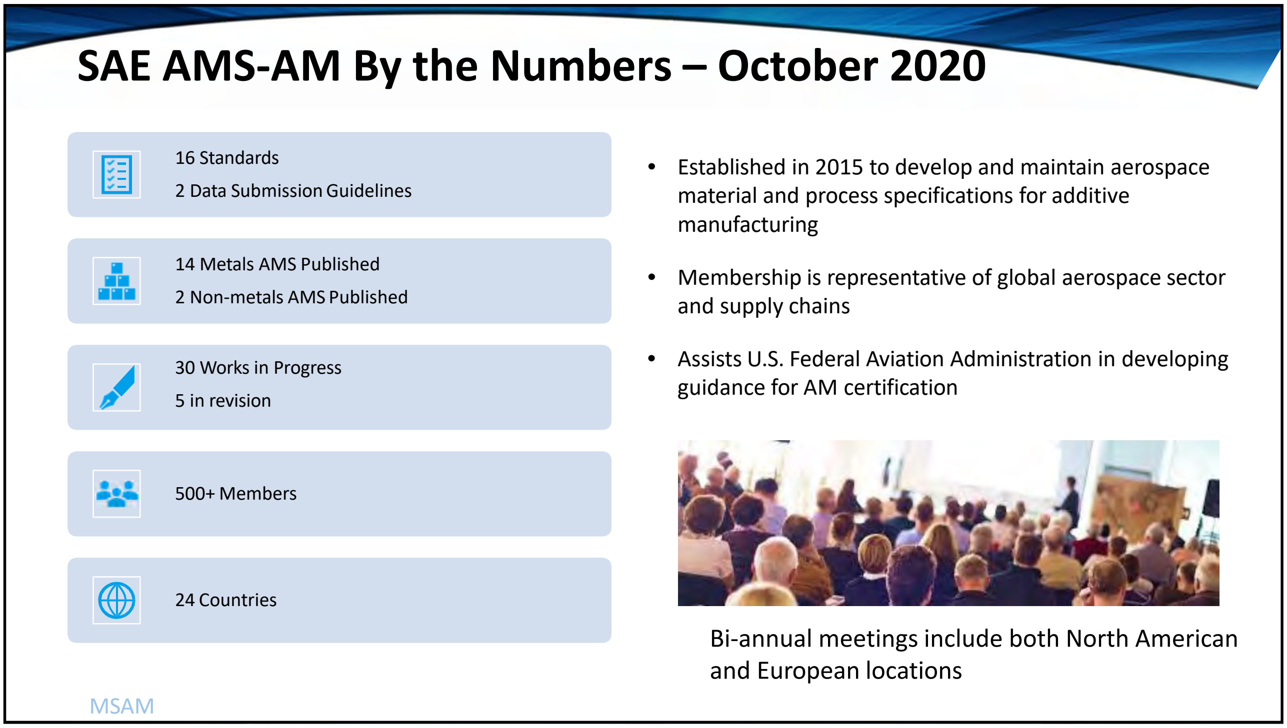


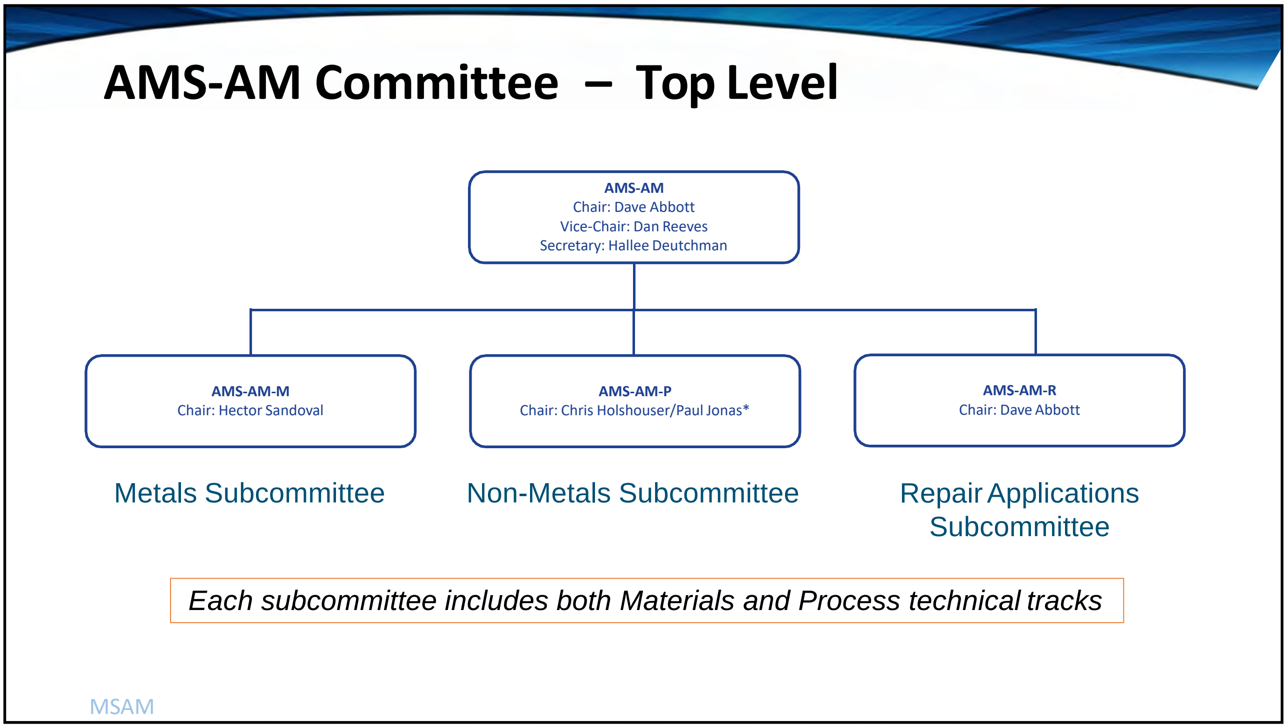
# SAE AMS-AM By the Numbers – October 2020

- 16 Standards
  2 Data Submission Guidelines
- 14 Metals AMS Published
  2 Non-metals AMS Published
- 30 Works in Progress
  5 in revision
- 500+ Members
- 24 Countries

- Established in 2015 to develop and maintain aerospace material and process specifications for additive manufacturing
- Membership is representative of global aerospace sector and supply chains
- Assists U.S. Federal Aviation Administration in developing guidance for AM certification

Bi-annual meetings include both North American and European locations

MSAM



# AMS-AM Committee – Top Level

**AMS-AM**
Chair: Dave Abbott
Vice-Chair: Dan Reeves
Secretary: Hallee Deutchman

**AMS-AM-M**
Chair: Hector Sandoval

Metals Subcommittee

**AMS-AM-P**
Chair: Chris Holshouser/Paul Jonas*

Non-Metals Subcommittee

**AMS-AM-R**
Chair: Dave Abbott

Repair Applications Subcommittee

*Each subcommittee includes both Materials and Process technical tracks*

MSAM

# Current SAE Specification Framework

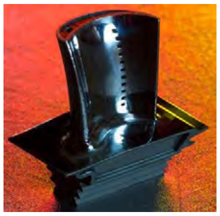
*Aerospace Material Specification*
- *Process Specification*
- *Feedstock Material Specification*
  - *Feedstock Process Specification*

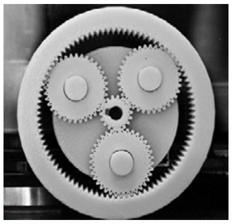
- Hierarchical framework
- Defines requirements and establishes controls
- Framework combines Performance-based and Pseudo-prescriptive (establish controls and provide substantiation)

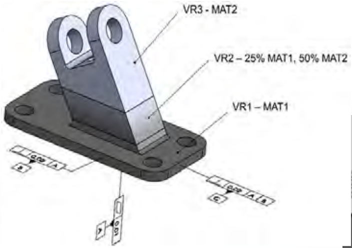
**Control = Quality + Consistency**

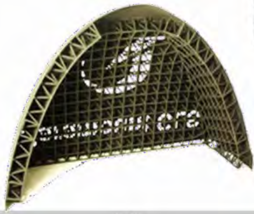
# ASME Y14.46 Standards Committee

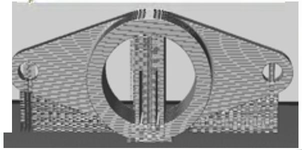
- ASME Y14.46-2017, Product Definition for AM
- Geometric Dimensioning & Tolerancing (GD&T) requirements that are ***unique to additive manufacturing***
  - free-form complex surfaces; internal features; lattice structures; support structures; as-built assemblies; build-direction dependent properties; multiple / functionally-gradient materials, etc.
- GD&T: the language for communicating geometric tolerance specification and design intent from designers to manufacturing / quality engineers







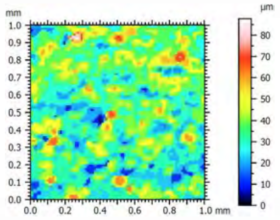




# ASME B46 Project 53 - Surface Finish for AM

- Composed of surface metrology experts associated with ASME B46: Classification and Designation of Surface Qualities
- White paper and preliminary work item for surface attributes and corresponding characterization methods relevant to components made with additive manufacturing
- Several open research questions remain; no consensus at this time; associated standards are in early phase of discussion / development
    - For example: typical surface characterization parameters (such as Ra, arithmetic average of roughness profile) may not be the best approach for describing complex AM surfaces

ASME
SETTING THE STANDARD



Sample surface map

# Other Related ASME Standards Activities

ASME Y14 Committee
- Y14.41-2019, Digital Product Definition Data Practices
- Y14.47-2019, Model Organization Practices
- Y14.48, Universal Direction and Load Indicators (in development)

ASME Manufacturing and Advanced Manufacturing (MAM) Standards Committee
- New subcommittee on Additive Manufacturing

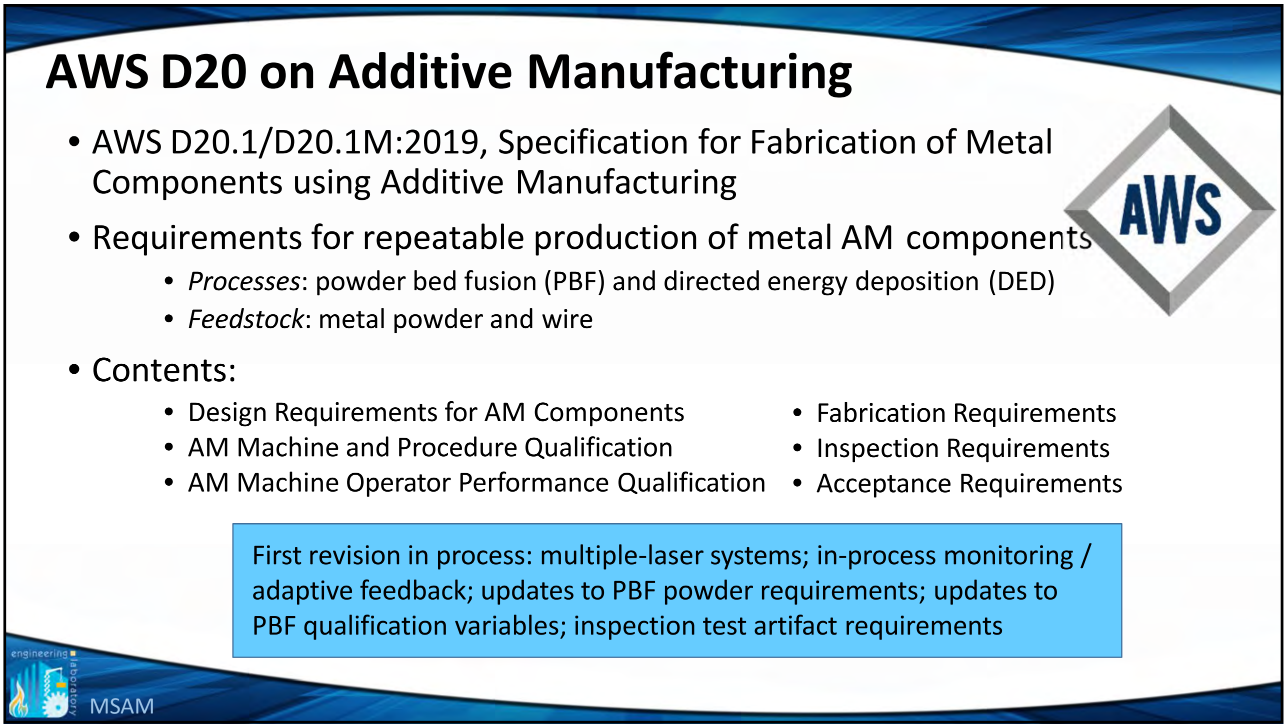
ASME Model-Based Enterprise (MBE)
- Rules, guidance, and examples for the creation, use, and reuse of model-based datasets, data models, and related topics within a Model-Based Enterprise
- Starting point:
  MBE Standards Recommendation Report (Dec 2018): direction, activities, priorities, organization, roadmap for standards process

ASME Special Committee On Use Of Additive Manufacturing For Pressure Retaining Equipment
- To develop a technical baseline to support development of a proposed BPTCS standard or guideline addressing the pressure integrity governing the construction of pressure retaining equipment by additive manufacturing processes.

ASME Verification and Validation (V&V) Committee
- V&V 50, Computational Modeling for Advanced Manufacturing (launched in 2016)

ASME B89.4.23 Committee
- Performance Evaluation of Computed Tomography Systems

ASME Committee on Digital Engineering / Big Data / Digital Transformation (forming in 2021)



# AWS D20 on Additive Manufacturing

- AWS D20.1/D20.1M:2019, Specification for Fabrication of Metal Components using Additive Manufacturing
- Requirements for repeatable production of metal AM components
  - *Processes*: powder bed fusion (PBF) and directed energy deposition (DED)
  - *Feedstock*: metal powder and wire
- Contents:
  - Design Requirements for AM Components
  - AM Machine and Procedure Qualification
  - AM Machine Operator Performance Qualification
  - Fabrication Requirements
  - Inspection Requirements
  - Acceptance Requirements

First revision in process: multiple-laser systems; in-process monitoring / adaptive feedback; updates to PBF powder requirements; updates to PBF qualification variables; inspection test artifact requirements

MSAM

# NIST Perspectives on AM Standards

- NIST continues to support and influence AM standards development through measurement science research and service on standards committees
  - Contributions to more than 40 AM standards activities across several standards bodies
  - Multiple leadership roles, including with ANSI Additive Manufacturing Standards Collaborative
- **NIST Motivations / Future Vision:**
  - 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 essential to achieve this vision and to drive consensus standards that enable trade in global markets
  - AM users, standards bodies, vendors, technology providers, regulatory agencies, etc. all play a role
  - Challenges continue to grow due to technology advancements and rapidly-changing environment
- Much progress and cooperation to-date; definitely **successes to build upon**!
  - e.g., AMSC interactions; multi-logo standards; AM standards structure; many liaisons; terminology

**Your ideas, participation, expertise, and help are welcomed and appreciated!**

# Questions and Discussion

**Contact:**

**Kevin Jurrens**

**[kevin.jurrens@nist.gov](mailto:kevin.jurrens@nist.gov)**

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

# Key References for AM Standards Landscape

- AMSC, AM Standardization Roadmap and AM Standards Landscape: https://www.ansi.org/amsc
- ASTM F42: https://www.astm.org/COMMITTEE/F42.htm
- ASTM AM Center of Excellence: https://amcoe.org/
- ISO TC261: https://www.iso.org/committee/629086.html
- SAE: https://www.sae.org/works/committeeHome.do?comtID=TEAAMSAM
- SAE AM Data Consortium: https://www.sae-itc.com/amdc
- AWS D20: https://www.aws.org/standards/committee/d20-committee-on-additive-manufacturing-2
- ASME Y14.46: https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=100749850
- ASME MBE Standards Recommendations Report: http://go.asme.org/MBEreport
- MMPDS: https://www.mmpds.org/
- CMH-17: https://www.cmh17.org/HOME/AdditiveManufacturing.aspx
- Workshop Proceedings, Strategic Guide for AM Data Management and Schema: https://amcoe.org/rd-publications

Savannah River
National Laboratory®

# ASME Criteria for Powder Bed Fusion Additive Manufacturing

*ASME Special Committee on Additive Man*

George Rawls
Advisory Engineer SRNL

*NRC Advanced Manufacturing Workshop*
*December,3 2020*

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- What is Additive Manufacturing
- Additive Manufacturing (AM) - a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.
- Subtractive Manufacturing - making objects by removing material (for example, milling, drilling, grinding, etc.) from a bulk solid to leave a desired shape.

Subtractive

Additive

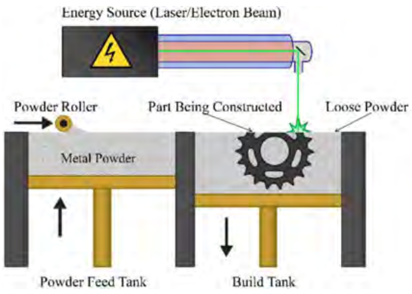
Additive + Subtractive

Application will require additive joined to non-additive

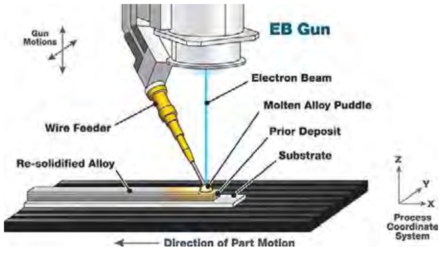
## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Additive Manufacturing Technologies

Powder Bed Fusion



Direct Energy Deposition



## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- The ASME Special Committee has produced a final draft document providing <u>Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing.</u>

- The document is intended to provide criteria on the materials, design, fabrication, examination, inspection, testing and quality control essential to be addressed in any proposed standard for the construction of metallic pressure retaining equipment using powder bed fusion additive manufacturing.
- The additive manufacturing criteria document addresses the follow areas.

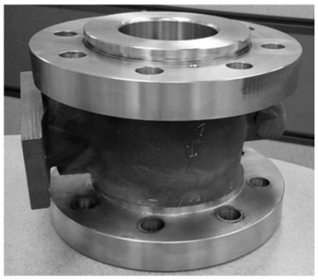
- Scope
- Additive Manufacturing Specification
- Materials
- Thermal Treatment
- Powder Requirements
- Additive Manufacturing Design Requirements
- Additive Manufacturing Procedure
- Additive Manufacturing Procedure Qualification
- Qualification Testing of Additive Manufactured Components
- Production Builds
- Chemistry Testing
- Mechanical Property Testing
- Metallographic Evaluation
- Referenced Standards
- Definitions
- Records
- Quality Program

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Scope
  - These criteria address the construction of pressure retaining equipment using the Additive Manufacturing (AM) Powder Bed Fusion process using both Laser and Electron Beam energy sources.
  - Hybrid construction incorporating AM components joined (Welded or Brazed) to non-AM components is acceptable. Additive manufactured components joined to other AM components or non-AM components shall follow the requirements for the applicable ASME Construction Code or Standard.
  - The pressure design for components shall follow the requirements of the applicable ASME Construction Code or Standard.
  - The maximum design temperature shall be at least 50°F (25° C) colder than the temperature where time-dependent material properties begin to govern for the equivalent wrought ASME material specification, as indicated in ASME Section II, Part D [15.1].
  - The minimum design temperature shall follow the requirements for the applicable ASME Construction Code or Standard.

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Materials
  - Material for the purpose of this specification is defined as the additively manufactured component in its final heat-treated condition.
  - The Additive Manufacturer shall select a listed wrought ASME material specification from ASME Section II for the component material.
  - The requirements for chemical composition, grain size, hardness, final heat treatment and mechanical properties shall be identical to the requirement of the ASME material specification.

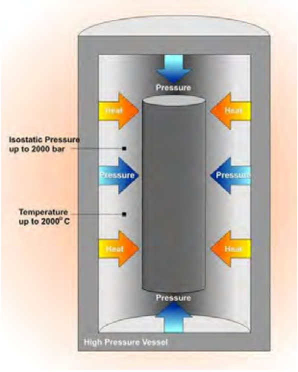


Valve Body Fabricated Using
Powder Bed Fusion AM
Courtesy of Emerson

- The AM Committee basically followed the same criteria for materials that was used in the codification of component fabricated using the powder  metallurgy

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

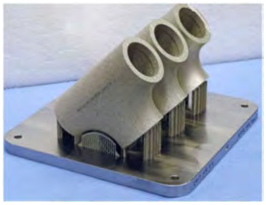
- Thermal Treatment
  - The final heat treatment requirements applied to the AM material shall be identical to those applied to the ASME material specification.
  - Additional intermediate thermal treatment is acceptable. Intermediate thermal treatment may include stress relief, hot isostatic pressing or other thermal processing.
  - When intermediate thermal treatment is performed ASTM F3301 [15.2] may be used as guidance.
  - When hot isostatic pressing is performed ASTM A988 [15.3] or ASTM A1080 [15.4] may be used as guidance.
  - All material testing shall be performed on material specimens in the final heat-treated condition ASME material specification.



Schematic of the Hot Isostatic Pressing Process

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Design
  - In addition to the design requirements of the ASME Construction Code or Standard the following design requirements apply for components produced using the powder bed fusion AM process.
  - Any material produced during the AM build that is specified as cosmetic material shall not be credited as load bearing material in the stress analysis.
  - Fatigue critical surfaces shall be designed to be accessible for liquid penetrant examination.
  - Surfaces interfacing with sacrificial supports shall be fully accessible for removal of supports and for liquid penetrant examination.
  - The effect of any support that will not be removed following the AM build shall be included in the stress analysis.

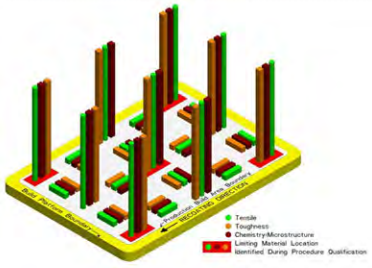


Sacrificial Supports
Courtesy of Rolls- Royce

Permanent Supports

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

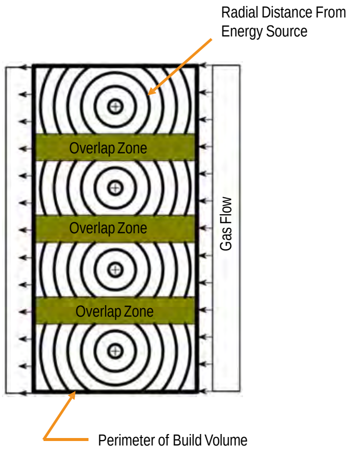
- Additive Manufacturing Procedure
  - Additive Manufacturing Procedure
    - The Additive Manufacturer shall prepare an Additive Manufacturing Procedure.
    - The AM Procedure shall address applicable process variables.
    - The Additive Manufacturer shall complete sufficient qualification builds and produce sufficient material qualification specimens to support a 95% confidence that 99% of the produced material is in accordance the ASME material specification.
    - The Additive Manufacturer shall identify the locations of limiting material conditions for each energy source.

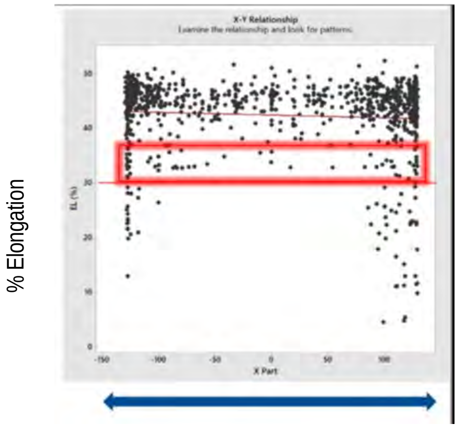


Material Qualification Specimens for Additive Manufacturing Procedure Qualification
Courtesy of Emerson

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Additive Manufacturing Procedure Qualification
  - Limiting material conditions for each energy source.





Radial Distance From Energy Source
Courtesy of Emerson

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Qualification Testing of Additive Manufactured Components
  - Fabricated components shall be subjected to qualification testing.
  - Correlation between the samples and the actual component.
- Prototype Testing Requirements

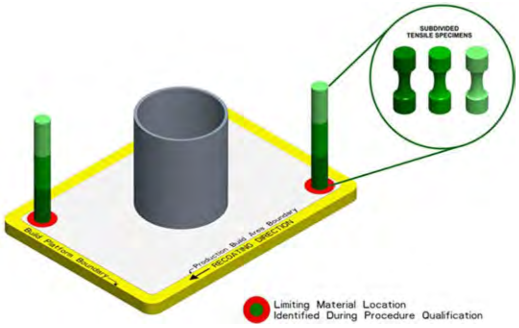
| Prototype Test | Number of Prototypes | Test Criteria |
|---|---|---|
| Proof | 1 | Section 9.12 |
| Fatigue | 2 to 5 | Section 9.13 |
| Material Properties | 1 | Sections 12-14 |
| Toughness | 1 | Construction Code |

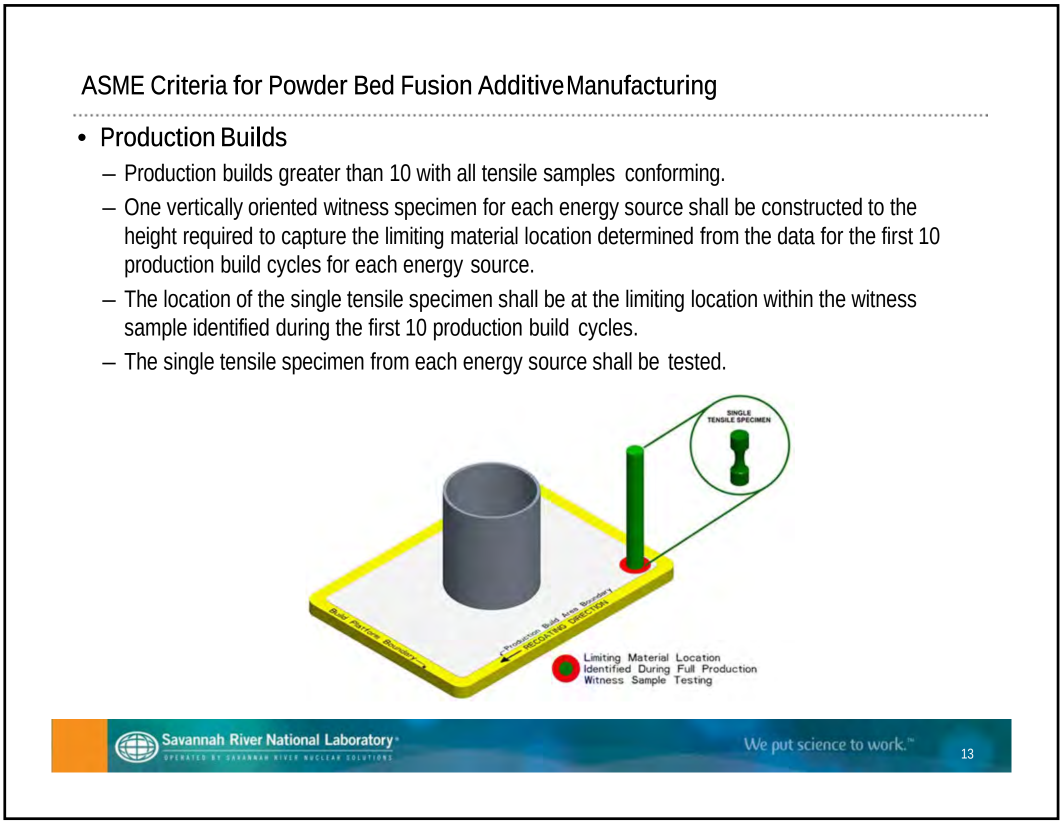
- Locations for Material Qualification Specimens for Component Qualification Build

| Location | Description | Minimum Samples |
|---|---|---|
| CQ1 | Locations of limiting material conditions identified during the procedure qualification. | 2 per Energy Source |
| CQ2 | Thinnest pressure retaining feature in the component | 1 |
| CQ3 | Highest stressed location in the component | 1 |

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

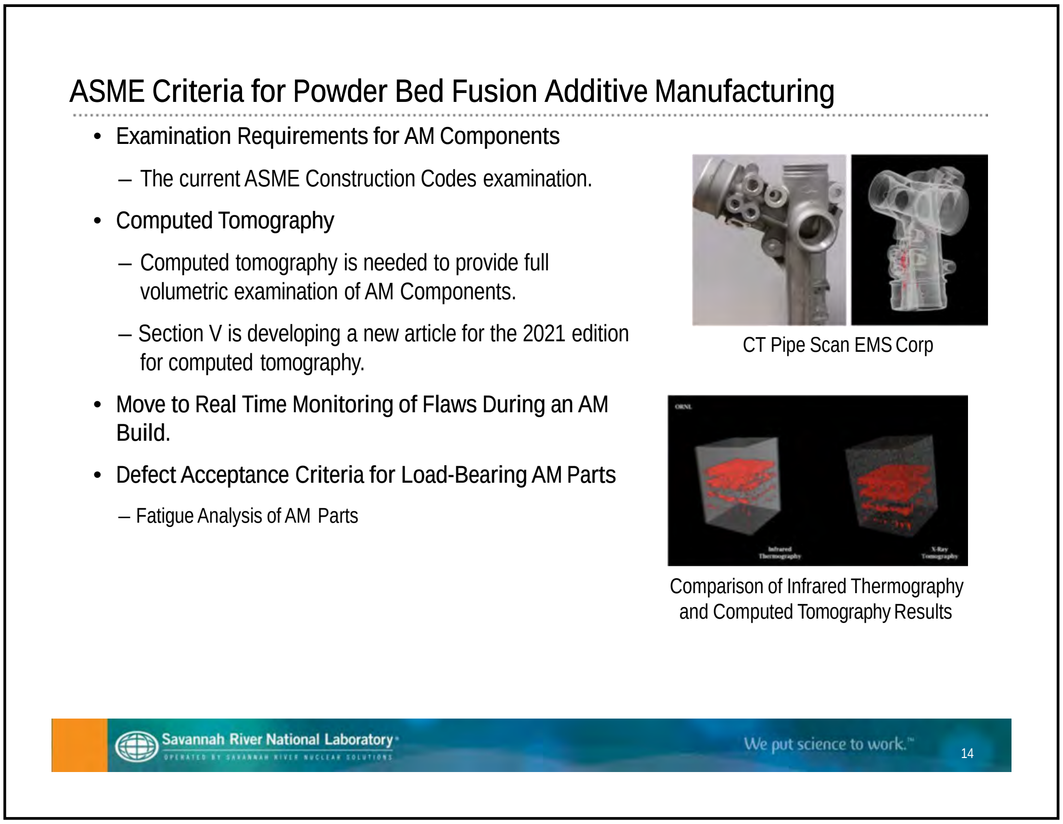
- Production Builds
  - First 10 Production Builds
  - A vertically oriented witness specimen shall be constructed over the total height of the build volume at a minimum of 2 locations of limiting material conditions determined during procedure qualification for each energy source.
  - Witness specimens shall be subdivided when required to meet the requirement of ASTM E8.
  - All tensile specimens from each energy source shall be tested.





## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Production Builds
  - Production builds greater than 10 with all tensile samples conforming.
  - One vertically oriented witness specimen for each energy source shall be constructed to the height required to capture the limiting material location determined from the data for the first 10 production build cycles for each energy source.
  - The location of the single tensile specimen shall be at the limiting location within the witness sample identified during the first 10 production build cycles.
  - The single tensile specimen from each energy source shall be tested.



## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Examination Requirements for AM Components
  - The current ASME Construction Codes examination.
- Computed Tomography
  - Computed tomography is needed to provide full volumetric examination of AM Components.
  - Section V is developing a new article for the 2021 edition for computed tomography.
- Move to Real Time Monitoring of Flaws During an AM Build.
- Defect Acceptance Criteria for Load-Bearing AM Parts
  - Fatigue Analysis of AM Parts

CT Pipe Scan EMS Corp

Comparison of Infrared Thermography and Computed Tomography Results

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

- Path Forward
  - The intent is to publish the ASME Criteria for Powder Bed Fusion Additive Manufacturing as a Pressure Technology Book (PTB) for use as a reference document for additive manufacturing Code Cases or incorporation of additive manufacturing into construction codes.
  - It will also serve as the baseline for future development of an ASME AM standard by an ASME Standards Committee.
    - *ASME has submitted a* Project Initiation Notification *with ANSI stating that they will develop a standard for additively manufactured pressure equipment.*

## ASME Criteria for Powder Bed Fusion Additive Manufacturing

# QUESTIONS

# Approach to Codifying New Manufacturing Methods (e.g., PM-HIP, LPBF, EBW)

Brian Frew
Consulting Engineer, Materials and Chemistry, GEH
David W. Gandy,
Sr. Technical Executive, Nuclear Materials, EPRI

NRC Advanced Manufacturing Virtual Workshop
December 7-10, 2020

www.epri.com

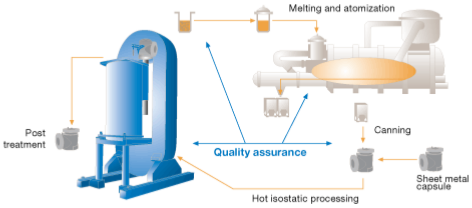
## Outline

- What's missing today from the Code?
- What are the gaps that need to be addressed?
- What alloys need to be qualified?

- Four manufacturing methods reviewed herein:
  - Powder metallurgy-hot isostatic pressing
  - Cold spray welding/cladding
  - Laser powder bed fusion-additive manufacturing
  - Electron beam welding

# Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

- **What's missing today from the Code?**
  - Permitted by several Code Cases (see next slide
- **What alloys need to be qualified?**
  - **Alloy 600M (N-580-2)**
  - **Alloy 625**
  - **Alloy 690**
  - **Alloy 718**
  - **Low Alloy Steel**



https://www.materials.sandvik/en-us/products/hot-isostatic-pressed-hip-products/production-process/

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# ASME Code Cases

- ASME Code Cases
  - **CC N-834** – 316L SS (nuclear)
  - **CC 2770** – Grade 91 (fossil)
  - **B31.1 CC** Approved—Grade 91
  - **Section VIII CC – Div. 1 and 2** -- 29Cr-6.5Ni-2Mo-N (S32906)—Duplex SS
- *Incorporation* ASTM A988, A989, and B834 into ASME Section II
- Section II—Appendix 5

Designation: A989/A989M – 11

Standard Specification for
Hot Isostatically-Pressed Alloy Steel Flanges, Fittings, Valves, and Parts for High Temperature Service[1]

1. Scope*

1.1 This specification covers hot isostatically-pressed, powder metallurgy, alloy steel piping components for use in pressure systems. Included are flanges, fittings, valves, and similar parts made to specified dimensions or to dimensional standards, such as in ASME Specification B16.5.

1.2 Several grades of alloy steels are included in this specification.

1.3 Supplementary requirements are provided for use when additional testing or inspection is desired. These shall apply only when specified individually by the purchaser in the order.

1.4 This specification is expressed in both inch-pound units and in SI units. Unless the order specifies the applicable "M" specification designation (SI units), however, the material shall be furnished to inch-pound units.

1.5 The values stated in either inch-pound units or SI units are to be regarded separately as the standard. Within the text, the SI units are shown in parentheses. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the specification.

1.6 The following safety hazards caveat pertains only to test methods portions, 8.1, 8.2, and 9.5-9.7 of this specification: *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
A275/A275M Practice for Magnetic Particle Examination of Steel Forgings
A751 Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
A961/A961M Specification for Common Requirements for Steel Flanges, Forged Fittings, Valves, and Parts for Piping Applications
B311 Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
E165 Practice for Liquid Penetrant Examination for General Industry
E340 Test Method for Macroetching Metals and Alloys
E606 Practice for Strain-Controlled Fatigue Testing

2.2 *MSS Standard:*
SP 25 Standard Marking System for Valves, Fittings, Flanges, and Unions[3]

2.3 *ASME Specifications and Boiler and Pressure Vessel Codes:*
B16.5 Dimensional Standards for Steel Pipe Flanges and Flanged Fittings[4]

2.4 *ASME Section IX Welding Qualifications:*
SFA 5.5 Specification for Low-Alloy Steel Covered Arc-Welding Electrodes[4]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

* This CC initiated by Sandvik

## Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

- **What are the gaps that need to be addressed?**
  - ***Material standards*: Additional ASTM specifications need to be developed for Ni-base alloys and low alloy steel (A 508 equivalent)**
  - ***Code Cases:*** Needed for the additional alloys
  - ***Environmental data****:* stress corrosion cracking needs to be developed for Ni-base alloys
  - ***Low Alloy Steels:*** welding acceptability needs to be confirmed.
  - ***Fracture toughness****:* Needed for low alloy steels
  - ***Irradiation Data*** –Some data under development by EPRI/INL.
  - ***Creep data***– necessary for Division 5 applications

## Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

- Near term needs
  - Low Alloy steel (A 508 equivalency)
    - Material specification
    - Section III Code Case
  - Nickel Base Alloys
    - Alloy 600M, 625, 690, 718
    - Code Cases
- Longer term
  - Grade 91
  - Type 316H
  - Alloy 617
  - Hardfacing alloys (composite PM-HIP)

## Cold Spray Additive Manufacturing

- Technique results in a mechanical bond
  - Repair of existing material
  - Surface cladding

Image courtesy of GE reports

## Cold Spray Additive Manufacturing

- What's missing today from the Code?
  - Process is not recognized by the Code
- **What alloys need to be qualified?**
  - **Austenitic stainless steel**
  - **Alloy 625**
  - **Alloy 690**
  - **Alloy 718**
  - **Low Alloy Steel**

## Cold Spray Additive Manufacturing

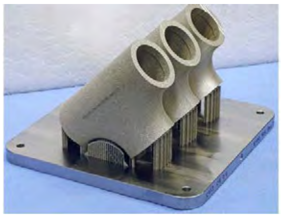
- What are the gaps that need to be addressed?
  - Material Standard necessary
  - Material sampling plan for mechanical properties
  - Process qualification requirements - not covered by Section IX
  - RT is typically used for castings
  - UT examination for bond
  - Alternative methods may be necessary

## Laser Powder Bed Fusion-Additive Manufacturing

- **What's missing today from the Code?**
  - LPBF-AM is not currently addressed by ASME or NRC.
  - ASME BPTCS/BNCS *Special Committee on AM for Pressure Retaining Equipment* is currently assembling a Guidelines for "Control of PBF processes to fabricate and test AM pressure-retaining components."
  - Each ASME Book Section will then need to incorporate the guidance into the appropriate Book (I, III, VIII, etc.) for application
  - DRAFT Code Case for 316L SS LPBF-AM submitted to BPV-III (by Westinghouse/EPRI)

- **What alloys need to be qualified?**
  - Stainless steels: 316L, 304L, 316H, 709, 17-4PH
  - Nickel-based alloys: 617, 625, 690, 725, X-750, Alloy X
  - Titanium-based alloys: Ti6Al4V
  - Zirconium-based alloys: Zircaloys?

## Laser Powder Bed Fusion-Additive Manufacturing



- **What are the gaps that need to be addressed?**

Materials Properties Gaps

- Time dependent and independent materials properties
- Fatigue (smooth and as deposited) properties
- Fracture toughness properties
- Irradiation and thermal aging properties
- SCC properties

Processing Gaps

- Processing—Establish essential variables (next slide)
- HIP vs no-HIP application and properties

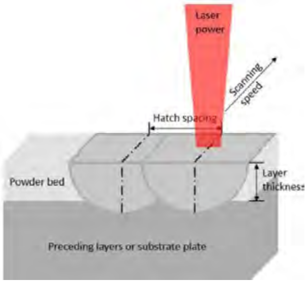
NDE Gaps

- Defect acceptance criteria
- Detection limits
- Disposition

## Laser Powder Bed Fusion-Additive Manufacturing

Essential Variables may include:

- Laser power
- Exposure time
- Point distance
- Scanning speed
- Layer thickness
- Hatch spacing or hatch distance
- Stripe width
- Scan strategy
- Pulse characteristics
- Beam diameter
- Energy density
- Gas flow and gas composition
- Re-coater blade type
- Beam focus distance



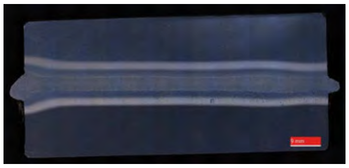
Overview of LPBF-AM deposition on a substrate plate

# Electron Beam Welding

## – List of Pertinent ASME Docs for EBW of Thick Section Components

**Section III**

- NB-4311 *Types of Processes Permitted*
  - Any process used shall meet the records required by NB-4320
- NB-4320 *Welding Qualifications, Records and Identifying Stamps*
- NB-5277 *Examination of EB Welds*



**110mm (thick) EB Weld**

**Section IX**

- QW-215 *Electron Beam Welding and Laser Beam Welding*
  - WPS qualification test coupons shall be prepared w/ the joint geometry duplicating that to be used in production.
  - If the production weld is to include a lap-over (completing the weld by rewelding over the starting area of the weld, as a girth weld), such lap-over shall be included in the WPS qualification test coupon.
  - The mechanical testing requirements of QW-451 shall apply.
- QW-260 – *Essential Variable Procedure Specifications (WPS) for Electron Beam Welding*
- QW-451 – *Procedure Qualification Thickness Limits and Test Specimens*
  - Groove-Weld Tension Tests and Transverse Bend Tests

# Electron Beam Welding

*Photograph provided courtesy: Nuclear AMRC (UK)*

- **What's missing today from the Code?**
  - EBW <u>is already permitted</u> for nuclear pressure retaining components under Section III, NB-4311 and Section IX QW-215.
- **What alloys need to be qualified?**
  - No preheat on low alloy steel (SA 508 Class 1-2) – see next slide.
  - No additional requirements for Stainless steels or Nickel-based alloys

## Electron Beam Welding

- **What are the gaps that need to be addressed?**
  - EBW is performed in a vacuum chamber, thus ***moisture/hydrogen*** is not present and not an issue.
  - For Low Alloy Steels, welding ***without preheat*** will need to be qualified and codified.
  - ***Irradiation Data*** – US & UK Naval programs have this information. Some data under development by Purdue/EPRI/ATR.
  - ***Long-term Thermal Embrittlement*** – Same, US & UK Naval programs
  - ***Residual Stress Data*** – Collaborative project (EPRI, U. of Manchester, Nuclear AMRC developed data). Also, TWI.
  - ***Operator Qualification*** – Difficult to convert conventional welder to EBW operators. CNC machinists can often be converted to EBW operators.

## Summary – Major Gaps

- Powder metallurgy-hot isostatic pressing
  - Limited material acceptance (Nuclear)
  - Material data
  - Size limitations
- Cold spray welding/cladding
  - Not accepted currently by ASME BPVC
  - Additional alloys, Process qualification, NDE gaps
- Laser powder bed fusion-additive manufacturing
  - Not accepted currently by ASME BPVC
  - Additional alloys, processing gaps, NDE gaps
- Electron beam welding
  - No preheat (in vacuum)
  - Irradiation and long-term thermal embrittlement
  - Welding residual stresses

Together…Shaping the Future of Electricity

HITACHI

EPRI ELECTRIC POWER RESEARCH INSTITUTE

# America Makes Efforts Relevant to AM for Nuclear Applications

9 December 2020

**Brandon D. Ribic, PhD.**
Technology Director, America Makes
Brandon.Ribic@ncdmm.org

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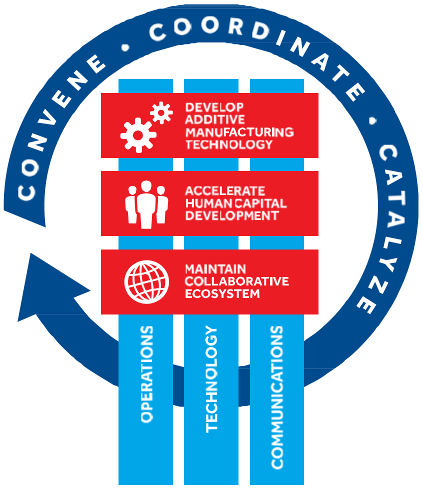
## Overview

*The three core activities of the Institute are:*

- **Develop Additive Manufacturing Technology:** Projects, Innovation, Technology Transfer, Implementation
- **Accelerate Human Capital Development:** Workforce, Education, Training, Outreach
- **Maintain Collaborative Ecosystem:** Government, Membership, Community

*These focus areas are enabled by:*

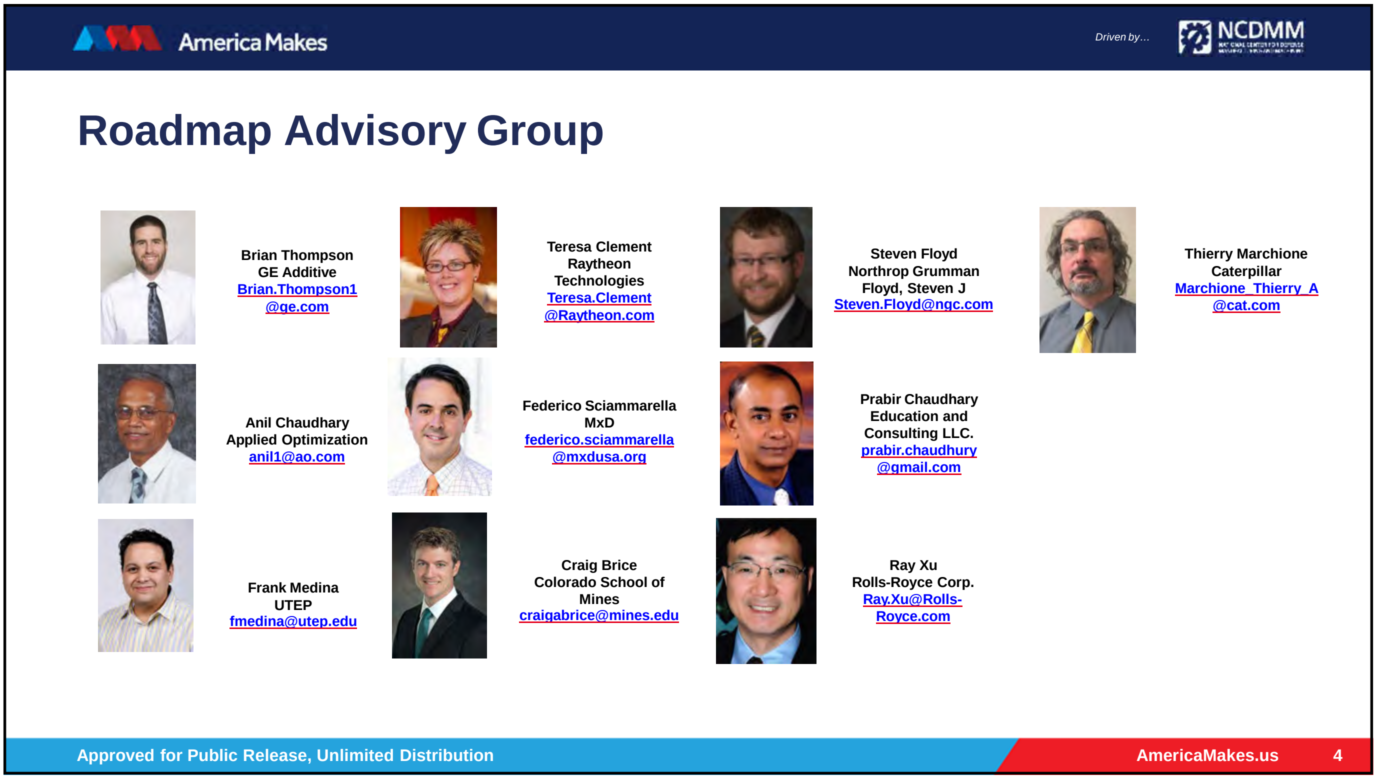
- **Operations:** Run by a not-for-profit organization with a lean and collaborative structure
- **Technology:** A dynamic advanced manufacturing technology including the core AM technologies as well as supporting technologies like the digital thread, standards, etc.
- **Communications:** Spreading the word to government, members, stakeholders, community



# Collaboration Drives Our Strategic Focus

- Focus and strategy is documented within the Technology Roadmap
  - Application/process agnostic
  - Informed by not only end users
- Multitude of interconnected technical considerations
  - TRL 4-7
  - Address risk and maturation
  - Assess performance/function
- Roadmap is a data model
  - Integral to institute operation
  - Connects research efforts to roadmap taxonomy
  - Identifying needs/opportunities
  - Charting progress
  - Organizes lessons learned

| Swimlane | CTE |
|---|---|
| Design | Bio-Inspired Design & Manufacturing |
| Design | Product & Process Design Aides/Apps |
| Material | Material Property Characterization |
| Material | Next-Gen Materials |
| Material | Additive Manufacturing Tech Data Packages |
| Process | Multi-Material Delivery & Deposition Systems |
| Process | Next-Gen Machines |
| Process | Process Temperature Gradient Control |
| Value Chain | Advanced Sensing & Detection Methods |
| Value Chain | Cost & Energy Driver Analysis/Modeling |
| Value Chain | Digital Thread Integration |
| Value Chain | Intelligent Machine Control Methods |
| Value Chain | Rapid Inspection (Post-Build) |
| Value Chain | Repair Technologies |
| Value Chain | Standards/Schemas/Protocols |
| AM Genome | Benchmark Validation Use Cases |
| AM Genome | Model-Assisted Property Prediction |
| AM Genome | Physics-Based Modeling & Simulation |



# Roadmap Advisory Group

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## Addressing Technology Gaps to Strengthen Domestic Supply Chain

**Supply Chain & Sourcing**

**Design**

**Performance & Durability**

**Post-Processing & Finishing**

**Inspection/ NDE**

**Cost & Rate**

**Key Additive Manufacturing Technology Focus Areas**

**Strengthen Warfighter Capability Needs**

## Previous and Current Applications

Image courtesy DARPA

http://www.optisurf.com/index.php/mirror-mounts-for-high-precision-optics/

Image credits: Dr. Beth Ripley and Timothy Prestero

Demo part 1: aircraft vent

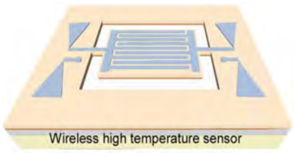
# Merits of Additive Manufacturing for Nuclear Applications

- Design
  - Filtering
  - Thermal management
  - Vibration/shock
  - Part consolidation
  - Tooling, jigs, and brackets

- Materials & Process
  - Tailored material chemistries and microstructures for performance
    - Shielding/passivation
    - Mechanical performance
    - Thermophysical properties
  - Multi-material
    - Metal, polymer, ceramic, composite
    - Part count reduction
    - Embedded sensors
  - Repair, cladding, hard facing
  - Reverse engineering

- Adaptive distributed manufacturing base
  - Adaptable and readily adjusts to iterative/evolving product definition
  - Single article production lots are tolerable
  - Lead time reduction

Image Courtesy of Westinghouse



Lu et al. *AOI2 Wireless High-Temperature Sensor Network for Smart Boiler Systems.* 2020

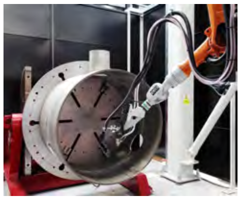


Image Courtesy of Nuclear AMRC

GE Hitachi 2017

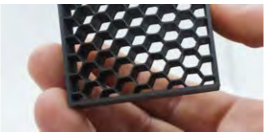


Image Courtesy of Additive Composite

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# Design

- GD&T of metals, polymers, composites

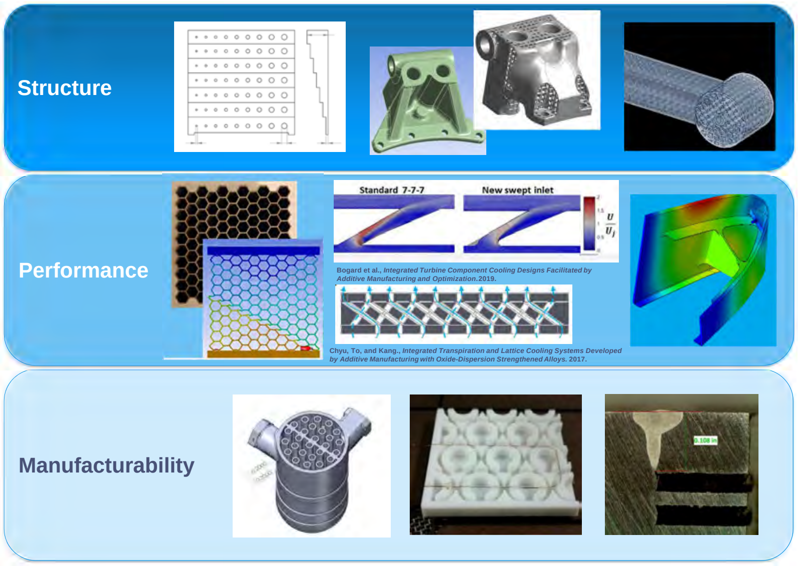
- DfAM
  - Guides, process selection aides, and apps
  - Product development and qualification

- Structural Optimization
  - Including lattice structures

- Materials and data play a vital role

- Design for:
  - Life limited applications
  - Complex parts/assemblies
  - Anisotropic materials
  - Multi-material
  - Multi-process
  - Multi-physics

- Validation and vetting manufacturability and product equivalence to known designs



Structure

Performance

Bogard et al., *Integrated Turbine Component Cooling Designs Facilitated by Additive Manufacturing and Optimization.* 2019.

Chyu, To, and Kang., *Integrated Transpiration and Lattice Cooling Systems Developed by Additive Manufacturing with Oxide-Dispersion Strengthened Alloys.* 2017.

Manufacturability

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# Material

- Material Types
  - Ti, Ni, Al
  - Polymers
  - Composites
- Evaluation of austenitic, ferritic, or PH stainless steels
  - Beyond 718 and 625 nickel alloys
- Pedigreed materials allowable data sets
- Service life modeling – probabilistic approaches
  - Dissimilar materials
  - Elevated temperature
  - Various degradation mechanisms
- Materials which improve system performance
  - Certified as-built
  - Recycling
  - Methods for AM materials development
- Functional testing for equivalence
- Feedstock production capability

**Process**

**Structure**

Chyu, To, and Kang., *Integrated Transpiration and Lattice Cooling Systems Developed by Additive Manufacturing with Oxide-Dispersion Strengthened Alloys.* 2017.

Acharya et al., *Computational Tools for Additive Manufacturing of Tailored Microstructure and Properties.* 2020.

**Properties**

Dryepondt et al., *AM of Nickel Components and Joining of Dissimilar Metal Welds.* 2020.

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# Process

- Advancements in controls, software, and hardware
  - Geometric, microstructural, and performance (quality) enhancements
- Multi-laser/multi-deposition
  - Larger build volumes
  - Increased productivity
  - Expanded capacity/capability
- New capabilities can come with new challenges
- Increased degrees of freedom for operators
  - Scan path optimization tools/methods
  - Process control methods and validation
  - Repeatability
- Transferability between different machine platforms
- Process calibration methods and tools
  - Equipment maintenance

**Control**

**Maintenance & Calibration**

**Expanded Capability**

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## Value Chain

- Physical limits of sensing and inspection technologies
    - Probability of detection
    - Overcoming complexity
- Sourcing and acquisition technology
- Business case analysis
    - Understanding value proposition of AM
- Novel test methods needed
    - Validation
- Cybersecurity
- Rapid inspection
- Digital twins which account for:
    - Manufacturability
    - Multiple manufacturing operations
    - Product variability/quality control

Qual/ Cert

Cost

Digital Capability

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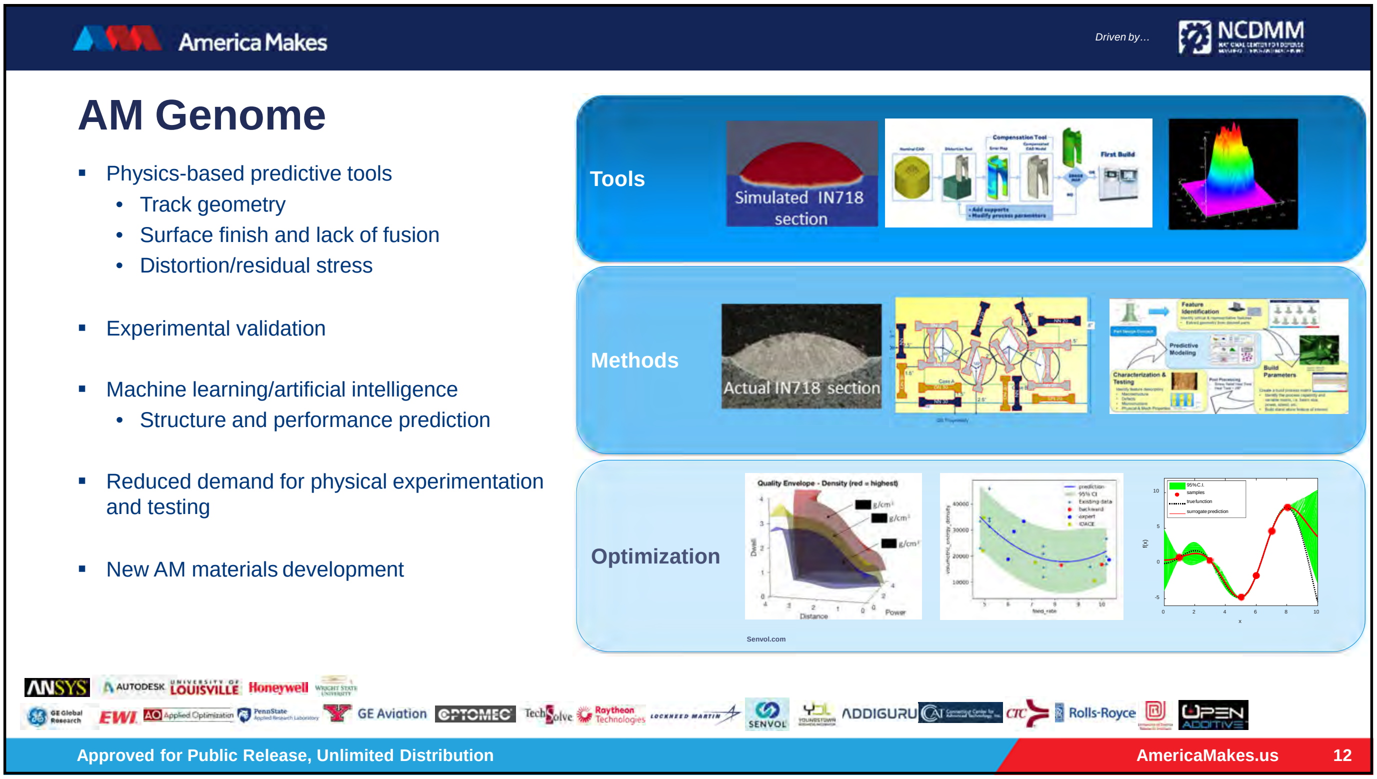
11



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## AM Genome

- Physics-based predictive tools
    - Track geometry
    - Surface finish and lack of fusion
    - Distortion/residual stress
- Experimental validation
- Machine learning/artificial intelligence
    - Structure and performance prediction
- Reduced demand for physical experimentation and testing
- New AM materials development

Tools

Methods

Optimization

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12

# Scaling AM Technology for Nuclear Applications

- Demand volume for nuclear application components exhibits potential for considerable benefit from AM
- Reliability and familiarity with product performance and materials behavior must be addressed to insure expanded adoption
  - Repeatability and transferability of manufacturing capability will be important
  - Supply chain resilience = potential for lead time reduction
- Inspection is a critical component of nuclear product certification and may not deter broader application of the technology
  - May not always be true, now is the time to explore
- Continued exploration and documentation of productivity and lead time improvements gained by AM
  - DED vs. GMAW
  - Repair and prototyping before super-critical applications – crawl, walk, run mentality
  - Refined cost modeling
- Compatibility with legacy sub-systems, assemblies, or manufacturing operations
  - New materials may not exhibit same compatibilities or behaviors
- Some cost and lead time savings may come immediately
  - Like for like replacement of legacy designs/material forms
  - Often realization of performance or unique benefits requires development, testing, data and investment

# Regulation and Standards

- These appear to be encouraging times for advanced manufacturing in nuclear industry
  - AMT Application Guidance Draft Framework June 2020
- 10CFR 50.55a(z)(1)
  - Equivalency according to ASME Code Section III design allowables
  - This is a challenging and evolving topic within AM industry which is impact no just nuclear industry
- 10CFR 50.55a(z)(2)
  - Functional testing has served as a meaningful method to determining product function in a relevant operating environment
  - Aerospace
- Direction and recommendation of guidance mirrors much of the AM industries understanding
- The guidance suggests now is a great time to get engaged with SDO's and share your needs with broader community
  - Opportunity to benefit your organization and your industry
  - Standards development requires data and perseverance
  - Change requires time and effort
  - There has been much learned about AM, but additional effort is required
- Take advantage of opportunities to connect with your peers and learn from others
  - Sharing information (familiarity with the technology) tends to reduce barriers to entry and uncertainty

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# Future Opportunities

- Additive has demonstrated value proposition for nuclear applications
  - These benefits build upon prior lessons learned across various (but similar) industries
  - Expansion of technology's recognized value
- Operating conditions and materials offer reasonable transition opportunities
- With expanded familiarity, additional validated design tools and methods are likely to follow
- Capture of key lessons learned will serve as the foundation for workforce development and new standards
  - R&D, materials data, and functional (performance based) testing will play a key role
- Successful demonstration of lower risk components can continue to serve as useful opportunities to bolster industry's familiarity with the technology
  - Scale and expand adoption for a variety of applications
- It is important to recognize the value of collaboration
  - Sharing (pre-competitive) lessons learned will allow the nuclear industry to focus on application specific challenges rather than redeveloping AM best practices from scratch
  - Accelerate primary focus/efforts to product evaluation and performance monitoring (terminology adopted from AMT Application Guidance Draft Framework)

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# When America Makes America Works

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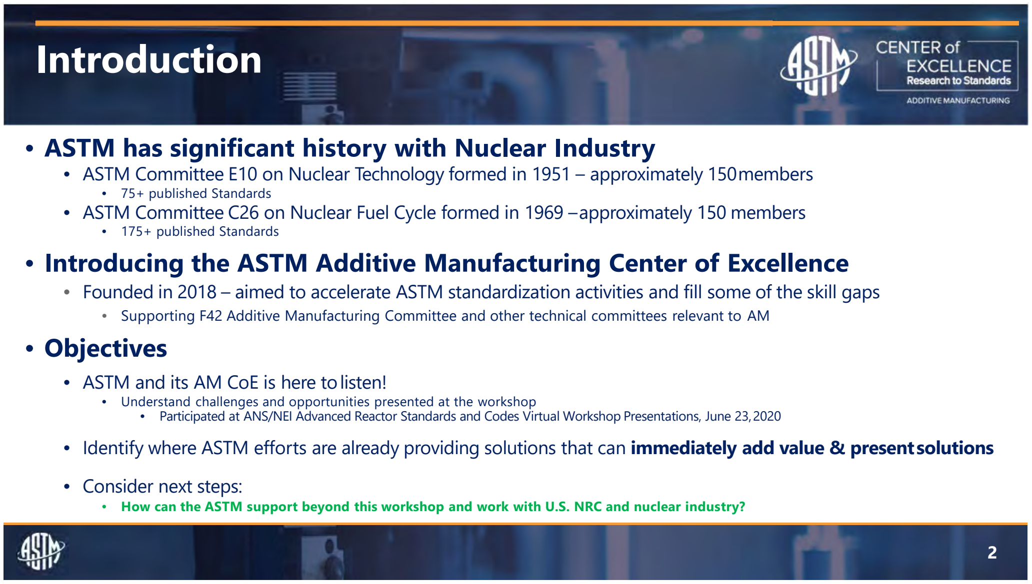
# Recent Progress on ASTM AM Standardization and R&D Efforts

*U.S. NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications*

December 9th, 2020

**Dr. Mohsen Seifi**

- *Director, Global Additive Manufacturing Programs, ASTM International, Washington DC, USA*
- *Adjunct Faculty, Case Western Reserve University, Cleveland, OH, USA*



## Introduction

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- **ASTM has significant history with Nuclear Industry**
  - ASTM Committee E10 on Nuclear Technology formed in 1951 – approximately 150 members
    - 75+ published Standards
  - ASTM Committee C26 on Nuclear Fuel Cycle formed in 1969 – approximately 150 members
    - 175+ published Standards
- **Introducing the ASTM Additive Manufacturing Center of Excellence**
  - Founded in 2018 – aimed to accelerate ASTM standardization activities and fill some of the skill gaps
    - Supporting F42 Additive Manufacturing Committee and other technical committees relevant to AM
- **Objectives**
  - ASTM and its AM CoE is here to listen!
    - Understand challenges and opportunities presented at the workshop
      - Participated at ANS/NEI Advanced Reactor Standards and Codes Virtual Workshop Presentations, June 23, 2020
  - Identify where ASTM efforts are already providing solutions that can **immediately add value & present solutions**
  - Consider next steps:
    - **How can the ASTM support beyond this workshop and work with U.S. NRC and nuclear industry?**

# ASTM Nuclear Pedigree

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## • E10 – Nuclear Technology & Applications:

*"To promote the advancement of nuclear science and technology and the safe application of energy, including end-of-fuel-cycle activities such as decontamination and decommissioning"*

- Standardizing measurement techniques and specifications for:
    - Radiation effects
    - Dosimetry, including materials response
    - Instrument response
    - Determination of radiation exposure
    - Fuel burnup
- Standardizing the nomenclature and definitions used
- Maintaining a broad expertise in the application of nuclear science and technology, especially the measurement of radiation effects from environments of nuclear reactors, charged particle accelerators, indigenous space, spacecraft, and radioisotopes.
- Sponsoring scientific and technical symposia, workshops, and publications in the Committee's fields of specialization.

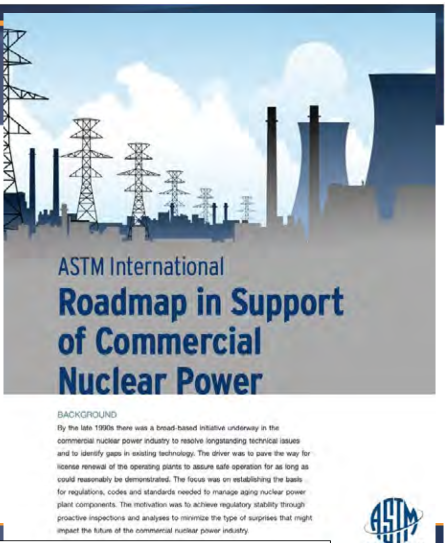
## • C26 – Nuclear Fuel Cycle:

*"To develop consensus standards for, and promote commercialization of, nuclear fuel cycle, materials, products and processes"*

- Provide internationally accepted standards which facilitate the commerce; worker safety; public and environmental health; and regulatory compliance within the Nuclear Fuel Cycle.
- All aspects of the nuclear fuel cycle are included with emphasis on
    - Nuclear fuel
    - Reactor materials processing
    - Analysis
    - Disposal/disposition technologies and applications.
    - Nuclear fuel cycle activities of both the commercial nuclear industry and the defense community fall within the scope of this committee.
- The work of the Committee(s) will be coordinated with other ASTM International committees and national and international organizations having mutual interest.

# ASTM Nuclear Pedigree
## Roadmap published in 2012

- This roadmap identifies top priorities and opportunities in the commercial nuclear energy sector that:
    - Encompass the objectives of NESCC Task Group on Standards Prioritization;
    - Build on the results of the ASTM nuclear survey and Nuclear Standards Workshop (described further in this roadmap); and
    - Manage gaps in the underlying technology and standards based on their significance to the NESCC goals.
- The roadmap is of importance to ASTM International because it provides:
    - The formation of a self-sustaining nuclear energy focal point within ASTM;
    - The strengthening of alliances with other societies and international organizations;
    - An increased understanding of the nuclear energy sector and how to effectively contribute to this industry through the actions of ASTM technical committees;
    - The identification of gaps in current and emerging technologies and related standards;



ASTM International
Roadmap in Support of Commercial Nuclear Power

BACKGROUND

By the late 1990s there was a broad-based initiative underway in the commercial nuclear power industry to resolve longstanding technical issues and to identify gaps in existing technology. The driver was to pave the way for license renewal of the operating plants to assure safe operation for as long as could reasonably be demonstrated. The focus was on establishing the basis for regulations, codes and standards needed to manage aging nuclear power plant components. The motivation was to achieve regulatory stability through proactive inspections and analyses to minimize the type of surprises that might impact the future of the commercial nuclear power industry.

INTERNATIONAL
Standards Worldwide

Download at: https://www.astm.org/portals/nuclear_roadmap.pdf

## ANS/NEI Advanced Reactor Standards and Codes Virtual Workshop, June 2020

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- Purpose of the workshop:
  - Facilitate discussions on needs for codes/standards
- Recommended actions:
  - Conduct gap analysis
  - Development of standards that were identified high priority for this sector
  - Many more

https://www.ans.org/file/1716/2/NEI-ANS%20Advanced%20Reactor%20Codes%20&%20Standards%20Workshop%20Presentations.pdf

## New Sub-Committee on Applications

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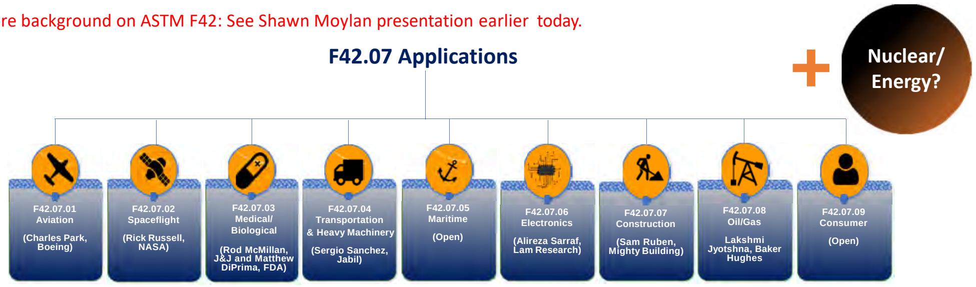
More background on ASTM F42: See Shawn Moylan presentation earlier today.



**Scope**

- The development of **standards for additive manufacturing** in a variety of industry-specific applications, settings, & conditions.
- The work of this subcommittee will be coordinated with other F42 subcommittees, ASTM technical committees, and national/international organizations having mutual or related interests.

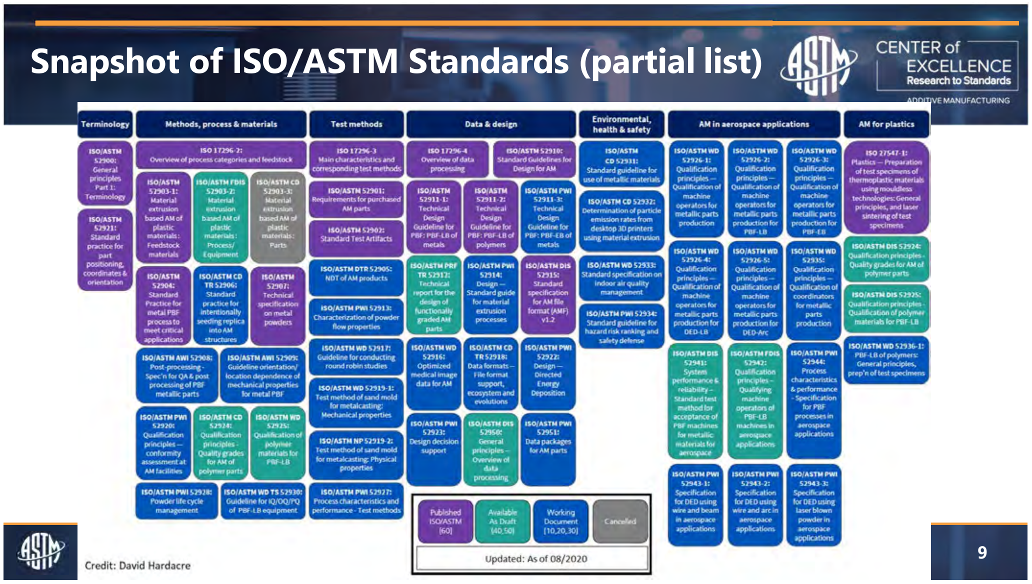
# ASTM AM Footprint: Collaborative nature

- Partnership with ISO TC261 (& CEN TC438): Agreement since 2011
- Strategic Relationships:
  - America Makes: MoU since 2013
  - Government agencies: NIST, NASA, FAA, FDA, DoD, U.S. NRC, etc.
  - Other groups: MMPDS (MoU), CMH17, etc.
- AM Center of Excellence partnership:
  - AU, EWI, MTC, NIAR, NASA, NAMIC
- Certification bodies:
  - SEI (ASTM Subsidiary)
  - UL: MoU to develop AM Safety standard (UL3400)
  - TUV SUD: MoU to develop joint programs
- Other SDOs:
  - ASME, AWS, SAE, etc.

More background on ASTM F42: See Shawn Moylan presentation earlier today.

# The Impact of Standards

- Recent Key Standards/Drafts for AM
  - Installation, Operation, and Performance Qualification for Production (**ISO/ASTM 52930**)
  - Best Practices for Metal Powder Bed Fusion Process to Meet Critical Applications (**ISO/ASTM 52904**)
  - Qualifying machine operators of LB-PBF machines and equipment used in aerospace applications (**ISO/ASTM 52942**)
  - Feedstock materials technical specifications on metal powder (**WK62190**)
  - Standard Guide for In-Situ Monitoring of Metal AM Parts (**WK62181**)
- How ASTM Standards interact
  - See example Quality System in slide 9



# Snapshot of ISO/ASTM Standards (partial list)

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**Terminology**

- ISO/ASTM 52900: General principles Part 1: Terminology
- ISO/ASTM 52921: Standard practice for part positioning, coordinates & orientation

**Methods, process & materials**

- ISO 17296-2: Overview of process categories and feedstock
- ISO/ASTM 52903-1: Material extrusion based AM of plastic materials: Feedstock materials
- ISO/ASTM FDIS 52903-2: Material extrusion based AM of plastic materials: Process/ Equipment
- ISO/ASTM CD 52903-3: Material extrusion based AM of plastic materials: Parts
- ISO/ASTM 52904: Standard Practice for metal PBF process to meet critical applications
- ISO/ASTM CD TR 52906: Standard practice for intentionally seeding replica into AM structures
- ISO/ASTM 52907: Technical specification on metal powders
- ISO/ASTM AWI 52908: Post-processing - Spec'n for QA & post processing of PBF metallic parts
- ISO/ASTM AWI 52909: Guideline orientation/ location dependence of mechanical properties for metal PBF
- ISO/ASTM PWI 52920: Qualification principles — conformity assessment at AM facilities
- ISO/ASTM CD 52924: Qualification principles - Quality grades for AM of polymer parts
- ISO/ASTM WD 52925: Qualification of polymer materials for PBF-LB
- ISO/ASTM PWI 52928: Powder life cycle management
- ISO/ASTM WD TS 52930: Guideline for IQ/OQ/PQ of PBF-LB equipment

**Test methods**

- ISO 17296-3 Main characteristics and corresponding test methods
- ISO/ASTM 52901: Requirements for purchased AM parts
- ISO/ASTM 52902: Standard Test Artifacts
- ISO/ASTM DTR 52905: NDT of AM products
- ISO/ASTM PWI 52913: Characterization of powder flow properties
- ISO/ASTM WD 52917: Guideline for conducting round robin studies
- ISO/ASTM WD 52919-1: Test method of sand mold for metalcasting: Mechanical properties
- ISO/ASTM NP 52919-2: Test method of sand mold for metalcasting: Physical properties
- ISO/ASTM PWI 52927: Process characteristics and performance - Test methods

**Data & design**

- ISO 17296-4 Overview of data processing
- ISO/ASTM 52910: Standard Guidelines for Design for AM
- ISO/ASTM 52911-1: Technical Design Guideline for PBF: PBF-LB of metals
- ISO/ASTM 52911-2: Technical Design Guideline for PBF: PBF-LB of polymers
- ISO/ASTM PWI 52911-3: Technical Design Guideline for PBF: PBF-EB of metals
- ISO/ASTM PRF TR 52912: Technical report for the design of functionally graded AM parts
- ISO/ASTM PWI 52914: Design — Standard guide for material extrusion processes
- ISO/ASTM DIS 52915: Standard specification for AM file format (AMF) v1.2
- ISO/ASTM WD 52916: Optimized medical image data for AM
- ISO/ASTM CD TR 52918: Data formats – File format support, ecosystem and evolutions
- ISO/ASTM PWI 52922: Design — Directed Energy Deposition
- ISO/ASTM PWI 52923: Design decision support
- ISO/ASTM DIS 52950: General principles – Overview of data processing
- ISO/ASTM PWI 52951: Data packages for AM parts

**Environmental, health & safety**

- ISO/ASTM CD 52931: Standard guideline for use of metallic materials
- ISO/ASTM CD 52932: Determination of particle emission rates from desktop 3D printers using material extrusion
- ISO/ASTM WD 52933: Standard specification on indoor air quality management
- ISO/ASTM PWI 52934: Standard guideline for hazard risk ranking and safety defense

**AM in aerospace applications**

- ISO/ASTM WD 52926-1: Qualification principles — Qualification of machine operators for metallic parts production
- ISO/ASTM WD 52926-2: Qualification principles — Qualification of machine operators for metallic parts production for PBF-LB
- ISO/ASTM WD 52926-3: Qualification principles — Qualification of machine operators for metallic parts production for PBF-EB
- ISO/ASTM WD 52926-4: Qualification principles — Qualification of machine operators for metallic parts production for DED-LB
- ISO/ASTM WD 52926-5: Qualification principles — Qualification of machine operators for metallic parts production for DED-Arc
- ISO/ASTM WD 52935: Qualification principles — Qualification of coordinators for metallic parts production
- ISO/ASTM DIS 52941: System performance & reliability – Standard test method for acceptance of PBF machines for metallic materials for aerospace
- ISO/ASTM FDIS 52942: Qualification principles – Qualifying machine operators of PBF-LB machines in aerospace applications
- ISO/ASTM PWI 52944: Process characteristics & performance - Specification for PBF processes in aerospace applications
- ISO/ASTM PWI 52943-1: Specification for DED using wire and beam in aerospace applications
- ISO/ASTM PWI 52943-2: Specification for DED using wire and arc in aerospace applications
- ISO/ASTM PWI 52943-3: Specification for DED using laser blown powder in aerospace applications

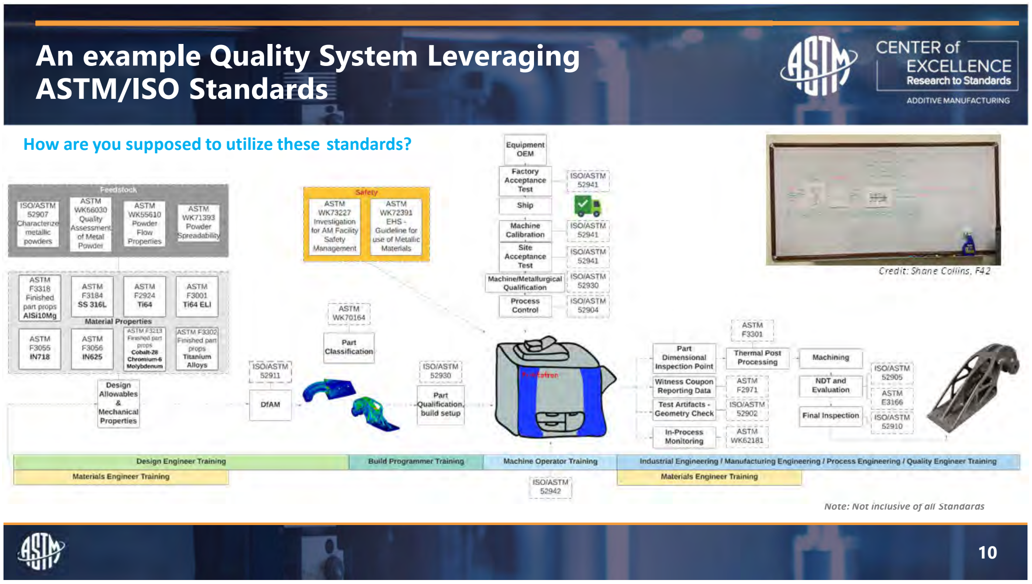
**AM for plastics**

- ISO 27547-1: Plastics — Preparation of test specimens of thermoplastic materials using mouldless technologies: General principles, and laser sintering of test specimens
- ISO/ASTM DIS 52924: Qualification principles - Quality grades for AM of polymer parts
- ISO/ASTM DIS 52925: Qualification principles - Qualification of polymer materials for PBF-LB
- ISO/ASTM WD 52936-1: PBF-LB of polymers: General principles, prep'n of test specimens

| Published ISO/ASTM [60] | Available As Draft [40,50] | Working Document [10,20,30] | Canceled |
|---|---|---|---|

Updated: As of 08/2020

Credit: David Hardacre



# An example Quality System Leveraging ASTM/ISO Standards

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

How are you supposed to utilize these standards?

Feedstock
- ISO/ASTM 52907 Characterize metallic powders
- ASTM WK66030 Quality Assessment of Metal Powder
- ASTM WK55610 Powder Flow Properties
- ASTM WK71393 Powder Spreadability

Material Properties
- ASTM F3318 Finished part props **AlSi10Mg**
- ASTM F3184 **SS 316L**
- ASTM F2924 **Ti64**
- ASTM F3001 **Ti64 ELI**
- ASTM F3055 **IN718**
- ASTM F3056 **IN625**
- ASTM F3213 Finished part props **Cobalt-28 Chromium-6 Molybdenum**
- ASTM F3302 Finished part props **Titanium Alloys**

Design Allowables & Mechanical Properties

Safety
- ASTM WK73227 Investigation for AM Facility Safety Management
- ASTM WK72391 EHS - Guideline for use of Metallic Materials

ISO/ASTM 52911 — DfAM

ASTM WK70164 — Part Classification

ISO/ASTM 52930 — Part Qualification, build setup

Equipment OEM
- Factory Acceptance Test — ISO/ASTM 52941
- Ship
- Machine Calibration — ISO/ASTM 52941
- Site Acceptance Test — ISO/ASTM 52941
- Machine/Metallurgical Qualification — ISO/ASTM 52930
- Process Control — ISO/ASTM 52904

- Part Dimensional Inspection Point
- Witness Coupon Reporting Data — ASTM F2971
- Test Artifacts - Geometry Check — ISO/ASTM 52902
- In-Process Monitoring — ASTM WK62181
- Thermal Post Processing — ASTM F3301
- Machining
- NDT and Evaluation — ISO/ASTM 52905; ASTM E3166; ISO/ASTM 52910
- Final Inspection

Design Engineer Training | Build Programmer Training | Machine Operator Training | Industrial Engineering / Manufacturing Engineering / Process Engineering / Quality Engineer Training

Materials Engineer Training | Materials Engineer Training

ISO/ASTM 52942

Credit: Shane Collins, F42

*Note: Not inclusive of all Standards*

# Guidelines for Installation, Operation and Performance Qualification (LB-PBF)

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Research to Standards
ADDITIVE MANUFACTURING

- **ISO/ASTM 52930**
  - Ballot ended in April, currently available as *ASTM F3434-20*
  - Covers the key elements for Process Validation
- **Installation Qualification:**
  - Equipment design & validation: FAT/SAT, Installation conditions, environmental operating limits, calibration…
- **Operational Qualification:**
  - Show the relationship of the input variables to the measured output for the specific combination of equipment with specific parts produced
  - KPVs, control of variability, optimal processing parameters…
- **Performance/Part Qualification:**
  - Validation vs requirements, Failure modes, Production Controls, In Process monitoring, data to be collected…
  - Scenarios requiring **Revalidation**:
    - Software/firmware updates, installation of additional components, repair/replacement of components, changes to location/environment

Designation: F3434 – 20

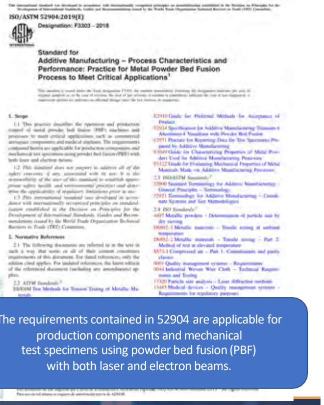
Guide for
Additive manufacturing – Installation/Operation and Performance Qualification (IQ/OQ/PQ) of Laser-Beam Powder Bed Fusion Equipment for Production Manufacturing[1]

This guideline addresses IQ, OQ, and PQ issues directly related to the AM machine and connected equipment. Physical facility, personnel, process and material issues are included to the extent necessary to support machine qualification

# Process Characteristics and Performance: Practice for Metal Powder Bed Fusion to Meet Critical Applications

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

- **ISO/ASTM 52904**
  - Released in June 2020
  - Covers the control of machines (**Laser and Electron Beam**) and process required to meet critical applications such as aerospace components
- **Feedstock Batches:**
  - Powder container requirements, CoC, approval of material suppliers, feedstock material specification, guidance on used powder
- **Qualification:**
  - Pre-build checks, periodic preventative maintenance, machine/process/part qualification
- **Manufacturing Plan:**
  - Plan to detail the steps required for the PBF process, including pre-build check records, machining stock added, part nesting, reference parts etc.
  - Guidance on **Configuration Control** of digital data and software control



ISO/ASTM 52904:2019(E)

Designation: F3303 – 2018

Standard for
Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications[1]

The requirements contained in 52904 are applicable for production components and mechanical test specimens using powder bed fusion (PBF) with both laser and electron beams.

# Material Standards:

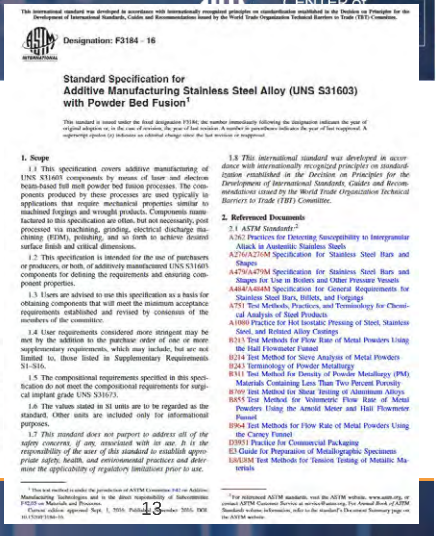
## 316 L as an example

- Covers AM components made from Electron Beam and Laser Powder Bed
- Provides Minimum Tensile Properties
  - Similar to machined forgings & wrought
- This specification intended to be used by both the Purchaser and the Producer of AM Material
- Serves as a link to other key standards (testing, quality, terminology, etc.)

TABLE 3 Minimum Tensile Requirements[A]

| Room Temperature Condition | Tensile Strength, MPa (ksi), X and Y Directions | Tensile Strength, MPa (ksi), Z Direction | Yield Strength at 0.2% Offset, MPa (ksi), X and Y Directions | Yield Strength at 0.2% Offset, MPa (ksi), Z Direction | Elongation in 50 mm (2 in.) or 4D, (%), X and Y Directions | Elongation in 50 mm (2 in.) or 4D, (%), Z Direction | Reduction of Area, %, X and Y Directions | Reduction of Area, %, Z Direction |
|---|---|---|---|---|---|---|---|---|
| A - Stress Relieved[B] | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 40 | 40 |
| A - Solution Annealed | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 30 | 30 |
| B | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 30 | 30 |
| C | 515 (75) | 515 (75) | 205 (30) | 205 (30) | 30 | 30 | 30 | 30 |
| E | no requirement | no requirement | no requirement | no requirement | no requirement | no requirement | no requirement | no requirement |

[A] A gauge length corresponding to ISO 6892 may be used when agreed upon by the component supplier and purchaser.
[B] Mechanical properties conform to Specification A479/A479M.



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.

Designation: F3184 – 16

### Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion[1]

This standard is issued under the fixed designation F3184; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

**1. Scope**

1.1 This specification covers additive manufacturing of UNS S31603 components by means of laser and electron beam-based full melt powder bed fusion processes. The components produced by these processes are used typically in applications that require mechanical properties similar to machined forgings and wrought products. Components manufactured to this specification are often, but not necessarily, post processed via machining, grinding, electrical discharge machining (EDM), polishing, and so forth to achieve desired surface finish and critical dimensions.

1.2 This specification is intended for the use of purchasers or producers, or both, of additively manufactured UNS S31603 components for defining the requirements and ensuring component properties.

1.3 Users are advised to use this specification as a basis for obtaining components that will meet the minimum acceptance requirements established and revised by consensus of the members of the committee.

1.4 User requirements considered more stringent may be met by the addition to the purchase order of one or more supplementary requirements, which may include, but are not limited to, those listed in Supplementary Requirements S1–S16.

1.5 The compositional requirements specified in this specification do not meet the compositional requirements for surgical implant grade UNS S31673.

1.6 The values stated in SI units are to be regarded as the standard. Other units are included only for informational purposes.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.8 *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. Referenced Documents**

2.1 *ASTM Standards:*[2]

A262 Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels
A276/A276M Specification for Stainless Steel Bars and Shapes
A479/A479M Specification for Stainless Steel Bars and Shapes for Use in Boilers and Other Pressure Vessels
A484/A484M Specification for General Requirements for Stainless Steel Bars, Billets, and Forgings
A751 Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
A1080 Practice for Hot Isostatic Pressing of Steel, Stainless Steel, and Related Alloy Castings
B213 Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
B214 Test Method for Sieve Analysis of Metal Powders
B243 Terminology of Powder Metallurgy
B311 Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
B769 Test Method for Shear Testing of Aluminum Alloys
B855 Test Method for Volumetric Flow Rate of Metal Powders Using the Arnold Meter and Hall Flowmeter Funnel
B964 Test Methods for Flow Rate of Metal Powders Using the Carney Funnel
D3951 Practice for Commercial Packaging
E3 Guide for Preparation of Metallographic Specimens
E8/E8M Test Methods for Tension Testing of Metallic Materials

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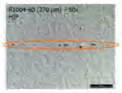
[1] This test method is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.05 on Materials and Processes.
Current edition approved Sept. 1, 2016. Published November 2016. DOI: 10.1520/F3184-16.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

# NDT Standards led by E07 committee on NDT

**Relevant standards:**

- **ASTM E3166** – Guide for Nondestructive Testing of Metal Additively Manufactured Metal Aerospace Parts After Build
- **ASTM WK62181** – Standard Guide for In-Situ Monitoring of Metal AM Aerospace Parts
- **ASTM WK56649** - Additive Manufacturing — Non-Destructive Testing and Evaluation — Standard Guideline for Intentionally Seeding Flaws Metallic Parts
- **ISO/ASTM JG59 DTR 52905** - Standard Guideline for Defect Detection in Metallic Parts



**Layer Defect**
(Skipped layer/stop-start, horizontal LOF)

**Cross-Layer Defect**
(vertical LOF)

**Unconsolidated Powder**

**Trapped Powder**

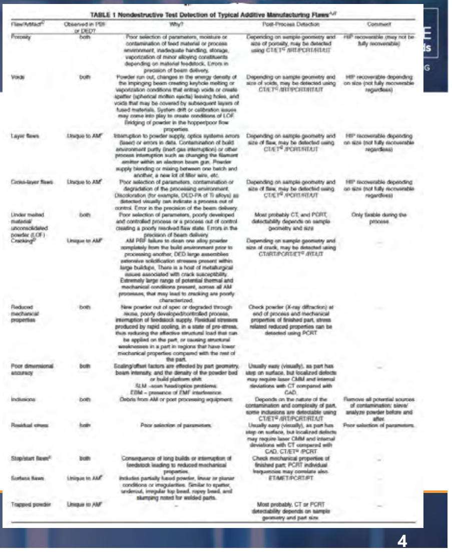


TABLE 1 Nondestructive Test Detection of Typical Additive Manufacturing Flaws[A,B]

| Flaw/Artifact[C] | Observed in PBF or DED? | Why? | Post-Process Detection | Comment |
|---|---|---|---|---|
| Porosity | both | Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery. | Depending on sample geometry and size of porosity, may be detected using CT/ET[C] /IRT/PCRT/RT/UT | HIP recoverable (may not be fully recoverable) |
| Voids | both | Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper/poor flow properties. | Depending on sample geometry and size of voids, may be detected using CT/ET[C] /IRT/PCRT/RT/UT | HIP recoverable depending on size (not fully recoverable regardless) |
| Layer flaws | Unique to AM[F] | Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption) or other process interruption such as changing the filament emitter within an electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc. | Depending on sample geometry and size of flaw, may be detected using CT/ET[C] /PCRT/RT/UT | HIP[E] recoverable depending on size (not fully recoverable regardless) |
| Cross-layer flaws | Unique to AM[F] | Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (for example, DED-PA of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery. | Depending on sample geometry and size of flaw, may be detected using CT/ET[C] /PCRT/RT/UT | HIP[E] recoverable depending on size (not fully recoverable regardless) |
| Under melted material/ unconsolidated powder (LOF) | both | Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery. | Most probably CT, and PCRT, detectability depends on sample geometry and size | Only fixable during the process. |
| Cracking[D] | Unique to AM[F] | AM PBF failure to clean one alloy powder completely from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups. There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present, across all AM processes, that may lead to cracking are poorly characterized. | Depending on sample geometry and size of crack, may be detected using CT/IRT/PCRT/ET[C] /RT/UT | — |
| Reduced mechanical properties | both | New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply. Residual stresses produced by rapid cooling, in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, or causing structural weaknesses in a part in regions that have lower mechanical properties compared with the rest of the part. | Check powder (X-ray diffraction) at end of process and mechanical properties of finished part, stress related reduced properties can be detected using PCRT | — |
| Poor dimensional accuracy | both | Scaling/offset factors are effected by part geometry, beam intensity, and the density of the powder bed or build platform shift.<br>SLM –scan head/optics problems.<br>EBM – presence of EMF interference. | Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD. | — |
| Inclusions | both | Debris from AM or post processing equipment. | Depends on the nature of the contamination and complexity of part, some inclusions are detectable using CT/ET[C] /IRT/PCRT/RT/UT | Remove all potential sources of contamination; sieve/ analyze powder before and after. |
| Residual stress | both | Poor selection of parameters. | Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD. CT/ET[C] /PCRT | Poor selection of parameters. |
| Stop/start flaws[E] | both | Consequence of long builds or interruption of feedstock leading to reduced mechanical properties. | Check mechanical properties of finished part. PCRT individual frequencies may correlate also. ET/MET/PCRT/PT | — |
| Surface flaws | Unique to AM[F] | Includes partially fused powder, linear or planar conditions or irregularities. Similar to spatter, undercut, irregular top bead, ropey bead, and slumping noted for welded parts. | — | — |
| Trapped powder | Unique to AM[F] | — | Most probably, CT or PCRT detectability depends on sample geometry and part size | — |

## ASTM AM Center of Excellence (CoE)

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

- Overview of AM R&D portfolio and their impact on AM standards portfolio
- New program development in workforce development
- Expansion of in-person workshops attracting over 300 AM professionals in Paris, Virginia and Texas
- AM CoE's COVID-19 response
- And more…

CENTER of EXCELLENCE Research to Standards

2019-20

Annual Report

ASTM INTERNATIONAL

Additive Manufacturing Center of Excellence

www.amcoe.org

## ASTM AM Center of Excellence (CoE)

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

### Why ASTM create the AM CoE?

**About the CoE**

**Rationale:**

- Critical need to support accelerate development of globally accepted AM standards due to large gaps
- Critical need to educate the next generation of AM professionals and implementation of standards

**Objective:**

- To coordinate and conduct R&D that supports AM standards development
- To support related education, training and other programs

**Expected outcome:** AM standards via committees and standards related products and services

- Reducing time-to-market
- Increasing widespread adoption

**CoE relation with respect to F42 Committee:** ***F42 membership and other committees can leverage AM CoE as a platform*** to conduct research that can fill gaps in ongoing standardization efforts

**Mission**

**The Center bridges standards development with R&D** to better enable efficient development of:

- Standards
- Education and training and
- Certification and proficiency testing programs

**Vision**

**The Center facilitates collaboration and coordination among government, academia, and industry to:**

- Advance AM standardization
- Expand ASTM International's and our partners' capabilities.

# Role of AM CoE with respect to F42

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

## ASTM Committee F42

Dedicated to AM and has technical subcommittees focused on the **development of consensus-based standards. This is happening in partnership with ISO TC261.**

## ASTM AM CoE

**A collaborative partnership among ASTM** and organization representing government, industry, and academia that **conducts strategic R&D to advance standards across all aspects of AM in addition to develop E&WD and Certification Programs.**

**Platform for F42 members and AM community**

- AM CoE is a platform that F42 members can tap into to conduct research to fill gaps in the AM standards.
- AM CoE is also a platform open for other ASTM technical committees to utilize resources.

**Focal point for standard-related R&D activities**

- AM CoE houses and facilitates AM R&D generation to support global standardization efforts

**Global hub for AM innovation to support standardization**

- Create strong national and international industry-government-university partnerships;
- Develop education, training, proficiency testing, and certification programs; and
- Host ASTM committee related events, workshops, and symposia.

# AM CoE R&D: High Priority Areas

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

## AM CoE R&D Themes

1. Defined based on the input of the AM CoE R&D team
2. Short-term
3. Highly-focused
4. High-priority (linked to AMSC roadmap and Committee F42)
5. Aligned with America Makes projects
6. Coordination/collaboration with NIST, other agencies

# AM CoE R&D Projects (Rounds 1 & 2)

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

**R&D Projects**

## Round 1: 2018-2019 (5 projects)

| | | | |
|---|---|---|---|
| EWI | Post Processing (Surface finishing and Characterization) | NASA AUBURN | LB-PBF Process Qualification |
| mtc | Feedstock (Powder quality guide) | NIAR | Polymer AM Test Specimen Design |
| AUBURN | Mechanical Testing of Metal AM | | |

## Round 2: 2019-2020 (9 projects)

| | | | |
|---|---|---|---|
| EWI | Standardization of Data Pedigree | NASA AUBURN | LB-PBF Process Qualification – Phase II |
| mtc | Design Guide for Post-Processing | NIAR | Polymer AM Design Value Tests |
| mtc | Powder Spreadability | NIAR | Dynamic Testing of Polymer AM |
| AUBURN | Rapid Quality Inspection Specimen (RQIS) | NAMIC | In-process Monitoring |
| | | NAMIC | Design Guides for AM Processes |

LAUNCHED **14** Total Research Projects

ADDRESSING **25** Total Standards Gaps

IMPACTING **53** Total Standards

https://www.amcoe.org/projects

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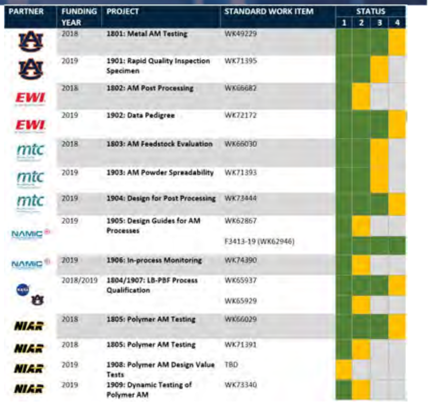
# Research to Standardization

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

| 1. Work item scoping and registration | 2. Draft under development | 3. Editorial support and pre-ballot | 4. Undergoing balloting and final approval of a standard |
|---|---|---|---|
| TBD | WK62867<br>WK65929<br>WK66682<br>WK71391<br>WK73340<br>WK74390 | WK66030<br>WK71393<br>WK71395 | *WK49229**<br>*WK65937**<br>WK66029<br>WK72172<br>WK73444<br><br>**Approved:**<br>ASTM F3413 – 19 |

* Existing Work Items



| PARTNER | FUNDING YEAR | PROJECT | STANDARD WORK ITEM | STATUS 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|
| | 2018 | **1801: Metal AM Testing** | WK49229 | 🟩 | 🟩 | 🟩 | 🟨 |
| | 2019 | **1901: Rapid Quality Inspection Specimen** | WK71395 | 🟩 | 🟩 | 🟨 | ⬜ |
| EWI | 2018 | **1802: AM Post Processing** | WK66682 | 🟩 | 🟨 | ⬜ | ⬜ |
| EWI | 2019 | **1902: Data Pedigree** | WK72172 | 🟩 | 🟩 | 🟩 | 🟨 |
| mtc | 2018 | **1803: AM Feedstock Evaluation** | WK66030 | 🟩 | 🟩 | 🟨 | ⬜ |
| mtc | 2019 | **1903: AM Powder Spreadability** | WK71393 | 🟩 | 🟩 | 🟨 | ⬜ |
| mtc | 2019 | **1904: Design for Post Processing** | WK73444 | 🟩 | 🟩 | 🟩 | 🟨 |
| NAMIC | 2019 | **1905: Design Guides for AM Processes** | WK62867 | 🟩 | 🟨 | ⬜ | ⬜ |
| | | | F3413-19 (WK62946) | 🟩 | 🟩 | 🟩 | 🟩 |
| NAMIC | 2019 | **1906: In-process Monitoring** | WK74390 | 🟩 | 🟨 | ⬜ | ⬜ |
| NASA | 2018/2019 | **1804/1907: LB-PBF Process Qualification** | WK65937 | 🟩 | 🟩 | 🟩 | 🟨 |
| | | | WK65929 | 🟩 | 🟨 | ⬜ | ⬜ |
| NIAR | 2018 | **1805: Polymer AM Testing** | WK66029 | 🟩 | 🟩 | 🟩 | 🟨 |
| NIAR | 2018 | **1805: Polymer AM Testing** | WK71391 | 🟩 | 🟨 | ⬜ | ⬜ |
| NIAR | 2019 | **1908: Polymer AM Design Value Tests** | TBD | 🟨 | ⬜ | ⬜ | ⬜ |
| NIAR | 2019 | **1909: Dynamic Testing of Polymer AM** | WK73340 | 🟩 | 🟨 | ⬜ | ⬜ |

🟩 Completed
🟨 In process
⬜ Upcoming

**Status Key:**
1. Work item scoping and registration
2. Draft under development
3. Editorial Support and Pre-Ballot
4. Undergoing Balloting and Final approval as a standard

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# 3rd Round of Projects

## 2020 Request for Ideas

- The idea solicitation process was expanded to all ASTM members as a membership benefit
  - Over 60 ideas were received during the survey
- Submissions addressed a wide range of challenges in AM that members face, including:
  - Design, Data, and Modeling
  - Feedstock
  - Processes and Post processing
  - AM Testing
  - Inspection and Qualification
- Project selection process
  - Ideas were evaluated by the F42.90.05 team
  - AM CoE Partners are developing SOWs
  - Projects will start in October 2020

**ASTM Member Benefit:**
Share Your Research Ideas for AM Standardization

**ASTM Members** Submit Ideas for Standardization

**AM CoE** Conducts R&D and Generates Data

**ASTM Technical Committes** Develop AM Standards

# 3rd Round of Projects

## Summary of Ideas

- Over 60 ideas were received during the RFI

| Design, Data, and Modelling | Feedstock | Processes/ Post Processes | Testing | Qualification |
|---|---|---|---|---|
| ❖ Standard data formats and terminology to enable exchange of data between organizations and across process steps<br>❖ Definition of minimum viable data packages for process steps<br>❖ Data processing techniques to improve visualizations and usefulness<br>❖ Benchmark datasets for calibration of models and simulations | ❖ Recycling & reuse guidelines for powders and resins<br>❖ Methods for evaluating contamination (e.g. chemical, moisture) of metal powders<br>❖ Methods for evaluating feedstock variability<br>❖ Material standards specifically for additive manufacturing applications<br>❖ Material safety guidance and considerations | ❖ Calibration and maintenance of AM machines; particularly multi-laser systems<br>❖ Guidance for use of post-processing methods (e.g. hot isostatic pressing, wet-chemical support removal)<br>❖ Process safety guidance and considerations (e.g. fume, safety incident database)<br>❖ Methods for manufacturing multi-material/functionally graded components | ❖ Test methods and specimen designs for mechanical testing<br>❖ Guidelines for implementation and use of witness testing<br>❖ Test methods for evaluating lattice structures<br>❖ Guidelines for non-destructive evaluation | ❖ Guidance for acceptance criteria of surface finish in fatigue-critical applications<br>❖ Guidance for acceptance criteria based on size, type, and location of defects<br>❖ Framework for quality control in an environment with multiple AM machines<br>❖ Guidance for implementation, analysis, and use of in-process monitoring data for qualification |

# 3rd round of R&D Projects

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Research to Standards
ADDITIVE MANUFACTURING

| Lead | Project Title | Material | Topic |
|---|---|---|---|
| AU | Specimen Design for Compression Testing of Metallic Lattice Structures | 🟧 | 📋 |
| EWI | Common Data Exchange Format (CDEF) for Powder Characterization | 🟧 | 🟩 |
| mtc | Metal Powder Feedstock Recycling and Sampling Strategies | 🟧 | 🟠 |
| mtc | Recycling and Re-Use of Polymer Powders | 🟦 | 🟠 |
| NAMIC | Miniature Tensile Specimens for Additive Manufacturing | 🟧 | 📋 |
| NAMIC | Volume-Traceability (VT) Development in Porosity Characterization with XCT for Integrity and Quality Assurance of AM Parts | 🟧 | 📋 |
| NAMIC | Development of Specification for Maraging Steel | 🟧 | 🟠 |
| NASA<br>AU | Thermal Tolerance Test for LB-PBF Process Parameters | 🟧 | 🟡 |
| NIAR | Continuation of AM Polymer Projects (Design Value and Dynamic Testing)* | 🟦 | 📋 |

Material
- 🟧 Metal
- 🟦 Polymer
- 🟨 Ceramic

Topic
- 🟩 Design, Data, & Modeling
- 🟠 Feedstock
- 🟡 Processes & Post-Processes
- 📋 Testing
- ▨ Qualification

* Continuation of projects initiated in 2019

# Other notable efforts

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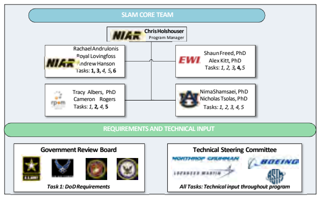
## ATRQ (Advanced Tools for Rapid Qualification)

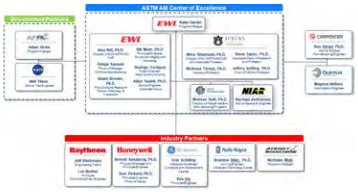
Total Federal Funding: ~$1M



- **Problem Statement:** Service life predictive tools for application specific characterization do not exist for polymer AM materials exposed to harsh environmental conditions
- **Objective:** Quantify service life of AM polymer parts used in harsh/severe field environments

## AAPT (Advancing Additive Manufacturing Post-Processing Techniques)

Total Federal Funding: ~$800K



- **Problem Statement:** lack of best practices for post-processing of AM components
- **Objective:** determine and enable the use of quantitative mechanical performance debits for both as-built and HIP'ed thin-walled components and components with narrow flow channels

Standard transition phase has defined in both projects – multiple work items has been registered

## New Project Call Mechanism

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**New Call for Projects (CFP) mechanism allowing <u>non-AM CoE partners to receive support to conduct targeted R&D projects</u>**

- **Objectives**
  - Allow the AM community to participate in Research to Standardization initiative
  - Evaluate the possibility of bringing on additional partners to the AM CoE team, to further accelerate standard development in AM

| | |
|---|---|
| PROPOSAL DUE | NOVEMBER 24, 2020 |
| SELECTION ANNOUNCEMENT | JANUARY 2021 |
| ANTICIPATED START DATE | MARCH 2021 |

2020 Call for Projects

Submit Your Proposal!

Funding Opportunities for Research Organizations

Informational Webinar: November 2, 2020

Proposal Deadline: November 24, 2020

Review by F42.90.05 (Research and Innovation) is in progress

## Research & Development

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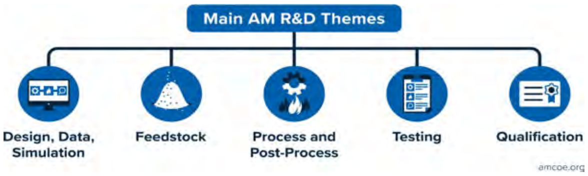
### Public R&D Roadmap Objectives

- Communicate the **goals and current progress** of the AM CoE's R&D program
- Provide a **common vision for AM R&D's future** for the AM community to work toward



STRATEGIC ROADMAP FOR RESEARCH & DEVELOPMENT

## AM Data Management and Schema

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- Collaborative workshop with America Makes
- Workshop held December 2019
- Two-day event: 20 technical talks, panel, roadmapping session
- Objective:
  - Identify challenges, gaps, and pain points
  - Discuss solutions
  - Build a momentum
- **Gaps and Challenges**: Participants brainstormed gaps and challenges in small groups and voted on the highest priorities for the AM community.
- **Potential Solutions:** Participants brainstormed solutions to the priority gaps and challenges from the previous exercise and again voted on the highest priority solutions for the AM community.
- **Detailed Action Plans:** Participants worked in small groups to develop detailed action plans for the highest priority solutions by identifying major tasks, milestones, stakeholder roles, and resource requirements.

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## Data - Highest Rated Gaps

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**Data Acquisition**
- Potential for manual data entry to lead to human error

**Data Security**
- Data traceability/integrity/provenance
- Protection of intellectual property (IP) during data sharing

**Data Practices**
- Minimum viable data packages
- Common terms and semantics for data definition

**Data Management**
- The need for unique, unified data identifiers (e.g., bar codes, alphanumeric tags, etc.) for AM data

**Data Use**
- Correlating data to part performance
- Format or presentation mode of data

37 Gaps

- **Formation of F42.08:** Sub-committee dedicated to data
- **ASTM WK72172:** New Practice for Additive manufacturing -- General principles -- Overview of data pedigree
  - The standard identifies classes of AM data (buckets), important terms for data that fit within those buckets, and relationships that exist between the buckets.
  - Balloting completed, negative comments are being addressed (Tech contact: Yan Lu, NIST)
- **Common Data Exchange Format (CDEF)**
  - Facilitates data sharing among data management systems, Will be registered in Nov. 2020 (Lead org: EWI)
- **ASTM WK73978:** New Specification for Additive Manufacturing - Data Registration
  - This standard practice comprises actions that users need take to register datasets and store them in a repository.
- Several other data related activities at F42 ISO/ASTM joint groups such as JG64, JG67, JG70, JG7

# Highest Rated Action Plans

- Summarized gaps and challenges with respect to Data in AM, and provided solutions and action plans

**Common Data Dictionary (Underway: WK72172)**
To standardize data elements that are collected during an AM process

**Common Data Exchange Format (Underway: work item to be registered next month)**
A neutral and open data format that simplifies data exchange between data management systems that have built the appropriate translators.

**Automated Data Acquisition**
To reduce human error, and enable application of advanced analytics

**Minimum Viable Datable Package**
To correlate key AM variables to part performance

**Public Use Cases**
To understand the ROI of the AM Data Ecosystem (Qual./Cert., Supply Chain, R&D)

Download at: https://amcoe.org/rd-publications

# Other Initiatives/Activities

## In-Process Monitoring Project

- Assessment of State-of-the-Art of In-Process Control and In-Situ Monitoring for Additive Manufacturing
  - Conducted literature review of available monitoring technique
  - Evaluated TRL/MRL level
  - Conducted survey (20+ experts in North America and Europe)
  - Report to be published for public before end of the year
- Data structure a primary concern
  - High spatial resolution sensor data produces very large volumes of data
  - Real time data processing is challenging and expensive
  - Parameterization reduces data volume for analysis and storage, but loses fidelity
  - Variation between companies constrains development of universal acceptance criteria
  - Standardization of data simplification will be necessary for allowance in certification/qualification

Clearance from NASA to publish Soon.

## Other Initiatives/Activities

### NASA-ASTM Cooperative Agreement

- This cooperative agreement will be the basis to expand the AM CoE and NASA's evolving partnership
  - Three-year contract
  - Formalize collaboration aimed at supporting projects identified by NASA for the AM CoE execution
- First project
  - Qualification framework for laser beam powder bed fusion (LB-PBF) AM processes
    - One of the largest impediments to the growing implementation of AM into many applications.
    - Need to standardize process qualification that ultimately contribute to robust data generation, collection and specification

## Other Initiatives/Activities

### AM Cyber Security Training Project

- America Makes Open Project Call
  - ASTM and Auburn University: AM Cyber Security training
- Security is a critical gap for digital manufacturing-related technologies
- The contribution ensures the creation of new curricula and programs to train the AM industry in the subject and help ensure the integrity and security of the entire value chain

# ASTM ICAM 2020: 5th event in a row

**18 Symposium topics linked to ASTM technical committees**

1. Structural Integrity
2. i4.0
3. Feedstock
4. Microstructure
5. NDE
6. In-Situ Monitoring/Control
7. Fatigue
8. Mechanical testing
9. General topics
10. Ceramics
11. Polymers

11

AM related topics

+Nuclear /Energy?

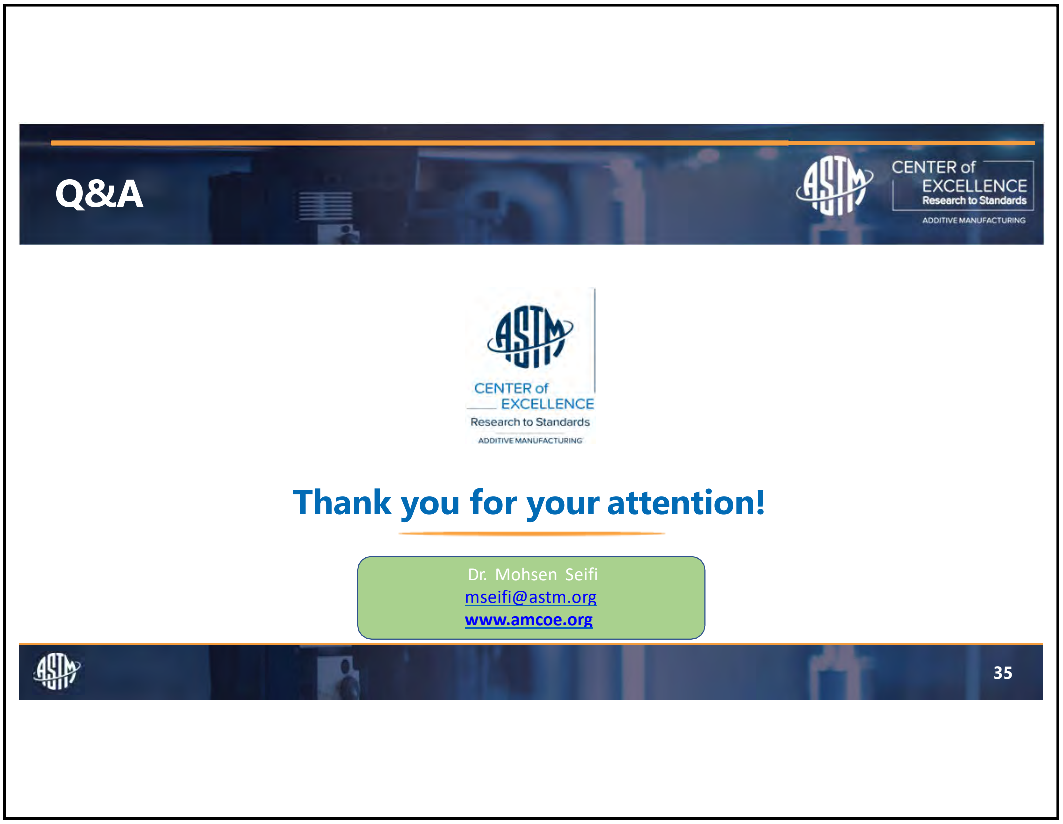
7

Application topics

1. Construction
2. Maritime and Oil & Gas
3. Electronics
4. Medical
5. Aviation and Spaceflight
6. Transportation/Heavy Machinery
7. Defense

# ASTM Perspective on AM Standardization

- AM technologies continue to rapidly evolve across several industry sectors
  - We continue to see evolution of applications in the energy sector including nuclear, renewables, oil/gas, etc.
- ASTM continues to support closure of standardization gaps by relying on key roadmaps, industry needs, coordination, etc.
- We believe in developing agile and innovative solutions as the needs of industry continue to evolve
- Opportunities exist to accelerate standardization
  - Role of government agencies by defining standard deliverables in project calls is key
  - ASTM will actively participate in research to standardization projects
- No need to reinvent the wheel and duplicate efforts
- ASTM continues to collaborate and coordinate with other active bodies and open to new collaborations (example is interaction with ISO)
- Ultimately, what drives the industry forward in terms of implementation is the quality and utility of the standards that are coming out



## Q&A

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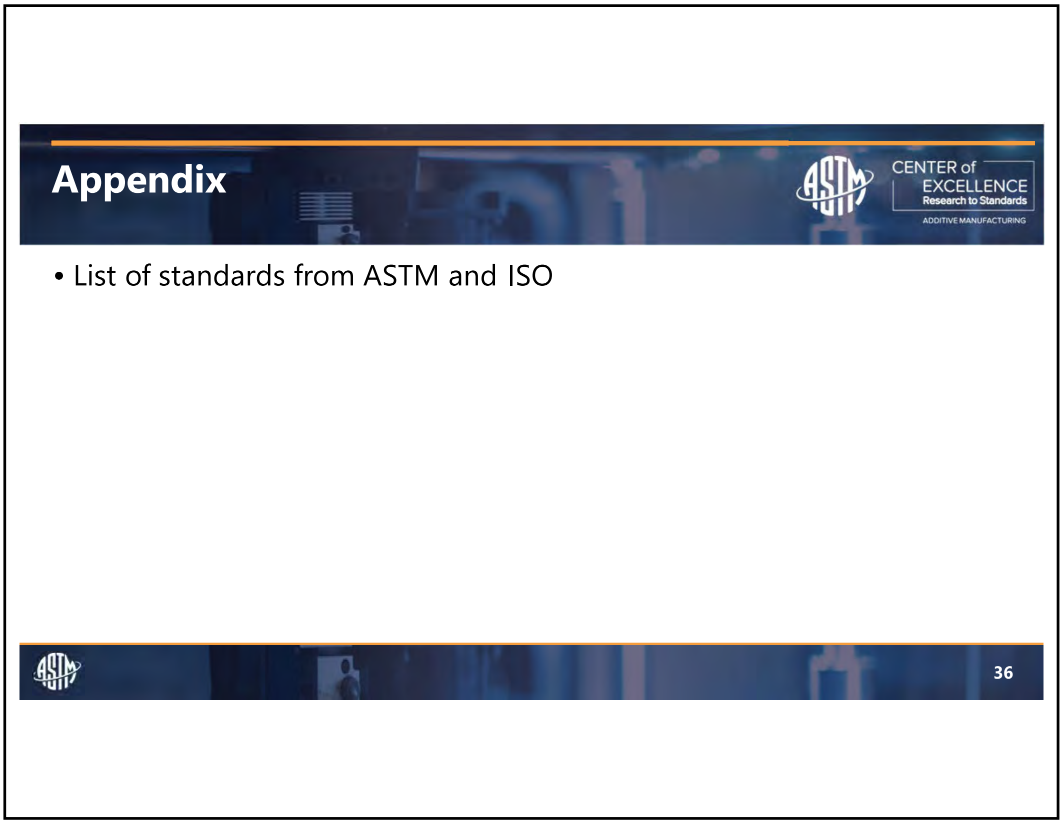
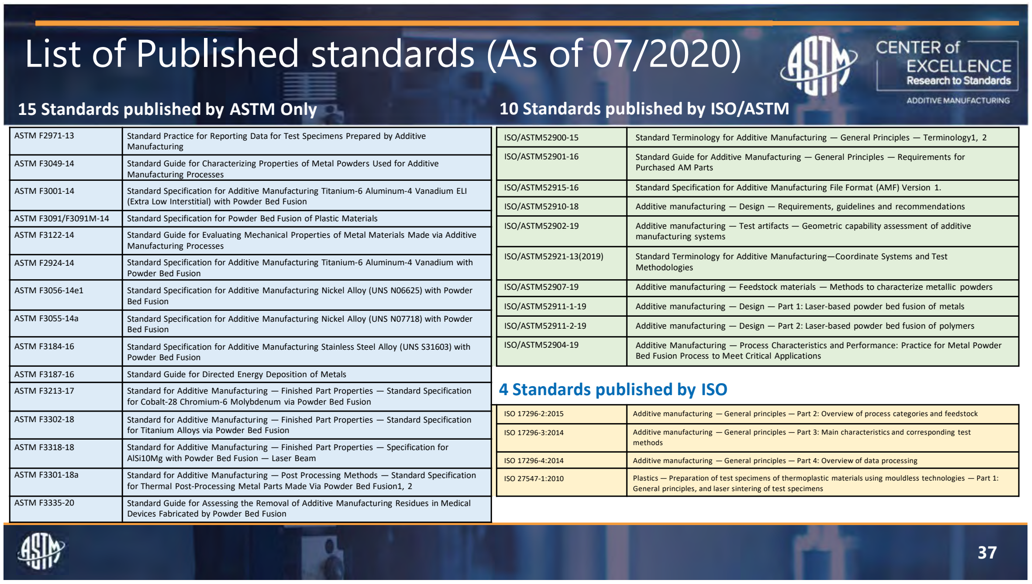
**Thank you for your attention!**

Dr. Mohsen Seifi
mseifi@astm.org
www.amcoe.org



## Appendix

- List of standards from ASTM and ISO



# List of Published standards (As of 07/2020)

## 15 Standards published by ASTM Only

| | |
|---|---|
| ASTM F2971-13 | Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing |
| ASTM F3049-14 | Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes |
| ASTM F3001-14 | Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion |
| ASTM F3091/F3091M-14 | Standard Specification for Powder Bed Fusion of Plastic Materials |
| ASTM F3122-14 | Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes |
| ASTM F2924-14 | Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion |
| ASTM F3056-14e1 | Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion |
| ASTM F3055-14a | Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion |
| ASTM F3184-16 | Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion |
| ASTM F3187-16 | Standard Guide for Directed Energy Deposition of Metals |
| ASTM F3213-17 | Standard for Additive Manufacturing — Finished Part Properties — Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion |
| ASTM F3302-18 | Standard for Additive Manufacturing — Finished Part Properties — Standard Specification for Titanium Alloys via Powder Bed Fusion |
| ASTM F3318-18 | Standard for Additive Manufacturing — Finished Part Properties — Specification for AlSi10Mg with Powder Bed Fusion — Laser Beam |
| ASTM F3301-18a | Standard for Additive Manufacturing — Post Processing Methods — Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion1, 2 |
| ASTM F3335-20 | Standard Guide for Assessing the Removal of Additive Manufacturing Residues in Medical Devices Fabricated by Powder Bed Fusion |

## 10 Standards published by ISO/ASTM

| | |
|---|---|
| ISO/ASTM52900-15 | Standard Terminology for Additive Manufacturing — General Principles — Terminology1, 2 |
| ISO/ASTM52901-16 | Standard Guide for Additive Manufacturing — General Principles — Requirements for Purchased AM Parts |
| ISO/ASTM52915-16 | Standard Specification for Additive Manufacturing File Format (AMF) Version 1. |
| ISO/ASTM52910-18 | Additive manufacturing — Design — Requirements, guidelines and recommendations |
| ISO/ASTM52902-19 | Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems |
| ISO/ASTM52921-13(2019) | Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies |
| ISO/ASTM52907-19 | Additive manufacturing — Feedstock materials — Methods to characterize metallic powders |
| ISO/ASTM52911-1-19 | Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals |
| ISO/ASTM52911-2-19 | Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers |
| ISO/ASTM52904-19 | Additive Manufacturing — Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications |

## 4 Standards published by ISO

| | |
|---|---|
| ISO 17296-2:2015 | Additive manufacturing — General principles — Part 2: Overview of process categories and feedstock |
| ISO 17296-3:2014 | Additive manufacturing — General principles — Part 3: Main characteristics and corresponding test methods |
| ISO 17296-4:2014 | Additive manufacturing — General principles — Part 4: Overview of data processing |
| ISO 27547-1:2010 | Plastics — Preparation of test specimens of thermoplastic materials using mouldless technologies — Part 1: General principles, and laser sintering of test specimens |

# List of Under Development standards (continued)

## 20 Standards currently under development: ASTM

| | |
|---|---|
| ASTM WK66029 | New Guide for Mechanical Testing of Polymer Additively Manufactured Materials |
| ASTM WK66030 | Quality Assessment of Metal Powder Feedstock Characterization Data for Additive Manufacturing |
| ASTM WK67454 | Additive manufacturing -- Feedstock materials -- Methods to characterize metallic powders |
| ASTM WK69371 | Standard practice for generating mechanical performance debits |
| ASTM WK69731 | New Guide for Additive Manufacturing -- Non-Destructive Testing (NDT) for Use in Directed Energy Deposition (DED) Additive Manufacturing Processes |
| ASTM WK71391 | Additive Manufacturing -- Static Properties for Polymer AM (Continuation) |
| ASTM WK71393 | Additive manufacturing -- assessment of powder spreadability for powder bed fusion (PBF) processes |
| ASTM WK71395 | Additive manufacturing -- accelerated quality inspection of build health for laser beam powder bed fusion process |
| ASTM WK48549 | AMF Support for Solid Modeling: Voxel Information, Constructive Solid Geometry Representations and Solid Texturing |
| ASTM WK72172 | Additive manufacturing -- General principles -- Overview of data pedigree |
| ASTM WK65937 | Additive Manufacturing -- Space Application -- Flight Hardware made by Laser Beam Powder Bed Fusion Process |
| ASTM WK69730 | Additive Manufacturing -- Wire for Directed Energy Deposition (DED) Processes in Additive Manufacturing |
| ASTM WK69732 | Additive Manufacturing -- Wire Arc Additive Manufacturing |
| ASTM WK72317 | Additive Manufacturing -- Powder Bed Fusion -- Multiple Energy Sources |
| ASTM WK72457 | Additive manufacturing processes -- Laser sintering of polymer parts/laser-based powder bed fusion of polymer parts -- Qualification of materials |
| ASTM WK66637 | Additive Manufacturing -- Finished Part Properties -- Specification for 4340 Steel via Laser Beam Powder Bed Fusion for Transportation and Heavy Equipment Industries |
| ASTM WK67583 | Additive Manufacturing -- Feedstock Materials -- Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications |
| ASTM WK70164 | Additive Manufacturing -- Finished Part Properties -- Standard Practice for Assigning Part Classifications for Metallic Materials |
| ASTM WK71891 | Additive Manufacturing of Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion for Medical Devices |
| ASTM WK66682 | Evaluating Post-processing and Characterization Techniques for AM Part Surfaces |

# List of standards (continued)

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## 45 Standards currently under development: ISO/ASTM

| | |
|---|---|
| ISO/ASTM 52903-1 | Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials |
| ISO/ASTM DIS 52903-2 | Additive manufacturing — Standard specification for material extrusion based additive manufacturing of plastic materials — Part 2: Process — Equipment |
| ISO/ASTM DTR 52905 | Additive manufacturing — General principles — Non-destructive testing of additive manufactured products |
| ISO/ASTM CD TR52906 | Additive manufacturing — Non-destructive testing and evaluation — Standard guideline for intentionally seeding flaws in parts |
| ISO/ASTM AWI 52908 | Additive manufacturing — Post-processing methods — Standard specification for quality assurance and post processing of powder bed fusion metallic parts |
| ISO/ASTM AWI 52909 | Additive manufacturing — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion |
| ISO/ASTM PWI 52911-3 | Additive manufacturing -- Technical design guideline for powder bed fusion -- Part 3: Standard guideline for electron-based powder bed fusion of metals |
| ISO/ASTM PRF TR52912 | Additive manufacturing - Design -Functionally graded additive manufacturing |
| ISO/ASTM PWI 52913-1 | Additive manufacturing -- Test methods for characterization of powder flow properties for AM applications - Part 1: General requirements |
| ISO/ASTM PWI 52914 | Additive manufacturing -- Design -- Standard guide for material extrusion processes |
| ISO/ASTM WD 52916 | Additive manufacturing — Data formats — Standard specification for optimized medical image data |
| ISO/ASTM WD 52917 | Additive manufacturing — Round Robin Testing — Guidance for conducting Round Robin studies |
| ISO/ASTM CD TR52918 | Additive manufacturing — Data formats — File format support, ecosystem and evolutions |
| ISO/ASTM WD 52919-1 | Additive manufacturing — Test method of sand mold for metalcasting — Part 1: Mechanical properties |
| ISO/ASTM WD 52919-2 | Additive manufacturing — Test method of sand mold for metalcasting — Part 2: Physical properties |
| ISO/ASTM PWI 52920-1 | Additive manufacturing — Qualification principles — Part 1: Conformity assessment for AM system in industrial use |
| ISO/ASTM WD 52920-2 | Additive manufacturing — Qualification principles —Part 2: Requirements for industrial additive manufacturing sites |
| ISO/ASTM DIS 52921 | Additive manufacturing — General principles — Standard practice for part positioning, coordinates and orientation |
| ISO/ASTM PWI 52922 | Additive manufacturing -- Design -- Directed energy deposition |
| ISO/ASTM PWI 52923 | Additive manufacturing -- Design decision support |
| ISO/ASTM DIS 52924 | Additive manufacturing — Qualification principles — Classification of part properties for additive manufacturing of polymer parts |
| ISO/ASTM DIS 52925 | Additive manufacturing — Qualification principles — Qualification of polymer materials for powder bed fusion using a laser |
| ISO/ASTM WD 52926-1 | Additive manufacturing — Qualification principles — Part 1: Qualification of machine operators for metallic parts production |
| ISO/ASTM WD 52926-2 | Additive manufacturing — Qualification principles — Part 2: Qualification of machine operators for metallic parts production for PBF-LB |
| ISO/ASTM WD 52926-3 | Additive manufacturing — Qualification principles — Part 3: Qualification of machine operators for metallic parts production for PBF-EB |
| ISO/ASTM WD 52926-4 | Additive manufacturing — Qualification principles — Part 4: Qualification of machine operators for metallic parts production for DED-LB |
| ISO/ASTM WD 52926-5 | Additive manufacturing — Qualification principles — Part 5: Qualification of machine operators for metallic parts production for DED-Arc |
| ISO/ASTM PWI 52927 | Additive manufacturing -- Process characteristics and performance - Test methods |
| ISO/ASTM PWI 52928 | Powder life cycle management |
| ISO/ASTM NP 52930 | Guideline for installation -- Operation -- Performance Qualification (IQ/OQ/PQ) of laser-beampowder bed fusion equipment for production manufacturing |
| ISO/ASTM CD 52931 | Additive manufacturing — Environmental health and safety — Standard guideline for use of metallic materials |
| ISO/ASTM WD 52932 | Additive manufacturing — Environmental health and safety — Standard test method for determination of particle emission rates from desktop 3D printers using material extrusion |
| ISO/ASTM NP 52933 | Additive manufacturing — Environment, health and safety — Consideration for the reduction of hazardous substances emitted during the operation of the non-industrial ME type 3D printer in workplaces, and corresponding test method |
| ISO/ASTM PWI 52934 | Additive manufacturing -- Environmental health and safety -- Standard guideline for hazard risk ranking and safety defense |
| ISO/ASTM NP 52935 | Additive manufacturing — Qualification Principles — Qualification of coordinators for metallic parts production |
| ISO/ASTM WD 52936-1 | Additive manufacturing — Qualification principles — Laser-based powder bed fusion of polymers — Part 1: General principles, preparation of test specimens |
| ISO/ASTM PWI 52937 | Additive manufacturing — Qualification principles — Qualification of designers for metallic parts production |
| ISO/ASTM DIS 52941 | Additive manufacturing — System performance and reliability — Standard test method for acceptance of powder-bed fusion machines for metallic materials for aerospace application |
| ISO/ASTM DIS 52942 | Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications |
| ISO/ASTM PWI 52943-1 | Additive manufacturing -- Process characteristics and performance -- Part 1: Standard specification for directed energy deposition using wire and beam in aerospace applications |
| ISO/ASTM PWI 52943-2 | Additive manufacturing -- Process characteristics and performance -- Part 2: Standard specification for directed energy deposition using wire and arc in aerospace applications |
| ISO/ASTM PWI 52943-3 | Additive manufacturing -- Process characteristics and performance -- Part 3: Standard specification for directed energy deposition using laser blown powder in aerospace applications |
| ISO/ASTM PWI 52944 | Additive manufacturing -- Process characteristics and performance -- Standard specification for powder bed processes in aerospace applications |
| ISO/ASTM DIS 52950 | Additive manufacturing — General principles — Overview of data processing |
| ISO/ASTM PWI 52951 | Additive manufacturing -- Data packages for AM parts |

# NASA activities and perspectives on standardization in the AM certification process: NASA-STD-6030 and beyond

*Douglas Wells*
*NASA Marshall Spaceflight Center*
*Douglas.N.Wells@nasa.gov*

United States Nuclear Regulatory Commission
Public Meeting (Virtual)
Workshop on Advanced Manufacturing Technologies for Nuclear Applications
November 7-10, 2020

## Contents of Discussion

- Overview of selected standardization activities
  - Within Agency – NASA-STD-6030 development
    - Review of status
    - Key concepts
  - Supporting Standards Development Organizations (SDOs)
    - ASTM CoE R&D in LB-PBF Process Qualification
- Considerations for critical, but uninspectable AM hardware
  - Cooperative work with FAA on DARWIN code development for AM applications

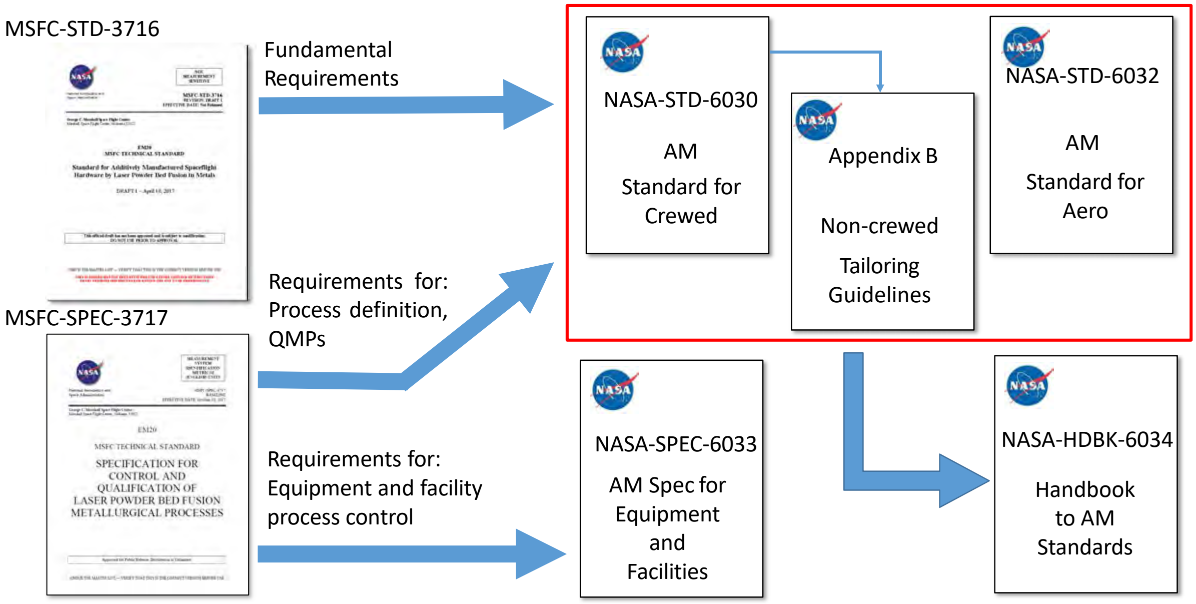
# Motivations for Agency Standards

NASA has been motivated to develop internal standards for AM to provide for a complete and common foundation while industry standards (and standards of practice) evolve.

NASA AM standards have the following intent:

- To provide a consistent methodology for AM on NASA projects
- To define a complete and integrated approach to AM hardware implementation
- To ensure NASA visibility into the introduction of additively manufactured hardware
    - To allow for awareness and evaluation of risk with AM implementation

# New Agency Document Structure



MSFC-STD-3716

Fundamental Requirements

MSFC-SPEC-3717

Requirements for: Process definition, QMPs

Requirements for: Equipment and facility process control

NASA-STD-6030 AM Standard for Crewed

Appendix B Non-crewed Tailoring Guidelines

NASA-STD-6032 AM Standard for Aero

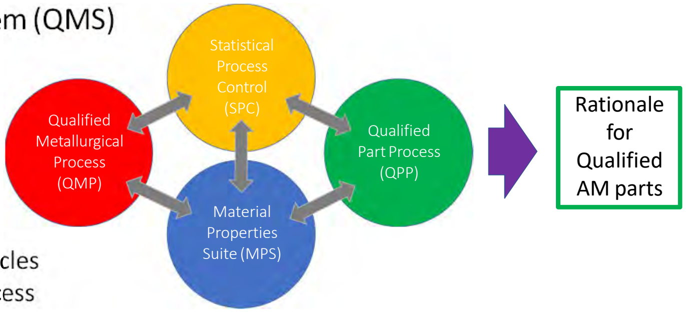
NASA-SPEC-6033 AM Spec for Equipment and Facilities

NASA-HDBK-6034 Handbook to AM Standards

# AM Certification: Governing Principles

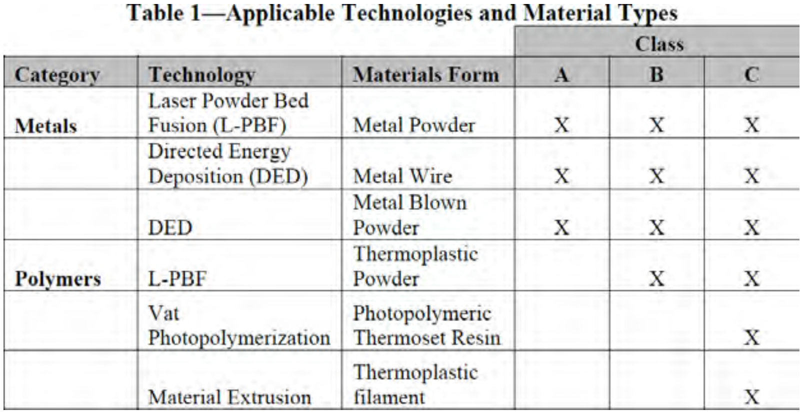
- *Understanding* and *Appreciation* of the AM process
- *Integration* across disciplines and throughout the process
- *Discipline* to define and follow the plan

- Have a plan
- Integrate a Quality Management System (QMS)
- Build a foundation
  - Equipment and Facility
  - Training
  - Process and machine qualification
  - Material Properties / SPC
- Plan each Part
  - Design, classification, Pre-production articles
  - Qualify and lock the part production process
- Produce to the plan – Stick to the plan



# Applicable Materials and Technologies in NASA-STD-6030

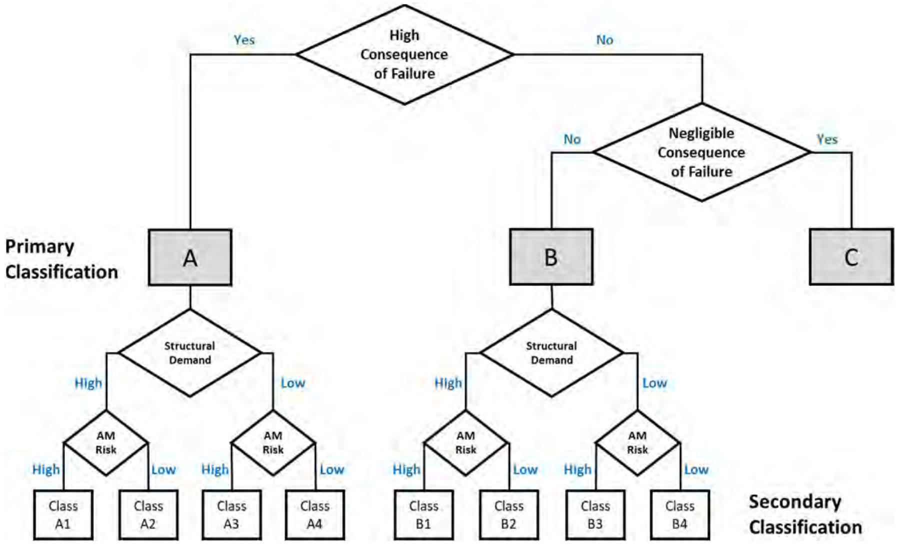
Table 1—Applicable Technologies and Material Types



| | | | Class | | |
|---|---|---|---|---|---|
| **Category** | **Technology** | **Materials Form** | **A** | **B** | **C** |
| **Metals** | Laser Powder Bed Fusion (L-PBF) | Metal Powder | X | X | X |
| | Directed Energy Deposition (DED) | Metal Wire | X | X | X |
| | DED | Metal Blown Powder | X | X | X |
| **Polymers** | L-PBF | Thermoplastic Powder | | X | X |
| | Vat Photopolymerization | Photopolymeric Thermoset Resin | | | X |
| | Material Extrusion | Thermoplastic filament | | | X |

Adaptive technologies—where process parameters change based on active feedback during the manufacturing process—are not allowed without a tailored, point-design methodology.

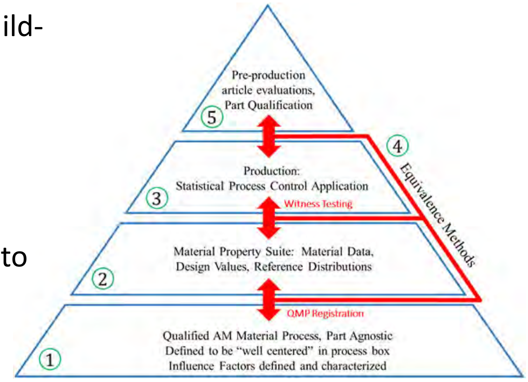
# NASA-STD-6030 AM Part Classification



# Material "Engineering Equivalence"

**Statistical process controls are important in sustaining certification rationale**

- *Statistical / Engineering* ***<u>equivalency</u>*** *evaluations* substantiate design values and process stability build-to-build
  - a) Process qualification
  - b) Witness testing
  - c) Integration to existing material data sets
  - d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts



## Standardizing AM Process Qualification

One example of NASA's involvement in the AM SDO landscape.

**Well-defined process qualification standards remain a clear gap in the AM standards framework**

- This gap impedes the diversification and responsiveness of AM part suppliers when qualification requirements are unique to each purchaser

Many fundamental concepts that define AM process qualification remain undetermined

- Terminology – What nomenclature is used to describe the process?
- Scope – What is within the scope of "process qualification"?
- Intent – What should the final outcome of a successful process qualification consist of?
- Rigor – How detailed and thorough should a process qualification be? Same for all parts?
- Application – How will a process qualification standard fit into the bigger picture of the AM standards framework?

## Standardizing AM Process Qualification

**Core fundamentals of the project approach remain the same:**

1. Develop consensus within the ASTM CoE community regarding minimum requirements for the qualification of L-PBF machines and processes.
2. Establish a standard set of procedures, test methods, and evaluations used to establish L-PBF qualification based on fundamental objectives.
3. Establish quantitative and/or qualitative metrics applicable to each evaluation to define successful machine and process qualification.
4. Conduct development and round-robin-style trials of the qualification evaluations and associated metrics.
5. Establish a set of recommendations to appropriate F42 sub-committees for standards implementation.

# Standardizing AM Process Qualification

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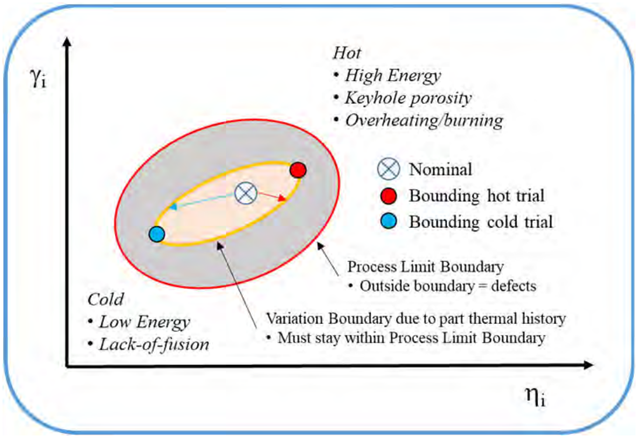
**Thermal Challenge Build for Process Box Confirmation (Auburn University)**

Subset of Process Qualification Standardization

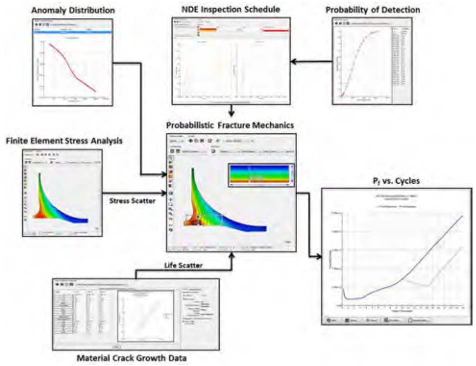
- <u>Objective</u>: confirm candidate parameter set is “well centered” in the process box.
- Develop standard parts or part design philosophy
- Challenge the AM process box through geometry, and potentially scan pattern
- <u>Not</u> used in defining process box during parameter development
- Needs to be able to work with fixed, “black box” parameter sets from OEMs



# Assessment of Non-inspectable Critical Parts

- **Risk level in AM parts for space applications continues to accelerate rapidly**
- **Need methodologies to assess damage tolerance (DT) in critical parts that, through mass or complexity, significantly limit or preclude traditional non-destructive inspection**

- **Challenges in work:**
  - Integration tools for deterministic or probabilistic DT assessment
  - DARWIN software through Southwest Research Institute
    - Projects complimentary to similar FAA efforts
    - Part zoning methodologies/considerations
    - AM defect characterization
      - Inherent
      - Rogue / process escapes
    - Leveraging NDI simulation to understand limits of coverage
    - Practical use of process data on a per-part basis
      - In situ monitoring data
  - Qualification of in situ monitoring systems



# Conclusions

1. NASA remains intently interested in standardization for AM
   - Working Agency (public) standards as well as with multiple SDOs
   - Standards for AM process qualification remains a focus
2. NASA has near-term challenges regarding risk management of high criticality parts with limited post-build structural integratory verification
   - Working on integrated methods to utilize all available data (traditional NDE, in-process data…) and assessment techniques (zoning, probabilistic assessments, …) to manage risk

# **Development of AWS D20.1/D20.1M,** *Specification for Fabrication of Metal Components using Additive Manufacturing*

Jessica Coughlin
AWS D20 Committee Chair

## AWS D20 COMMITTEE ON ADDITIVE MANUFACTURING

- **Charter:** Create a standard containing requirements for fabricating metal components using AM that, when adhered to, will result in the repeatable production of metal AM components that meet functional requirements

- **Result:** AWS D20.1/D20.1M:2019, *Specification for Fabrication of Metal Components using Additive Manufacturing*

## AWS D20.1/D20.1M – PROCESSES COVERED

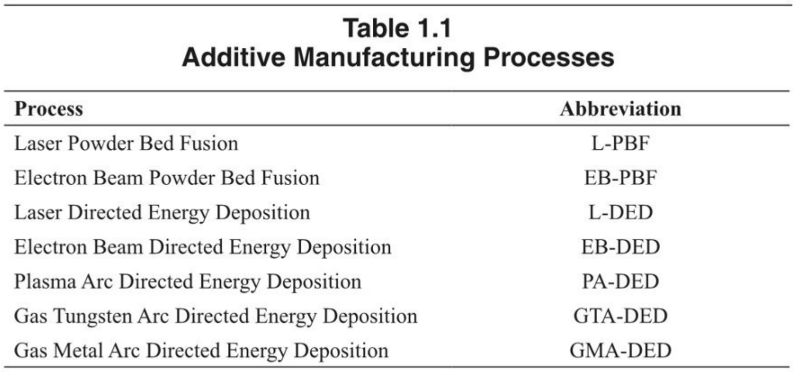


**Table 1.1**
**Additive Manufacturing Processes**

| Process | Abbreviation |
|---|---|
| Laser Powder Bed Fusion | L-PBF |
| Electron Beam Powder Bed Fusion | EB-PBF |
| Laser Directed Energy Deposition | L-DED |
| Electron Beam Directed Energy Deposition | EB-DED |
| Plasma Arc Directed Energy Deposition | PA-DED |
| Gas Tungsten Arc Directed Energy Deposition | GTA-DED |
| Gas Metal Arc Directed Energy Deposition | GMA-DED |

## AWS D20.1/D20.1M - COMPONENT CLASSIFICATION

AWS D20.1 contains graded requirements for qualification and inspection based on the classification of the AM component. (1.4)

- **Class A** – Critical application. A component whose failure would cause significant danger to personnel, loss of control, loss of a system, loss of a major component, or an operating penalty.
- **Class B** – Semi-critical application. A component whose failure would reduce the overall strength of the equipment or system or preclude the intended functioning or use of equipment, but loss of the system or the endangerment of personnel would not occur.
- **Class C** – Noncritical application. A component whose failure would not affect the operation of the system or endanger personnel.

# AWS D20.1/D20.1M:2019

## CLAUSES

1 General Requirements
2 Normative References
3 Terms and Definitions
4 Design Requirements for Additively Manufactured Components
5 Additive Manufacturing Machine and Procedure Qualification
6 Additive Manufacturing Machine Operator Performance Qualification
7 Fabrication
8 Inspection

AWS D20.1/D20.1M:2019
An American National Standard

Specification for Fabrication of Metal Components using Additive Manufacturing

American Welding Society

ANSI

# AWS D20.1/D20.1M:2019

## ANNEXES

A Additive Manufacturing Qualification Records
B Informative References
C Examples of Standard Qualification Build Designs for Powder Bed Fusion
D Suggested Format for Fabrication Records
E Process Flowcharts for Producing Components using AWSD20.1/D20.1M
F Requesting an Official Interpretation on an AWS Standard

Also contains: Commentary on the Specification for Fabrication of Metal Components using Additive Manufacturing

AWS D20.1/D20.1M:2019
An American National Standard

Specification for Fabrication of Metal Components using Additive Manufacturing

American Welding Society

ANSI

# AWS D20.1/D20.1M

## DESIGN REQUIREMENTS - CLAUSE 4

The Engineer is required to design and define component requirements to ensure compliance with all functional and system requirements. Responsibilities include:

- Develop or obtain appropriate material property requirements to satisfy the component design. (4.2)
- Design witness specimens for Class A and Class B PBF component builds. (4.3)
- Define component classification level, final dimensions, process restrictions, post-processing requirements, etc. (4.4)

# AWS D20.1/D20.1M

## MACHINE AND PROCEDURE QUALIFICATION – CLAUSE 5

As in the welding industry, qualification is achieved through the successful fabrication, inspection, and testing of material representative of the production component.

- Procedure Qualification Record (PQR) and Machine Qualification Record (MQR) required to document variables used during qualification builds. (5.1.1) Example records for each process provided in Annex A.
- Additive Manufacturing Procedure Specification (AMPS) must be qualified prior to fabrication of production components. Includes: AM process, component classification, build model file name, all applicable build platform, feedstock, machine, environment, build parameters, and post-processing information. (5.1.2)

# AWS D20.1/D20.1M

## MACHINE AND PROCEDURE QUALIFICATION

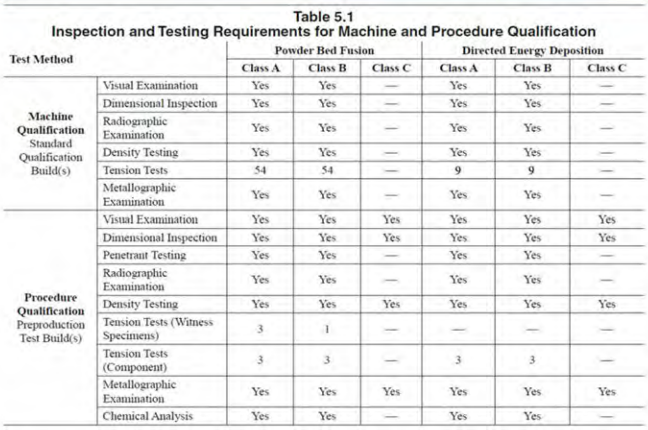


Table 5.1
Inspection and Testing Requirements for Machine and Procedure Qualification

| Test Method | | Powder Bed Fusion | | | Directed Energy Deposition | | |
|---|---|---|---|---|---|---|---|
| | | Class A | Class B | Class C | Class A | Class B | Class C |
| **Machine Qualification** Standard Qualification Build(s) | Visual Examination | Yes | Yes | — | Yes | Yes | — |
| | Dimensional Inspection | Yes | Yes | — | Yes | Yes | — |
| | Radiographic Examination | Yes | Yes | — | Yes | Yes | — |
| | Density Testing | Yes | Yes | — | Yes | Yes | — |
| | Tension Tests | 54 | 54 | — | 9 | 9 | — |
| | Metallographic Examination | Yes | Yes | — | Yes | Yes | — |
| **Procedure Qualification** Preproduction Test Build(s) | Visual Examination | Yes | Yes | Yes | Yes | Yes | Yes |
| | Dimensional Inspection | Yes | Yes | Yes | Yes | Yes | Yes |
| | Penetrant Testing | Yes | Yes | — | Yes | Yes | — |
| | Radiographic Examination | Yes | Yes | — | Yes | Yes | — |
| | Density Testing | Yes | Yes | Yes | Yes | Yes | Yes |
| | Tension Tests (Witness Specimens) | 3 | 1 | — | — | — | — |
| | Tension Tests (Component) | 3 | 3 | — | 3 | 3 | — |
| | Metallographic Examination | Yes | Yes | Yes | Yes | Yes | Yes |
| | Chemical Analysis | Yes | Yes | — | Yes | Yes | — |

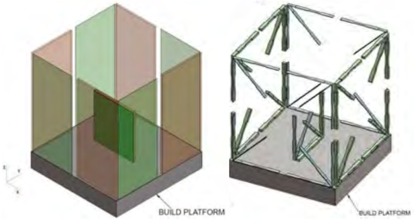
# AWS D20.1/D20.1M

## PBF MACHINE QUALIFICATION

PBF machine qualification requires a "standard qualification build" with 54 tension test specimens (minimum), representative of the component in the following ways:

- Thick and thin specimens shall be fabricated to represent a range of component feature geometries. (5.2.1.1)
- Specimen orientations shall include tensile axis within the X-Y plane, along the Z-axis, and at 45° from the Z-axis. (5.2.1.2)
- Specimens shall encompass the build volume to be used during component fabrication. (5.2.1.2)
- Dimensional inspection features shall be included in the build. (5.2.1.1)

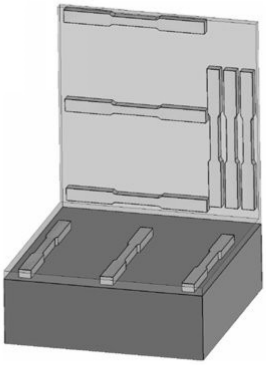
(support structure not shown)



# AWS D20.1/D20.1M
## DED MACHINE QUALIFICATION

DED machine qualification requires a “standard qualification build” from which a minimum of 9 tension test specimens can be removed.

- The build shall provide material with heat sink conditions representative of the component, with vertical and horizontal plane conditions at a minimum. (5.2.2.1)
- Dimensional inspection features shall be included in the build. (5.2.2.1)
- Three additional tension test specimens required across interface for components with integrated build platform. (5.2.3.2)



# AWS D20.1/D20.1M
## AM PROCEDURE QUALIFICATION

For PBF and DED components, AM procedure qualification requires fabrication and testing of a “preproduction test build,” which shall:

- Be fabricated from the same build file as will be used for the production component (i.e., shall have identical geometry to the production component, including witness specimens). (5.2.3)
- Undergo the same post-processing steps (e.g., surface finishing, thermal processing) as will be used for the production component. (5.2.3)
- Be fabricated using the same parameters as will be used for the production component, aside from changes within qualified limits. (5.2.3)

## AWS D20.1/D20.1M

### QUALIFICATION LIMITS

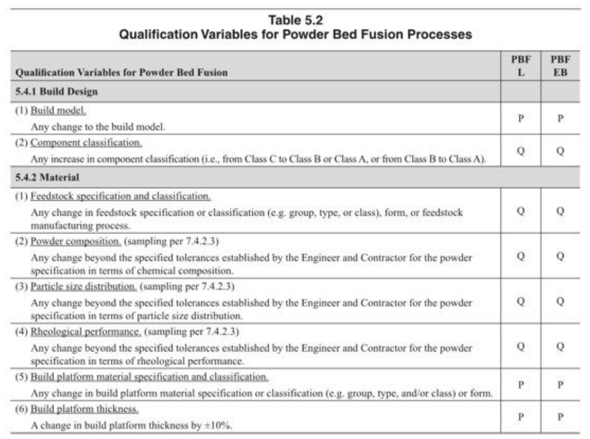


Table 5.2
Qualification Variables for Powder Bed Fusion Processes

| Qualification Variables for Powder Bed Fusion | PBF L | PBF EB |
|---|---|---|
| **5.4.1 Build Design** | | |
| (1) Build model.<br>Any change to the build model. | P | P |
| (2) Component classification.<br>Any increase in component classification (i.e., from Class C to Class B or Class A, or from Class B to Class A). | Q | Q |
| **5.4.2 Material** | | |
| (1) Feedstock specification and classification.<br>Any change in feedstock specification or classification (e.g. group, type, or class), form, or feedstock manufacturing process. | Q | Q |
| (2) Powder composition. (sampling per 7.4.2.3)<br>Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of chemical composition. | Q | Q |
| (3) Particle size distribution. (sampling per 7.4.2.3)<br>Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of particle size distribution. | Q | Q |
| (4) Rheological performance. (sampling per 7.4.2.3)<br>Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of rheological performance. | Q | Q |
| (5) Build platform material specification and classification.<br>Any change in build platform material specification or classification (e.g. group, type, and/or class) or form. | P | P |
| (6) Build platform thickness.<br>A change in build platform thickness by ±10%. | P | P |

AWS D20.1 lists all qualification variables for PBF (Table 5.2) and DED (Table 5.3) processes, along with the changes to each variable that require requalification of the AM machine (M), AM procedure (P), or both (Q).

Sections include Build Design, Material, Machine, Environment, Heat Source Characteristics, Deposition Characteristics, and Post-Processing.

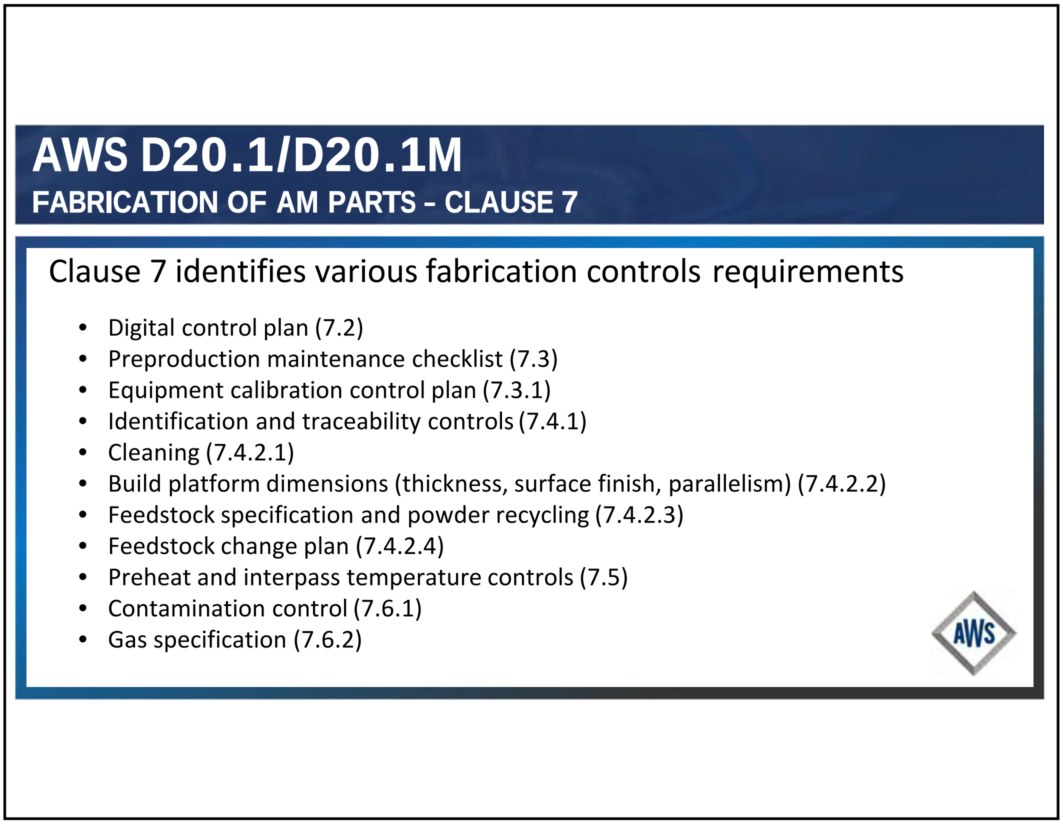
## AWS D20.1/D20.1M

### MACHINE OPERATOR PERFORMANCE QUALIFICATION – CLAUSE 6

AM machine operators must be capable of repeatedly fabricating acceptable AM components. Qualification is achieved through training, practical examination, and a completion of a demonstration build (6.3).

Training topics include (6.3.2.1):

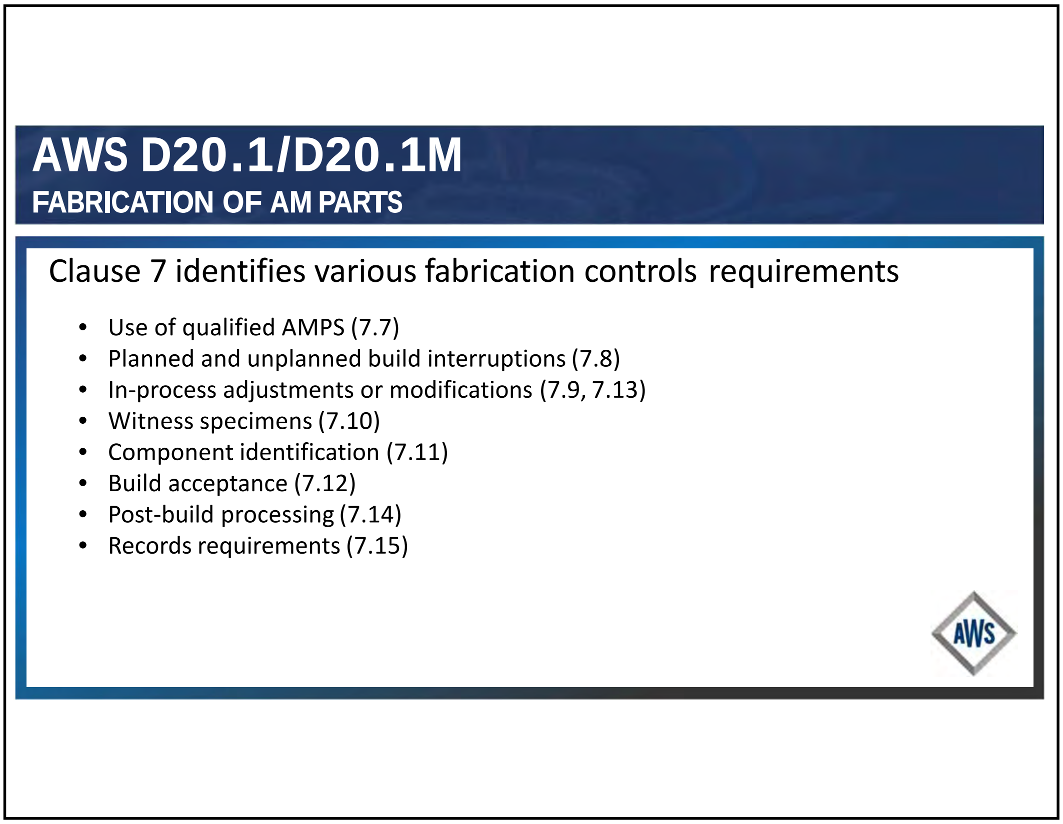
- Feedstock material storage, safety, and setup.
- Cleaning requirements and environmental controls.
- Machine calibration, preventative maintenance, and safety.
- Loading of qualified build parameters.
- Running and monitoring AM build cycles.
- Recording AM build cycle data.
- Common build defects, their causes, and means of prevention.
- Recovery from planned and unplanned build interruptions.



## AWS D20.1/D20.1M
### FABRICATION OF AM PARTS – CLAUSE 7

Clause 7 identifies various fabrication controls requirements

- Digital control plan (7.2)
- Preproduction maintenance checklist (7.3)
- Equipment calibration control plan (7.3.1)
- Identification and traceability controls (7.4.1)
- Cleaning (7.4.2.1)
- Build platform dimensions (thickness, surface finish, parallelism) (7.4.2.2)
- Feedstock specification and powder recycling (7.4.2.3)
- Feedstock change plan (7.4.2.4)
- Preheat and interpass temperature controls (7.5)
- Contamination control (7.6.1)
- Gas specification (7.6.2)



## AWS D20.1/D20.1M
### FABRICATION OF AM PARTS

Clause 7 identifies various fabrication controls requirements

- Use of qualified AMPS (7.7)
- Planned and unplanned build interruptions (7.8)
- In-process adjustments or modifications (7.9, 7.13)
- Witness specimens (7.10)
- Component identification (7.11)
- Build acceptance (7.12)
- Post-build processing (7.14)
- Records requirements (7.15)

## AWS D20.1/D20.1M
### INSPECTION OF AM PARTS - CLAUSE 8

Clause 8 contains inspection, testing, and acceptance requirements for qualification builds, production components, and witness specimens:

- Qualification of inspection personnel. (8.1)
- Nondestructive examination (NDE) requirements and acceptance:
  - Visual examination (8.2.1), dimensional examination (8.2.2), penetrant testing (PT) (8.2.3), magnetic particle testing (MT) (8.2.4), radiographic testing (RT) (8.2.5), density testing (8.2.6)
- Destructive evaluation requirements and acceptance:
  - Tension testing (8.3.1), metallographic examination (8.3.2), chemical analysis (8.3.3)

- AWS D20.1/D20.1M:2019 provides comprehensive design, qualification, fabrication, and inspection requirements for metal components using PBF and DED AM processes.
- Extensive testing and evaluation are required to ensure that AM parts will be produced with acceptable, repeatable properties.
- Potential material variability related to build orientation, thickness, and surface roughness demonstrates the importance of testing material representative of component features.
- Standardized test article builds using representative material provide a repeatable means for detecting quality concerns and sources of microstructural and mechanical property variability.

## CONCLUSIONS

# NRC Regulatory Approach for Advanced Manufacturing Technologies

Carolyn Fairbanks

Office of Nuclear Reactor Regulation
December 10, 2020

## Advanced Manufacturing Technologies

- Techniques and material processing methods
  - Not traditionally used in the U.S. nuclear industry
  - Not formally standardized/codified by the nuclear industry

- Initial AMTs based on industry interest:
  - Laser Powder Bed Fusion (LPBF)
  - Direct Energy Deposition (DED)
  - Cold Spray
  - Electron Beam Welding
  - Powder Metallurgy - Hot Isostatic Pressing (PM-HIP)

# Action Plan, Rev. 1 - Tasks

- Task 1 - Technical Preparedness
  - Technical information, knowledge and tools to prepare NRC staff to review AMT applications
- Task 2 - Regulatory Preparedness
  - Regulatory guidance and tools to prepare staff for efficient and effective review of AMT-fabricated components submitted to the NRC for review and approval
- Task 3 - Communications and Knowledge Management

  - Integration of information from external organizations into the NRC staff knowledge base for informed regulatory decision-making
  - External interactions and knowledge sharing, i.e. AMT Workshop

# Technical Preparedness Activities (Task 1)

**Subtask 1A: AMT Processes under Consideration**

- Perform a technical assessment of selected AMTs (Laser Powder Bed Fusion, Directed Energy Deposition, PM HIP, EB-welding, and Cold Spray)
- Gap assessment for each selected AMTs vs traditional manufacturing techniques

**Subtask 1B: Inspection and NDE**

- Assess the state of technologies in the testing and examination of AMTs
- Will inform staff decisions related to use of NDE on AMT-fabricated components

**Subtask 1C: Modeling and Simulation of Microstructure and Properties**

- Evaluate modeling and simulation tools used to predict the initial microstructure, material properties and component integrity of AMT components
- Identify existing gaps and challenges that are unique to AMT compared to conventional manufacturing processes
  - Survey of Modeling and Simulation Techniques for Advanced Manufacturing Technologies:
    - Volume I – Predicting Initial Microstructures (ML20269A301)
    - Volume II - Predicting Material Performance from Material Microstructure

# Regulatory Preparedness Activities (Task 2)

### Subtask 2A: Implementation using the 10 CFR 50.59 Process

- Provide guidance and support to regional inspectors regarding AMTs implemented under 50.59

### Subtask 2B: Assessment of Regulatory Guidance

- Assess whether any regulatory guidance needs to be updated or created to clarify the process for reviewing submittals with AMT components
- Complete: ML20233A693

### Subtask 2C: AMT Guidelines Document

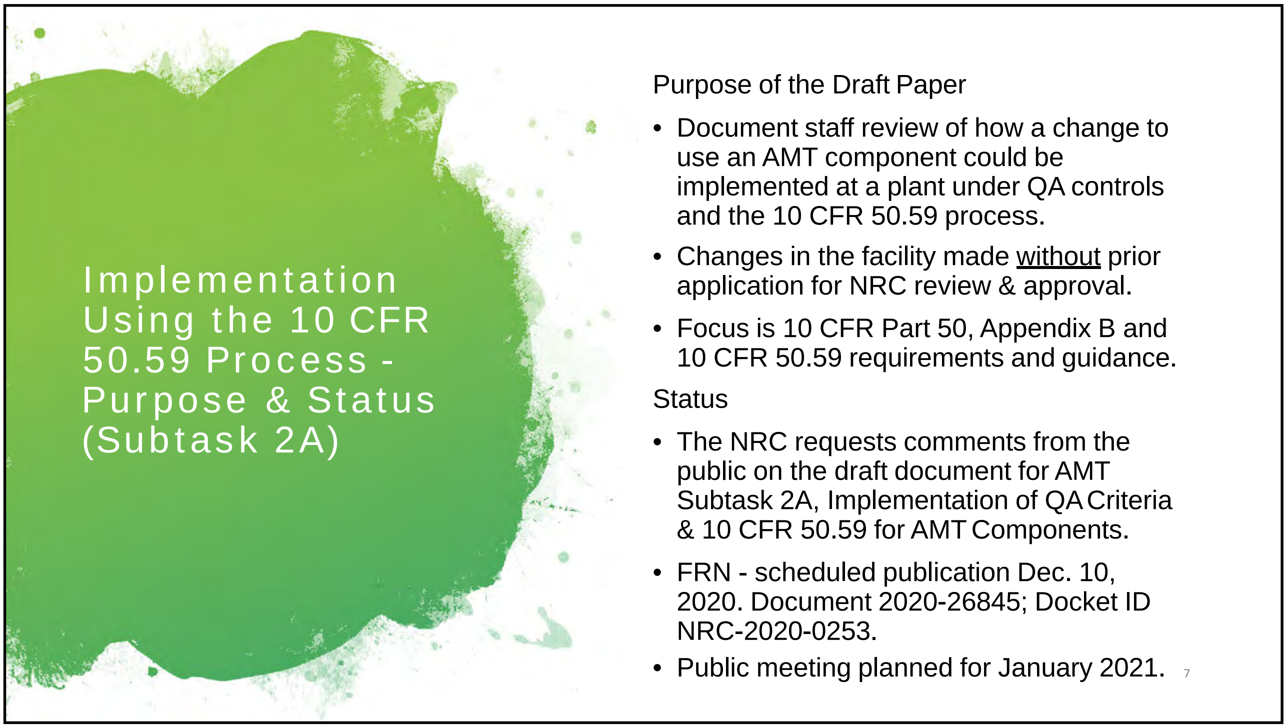
- Develop guidelines which describe the generic technical information to be addressed in AMT submissions
- Public meeting discussing initial framework was held July 30, 2020 https://www.nrc.gov/pmns/mtg?do=details&Code=20200816
- Meeting summary: ML20240A077

# Implementation Using the 10 CFR 50.59 Process - Background (Subtask 2A)

- Industry identified 10 CFR 50.59 as the regulatory path for initial AMT components at U.S. NPPs.
- Staff performed a preliminary review of the 50.59 process for changes to use AMT components.
- In-depth development based on consensus inputs from many NRC counterparts.

  Multiple rounds of review & comment from regulatory and technical subject matter experts in the Regions, NRR, and RES; and from OGC attorneys.

- Staff's review expanded to address technical QA criteria for design control & procurement in addition to 50.59.



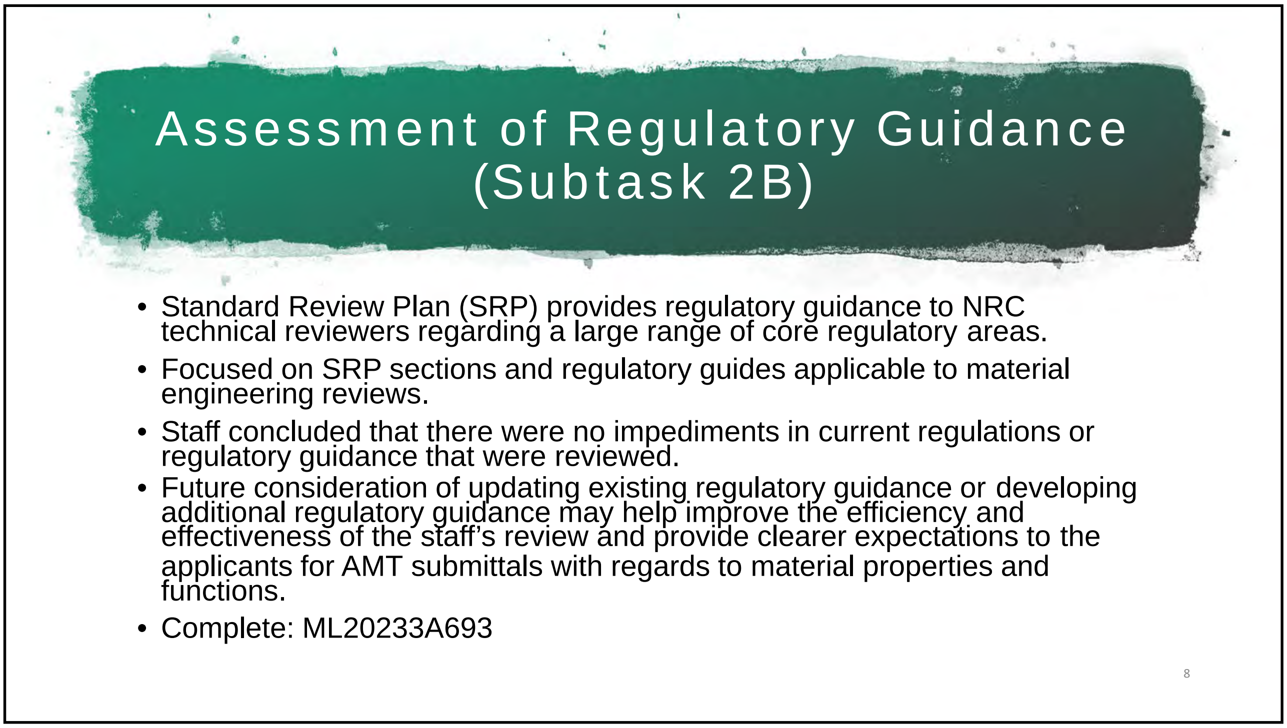
## Implementation Using the 10 CFR 50.59 Process - Purpose & Status (Subtask 2A)

Purpose of the Draft Paper

- Document staff review of how a change to use an AMT component could be implemented at a plant under QA controls and the 10 CFR 50.59 process.
- Changes in the facility made without prior application for NRC review & approval.
- Focus is 10 CFR Part 50, Appendix B and 10 CFR 50.59 requirements and guidance.

Status

- The NRC requests comments from the public on the draft document for AMT Subtask 2A, Implementation of QA Criteria & 10 CFR 50.59 for AMT Components.
- FRN - scheduled publication Dec. 10, 2020. Document 2020-26845; Docket ID NRC-2020-0253.
- Public meeting planned for January 2021.



## Assessment of Regulatory Guidance (Subtask 2B)

- Standard Review Plan (SRP) provides regulatory guidance to NRC technical reviewers regarding a large range of core regulatory areas.
- Focused on SRP sections and regulatory guides applicable to material engineering reviews.
- Staff concluded that there were no impediments in current regulations or regulatory guidance that were reviewed.
- Future consideration of updating existing regulatory guidance or developing additional regulatory guidance may help improve the efficiency and effectiveness of the staff's review and provide clearer expectations to the applicants for AMT submittals with regards to material properties and functions.
- Complete: ML20233A693

## AMT Application Guidelines Framework (Subtask 2C)

- Develop a report providing guidelines which describe the generic technical information to be addressed in AMT submissions.
- Public meeting discussing initial framework was held July 30, 2020:
  - https://www.nrc.gov/pmns/mtg?do=details&Code=20200816.
- Meeting summary: ML20240A077.
- Framework document has evolved further into a draft document.
- Future public comment period, public meeting on the draft document.

## AMT Application Guidelines Framework (Subtask 2C)

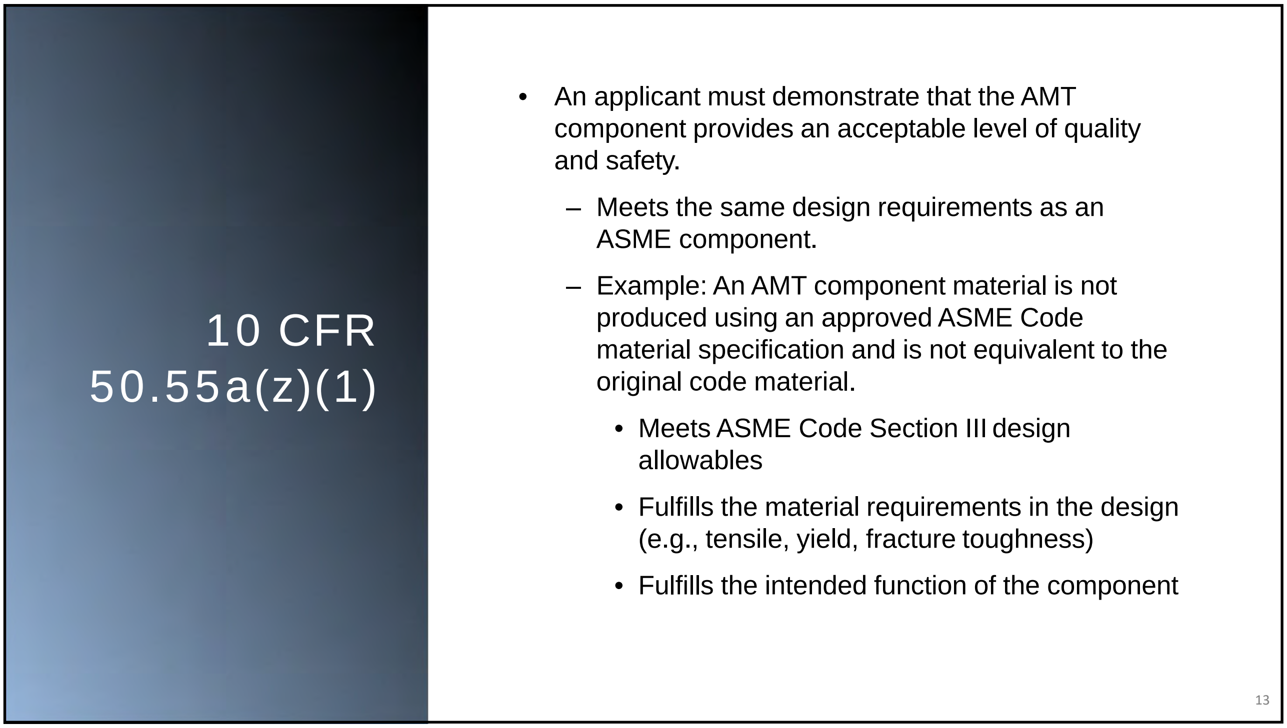
- The draft framework provides a starting point for discussion on potential guidance regarding the use of AMTs.
- AMTs include techniques and material processing methods not traditionally used in the US nuclear industry that have yet to be formally standardized by the nuclear industry and approved by the NRC (e.g., ASME Code, topical report).
- AMTs can include new ways to fabricate or join components, surface treatments, or other processing techniques to provide a performance or operational benefit.

## General Review Philosophy

- Framework and associated guidelines must be sufficient and flexible.
- Currently there are two conventional paths to demonstrating that an AMT component is acceptable and will fulfill its intended function.
  - Equivalency Approach: attributes of the AMT component meet or exceed the original design and performance requirements. (e.g., equal to or greater than tensile, yield, fracture toughness, SCC resistance).
  - Design Modification: Provide technical justification for changing existing requirements. For example, the original material provided significant margin compared to what is necessary for the component to meets its intended function.

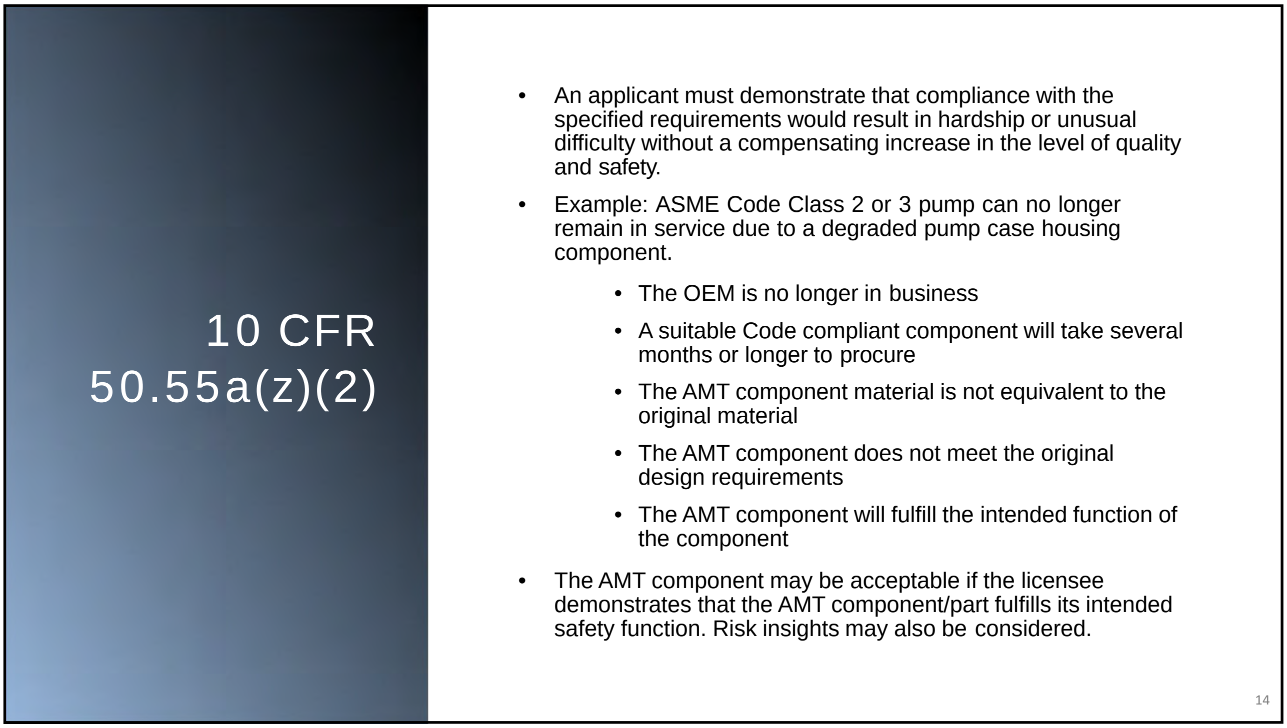
## Regulatory Pathways

- 10 CFR 50.59 and QA/design controls
  - Subtask 2A of AMT Action Plan, rev.1
  - Draft 2A document will be available for public comment Dec. 10, 2020
  - FRN Document Number 2020-26845
  - Docket ID NRC-2020-0253
- License amendment (Technical Specification change, etc.)
- 10 CFR 50.55a Codes and Standards
  - (z) Alternatives to codes and standards
    - (1) Acceptable level of quality and safety
    - (2) Hardship without a compensating increase in quality and safety



## 10 CFR 50.55a(z)(1)

- An applicant must demonstrate that the AMT component provides an acceptable level of quality and safety.
  - Meets the same design requirements as an ASME component.
  - Example: An AMT component material is not produced using an approved ASME Code material specification and is not equivalent to the original code material.
    - Meets ASME Code Section III design allowables
    - Fulfills the material requirements in the design (e.g., tensile, yield, fracture toughness)
    - Fulfills the intended function of the component



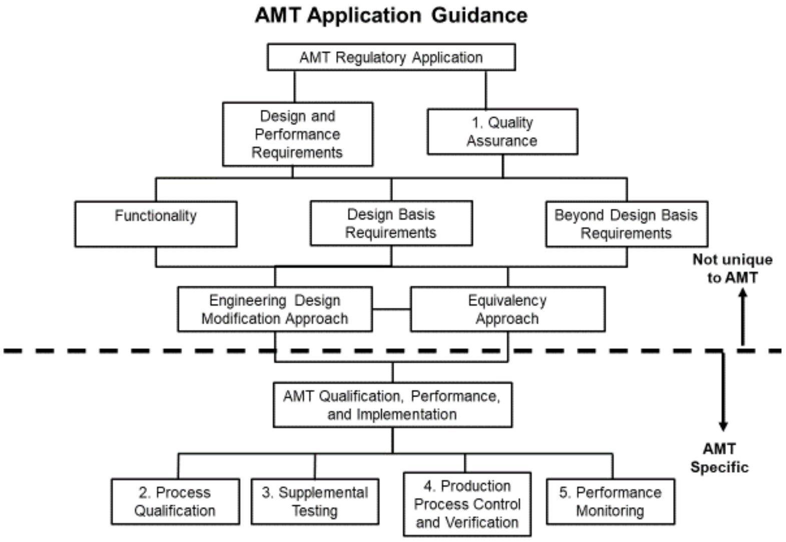
## 10 CFR 50.55a(z)(2)

- An applicant must demonstrate that compliance with the specified requirements would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety.
- Example: ASME Code Class 2 or 3 pump can no longer remain in service due to a degraded pump case housing component.
    - The OEM is no longer in business
    - A suitable Code compliant component will take several months or longer to procure
    - The AMT component material is not equivalent to the original material
    - The AMT component does not meet the original design requirements
    - The AMT component will fulfill the intended function of the component
- The AMT component may be acceptable if the licensee demonstrates that the AMT component/part fulfills its intended safety function. Risk insights may also be considered.

# Process Flow Chart

The process flow chart in Appendix A to the AMT Application Guidelines Framework document, along with definitions and short descriptions, describes a holistic approach to the qualification and performance considerations for any system, structure, or safety significant component (SSC), including the underlying material and fabrication process.

- The flow chart is intended to cover a broad range of AMTs and be a guide which outlines the types of information that could be included in a licensee's request to facilitate the NRC's review.
- Depending on the AMT process used, some of the information in the flow chart may not be necessary.
- The focus of the information should be on those unique attributes associated with AMT qualification and performance compared to conventionally manufactured SSCs.
- The application may leverage relevant aspects of ASME and ASTM standards that prescribe certain testing requirements for conventionally manufactured items.



**AMT Application Guidance**

AMT Regulatory Application

Design and Performance Requirements

1. Quality Assurance

Functionality

Design Basis Requirements

Beyond Design Basis Requirements

Engineering Design Modification Approach

Equivalency Approach

**Not unique to AMT**

**AMT Specific**

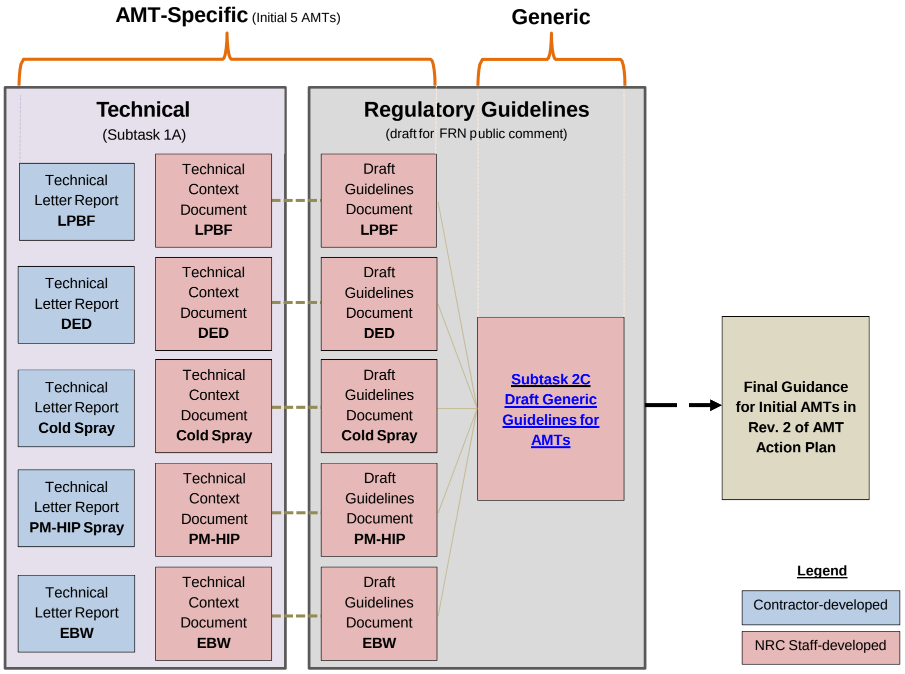
AMT Qualification, Performance, and Implementation

2. Process Qualification

3. Supplemental Testing

4. Production Process Control and Verification

5. Performance Monitoring



**AMT-Specific** (Initial 5 AMTs)

**Generic**

**Technical**
(Subtask 1A)

**Regulatory Guidelines**
(draft for FRN public comment)

| | | |
|---|---|---|
| Technical Letter Report **LPBF** | Technical Context Document **LPBF** | Draft Guidelines Document **LPBF** |
| Technical Letter Report **DED** | Technical Context Document **DED** | Draft Guidelines Document **DED** |
| Technical Letter Report **Cold Spray** | Technical Context Document **Cold Spray** | Draft Guidelines Document **Cold Spray** |
| Technical Letter Report **PM-HIP Spray** | Technical Context Document **PM-HIP** | Draft Guidelines Document **PM-HIP** |
| Technical Letter Report **EBW** | Technical Context Document **EBW** | Draft Guidelines Document **EBW** |

**Subtask 2C Draft Generic Guidelines for AMTs**

**Final Guidance for Initial AMTs in Rev. 2 of AMT Action Plan**

**Legend**

🟦 Contractor-developed

🟥 NRC Staff-developed

# Questions

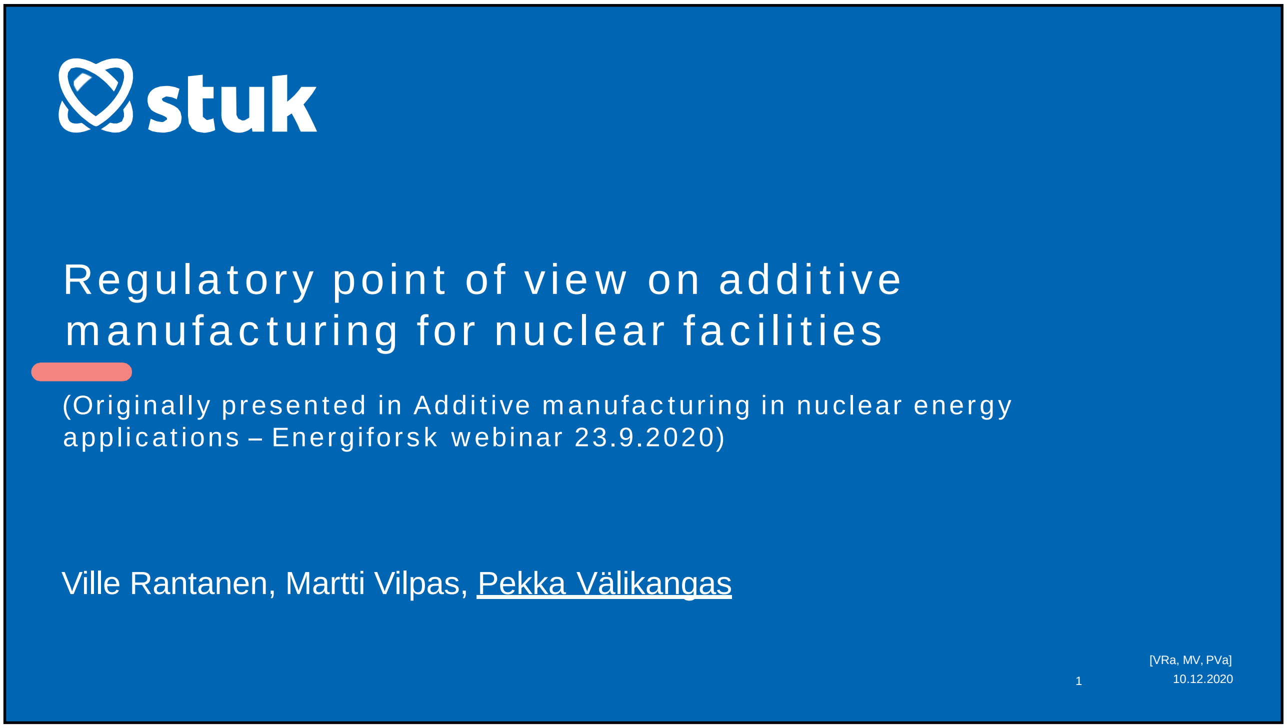
Acknowledgements:

AMT Project Team: NRR – Carolyn Fairbanks, Bob Davis, Isaac Anchondo-Lopez; RES – Matt Hiser, Mark Yoo

AMT Technical Advisory Team: NRR – Allen Hiser, Dave Rudland; RES – Rob Tregoning

AMT Steering Committee: NRR – Hipo Gonzalez; RES – Steve Frankl, Raj Iyengar

NRC Staff: Meg Audrain, Chris Sydnor, Dave Beaulieu, Dong Park, Dan Widrevitz



# Regulatory point of view on additive manufacturing for nuclear facilities

(Originally presented in Additive manufacturing in nuclear energy applications – Energiforsk webinar 23.9.2020)

Ville Rantanen, Martti Vilpas, Pekka Välikangas

[VRa, MV, PVa]
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10.12.2020

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## Content

- The Finnish Nuclear Facilities in brief
- Legal framework and guidelines from regulator
- Regulator oversight of additive manufacture
- Discussion of conventional standards in relation to additive manufacture

SÄTEILYTURVAKESKUS
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

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## Finnish Nuclear Facilities in Brief

- Operating NPPs
  - Loviisa LO1/LO2
  - Olkiluoto OL1/OL2
- NPP under construction
  - Olkiluoto OL3
- NPP in construction licensing phase
  - Hanhikivi FH1
- LLW & MLW repositories
- Spent fuel disposal facility under construction
- Research reactor FiR in decommissioning
- Uranium extraction, Terrafame, Talvivaara

WASTE MANAGEMENT:

- Repositories for LLW & MLW in operation at Olkiluoto and Loviisa
- Initial Decision in principle for spent fuel repository at Olkiluoto ratified by Parliament in 2001
- Confirming underground rock characterisation studies underway in ONKALO facility at Olkiluoto

HANHIKIVI, PYHÄJOKI

Owner: Fennovoima Oy
Planned: Hanhikivi 1

OLKILUOTO, EURAJOKI

Owner: Teollisuuden Voima Oyj
Reactor units 1&2: BWR 2 x 880 MWe (net)
Operation started: 1979, 1982
Production: 14.2 TWh (2010)
Load factor: 93.5 per cent (2010)
Under construction
Olkiluoto 3: EPR (PWR) 1600 MWe
Planned: Olkiluoto 4

HÄSTHOLMEN, LOVIISA

Owner: Fortum
Reactor units 1&2: PWR 2 x 488 MWe
Operation started: 1977, 1981
Production: 7.7 TWh (2010)
Load factor: 91.1 per cent (2010)

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## Finnish nuclear legislation and safety requirements

**Nuclear Energy Act**

- "nuclear energy utilisation shall be safe"; "licensee is responsible for safety", other principal safety req's (including security and on-site emergency preparedness)

**Nuclear Energy Decree**

- administrative details for licensing and regulatory oversight
- radiological acceptance criteria

**STUK Regulations**

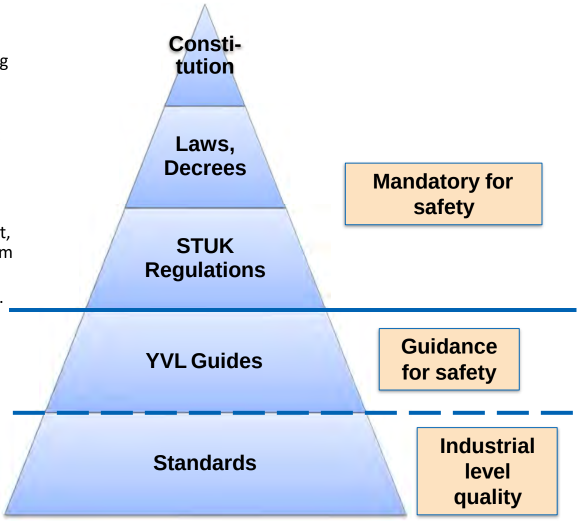
- mandatory requirements for Nuclear safety, Emergency preparedness, Nuclear security, Nuclear waste management, Safety of Mining and Milling Practices for Producing Uranium and Thorium
- general principles, fundamental technical requirements etc.

**YVL Guides**

- status as Reg. Guides in USA
- detailed technical requirements, acceptable practices, guidance for licensee-STUK interaction, STUK's oversight

***Standards***

- Detailed guidance to fulfil and follow contractual issues in industry



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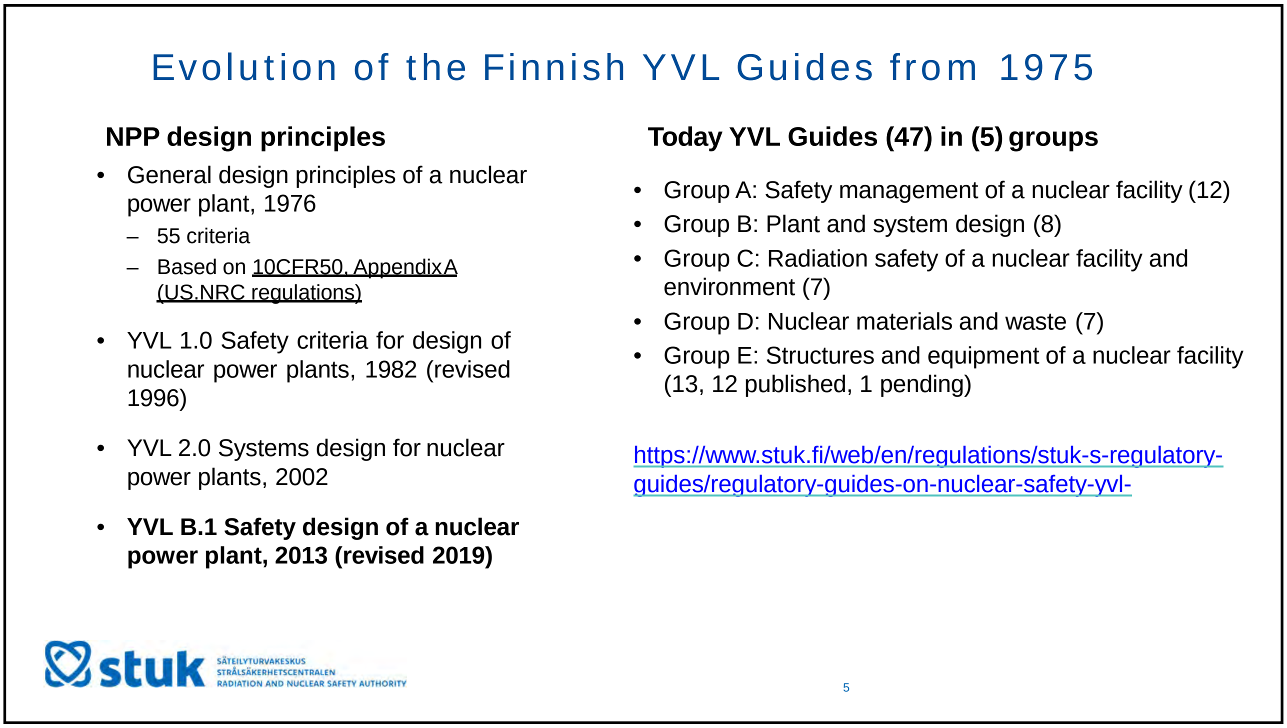

## Evolution of the Finnish YVL Guides from 1975

**NPP design principles**

- General design principles of a nuclear power plant, 1976
  - 55 criteria
  - Based on 10CFR50, Appendix A (US.NRC regulations)
- YVL 1.0 Safety criteria for design of nuclear power plants, 1982 (revised 1996)
- YVL 2.0 Systems design for nuclear power plants, 2002
- **YVL B.1 Safety design of a nuclear power plant, 2013 (revised 2019)**

**Today YVL Guides (47) in (5) groups**

- Group A: Safety management of a nuclear facility (12)
- Group B: Plant and system design (8)
- Group C: Radiation safety of a nuclear facility and environment (7)
- Group D: Nuclear materials and waste (7)
- Group E: Structures and equipment of a nuclear facility (13, 12 published, 1 pending)

https://www.stuk.fi/web/en/regulations/stuk-s-regulatory-guides/regulatory-guides-on-nuclear-safety-yvl-

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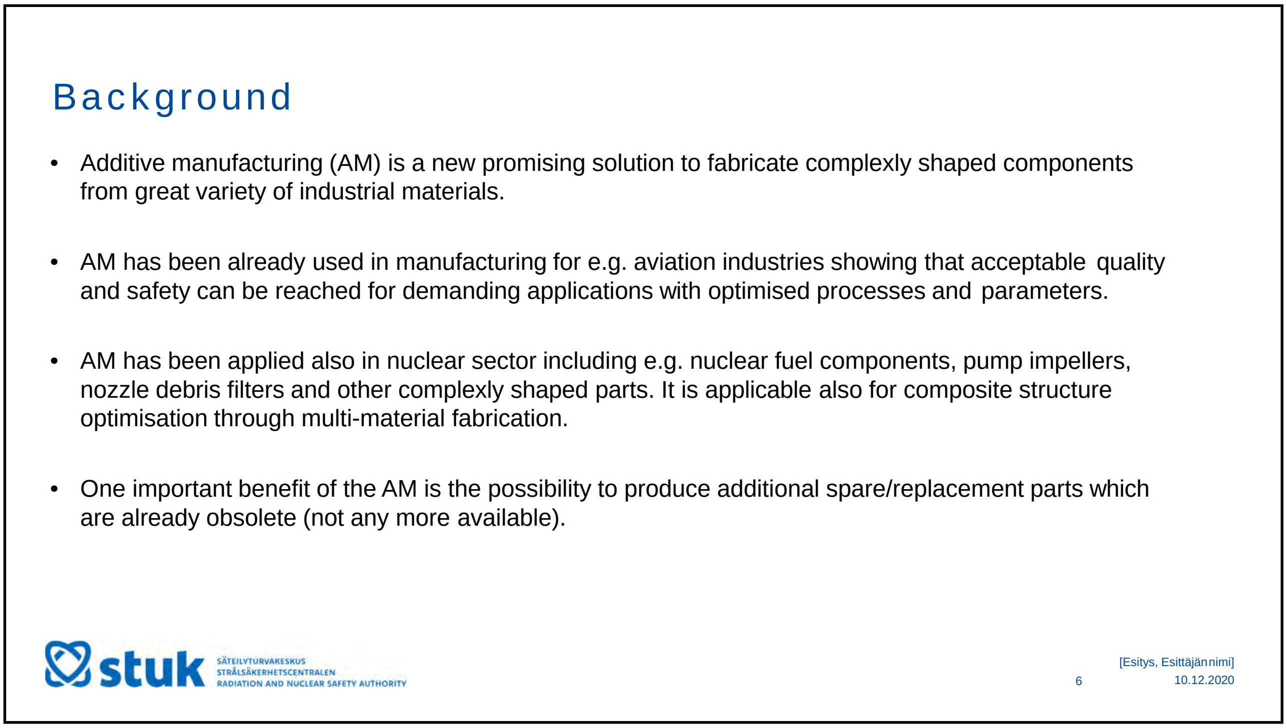

## Background

- Additive manufacturing (AM) is a new promising solution to fabricate complexly shaped components from great variety of industrial materials.
- AM has been already used in manufacturing for e.g. aviation industries showing that acceptable quality and safety can be reached for demanding applications with optimised processes and parameters.
- AM has been applied also in nuclear sector including e.g. nuclear fuel components, pump impellers, nozzle debris filters and other complexly shaped parts. It is applicable also for composite structure optimisation through multi-material fabrication.
- One important benefit of the AM is the possibility to produce additional spare/replacement parts which are already obsolete (not any more available).

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## Regulator oversight of additive manufacture (AM) (1/3)

- Oversee the reliability of AM processing and quality of parts
  - Compare AM to conventional manufacture
    - Detailed standards concatenate design, materials, manufacture, inspection and testing as well as quality management and qualification protocols for personnel
    - Lack of standards shall be compensated by R&D and testing
  - The structural performance of AM parts, including required inspections
    - Mock-ups in-line with safety classification
  - The service performance and aging degradation of AM parts
    - In-line with Aging Management plan starting from design through the whole life cycle of the nuclear facility

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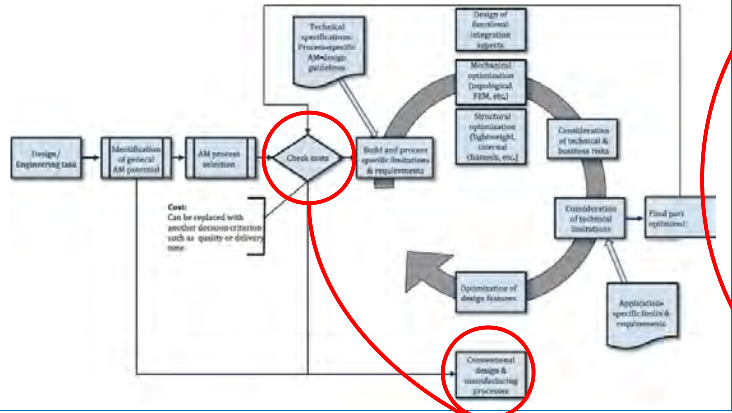
## Regulator oversight of additive manufacture (AM) (2/3)

**SFS-EN ISO/ASTM 52910:2019, overall strategy for AM**



**Issues in YVL Guides**

- Safety classification
- Design documentation
- Description of organisation
- Supervision of manufacture
- Quality control
- Commissioning
- Control during plant operation

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## Regulator oversight of additive manufacture (AM) (3/3)

- Follow the development of codes and standards for AM
  - Analogy between traditional standards and AM standards
  - Benchmarking between traditional and AM processes
  - Basic thinking for AM manufacture (SFS-EN ISO/ASTM 52910:2019) vs. safety requirements
- Follow research and international development of AM
  - Finnish safety research program SAFIR combine AM-technology, quality and safety thinking
  - International R&D, including co-op. with e.g. aviation industry etc.
- Gradual implementation of AM to Nuclear facilities
  - Starting from lower level safety classified systems and components
  - References from nuclear facilities abroad are appreciated

## Conventional standards vs. AM 1/2

| Commonly used for NPPs | Questions to AM standards |
|---|---|
| • Detailed standards for **design**:<br>– **PED, ASME** for reactor, primary and main circulation systems and containment<br>– **ASCE** for earthquake resistance to nuclear facilities<br>– **KTA** liner structures of radioactive fuel pools<br>– **PED, EN-ISO, Finnish Building Code (RakMK)** conventional steel and concrete structures<br>– **RCC** codes are under development for common European usage<br>• Advanced coordination between nuclear design codes and EN-ISO standards | • **Design**:<br>– How AM is introduced in detailed design standards?<br>• Selection criteria between AM and conventional manufacture<br>– How design criteria are set and ensured?<br>• Analysis / testing methodology<br>• Design margins / robustness |

## Conventional standards vs. AM 2/2

| Commonly used for NPPs according to design requirements | Questions to AM standards |
|---|---|
| • Materials:<br>– **KTA, ASTM, EN-ISO** for concrete, steel, welds<br>– **ASTM, EN-ISO** for coatings against radiation | • Materials:<br>– Standards not as specific as conventional standards? |
| • Manufacture / Execution:<br>– **PED, ASME**<br>– **KTA, RCC-M, EN-ISO, RakMK** | • Manufacture<br>– Not as specific as conventional standards?<br>– How manufacture is related to design and material standards? |
| • Inspection and testing:<br>– **ASME, ASTM, KTA, EN-ISO** | • Inspection and testing<br>– How inspections and testing is related to materials and manufacture? |
| • Quality management:<br>– **EN-ISO 9001:2015**<br>• **ISO 19443-2018** for supply chain management<br>• **IAEA 50-C-Q** nuclear safety related quality management | • Quality management<br>– Are there any AM standards? |

## Consideration needs

- Additional/continuous development work is still needed to ensure the quality of AM components for nuclear applications:
  - Qualification requirements stipulated for nuclear and radiation safety
  - Further development of applicable standardisation
  - Certification and qualification requirements for AM manufacturers
  - Qualification of the AM processes applied
  - Approval of the AM filler materials
  - Qualification of testing technology and personnel (NDT/DT)
  - Paying attention to Safety Culture as well as QA/QC

- These actions shall be supported with applicable R&D work
- Class EYT would be a reasonable starting point
- In higher safety classes ( 3 ❼2 ❼1 ) the Graded Approach principle shall be followed
- Pressure boundary components would need special attention (Pressure equipment legislation & PED)

U.S. FOOD & DRUG
ADMINISTRATION

# FDA REGULATORY APPROACH FOR ADDITIVE MANUFACTURING

**Matthew Di Prima, PhD**
Division of Applied Mechanics

Office of Science and Engineering Laboratories
Center for Devices and Radiological Health
U.S. Food and Drug Administration

10 December 2020

## Disclaimer

The mention of commercial products, their sources, or their use in connection with materials reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health and Human Services.

## Speaker Bio

Dr. Matthew Di Prima is a Materials Scientist in the US Food and Drug Administration's Office of Science and Engineering Laboratories, housed in the Center for Devices and Radiological Health. His areas of research are investigating how the additive manufacturing process can alter material properties, the interplay between corrosion and durability testing, and explant analysis. Along with his research duties, he is the head of the Additive Manufacturing Working Group which is spearheading efforts across the Agency to address how this technology affects medical devices and other regulate medical products

## Outline

- FDA and Medical Device Regulations
  - Device Classification
  - Regulatory Controls
  - Submission Types
- How this is applied to AM
  - Cleared AM Medical Devices
  - Patient Matched Devices
  - Anatomical Models

## FDA's Mission

- Protecting the public health by assuring that foods (except for meat from livestock, poultry and some egg products which are regulated by the U.S. Department of Agriculture) are safe, wholesome, sanitary and properly labeled; ensuring that human and veterinary drugs, and vaccines and other biological products and medical devices intended for human use are safe and effective
- Protecting the public from electronic product radiation
- Assuring cosmetics and dietary supplements are safe and properly labeled
- Regulating tobacco products
- Advancing the public health by helping to speed product innovations

**This equals ~25% of consumer spending in the US**

www.fda.gov/AboutFDA/Transparency/Basics/ucm194877.htm

## CDRH’s Role

- Regulates medical devices and radiation-emitting products
- Evaluate safety and effectiveness of medical devices
  - Before and after reaching market
- Assure patients and providers have timely, continued access to safe, effective, and high-quality medical devices

## CDRH Snapshot

**1900**
EMPLOYEES

**18k**
Medical Device Manufacturers

**183k**
Medical Devices
On the U.S. Market

**22k/year**
Premarket Submissions
including supplements and amendments

**570k**
Proprietary Brands

**25k**
Medical Device Facilities Worldwide

**1.4 MILLION/year**
Reports on medical device adverse events and malfunctions

## Medical Device, defined

- Instrument, apparatus, machine, implant, in vitro reagent, including component, part, or accessory
- Diagnoses, cures, mitigates, treats, or prevents disease or condition
- Affects structure or function of body
- Doesn't achieve purpose as a drug
- Excludes certain software functions
  - data storage, administrative support, electronic patient records

**Section 201(h) of FD&C Act**

## Device Regulations

- 21 Code of Federal Regulations (CFR): Parts 800-1050
  - 800-861: cross-cutting device requirements
    - Example: 812 - Investigational Device Exemption
  - 862-1050: device-specific requirements
    - Example: 876 - Gastroenterology and Urology Devices
- 21 CFR: Parts 1-99
  - general medical requirements that also apply to medical devices

## Device Classification

- Based on device description and intended use
- Determines extent of regulatory control
- Class I, II, or III
  - – increases with degree of risk
- Product Codes: three-letter coding to group similar devices and intended use

## How to determine classification

- Classification is defined under Code of Federal Regulations (e.g. 21 CFR 888.3350)

  (a)Identification: A hip joint metal/polymer semi-constrained cemented prosthesis is a device intended to be implanted to replace a hip joint. The device limits translation and rotation in one or more planes via the geometry of its articulating surfaces. It has no linkage across-the-joint. This generic type of device includes prostheses that have a femoral component made of alloys, such as cobalt-chromium-molybdenum, and an acetabular resurfacing component made of ultra-high molecular weight polyethylene and is limited to those prostheses intended for use with bone cement (888.3027).

  (b) Classification. Class II.
- This language is specific, slight changes in device design/function can change the regulation and therefore the classification
- If your device is not in the CFR, you have to request a designation and classification from the FDA, 513(g)

## Classes of Medical Devices

| Class | Risk | Controls | Submission |
|---|---|---|---|
| I | Lowest | General | • Exempt*<br>• 510(k) |
| II | Moderate | General and Special (if available) | • 510(k)*<br>• Exempt |
| III | Highest | General and PMA | • PMA |

*** More common submission requirement of this Class**

## General Controls: Examples

| Control | Regulation (21 CFR Part) | Brief Description |
|---|---|---|
| Labeling | 801 | provide information for users |
| Medical Device Reporting | 803 | report device-related injuries and deaths |
| Establishment Registration | 807 | register business with FDA |
| Device Listing | 807 | identify devices |
| Quality System | 820 | ensure safe, effective finished devices |
| Adulteration | FD&C Act 501 | provide device not proper for use |
| Misbranding | FD&C Act 502 | provide false or misleading labeling |

**FD&C Act = Federal Food Drug, and Cosmetic Act**

## Special Control

- Specific to Class II devices
- Usually for well-established device types
- Found in "(b) *Classification*" of regulation
  - example: 21 CFR 876.5860(b)

## 21 CFR 876.5860 High permeability hemodialysis system

- (a) Identification. A high permeability hemodialysis system is a device intended for use as an artificial kidney system for the treatment of patients with renal failure, ...
- (b) Classification. Class II. The special controls for this device are FDA's:
  - (1) "Use of International Standard ISO 10993 'Biological Evaluation of Medical Device - Part I: Evaluation and Testing,' "
  - (2) "Guidance for the Content of 510(k)s for Conventional and High Permeability Hemodialyzers,"
  - (3) "Guidance for Industry and CDRH Reviewers on the Content of Premarket Notifications for Hemodialysis Delivery Systems,"
  - (4) "Guidance for the Content of Premarket Notifications for Water Purification Components and Systems for Hemodialysis," and
  - (5) "Guidance for Hemodialyzer Reuse Labeling."

## Special Controls: Examples

- Design, Characteristics or Specifications
- Testing
- Special Labeling
- Guidance Documents

## Premarket Submission Types

- Investigational Device Exemption (IDE)
- Premarket Notification (510(k))
- Premarket Approval Application (PMA)
- De Novo
- Humanitarian Device Exemption (HDE)

## AM and Device Manufacturing

- Generally, manufacturing method does not change regulatory classification or regulatory controls
- This allows AM products to use existing regulatory pathways
  - The majority of AM devices have been cleared through the 510(k) pathway to date
  - Predicate devices can be AM or non-AM
  - Generally, we don't expect the "technological characteristics of the devices [to] raise different questions of safety and effectiveness"[1]
  - I.E., a spine cage is a spine cage and a bone plate is a bone plate

[1] FDA Guidance "Benefit Risk Factors to Consider When Determining Substantial Equivalence in Premarket Notifications (510(k)) with Different Technological Characteristics"

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## AM 510(k) Submissions

- FDA Guidance "Technical Considerations for Additively Manufactured Medical Devices" details pre-market submission expectations
- For a 510(k) submission, we are looking for the worst case AM condition to be determined in order to ensure subject device performance is substantially equivalent to the predicate
- This is different from most non-AM submissions as material performance can be assessed separately from the manufacturing process
  - In most cases purchasing controls and an understanding of tooling/post-processing effects **are** sufficient to address material performance
  - For AM controlling only the feedstock and understanding the tooling/post-processing effects **are not** generally sufficient to address material performance

## AM 510(k) Submissions – Establishing Worst Case Build Conditions

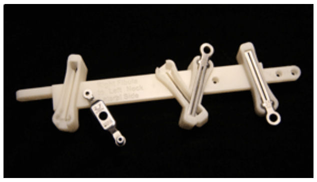
- Build location
  - Establish the worst case build location or that all build locations have comparable mechanical properties
- Build orientation
  - If multiple build orientations are used, which will have the worst mechanical properties
- Feedstock re-use
  - For AM processes that re-use feedstock, what is the re-use scheme and is there a worst-case feedstock condition in terms of performance and variability
- Residual feedstock in lattice/porous structures
  - How residual feedstock material is removed from lattice/porous structures and what is the worst case for residual feedstock in final device

## Evidence of this working: 510(k) Cleared 3D Printed Devices

- Patient matched implants
  - Skull plate
  - Maxillofacial implants

K121818
OsteoFab by OPM
http://www.accessdata.fda.gov/cdrh_docs/pdf12/K121818.pdf

- Patient matched surgical guides
  - Craniofacial
  - Knee
  - Ankle



K120956
VSP® by Medical Modeling
http://www.accessdata.fda.gov/cdrh_docs/pdf12/K120956.pdf

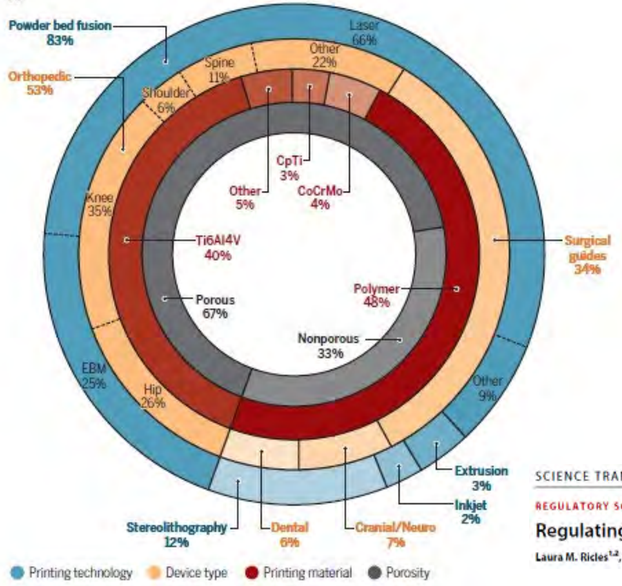
- Orthopedic devices
  - Hip Cups
  - Spinal Cages
  - Knee trays

K102975
Novation Crown by Exatech
http://www.accessdata.fda.gov/cdrh_docs/pdf10/K102975.pdf

- Dental
  - Temporary bridges
  - Reconstructive surgery support

K102776
e-DENT Temporary Resin
by DeltaMed GmbH
http://www.accessdata.fda.gov/cdrh_docs/pdf10/K102776.pdf

# Cleared 510(k) AM Products (2010 – 2016)



SCIENCE TRANSLATIONAL MEDICINE | PERSPECTIVE

REGULATORY SCIENCE

Regulating 3D-printed medical products

Laura M. Ricles[1,2], James C. Coburn[3], Matthew Di Prima[3], Steven S. Oh[1*]

# AM Device Adverse Events 2014

59 product-related adverse events for additive manufactured devices based on 836 reports to the Manufacturer and User Facility Device Experience (MAUDE) database in 2014

SCIENCE TRANSLATIONAL MEDICINE | PERSPECTIVE

REGULATORY SCIENCE

Regulating 3D-printed medical products

Laura M. Ricles[1,2], James C. Coburn[3], Matthew Di Prima[3], Steven S. Oh[1*]

## Patient Matched Devices

- Pairing 3D imaging (CT, MRI, optical scanning) with AM printing for personalized medical devices
  - Implants
  - Anatomical models
- Incorporating virtual surgical software allows for personalized cutting guide and tools
- Regulatory challenge is that there is no longer a discrete device to assess, instead we are looking at a design envelope

## Examples of Patient Matched Devices

K133809:

http://www.oxfordpm.com/news/article/2014-08-19_oxford_performance_materials_receives_fda_clearance_for_3d_printed_osteofab_patient-specific_facial_device.php

http://www.accessdata.fda.gov/cdrh_docs/pdf13/K133809.pdf

K121818:

http://www.oxfordpm.com/news/article/2013-02-18_osteofab_patient_specific_cranial_device_receives_510k_approval_-_osteofab_implants_ready_for_us_market_and_beyond.php

http://www.accessdata.fda.gov/cdrh_docs/pdf12/K121818.pdf

K122870:

http://www.conformis.com/customized-knee-implants/products/itotal/

http://www.accessdata.fda.gov/cdrh_docs/pdf12/K122870.pdf

## Patient Matched Regulatory Approach

- Not Custom Devices
  - Devices meeting the regulatory definition of “custom devices” are exempt from pre-market review
  - §V.E of FDA “Custom Device Exemption Guidance” explains why patient matched device generally don’t meet the custom device requirements
- Treating the design envelope as the device design requirements
  - Design envelope needs to be validated for the intended use
  - For 510(k)-eligible devices, substantial equivalence needs to be shown for the worst cases

## AM Anatomic Models

- Intended Use of the Anatomic model is key to determine if they are considered medical devices
- Diagnostic Use makes a model a medical device (i.e., the model will affect diagnosis, patient management, or patient treatment)
  - Models used to make a diagnosis based on examination or a physical measurement of structural changes from the 3D model
  - Using the model to size and/or select a device or surgical instrument based on a comparison, fitting, or measurements with the model
  - Using the model to determine whether a specific surgical procedure may be viable

## AM Anatomic Model Regulatory Approach

- A 3D printed patient-specific anatomic model that is intended for diagnostic use is, in essence, a physical representation of a digital 3D model that is produced by medical image analysis software.

- The software used to generate the 3D printed models based on medical images, will be regulated. There needs to be evidence that the 3D printed models are of equivalent accuracy to the digital 3D models (segmented volumes).

- The goal is not to have to clear every individual 3D printed model, or the 3D printers. Instead, FDA will clear software capable of generating diagnostic quality 3D printed anatomic models that has been tested and validated on a set of 3D printers based on the performance needed for the intended use and anatomy (i.e., orthopedic, cardiovascular, neurological, etc.).

## Summary of AM Regulatory Approach

- Existing FDA regulatory pathways and controls have been sufficient to handle the AM medical devices that we have reviewed
- Existing product performance requirements/predicate comparisons have generally been sufficient to ensure safety and efficacy
  - One product specific test standards has been developed to address fatigue concerns in AM acetabular (hip) cups
  - Ongoing research to evaluate adequacy of lattice/porous standardsfor AM Products
- Currently working to develop a framework to handle the adoption of AM technologies by hospitals and other points of care.

## Thank You For Your Attention

# Questions?

AdditiveManufacturing@fda.hhs.gov

# Regulatory Considerations for AM and “Lessons Learned” for Structural Alloys

***Presented at:***

**NRC Workshop on Advanced Manufacturing Technologies – *Session 6***

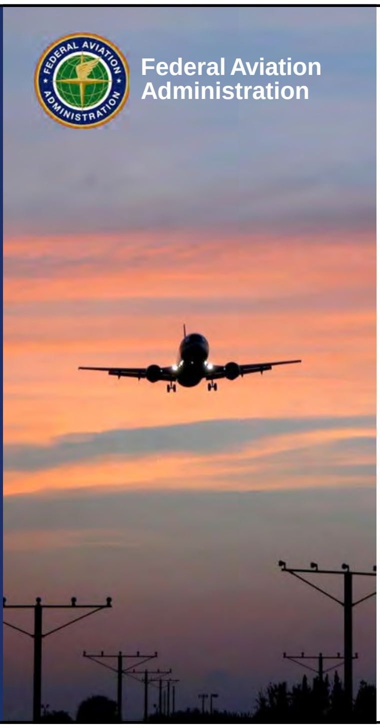
*December 10, 2020*

**Presented by:**

***Dr. Michael Gorelik***

FAA Chief Scientist and Technical Advisor
*for Fatigue and Damage Tolerance*

**Federal Aviation Administration**

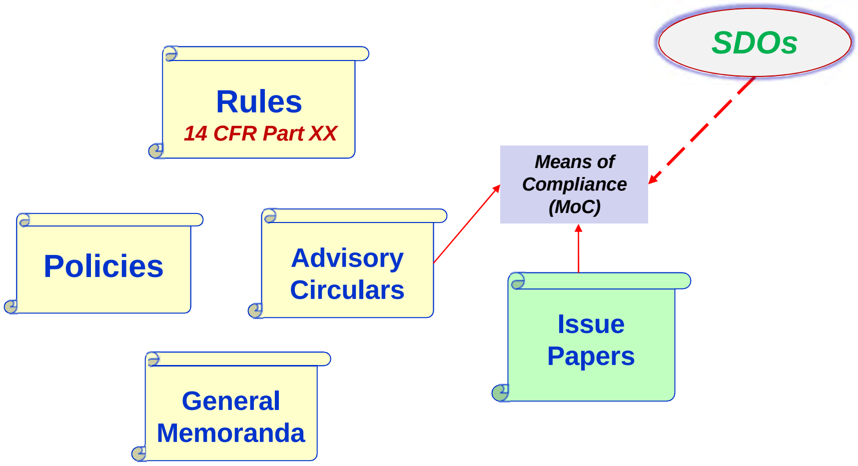


# BLUF *(bottom line upfront)*

- **All existing FAA *rules* apply to AM**
- **Leverage experience with other relevant material systems and historical "lessons learned"**
- ***However*… need to consider unique / *AM-specific attributes*, especially for high-criticality components**
- **Increasing role of public standards**
- **Increasing role of Computational Materials / ICME**

***The same message as in 12/09/20 presentation***

# FAA Regulatory Documents



SDOs

Rules
*14 CFR Part XX*

Means of Compliance (MoC)

Policies

Advisory Circulars

Issue Papers

General Memoranda

# H.R. 302 “FAA Reauthorization Act of 2018”

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

*Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen*

An Act

To provide protections for certain sports medicine professionals, to reauthorize Federal aviation programs, to improve aircraft safety certification processes, and for other purposes.

*Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,*

**SECTION 1. SHORT TITLE; TABLE OF CONTENTS.**

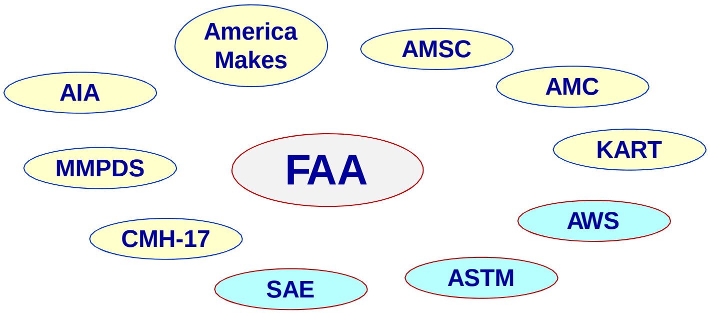
(a) SHORT TITLE.—This Act may be cited as the “FAA Reauthorization Act of 2018”.

**SEC. 329. PERFORMANCE-BASED STANDARDS.**

The Administrator shall, to the maximum extent possible and consistent with Federal law, and based on input by the public, ensure that regulations, guidance, and policies issued by the FAA on and after the date of enactment of this Act are issued *in the form of **performance-based** standards*, providing an equal or higher level of safety.

# Engagement with SDOs and Consortia

## *A partial list…*



America Makes
AMSC
AIA
AMC
MMPDS
FAA
KART
AWS
CMH-17
ASTM
SAE

🟦 **SDOs**
🟨 **Consortia / WGs**

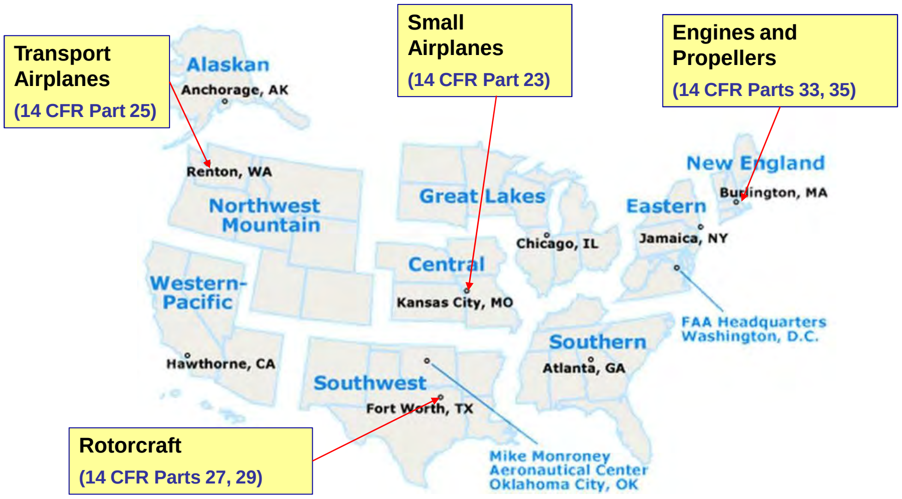
# Some AM-Specific Attributes

- Characterization and role of inherent (and rogue) material anomalies / defects
- Anisotropy
- Location-specific properties
- Residual stresses
- High process sensitivity / large number of controlling parameters
- Effects of post-processing (HIP, heat treatment, surface improvements, … )
- Material-specific NDI considerations
- Effect of surface conditions
- Susceptibility to environmental effects

- Each individual category has been encountered in other material systems
- Unique nature of AM – *all of these categories apply*

# FAA Regulatory Environment

*(driven by different product types)*



**Transport Airplanes**
(14 CFR Part 25)

**Small Airplanes**
(14 CFR Part 23)

**Engines and Propellers**
(14 CFR Parts 33, 35)

**Rotorcraft**
(14 CFR Parts 27, 29)

## 14 CFR Part 25 Regulations - Materials

*(Transport Category Aircraft)*

**§ 25.613 Material Strength Properties and Design Values**

**a) Material strength properties *must be based on enough tests of material meeting approved specifications to establish design values on a statistical basis*.**

**b) Design values must be chosen to minimize the probability of structural failures *due to material variability*.**

**d) The *strength, detail design, and fabrication* of the structure must *minimize the probability of disastrous fatigue failure*, particularly at points of stress concentration.**

## 14 CFR Part 25 Regulations – Special Factors

*(Transport Category Aircraft)*

**§ 25.619 Special Factors**

**The factor of safety prescribed in § 25.303 must be multiplied by the highest pertinent special factor of safety prescribed in §§ 25.621** *(Casting Factors)* **through 25.625 for each part of the structure whose strength is—**

**a) Uncertain;**

**b) Likely to deteriorate in service before normal replacement; or**

**c) Subject to appreciable variability because of uncertainties in manufacturing processes or inspection methods**

# Excerpts from 14 CFR 25.571

*(Transport Category Aircraft)*

**§ 25.571 Damage—tolerance and fatigue evaluation of structure**

(a) General. **An evaluation of the strength, detail design, and fabrication must show that *catastrophic failure* due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane.**

# AC 29-2C on Flaw Tolerance

*(Transport Category Rotorcraft)*

- **To determine types, locations, and sizes of the probable damages, considering the time and circumstances of their occurrence, the following should be considered:**
  - **Intrinsic flaws and other damage that could exist in an as-manufactured structure based on the evaluation of the details and potential sensitivities involved in the specific manufacturing work processes used.**
- **The flaw sizes to be considered should be representative of those which are likely to be encountered during the structure's service life resulting from the manufacturing, maintenance, and service environment.**
- **An analysis may be used combining the distribution of likely flaw sizes, the criticality of location and orientation, and the likelihood of remaining in place for a significant period of time.**

# AC 29-2C on Inspections

*(Transport Category Rotorcraft)*

- **The specific *inspection methods* that are used to accomplish fatigue substantiation *should be*:**
  - **Compatible with the threats identified in the threat assessment, paragraph f.(5), and provide a high probability of detection in the threat assessment and their development, under the operational loads and environment.**

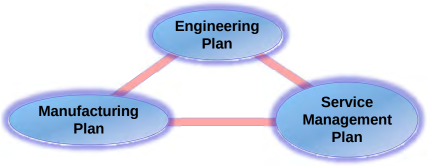
# Excerpts from 14 CFR 33.70

*(Aircraft Engines)*

- **WHY: Industry data has shown that manufacturing-induced anomalies have caused about 40% of rotor cracking and failure events**
- **WHAT: 33.70 rule requires applicants to develop coordinated engineering, manufacturing, and service management plans for each life-limited part**
  - This will ensure the attributes of a part that determine its life are identified and controlled so that the part will be consistently manufactured and properly maintained during service operation

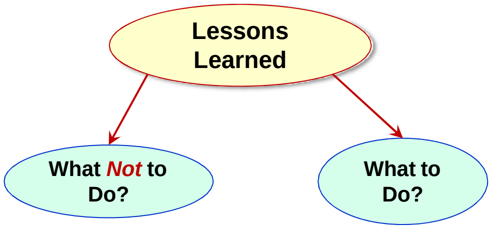
**"The *probabilistic approach to damage tolerance* assessment is one of two elements necessary to appropriately assess damage tolerance".**

***AC 33.70-1, GUIDANCE MATERIAL FOR AIRCRAFT ENGINE LIFE-LIMITED PARTS REQUIREMENTS, 7/31/2009.***



# "History is a Vast Early Warning System"

*Norman Cousins*



Lessons Learned

What *Not* to Do?

What to Do?

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# Relevant Material Technologies - *Examples*

- **Structural Castings**
  - Empirical life management system (design knock-downs, NDI acceptance criteria etc.)
  - Effect of material anomalies understood, but not well quantified
- **Powder Metallurgy (PM)**
  - Gave rise to PM-specific fatigue and DT methodologies, explicitly accounting for the presence of inherent material anomalies
- **Forgings**
  - Process controls (lessons learned), advanced NDI
  - Location-specific microstructure and residual stresses
- **Welding**
  - Highly process-sensitive
  - Susceptible to manufacturing anomalies
  - Defects detectability challenges

**Plan to leverage regulatory experience with other process-sensitive material systems**

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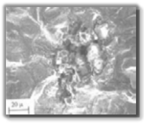
# Lessons Learned



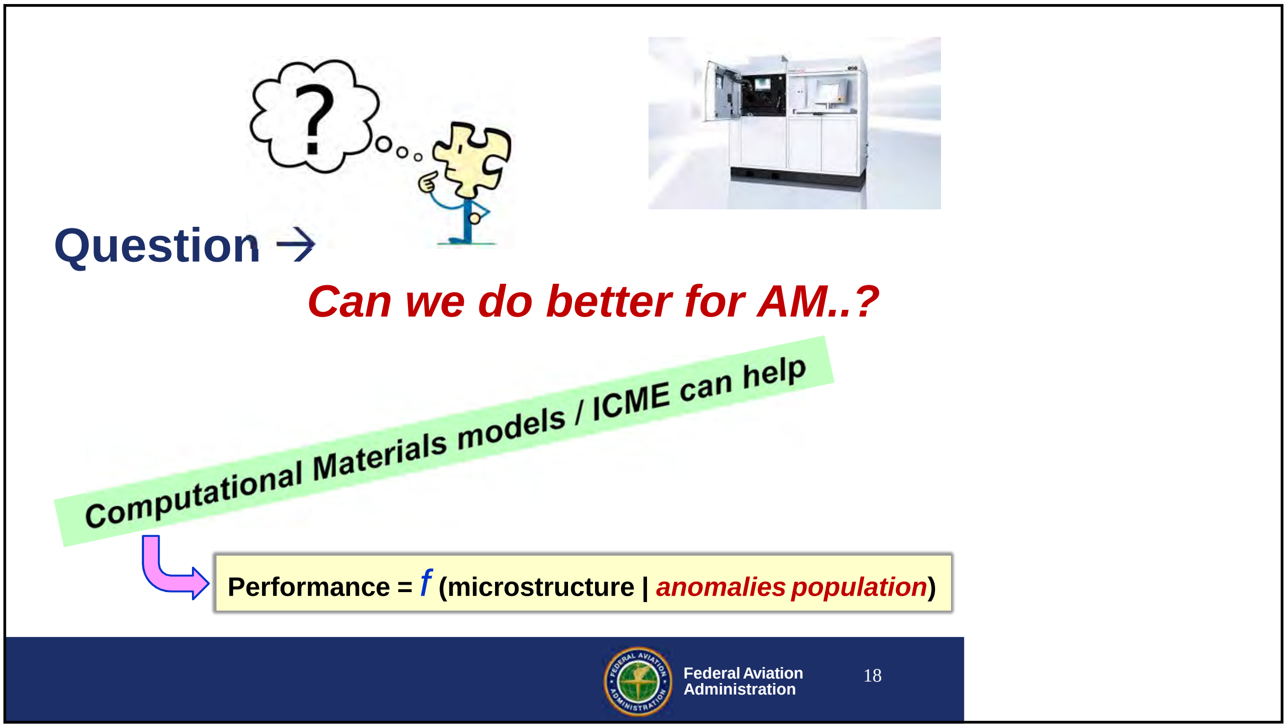
## *Powder Metallurgy (PM)*

- **Effect of defects may not be well understood for new technologies**
- **Transition from well-controlled development environment to full-scale production *may introduce new failure modes***
- **Solution: development of adequate process controls, NDI and *PM-specific life management system***
  - ❑ ***explicitly accounts for material anomalies (via probabilistic fracture mechanics)***
- ➢ ***Outcome: Several decades of successful field experience***

# Lessons Learned

## *Structural Castings*

- **Empirical – effects of material anomalies are not well understood or quantified → *no explicit feedback loop to process controls and QA***
- **No means to assess / quantify risk**
- **May be overly conservative in some cases**



Question →

*Can we do better for AM..?*

**Computational Materials models / ICME can help**

**Performance = *f* (microstructure | *anomalies population*)**

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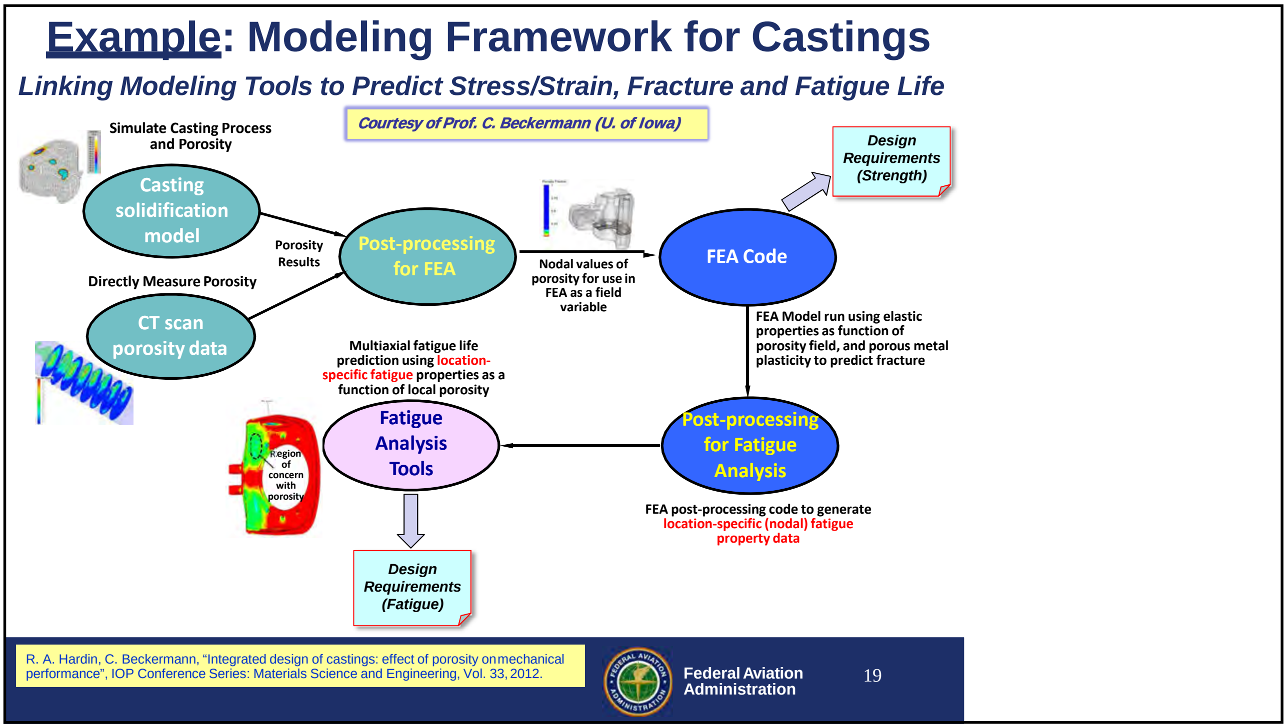


# Example: Modeling Framework for Castings

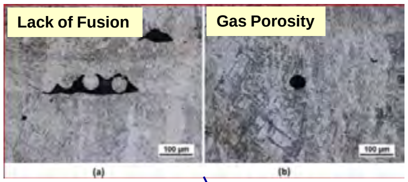
*Linking Modeling Tools to Predict Stress/Strain, Fracture and Fatigue Life*

*Courtesy of Prof. C. Beckermann (U. of Iowa)*

R. A. Hardin, C. Beckermann, "Integrated design of castings: effect of porosity on mechanical performance", IOP Conference Series: Materials Science and Engineering, Vol. 33, 2012.

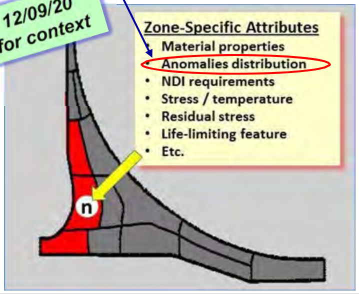
80

# AM Part Zoning and Probabilistic DT



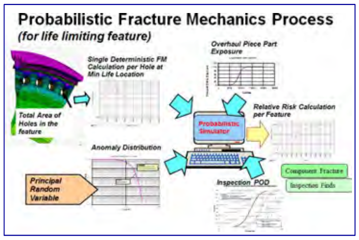
- AM parts are uniquely suited for *zone-based evaluation*
- Concept is similar to zoning considerations for castings…
- … however, modeling represents a viable *alternative to empirical* “casting factors”

Included from 12/09/20 presentation for context



**Zone-Specific Attributes**
- Material properties
- Anomalies distribution
- NDI requirements
- Stress / temperature
- Residual stress
- Life-limiting feature
- Etc.

*One Assessment Option – PFM *)*



*) PFM - Probabilistic Fracture Mechanics

Reference: M. Gorelik, “Additive Manufacturing in the Context of Structural Integrity”, International Journal of Fatigue 94 (2017), pp. 168–177.

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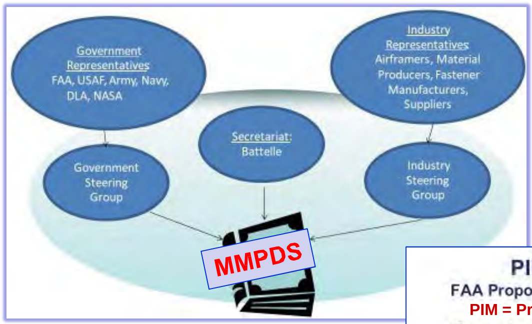
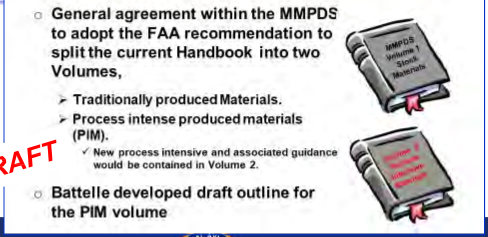
# Design Allowables Considerations



- Generation of design allowables is *contingent upon mature material and process specifications*
- Cross SDOs and WGs collaboration is essential



## PIM Historical Background

FAA Proposal to Create Separate Document for PIM

PIM = Process Intensive Materials

○ General agreement within the MMPDS to adopt the FAA recommendation to split the current Handbook into two Volumes,

- ➢ Traditionally produced Materials.
- ➢ Process intense produced materials (PIM).
  - ✓ New process intensive and associated guidance would be contained in Volume 2.

○ Battelle developed draft outline for the PIM volume

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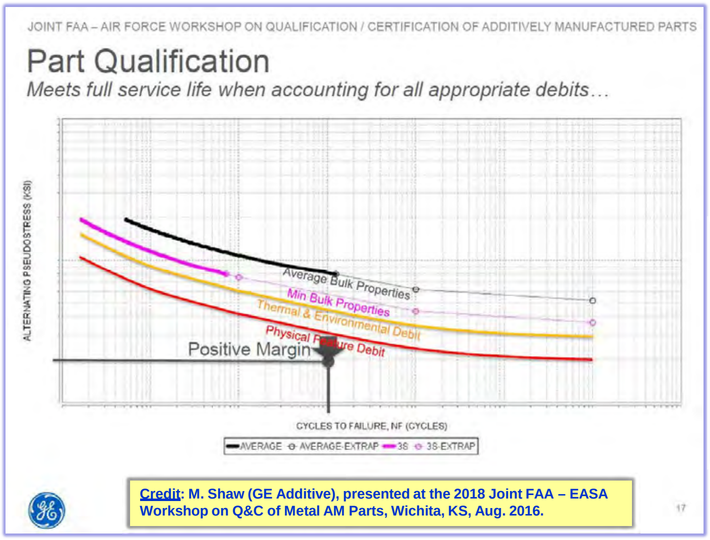
# Material Allowables vs. Design Values



JOINT FAA – AIR FORCE WORKSHOP ON QUALIFICATION / CERTIFICATION OF ADDITIVELY MANUFACTURED PARTS

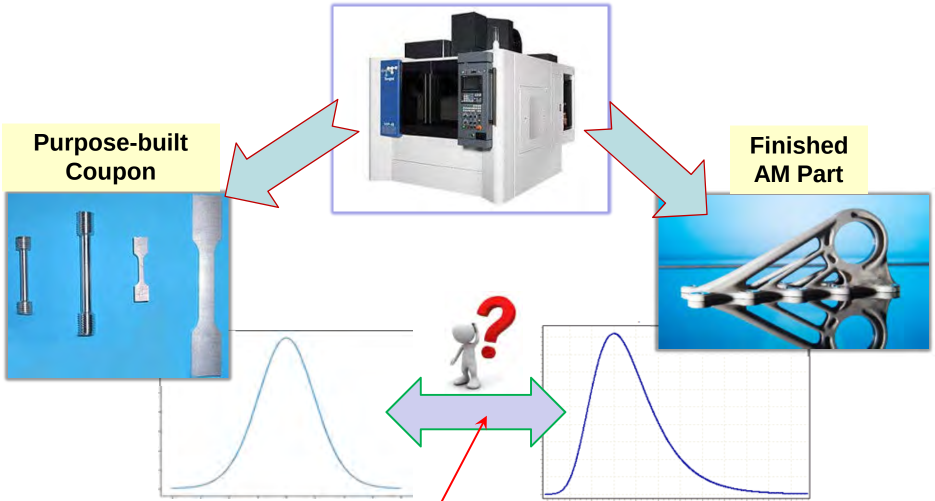
## Part Qualification

*Meets full service life when accounting for all appropriate debits…*

**Credit: M. Shaw (GE Additive), presented at the 2018 Joint FAA – EASA Workshop on Q&C of Metal AM Parts, Wichita, KS, Aug. 2016.**

- **Top 2 curves – “bulk” *material allowables***
- **Bottom (red) curve – *design values***

# Part vs. Coupon Properties



**Purpose-built Coupon**

**Finished AM Part**

***Property of Interest***

***Property of Interest***

**This understanding can be enabled by physics-based ICME models**

# *Example*: Industry Lessons Learned

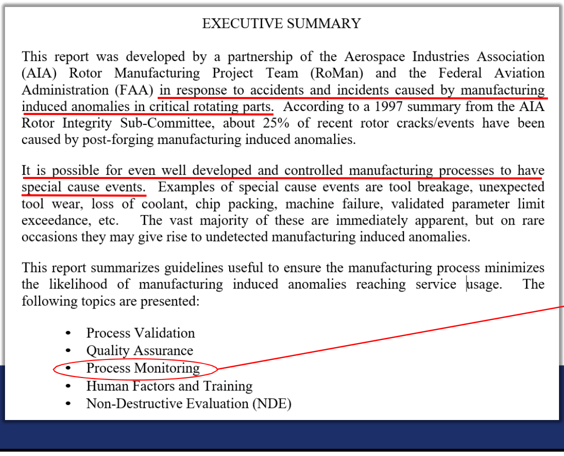
*Developed by AIA RoMan Working Group*

DOT/FAA/AR-06/3

Office of Aviation Research
and Development
Washington, D.C. 20591

**Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts**

*for conventional (i.e. subtractive) manufacturing processes*



EXECUTIVE SUMMARY

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Manufacturing Project Team (RoMan) and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by manufacturing induced anomalies in critical rotating parts. According to a 1997 summary from the AIA Rotor Integrity Sub-Committee, about 25% of recent rotor cracks/events have been caused by post-forging manufacturing induced anomalies.

It is possible for even well developed and controlled manufacturing processes to have special cause events. Examples of special cause events are tool breakage, unexpected tool wear, loss of coolant, chip packing, machine failure, validated parameter limit exceedance, etc. The vast majority of these are immediately apparent, but on rare occasions they may give rise to undetected manufacturing induced anomalies.

This report summarizes guidelines useful to ensure the manufacturing process minimizes the likelihood of manufacturing induced anomalies reaching service usage. The following topics are presented:

- Process Validation
- Quality Assurance
- Process Monitoring
- Human Factors and Training
- Non-Destructive Evaluation (NDE)

- **Leveraged industry experience to reduce the likelihood of manufacturing-induced defects**
- ***Emphasizes the role of real-time process monitoring systems***

# Recent Developments

- **Consortia / SDOs / Industry engagement**
- **R&D**
- **2020 FAA-EASA Workshop on Q&C of AM** *(appendix)*

# *Examples* of External Engagements

*(Consortia and WGs)*

**AIA AM WG**

**MMPDS**

***ETTG*** Emerging Technologies Task Group

***Volume 2***

- **Guidance**
- **Data**

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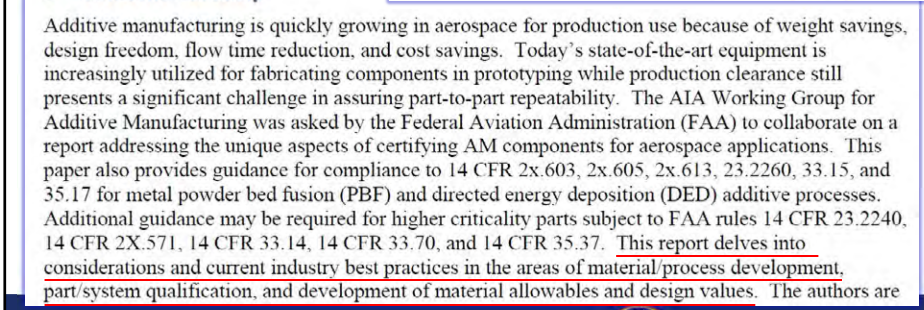
# AIA AM Working Group Report: **2/28/20**

## "Recommended Guidance for Certification of AM Component"

https://www.aia-aerospace.org/report/certification-of-am-component/



### 3 Executive Summary

Additive manufacturing is quickly growing in aerospace for production use because of weight savings, design freedom, flow time reduction, and cost savings. Today's state-of-the-art equipment is increasingly utilized for fabricating components in prototyping while production clearance still presents a significant challenge in assuring part-to-part repeatability. The AIA Working Group for Additive Manufacturing was asked by the Federal Aviation Administration (FAA) to collaborate on a report addressing the unique aspects of certifying AM components for aerospace applications. This paper also provides guidance for compliance to 14 CFR 2x.603, 2x.605, 2x.613, 23.2260, 33.15, and 35.17 for metal powder bed fusion (PBF) and directed energy deposition (DED) additive processes. Additional guidance may be required for higher criticality parts subject to FAA rules 14 CFR 23.2240, 14 CFR 2X.571, 14 CFR 33.14, 14 CFR 33.70, and 14 CFR 35.37. This report delves into considerations and current industry best practices in the areas of material/process development, part/system qualification, and development of material allowables and design values. The authors are

Federal Aviation Administration

# AIA AM Working Group Report (cont.)

*Figure 1: Additive Development and Qualification Areas*

# MMPDS and Additive Manufacturing

## MMPDS Efforts to Address Emerging Metallic Process Intensive Materials (PIM)

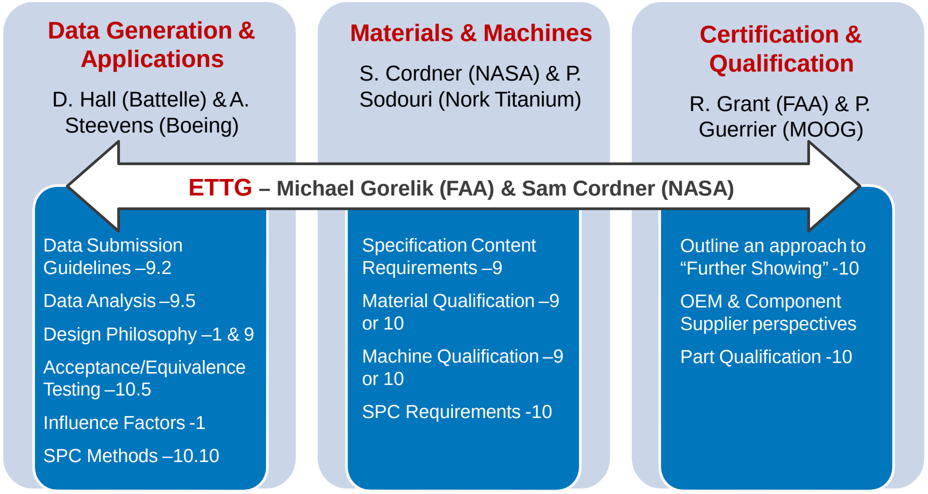
- ☐ **MMPDS recognizes the need to be proactive and keep pace with the rapid development of Emerging Metallic Structures Technologies by industry, *e.g., Additive Manufacturing (AM), Friction Stir Welding (FSW) that are considered PIM.***

- ☐ **Several efforts of PIM were presented to the MMPDS for allowables development but were found not to be compatible with current handbook procedures. Extensive amount of standardization efforts need to take place before design values for PIM can be considered for inclusion in the current handbook.**

- ☐ **General agreement within the MMPDS to create two Volumes:**
  - ➢ **Volume I – Current handbook for traditionally produced Materials.**
  - ➢ **Volume II - Properties for PIM ,e.g., Additive Manufacturing (AM), Friction Stir Welding (FSW).**

- ☐ **Emerging Technology Task Group (ETTG)** was established to develop processes and procedures best suited to derive and publish design information for PIM Volume II.

## Emerging Technologies Task Group (ETTG) and its *Working Groups*



**Data Generation & Applications**

D. Hall (Battelle) & A. Steevens (Boeing)

- Data Submission Guidelines – 9.2
- Data Analysis – 9.5
- Design Philosophy – 1 & 9
- Acceptance/Equivalence Testing – 10.5
- Influence Factors - 1
- SPC Methods – 10.10

**Materials & Machines**

S. Cordner (NASA) & P. Sodouri (Nork Titanium)

- Specification Content Requirements – 9
- Material Qualification – 9 or 10
- Machine Qualification – 9 or 10
- SPC Requirements - 10

**Certification & Qualification**

R. Grant (FAA) & P. Guerrier (MOOG)

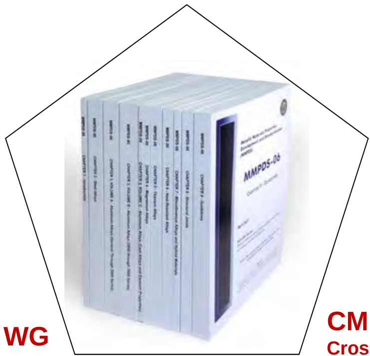
- Outline an approach to “Further Showing” - 10
- OEM & Component Supplier perspectives
- Part Qualification - 10

**ETTG** – Michael Gorelik (FAA) & Sam Cordner (NASA)

## MMPDS Interaction with SDOs and Working Groups

**SAE**
- AM Material and Process Specs (AMS-AM)
- Use of MMPDS data analysis tools for spec min values

**AWS**
- Welding Specs
- AM Specs



**ASTM**
- Testing Specs
- AM Material Specs
- *Signed MOU with Battelle*

**AIA AM WG**

Developing best practices for Q&C of metal AM parts

**CMH-17 AM WG**

Cross-coordination to explore synergies and streamline communication between two groups

# R&D – Internal / External

- **Development of material databases (joint with DoD and NASA) - *JMADD***
- **Seeded defects studies – effect of defects**
- **Understanding of process variability drivers**
- **Round-robin studies**
- **NASA ULI (University Leadership Initiative)**
- **Probabilistic DT framework for AM (collaboration with NASA, USAF and NAVAIR)**
- **CM*4*QC Steering Group – *see next slide***

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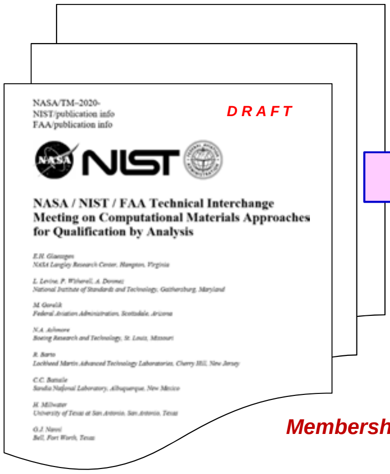
# *Example: Development of Computational Materials (CM) Capabilities for Metal AM*



NASA/TM–2020-
NIST/publication info
FAA/publication info

DRAFT

**NASA / NIST / FAA Technical Interchange Meeting on Computational Materials Approaches for Qualification by Analysis**

*E.H. Glaessgen*
*NASA Langley Research Center, Hampton, Virginia*

*L. Levine, P. Witherell, A. Donmez*
*National Institute of Standards and Technology, Gaithersburg, Maryland*

*M. Gorelik*
*Federal Aviation Administration, Scottsdale, Arizona*

*N.A. Ashmore*
*Boeing Research and Technology, St. Louis, Missouri*

*R. Barto*
*Lockheed Martin Advanced Technology Laboratories, Cherry Hill, New Jersey*

*C.C. Battaile*
*Sandia National Laboratory, Albuquerque, New Mexico*

*H. Millwater*
*University of Texas at San Antonio, San Antonio, Texas*

*O.J. Nanni*
*Bell, Fort Worth, Texas*

***Co-organizers: NASA and FAA***

Computational Materials *for* Qualification and Certification (CM*4*QC)
*of Process-Intensive Metallic Materials*

Industry – Government – Academia Steering Group
Kick-off Meeting (*virtual*)
*September 14, 2020*

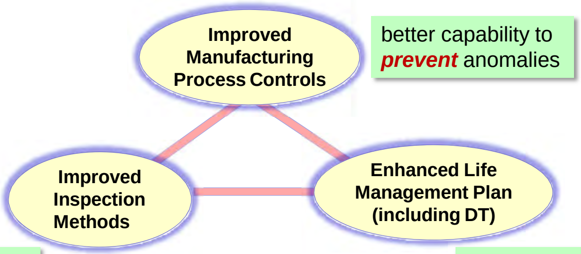
***Membership***

| Government | Industry | Academia |
|---|---|---|
| NIST | Boeing | Carnegie Mellon |
| AFRL | Lockheed-Martin / Sikorsky | UTSA |
| Sandia NL | Raytheon / P&W | Vanderbilt |
| NAVAIR | GE Aviation | Penn State |
| ORNL | Spirit Aerosystems | Northwestern |
| Army Aviation | Honeywell Aerospace | |
| | Howmet Aerospace | |
| | SwRI | |
| | Northrup-Grumman | |
| | Textron Aviation / Bell | |

**Federal Aviation Administration**

# Summary

- **What worked well historically to reduce the rate of failures induced by material / manufacturing anomalies → *a three-prong approach:***



**Improved Manufacturing Process Controls**

better capability to ***prevent*** anomalies

**Improved Inspection Methods**

better capability to ***find*** anomalies

**Enhanced Life Management Plan (including DT)**

better capability to ***design for*** anomalies

# Discussion

***Dr. Michael Gorelik***
Chief Scientist, *Fatigue and Damage Tolerance*
Aviation Safety
Federal Aviation Administration
michael.gorelik@faa.gov
(480) 284-7968

# APPENDIX

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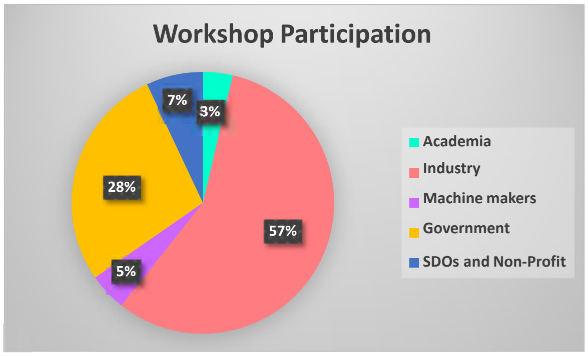
## 3rd Joint FAA – EASA AM Workshop

*November 2-6, 2020*

### Workshop "Demographics"

*over 300 participants*



https://www.faa.gov/aircraft/air_cert/step/events/2020_additive_mfg_workshop/

**16 Countries**

- *Austria*
- *Belgium*
- *Brazil*
- *Canada*
- *France*
- *Germany*
- *Italy*
- *Netherlands*
- *Norway*
- *Poland*
- *Portugal*
- *Singapore*
- *Spain*
- *Sweden*
- *UK*
- *US*

# Workshop Evolution

## 2018 → 2020

(joint FAA-EASA workshops)

### 2018 Workshop

- *First joint FAA – EASA workshop*
- *First workshop with parallel breakout sessions*
- Continued focus on Q&C
- Tracking of the key industry trends (in the Q&C context)
- Gradual increase in the industry "demographics" by segment

### 2019 Workshop

- Continued breakout sessions
- Significant participation from operators, Tier 2/3/… suppliers and machine makers
- Clear signs of Q&C framework maturation and common technical approaches
- Leveraged Machine Makers – End Users knowledge transfer workshop

### 2020 Workshop

- *First virtual workshop*
- More balanced international participation
- More than 2x increase in participation
- Continued breakout sessions
- *Focus on new technical developments, not "organizational updates"*
- Highly diverse industry "demographics"
- Big focus on standardization

*see next slide*

Federal Aviation Administration

# Agenda at a Glance

- **Opening remarks:**
  - *Ms. Di Reimold, Deputy Director of Policy and Innovation Division, FAA*
- **Keynote - *SpaceX***
  - *Dr. Charlie Kuehmann, VP of Materials Engineering and NDE*
  - *Mr. Will Heltsley, Vice President of Propulsion Engineering*
- **22 presentations from the industry, government, academia and SDOs / Consortia / WGs**
- **3 Breakout Sessions** →
  1. *Low Criticality AM Parts*
  2. *F&DT and NDI Considerations*
  3. *Knowledge transfer between machine makers and end users*
- **Standardization Day**
- **Regulatory Panel**

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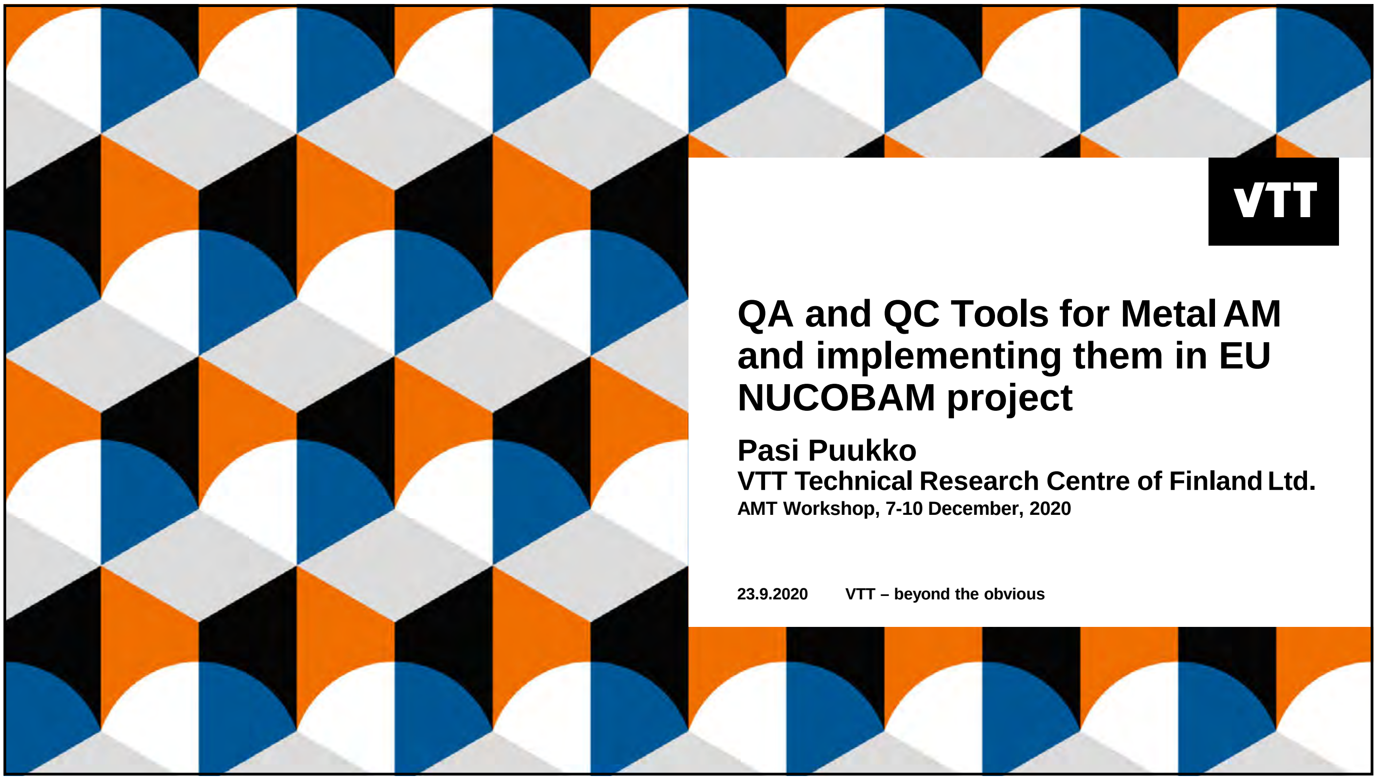


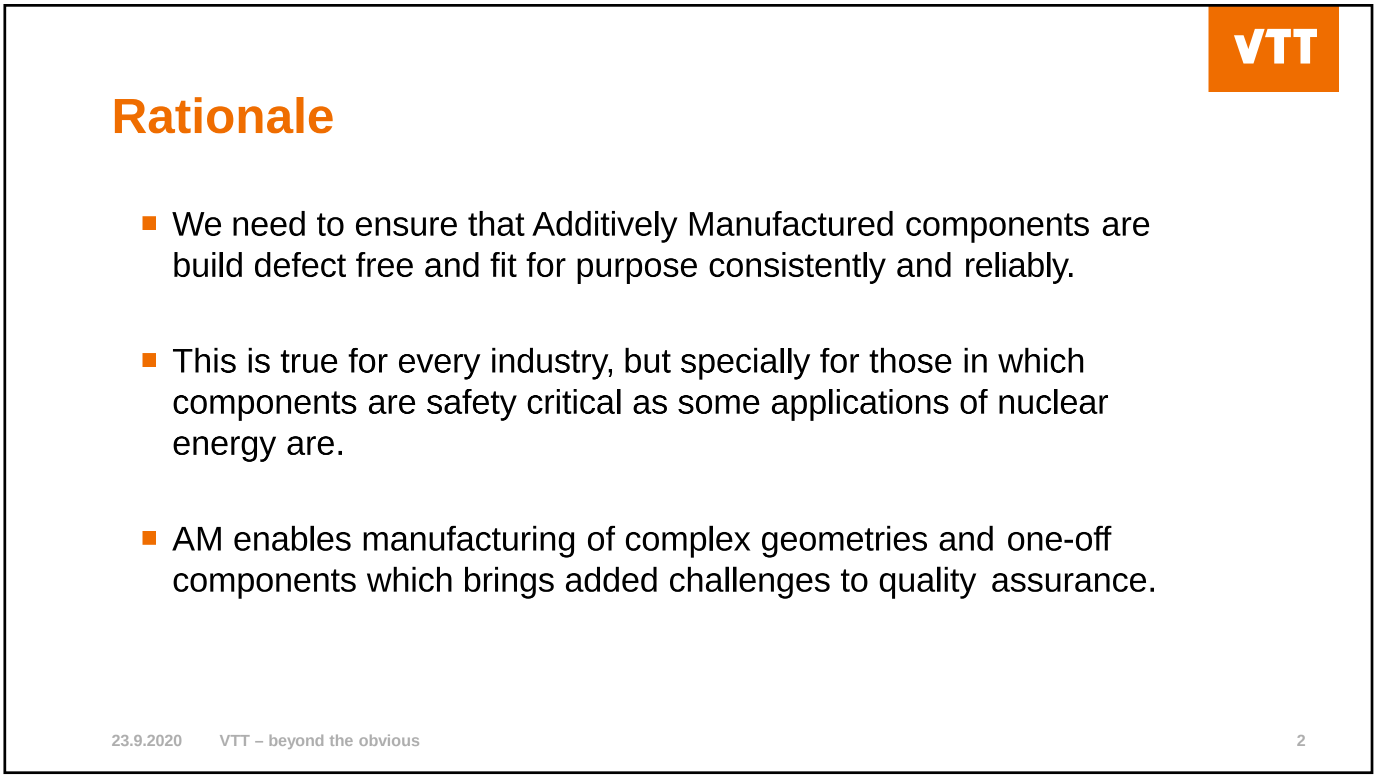
# QA and QC Tools for Metal AM and implementing them in EU NUCOBAM project

**Pasi Puukko**
**VTT Technical Research Centre of Finland Ltd.**

**AMT Workshop, 7-10 December, 2020**

23.9.2020 VTT – beyond the obvious

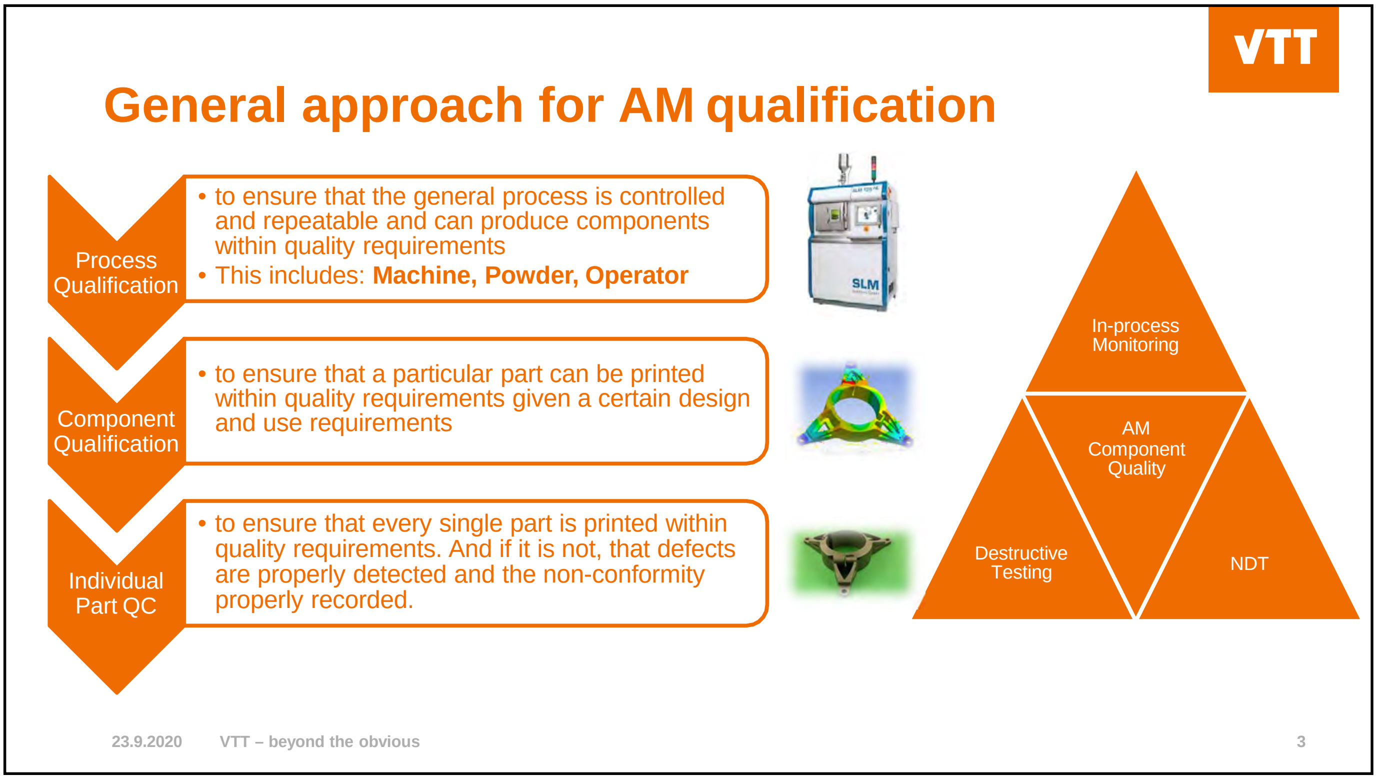
1



## Rationale

- We need to ensure that Additively Manufactured components are build defect free and fit for purpose consistently and reliably.
- This is true for every industry, but specially for those in which components are safety critical as some applications of nuclear energy are.
- AM enables manufacturing of complex geometries and one-off components which brings added challenges to quality assurance.

2



VTT

# General approach for AM qualification

**Process Qualification**

- to ensure that the general process is controlled and repeatable and can produce components within quality requirements
- This includes: **Machine, Powder, Operator**

**Component Qualification**

- to ensure that a particular part can be printed within quality requirements given a certain design and use requirements

**Individual Part QC**

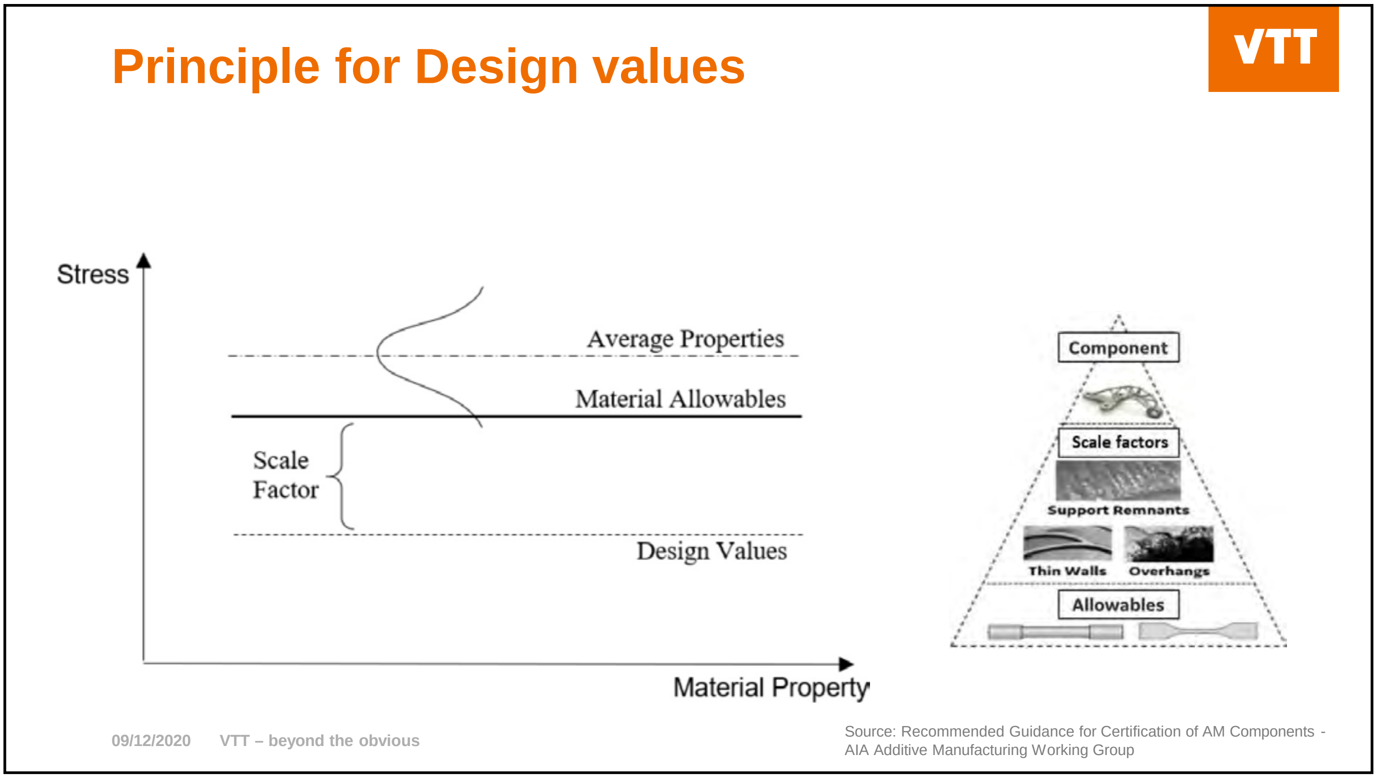
- to ensure that every single part is printed within quality requirements. And if it is not, that defects are properly detected and the non-conformity properly recorded.

In-process Monitoring

AM Component Quality

Destructive Testing

NDT



VTT

# Principle for Design values

Stress

Average Properties

Material Allowables

Scale Factor

Design Values

Material Property

Component

Scale factors

Support Remnants

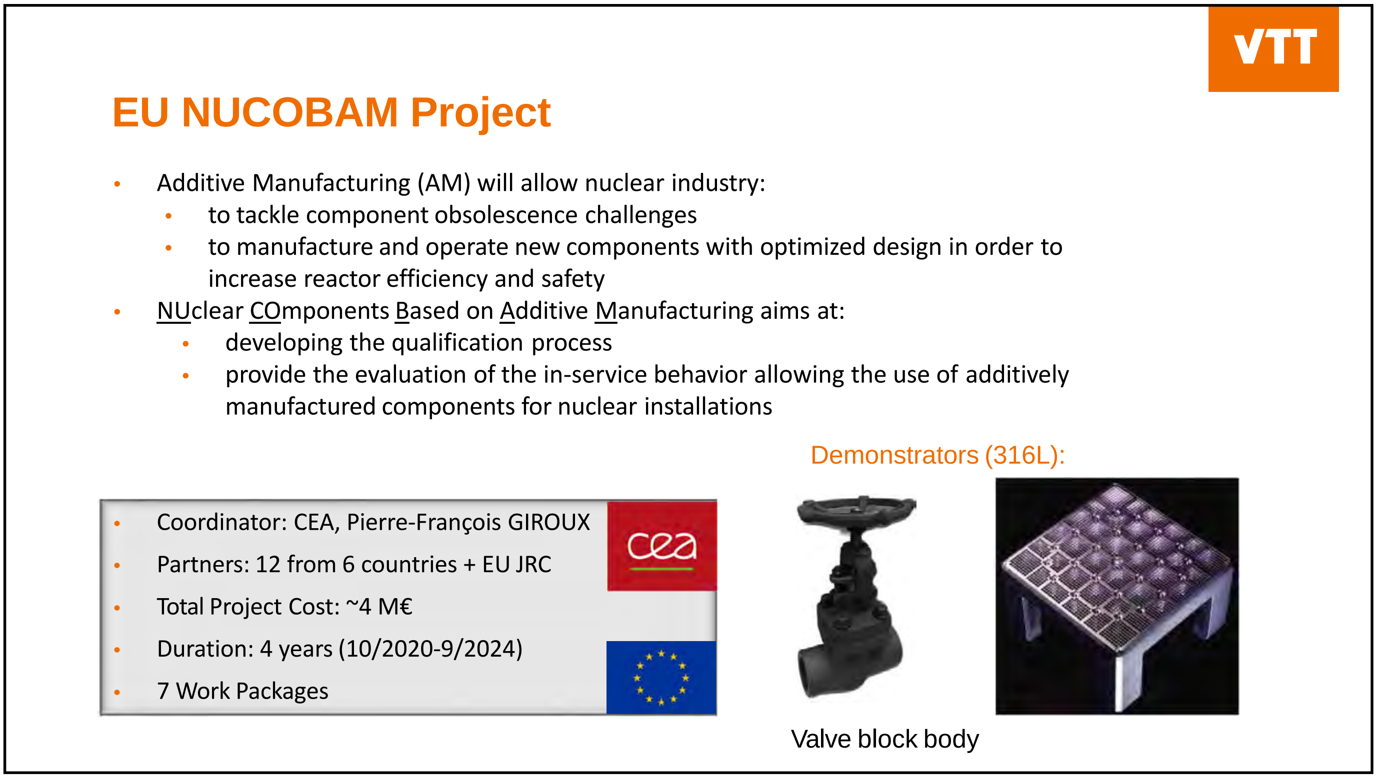
Thin Walls

Overhangs

Allowables

Source: Recommended Guidance for Certification of AM Components - AIA Additive Manufacturing Working Group

# EU NUCOBAM project



## EU NUCOBAM Project

- Additive Manufacturing (AM) will allow nuclear industry:
  - to tackle component obsolescence challenges
  - to manufacture and operate new components with optimized design in order to increase reactor efficiency and safety
- NUclear COmponents Based on Additive Manufacturing aims at:
  - developing the qualification process
  - provide the evaluation of the in-service behavior allowing the use of additively manufactured components for nuclear installations

- Coordinator: CEA, Pierre-François GIROUX
- Partners: 12 from 6 countries + EU JRC
- Total Project Cost: ~4 M€
- Duration: 4 years (10/2020-9/2024)
- 7 Work Packages

Demonstrators (316L):

Valve block body

VTT

## Workpackages:

- **WP1 "Methodology for AM qualification standardization" - CEA**
  - focus on establishment of a qualification methodology for AM components and on reviewing the existing standards and qualification processes
- **WP2 "AM process qualification" - VTT**
  - aim to create a general methodology for qualifying L-PBF process for nuclear energy industry applications so that components manufacture by L-PBF meet the quality expectations and design functions
- **WP3 "Qualification as processed: NDE & mechanical properties vs microstructure" – Naval Group**
  - focus on nondestructive tests and characterization as manufactured to ensure the capability to decide of the qualification as processed

## Workpackages

- **WP4 "In-pile Behaviour of Additively Manufactured Samples (IBAMS)" - FRAMATOME**
  - deal with the description of the sample sets, irradiation conditions (fluence, temperature…), microstructure characterization, determination of the mechanical properties and documentation
- **WP5 "Performance assessment of ex-core user case: valve component" - ENGIE Tractebel**
  - assess the operational performance of ex-core valve component that will be produced by L-PBF process
- **WP6 "Dissemination and exploitation" - EDF**
  - ensure dissemination and then exploitation, by reaching out to industry, standardization and regulatory bodies
- **WP7 "Project Management" - CEA**
  - ensure effective coordination and management to monitor the progress of the project towards its planned objectives

# WP2 Objective

- To create a general methodology for qualifying L-PBF process for nuclear energy industry applications so that components manufacture by L-PBF meet the quality expectations and design functions. The study of machine-to-machine variations in properties will be studied.
- Advanced quality control methods will be evaluated with the objective of increasing safety by detecting defects during production and ensure batch consistency.
- Demonstration components and test coupons to be tested in other WPs will be manufactured.

# WP2 focuses on different variation sources

**Improved Process Stability**

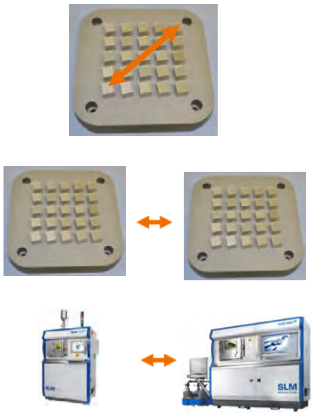
- High process stability within same platform (same manufacturing batch).

**Improved Process Repeatibility**

- High process repeatability from build to build on same equipment (different batch).

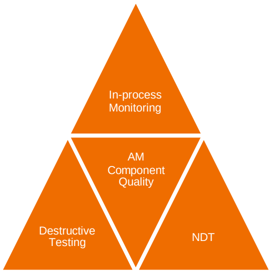
**Improved Process Reproducibility**

- High process reproducibility from build to build on different equipment



# Some challenge related to LB-PBF QA & QC

- Qualification procedures are laborous and require lot of experimental trials
- Due the differences between the machines – results are not directly transferable
- Complex geometrics poses challenges for utilizing conventional non-destcructive technologies (NDE)
- Destructive testing does not fit very well for single component testing
- Results of in-process monitoring are open to interpretations


In-process Monitoring

AM Component Quality

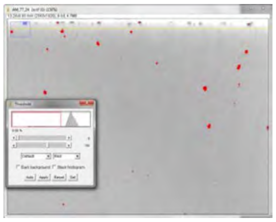
Destructive Testing

NDT

# Destructive Testing

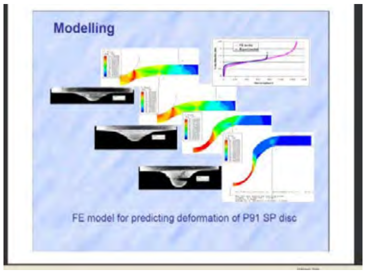
# Witness samples and microstructural microscopy

- Mechanical testing following recognized standards
- Specially useful for **process qualification**
- Usefulness reduced for component qualification and for single part quality control



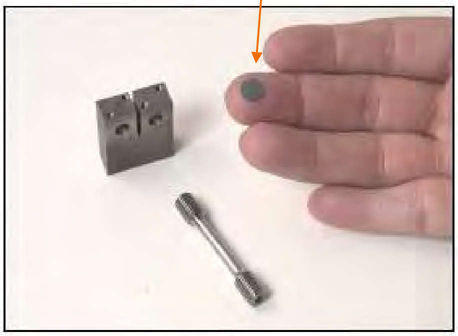
# Small Punch Testing

- Allows scooping small samples from critical areas
- Can complement standard methods for process and component qualification
- Can be used as a more cost alternative for batch QC
- **EN 10371** Small Punch Test Method for Metallic Materials to be voted in October 2020.



Modelling

FE model for predicting deformation of P91 SP disc



# Non-Destructive Examination

## NDI Technology applied to AM: gaps

- Geometrical complexity
  - AM has practically no geometry-related limitations
- New defect types
  - Porosity: no reliable, cheap and easy-to-use method exists.
- New materials
  - Elastic anisotropy: Several ultrasound related problems
- New reference standards are required
  - NDI devices must be calibrated using known defects
- No POD data
  - Without POD methodology, the actual reliability of inspection cannot be determined

VTT

# Applicability of NDI to AM

| NDI Technique | Geometry Complexity Group | | | | | Comments |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Visual Testing | Y | Y | P(c) | NA | NA | |
| Liquid Penetrant Testing | Y | Y | P(a) | NA | NA | |
| Magnetic Particle Testing | Y | Y | P(a) | NA | NA | Only for ferromagnetic materials |
| Leak Testing | P | P | P | P | P | Screening for containers, valves etc. |
| Eddie Current Testing | Y | Y | P(c) | NA | NA | |
| Ultrasonic Testing / Phased Array Ultrasonic Testing | Y | Y | P(b) | NA | NA | Quantitative methods are possible for GCG 1 |
| Alternate & Direct Current Potential Drop | Y | Y | P(c) | NA | NA | |
| Process Compensated Resonance Testing | Y | Y | Y | Y | Y | Screening, size restrictions |
| Radiographic Testing | Y | Y | P(d) | NA | NA | |
| Computed Tomography | Y | Y | Y | Y | Y | Restrictions how small defects are detectable |
| µ-focus Computer Tomography | Y | Y | Y | Y | Y | Size restrictions for sample |

VTT

# So, what NDE method to use?

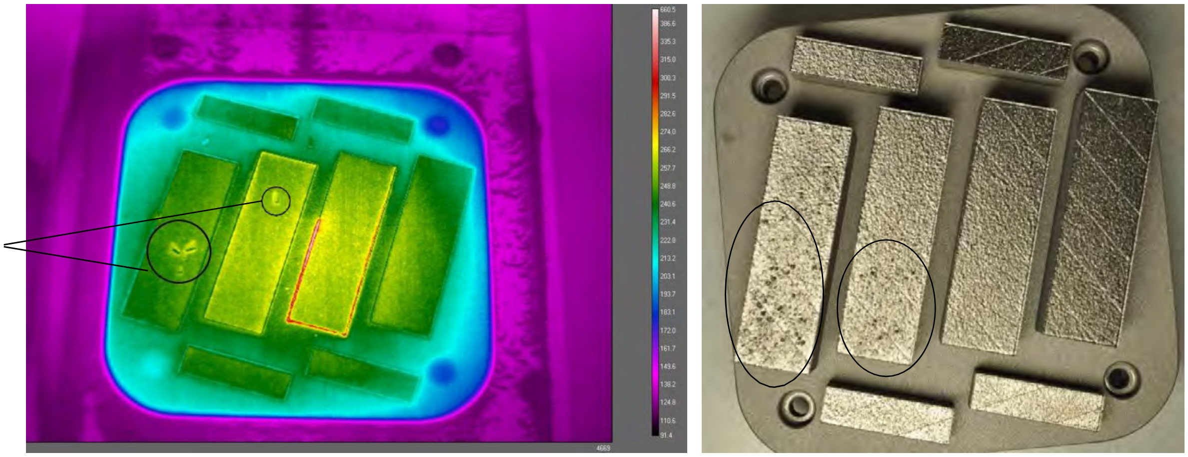
- CT/uCT is the method of choice currently as is the only method capable of handling complex geometries. But it is not a perfect solution:
  - Trade-off between resolution / sample size / equipment performance
  - For quality control quite expensive and time consuming technology
- For GCG1-2 parts, other methods can still have a major role:
  - Advantages in cost
  - Possibilities for in-service inspection.

# In-Process Monitoring

## AM Process Monitoring

- Detected process variations not necessarily linked to a specific defect. Can be used for AM process qualification leading to reduced NDT requirements
- As it is done simultaneously while manufacturing: it might reduce system downtime.
- There are several process monitoring types commercially available:
  - Basic process and environmental sensors (oxygen level, gas flow rate..)
  - Powder bed monitoring
  - Thermal signatures monitoring
    - Off-axis, platform scale field-of-view (usually with IR/near-IR-cameras)
    - On-axis, high spatial and temporal resolution (usually with photodiodes)
- Currently no closed-loop control available.

# Off-axis thermal monitoring



Spatter landing at the left hand side parts

- Thermal camera FLIR A655sc at VTT
- Experimental material, non-optimal powder size & parameters caused excessive spattering

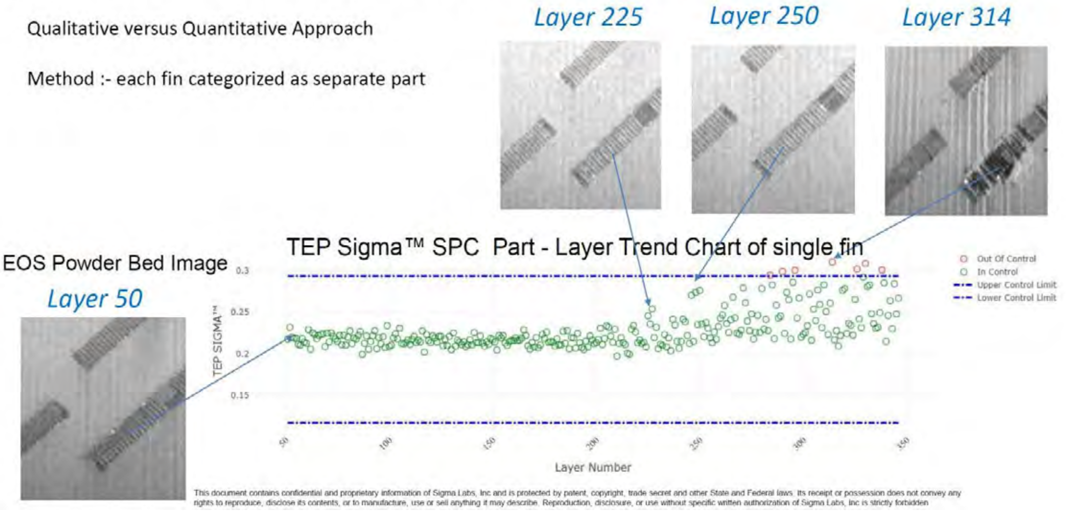
# Example of Melt Pool Monitoring

Inconel 625 : Evaluation of Thermal Signatures using Part-Layer SPC (Statistical Process Control) to detect powder disturbance

SIGMA LABS

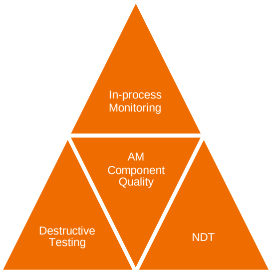
Qualitative versus Quantitative Approach

Method :- each fin categorized as separate part



# Summary

- General models for AM qualification procedures exist – the challenge is to implementing them on different industrial domains and different requirements
- EU NUCOBAM project aims to develop and implement qualification procedures for Nuclear Industry
- There is no single magic bullet to ensure quality on a component
  - Combination of in-process monitoring, NDT and destructive testing can support our efforts.



beyond
the obvious

**Pasi Puukko**
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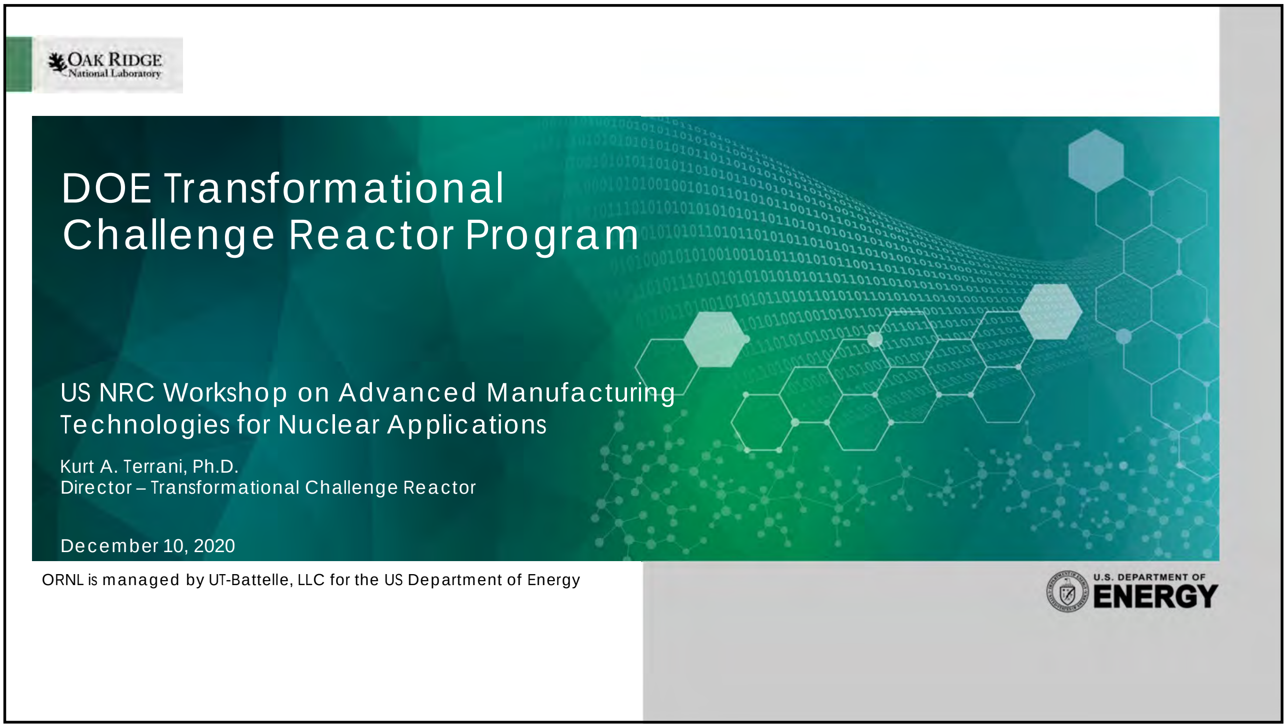


# DOE Transformational Challenge Reactor Program

US NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications

Kurt A. Terrani, Ph.D.
Director – Transformational Challenge Reactor

December 10, 2020

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

# TCR is bringing to bear additive manufacturing (AM) and artificial intelligence (AI) to deliver a new approach

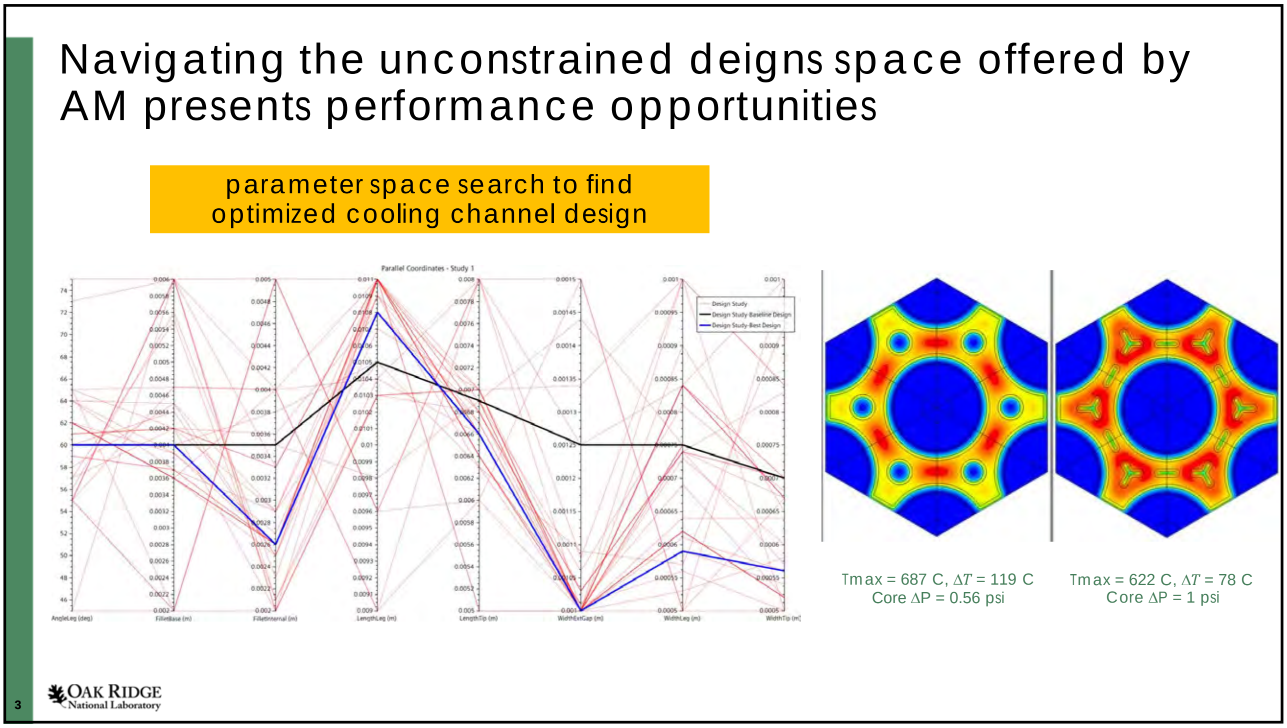
Using AI to navigate an unconstrained design space and realize superior performance

Leveraging AM to arrive at high-performance materials in complex geometries

Exploiting AM to incorporate integrated and distributed sensing in critical locations

Using AI to assess critical component quality using in situ manufacturing signatures

tcr.ornl.gov

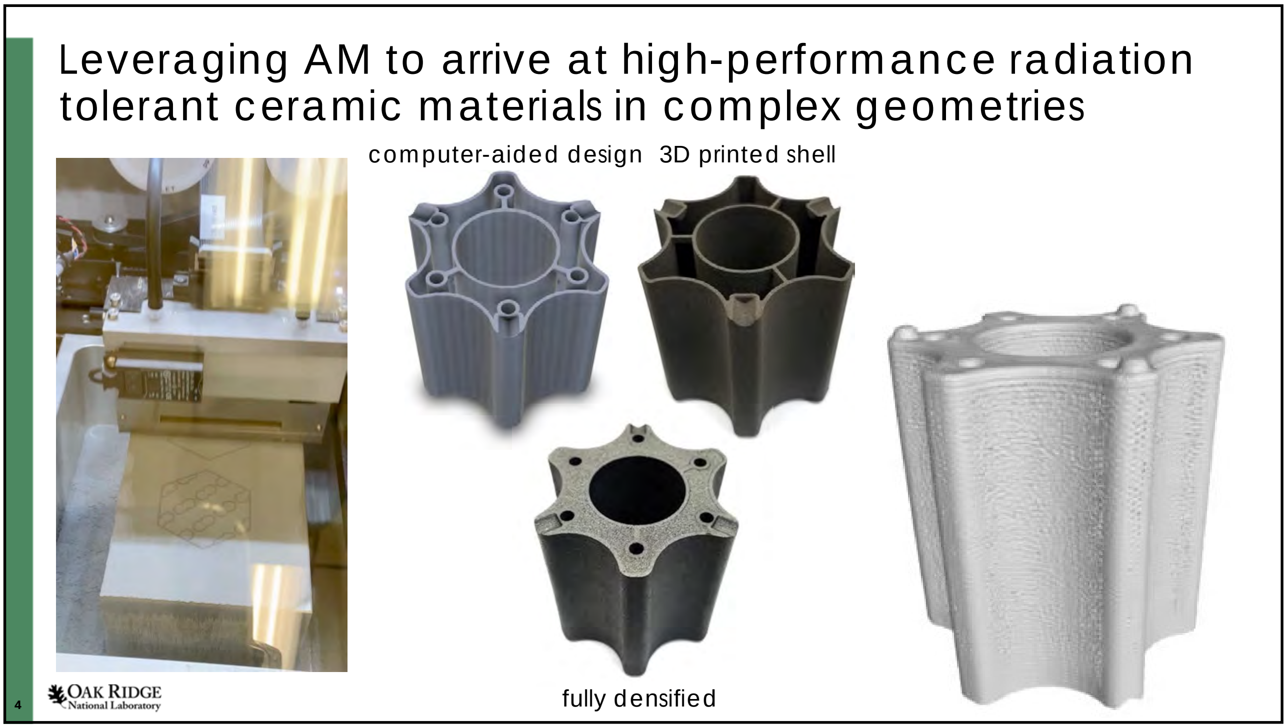


## Navigating the unconstrained deigns space offered by AM presents performance opportunities

parameter space search to find optimized cooling channel design

Tmax = 687 C, $\Delta T$ = 119 C
Core $\Delta$P = 0.56 psi

Tmax = 622 C, $\Delta T$ = 78 C
Core $\Delta$P = 1 psi

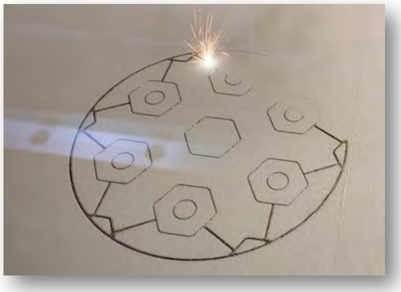


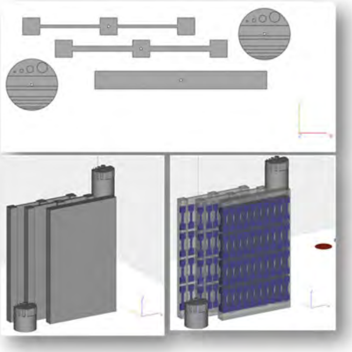
## Leveraging AM to arrive at high-performance radiation tolerant ceramic materials in complex geometries

computer-aided design 3D printed shell

fully densified

## Codification of metal additive manufacturing with a focus on powder bed methodologies was pursued in 2020





NOTICE: This document contains information of a preliminary nature and is not intended for release. It is subject to revision or correction and therefore does not represent a final report.

ORNL/TM-2020/1736

**Quality Procedures for TCR Metal Core Structure Advanced Manufacturing Processes Report**

Michael Russell
Ryan Dehoff

**September 2020**

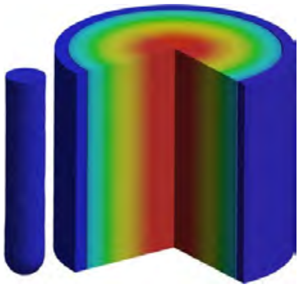
M2TC-20OR0402011 0

OAK RIDGE NATIONAL LABORATORY

OAK RIDGE National Laboratory

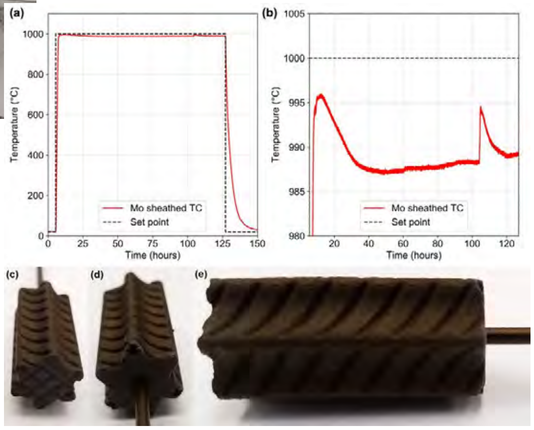
## Incorporating sensors into critical structure via AM to harvest operational data and facilitate health monitoring

**Conventional instrumentation**

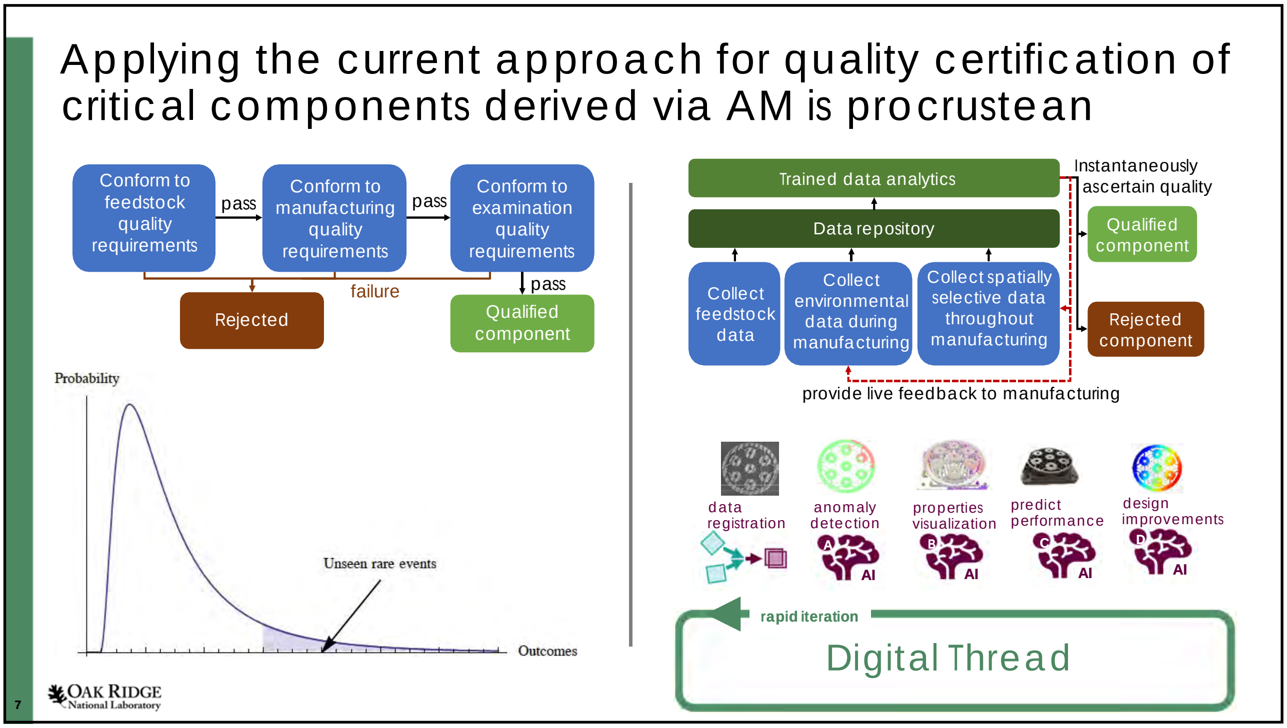


Embedded sensor sheathes in additively manufactured stainless steel and silicon carbide

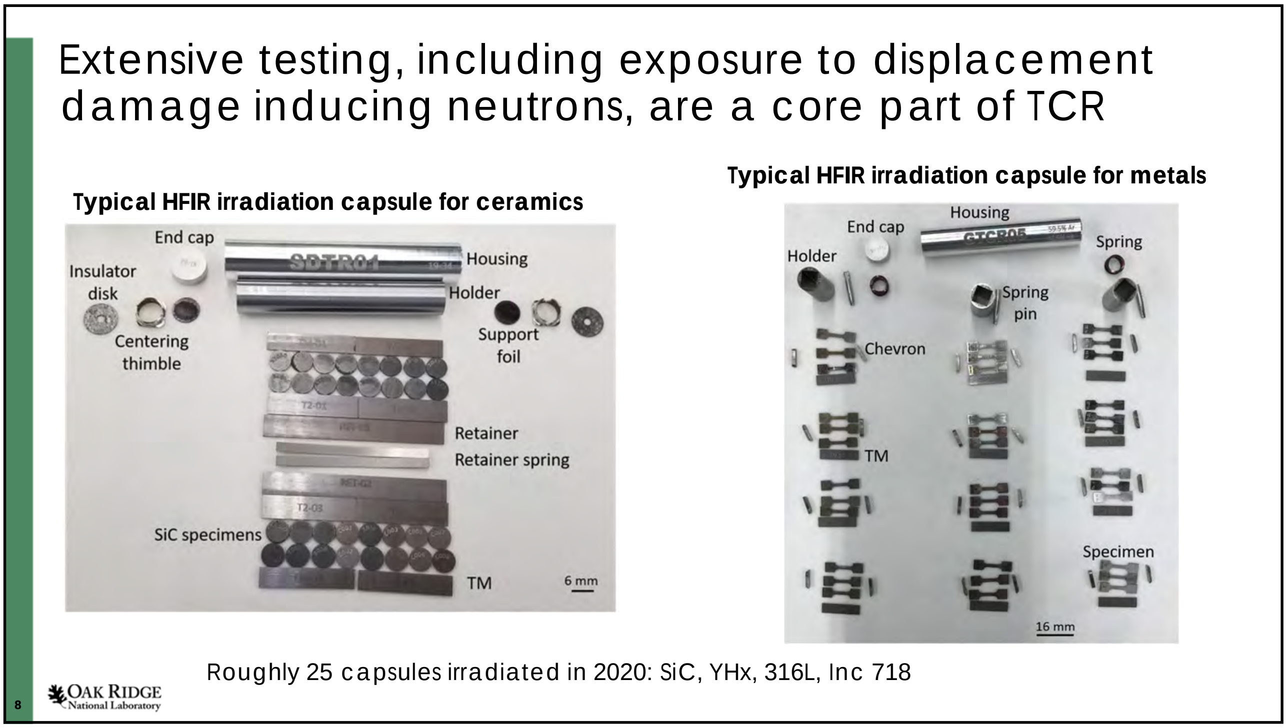
**Integrated instrumentation**



OAK RIDGE National Laboratory



# Applying the current approach for quality certification of critical components derived via AM is procrustean



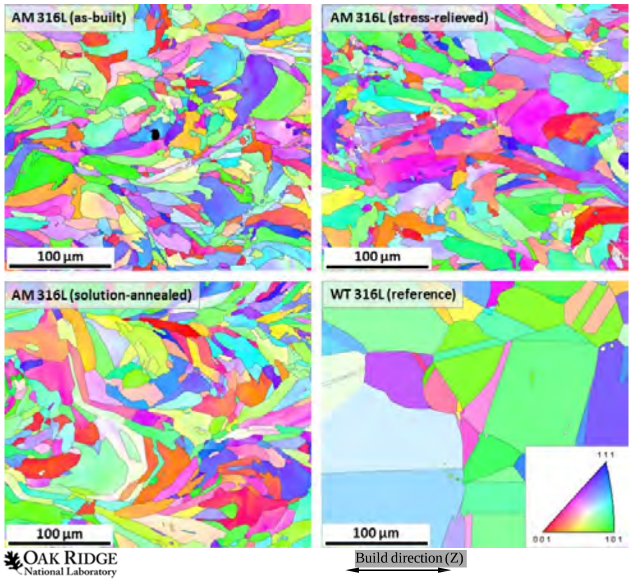
# Extensive testing, including exposure to displacement damage inducing neutrons, are a core part of TCR

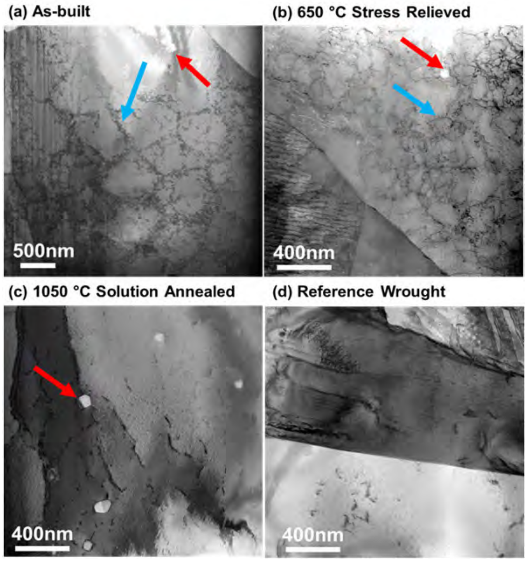
**Typical HFIR irradiation capsule for ceramics**

**Typical HFIR irradiation capsule for metals**

Roughly 25 capsules irradiated in 2020: SiC, YHx, 316L, Inc 718

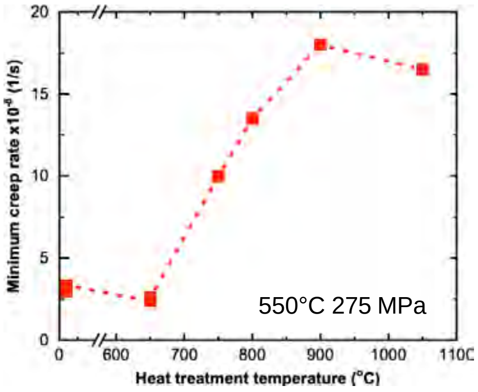
# 316L microstructure after additive manufacturing and prior to irradiation

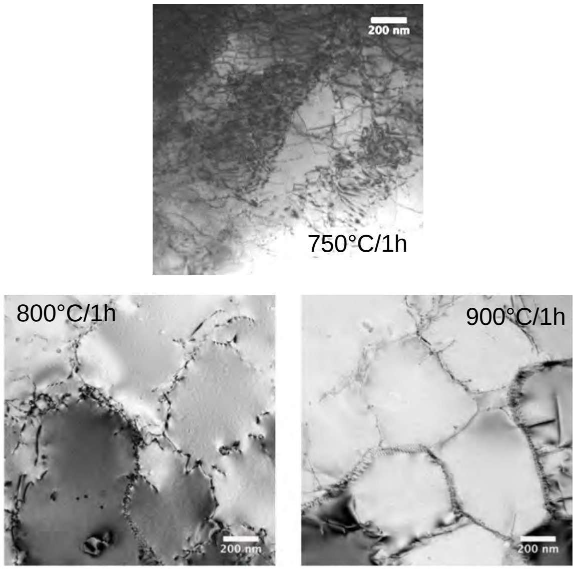




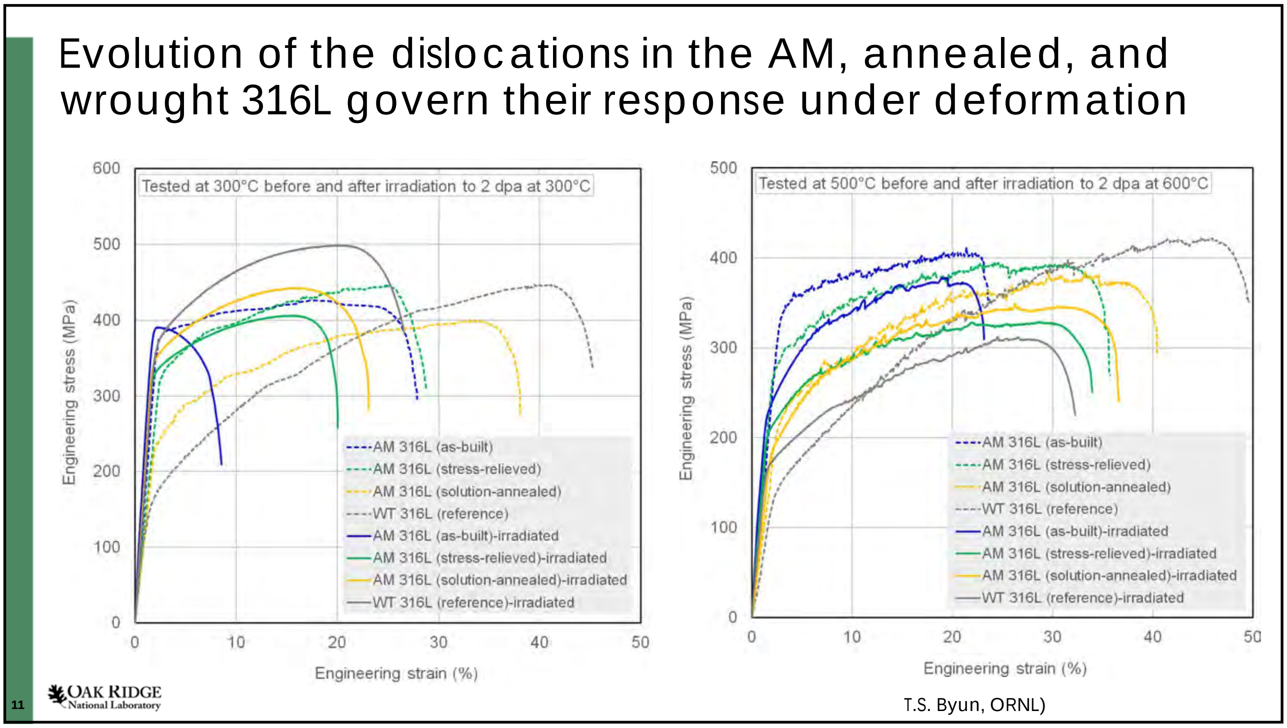
(M. Gussev, T. Lach, ORNL)

# The dislocation cells in AM 316L are tenacious, affect creep behavior of the material, and only disappear above 950°C



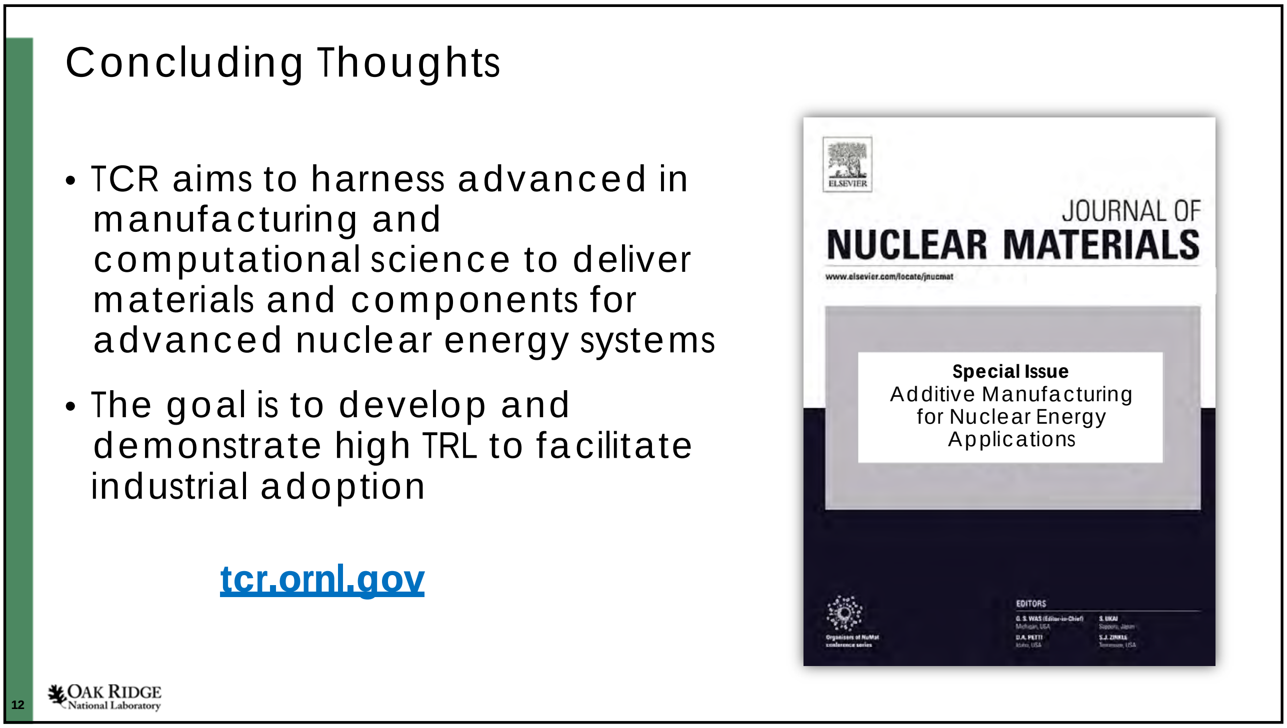


(M. Li, ANL)



# Evolution of the dislocations in the AM, annealed, and wrought 316L govern their response under deformation

T.S. Byun, ORNL)



# Concluding Thoughts

- TCR aims to harness advanced in manufacturing and computational science to deliver materials and components for advanced nuclear energy systems
- The goal is to develop and demonstrate high TRL to facilitate industrial adoption

tcr.ornl.gov

6

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

# Advanced Methods for Manufacturing Program Overview

NRC Public Workshop on Advanced Manufacturing

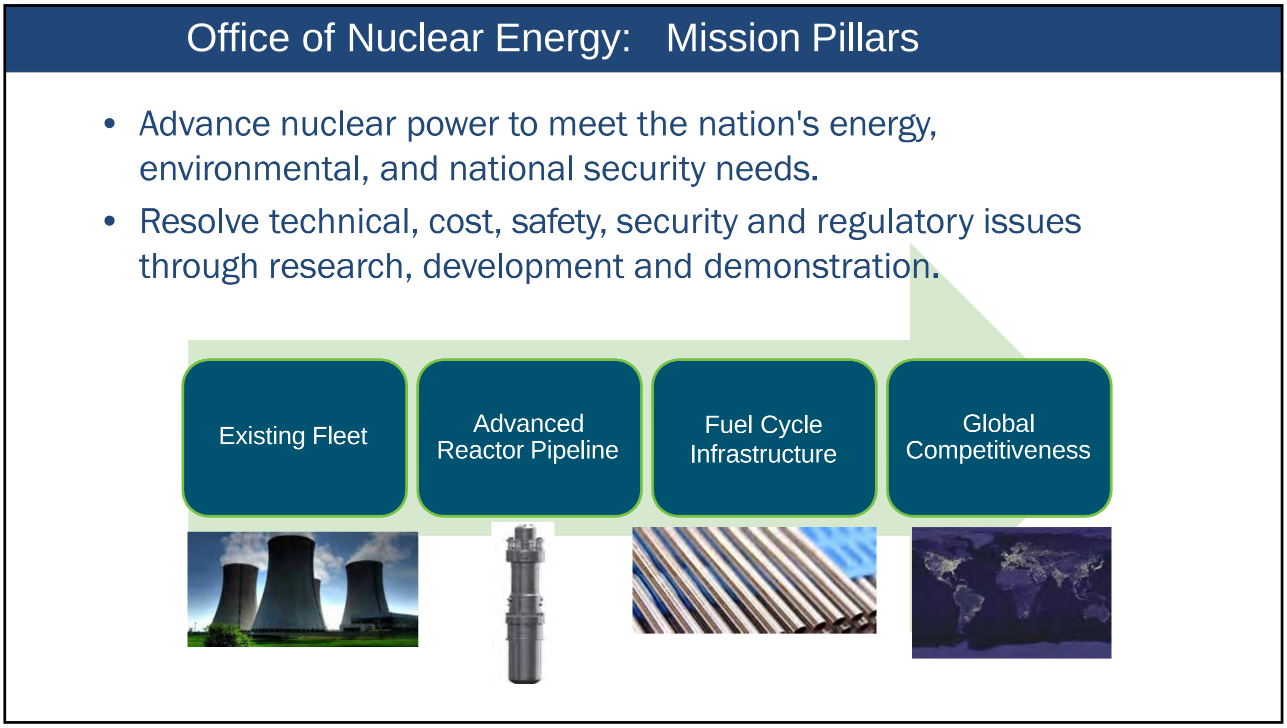
December 7-10, 2020

Isabella J. van Rooyen

National Technical Director: Advanced Methods for Manufacturing (AMM)

Dirk Cairns-Gallimore

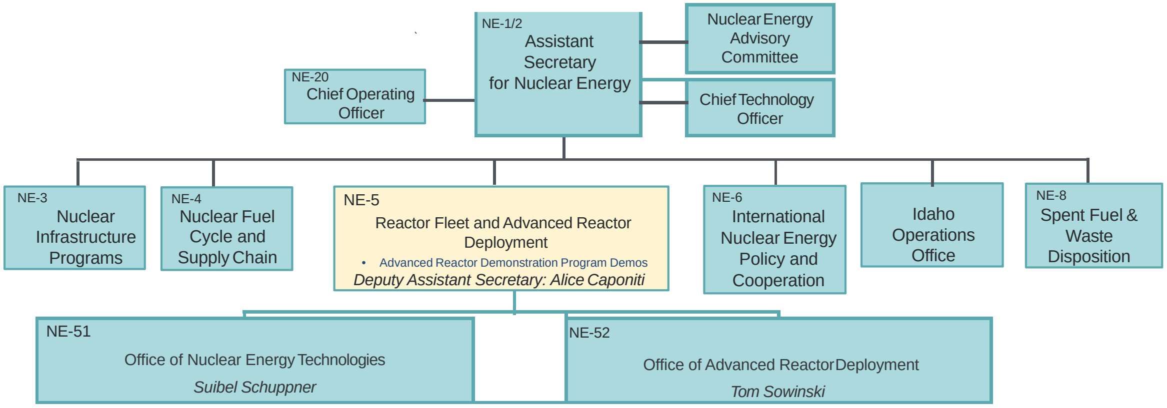
DOE-NEET-AMM Federal Program Manager



## Office of Nuclear Energy: Mission Pillars

- Advance nuclear power to meet the nation's energy, environmental, and national security needs.
- Resolve technical, cost, safety, security and regulatory issues through research, development and demonstration.

# Office of Nuclear Energy



NE-1/2
Assistant Secretary for Nuclear Energy

Nuclear Energy Advisory Committee

Chief Technology Officer

NE-20
Chief Operating Officer

NE-3
Nuclear Infrastructure Programs

NE-4
Nuclear Fuel Cycle and Supply Chain

NE-5
Reactor Fleet and Advanced Reactor Deployment
- Advanced Reactor Demonstration Program Demos

*Deputy Assistant Secretary: Alice Caponiti*

NE-6
International Nuclear Energy Policy and Cooperation

Idaho Operations Office

NE-8
Spent Fuel & Waste Disposition

NE-51
Office of Nuclear Energy Technologies
*Suibel Schuppner*

NE-52
Office of Advanced Reactor Deployment
*Tom Sowinski*

**Enabling Technologies Team**
- Advanced Sensors and Instrumentation (ASI)
- **Advanced Methods for Manufacturing (AMM)**
- Nuclear Energy Advanced Modeling and Simulation (NEAMS)
- Nuclear Science User Facilities (NSUF)
- Transformational Challenge Reactor (TCR)

**University and Competitive Research Team**
- Nuclear Energy University Program (NEUP)
- Integrated University Program (IUP)
- Research Reactor Infrastructure (RRI)
- Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR)
- Gateway for Accelerated Innovation in Nuclear (GAIN) Advanced Nuclear Industry Funding Opportunity (Industry FOA)
- Technology Commercialization Fund (TCF)

**Reactor Optimization and Modernization Team**
- Light Water Reactor Sustainability
- Advanced Small Modular Reactor R&D
- Integrated Energy Systems (IES)
- Nuclear Cyber Security (NCS)
- Advanced Reactors Safeguards (ARS)

**Advanced Reactor Development Team**
- Sodium-Cooled Fast Reactor
- Gas-Cooled High-Temperature Reactors
- Molten Salt Reactors
- Microreactors
- National Reactor Innovation Center (NRIC)
- Risk Reduction
- Advanced Reactor Regulatory Development

# Office of Reactor Fleet and Advanced Reactor Deployment Mission (NE-5)

- **Vision –** Be a catalyst for the commercialization of NE-sponsored research, development and demonstration products
- **Mission –** Integrate NE's research investments to achieve a productive and balanced portfolio of competitive and crosscutting research, development, and demonstration (RD&D) and research infrastructure to enable expansion of the U.S. commercial nuclear industry
- **Objectives**
  - Full and effective integration of NE RD&D planning, execution and oversight
  - Systematic management of NE investments in research capabilities
  - Alignment of NE's RD&D programs with industry-identified technical and regulatory needs
  - Accelerate the introduction of innovative technologies into the marketplace through multiple mechanisms

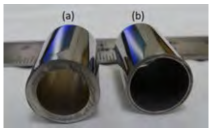
# Advanced Methods for Manufacturing (AMM)

**Vision**

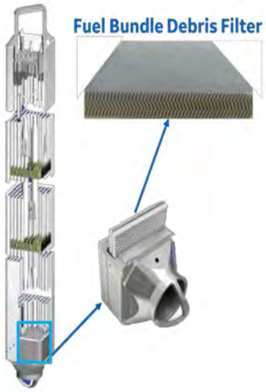
- To improve and demonstrate the methods by which nuclear equipment, components, and plants are manufactured, fabricated, and assembled by utilizing 'state of the art' methods

**Goal**

- To reduce cost and schedule for new nuclear plant construction
- To make fabrication of nuclear power plant (NPP) components faster, less expensive, and more reliable



Fuel tubes produced by cold spray



GEH BWR fuel bundle w/debris filter insert

# Connections of AMM program to other R&D programs, NRC, Industry

- NEAMS
- ART
- ASI
- GAIN
- NSUF & NMDQi
- TCR
- IES
- NE-4 - VTR -TREAT

NE – 5 & Other DOE NE Programs

NNSA & NASA

DoD Programs

Existing Fleet

Advanced Reactors, SMRs, & ARPs

Nuclear Battery & Micro Reactors

Space Reactors

Defense

Cross-cutting AMM research focus areas support all major Nuclear programs across DOE, DoD, NASA, and Industry Stakeholders

Factory and Field Fabrication Techniques

Modular Manufacturing

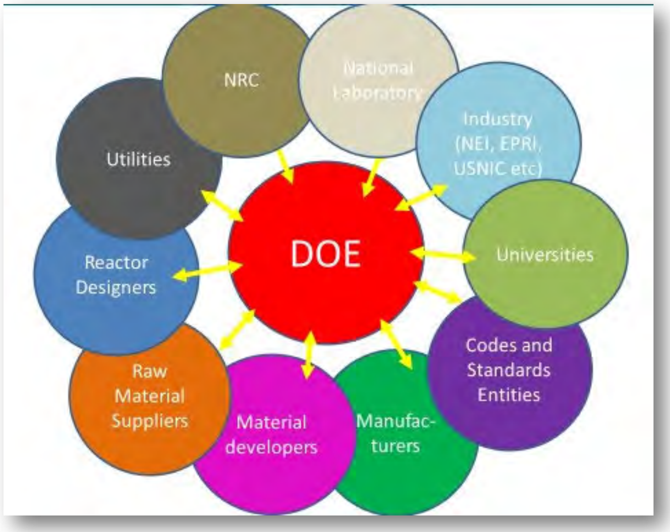
Advances in Manufacturing Processes

Advances in Concrete

New Adv. Man. Tech. for Qualification and Certification to Accelerate Licensing

Advanced Integrated Fuel System Concepts

# Stakeholder Engagement (“Customers”)



**Internal DOE Supported Programs**

- Advanced Reactors
- LWRS
- Other elements of NEET

**Industry Connections**

- NEI
- USNIC
- EPRI
- IFOA
- Fuel Vendors

**External Governmental Programmatic Synergies/Overlaps**

- **NRC**
- EERE
- NIST
- DoD

The Goal is for DOE-NE to be the nexus for AMM development and leadership

# FY21 Objectives and Priorities

**The Goal is for DOE-NE to be the nexus for AMM development and leadership**

- Increase **stakeholder participation** (Industry, DOE offices, Standards, NRC, National laboratories etc.)
- Leverage the **impact of research work** and understand how the technology can potentially be adopted & commercialized
- Continue to reevaluate strategic intent and **identify gaps, needs**
- Increase **collaboration** with DOE programs (identify cross cutting similar needs)
- Establish **direct funded** project(s)
- Re-evaluate Strategy

# Communication

AMM Newsletter

Advanced Methods for Manufacturing

Issue 11 • April 2020

**Dirk Cairns-Gillamore Joins AMM Program**

Dirk Cairns-Gallimore has joined the Advanced Methods for Manufacturing team as the DOE-NE headquarters program manager. Cairns-Gallimore is a native of the Pacific Northwest. He graduated in 2001 from Oregon State University with a degree in nuclear engineering and started his career in 2002 in the Department of Energy's Office of Nuclear Energy, working in the Office of Space and Defense Power Systems. Over the course of 18 years, he was program manager for the multi-mission thermoelectric generator (MMRTG) that was used on Curiosity Rover and will power the upcoming Mars 2020 mission of the Perseverance Rover. He was also the NE-headquarters manager for the activities at the Space and Security Power Systems Facility at INL during the fueling of the General Purpose Heat Source—Radioisotope Thermoelectric Generator (GPHS RTG) for the New Horizons mission to Pluto. Prior to joining the AMM program, he spent a year on detail with the U.S. Coast Guard at their headquarters in Anacostia, Virginia. There he helped further enhance and integrate the Coast Guard's enterprise risk-management system across 23 organizations.

**Dirk Cairns-Gillamore**
DOE-NE program manager

Mr. Cairns-Gallimore brings an interesting perspective to the program. Through his work with space and defense, he was able to be part of a program that integrated expertise from private industry, academia, the national labs, and multiple agencies into mission-critical, time-sensitive product delivery. The production of an RTG is complex, an interdisciplinary engineering process that requires knowledge of manufacturing and fabrication processes, including welding, chemistry, and materials science (including, e.g., carbon-carbon composites, aluminum, and iridium). Cairns-Gallimore's experience gained during the production of MMRTGs is germane to many of the processes involved in the AMM program: ball milling, powder metallurgy, hot isostatic pressing, and welding processes, including thermogravimetric analysis, laser and e-beam welding, and others. This background is crucial to the expansion of research and development towards commercial deployment of advanced manufacturing, in accordance with ASME NQA-1 standards.

Mr. Cairns-Gallimore is an ardent supporter of deploying AMM processes for use by the nuclear industry. He believes that it will be critical for the continued success of both the current reactor fleet and future investment in advance reactors. His time at the Coast Guard reemphasized the power of teamwork and showed that the focus of a determined group of people can create success despite a challenging environment. One of his main goals for the program is to establish priorities for materials and processes so that AMM can be deployed for first-of-a-kind uses. The ability of the AMM community to come together and push toward this goal will determine its success.

**In This Issue**

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- Advanced Manufacturing and Materials Engineering task force at Paris GIF workshop......p. 4
- Program outreach: Additive Manufacturing of Microreactor Component Test Articles ..........p. 5
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- Towards Intelligent Laser 3-D Manufacturing System ..............................p. 11
- Establishing Modular In-Chamber Electron Beam Welding Capability in the USA..............p. 14
- Optimized Dissolvable Supports for Laser Powder Bed Fusion Additive Manufacturing......p. 17

For more program information, including recent publications, please visit www.energy.gov/ne

U.S. DEPARTMENT OF ENERGY

AMM Advanced Methods for Manufacturing

Dec. 2 – 3, 2020 | 8 a.m. – 3 p.m. mst

AMM Technical Review Meeting

***Objectives:*** *1) Provide Principal Investigators (PIs) and researchers the opportunity to deliver a summary of their project achievements to DOE, and 2) Highlight to industry and other researchers the AMM project accomplishments and advantages, leading to potential collaborations and adoption of AMM technologies.*

- Surveys
- Conferences
- E-mail contact list
- Outreach presentations
- NEI workgroups
- Publications

SAVE THE DATE

GAIN-EPRI-NEI

**Advanced Methods for Manufacturing**

QUALIFICATION WORKSHOP

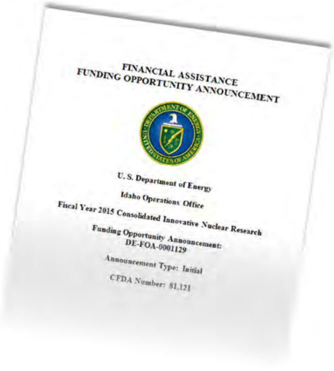
AMM

**AUGUST 24-26, 2021**

INL Meeting Center, 775 MK Simpson Blvd, Idaho Falls, ID 83401

# Addressing Challenges

- **Competitively selected projects via Consolidated Innovative Nuclear Research (CINR) & Industry FOA**
  - Open to universities, national laboratories and Industry
  - R&D and irradiation/PIE projects funded
  - FY 21 work scopes
    - MODULAR ADVANCED MANUFACTURING APPROACHES
    - NEW ADVANCED MANUFACTURING TECHNOLOGIES FOR QUALIFICATION AND CERTIFICATION TO ACCELERATE LICENSING
    - IRRADIATION TESTING OF MATERIALS PRODUCED BY INNOVATIVE MANUFACTURING TECHNIQUES
  - AMM Qualification Workshop
    - GAIN-EPRI-NEI
    - Develop an integrated approach to the AMM qualification process for materials and components



FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy

Idaho Operations Office

Fiscal Year 2015 Consolidated Innovative Nuclear Research

Funding Opportunity Announcement:
DE-FOA-0001129

Announcement Type: Initial

CFDA Number: 81.121

5

# AMM Focus Areas: FY2021

**Factory and Field Fabrication Techniques**

High Speed & High Productivity Welding

Welding technologies for large weldments and fabrications

Dissimilar Materials Joining

Robotics and advanced automation

**Modular Manufacturing**

Fabricated forgings

Factory fabrication of piping systems

PM-HIP

**Advances in Manufacturing Processes**

Additive Manufacturing of metals

Surface engineering

Metamorphic Manufacturing

Advanced sensors

**Improved Concrete Inspection, Acceptance, and Construction Methods**

Advances and innovation in high strength concrete and rebar

NDE and field inspection for first time quality assurance and repair

Improved methods to facilitate the curing of concrete

**New Advanced Manufacturing Technologies for Qualification and Certification to Accelerate Licensing**

Advanced Manufacturing Methods Qualification approaches

Verification and validation technologies

Advanced Manufacturing Codes and Standards

Big data

Digital Thread and Digital Twin

**Advanced Integrated Fuel System Concepts**

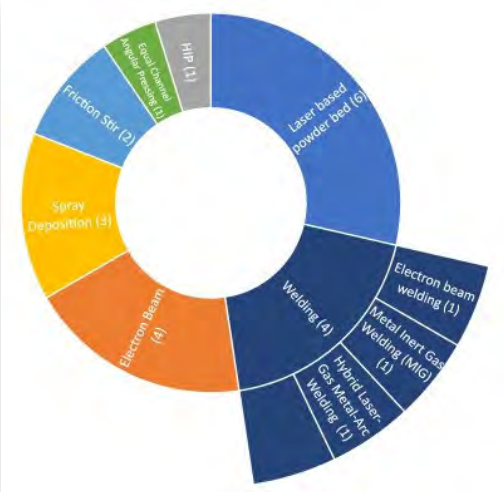
Advanced thermal processing approaches

Integrated manufacturing methods

# Evaluate AMM Program Award Impact (NEET Awards 2011-2019)

DRAFT

AMM Techniques

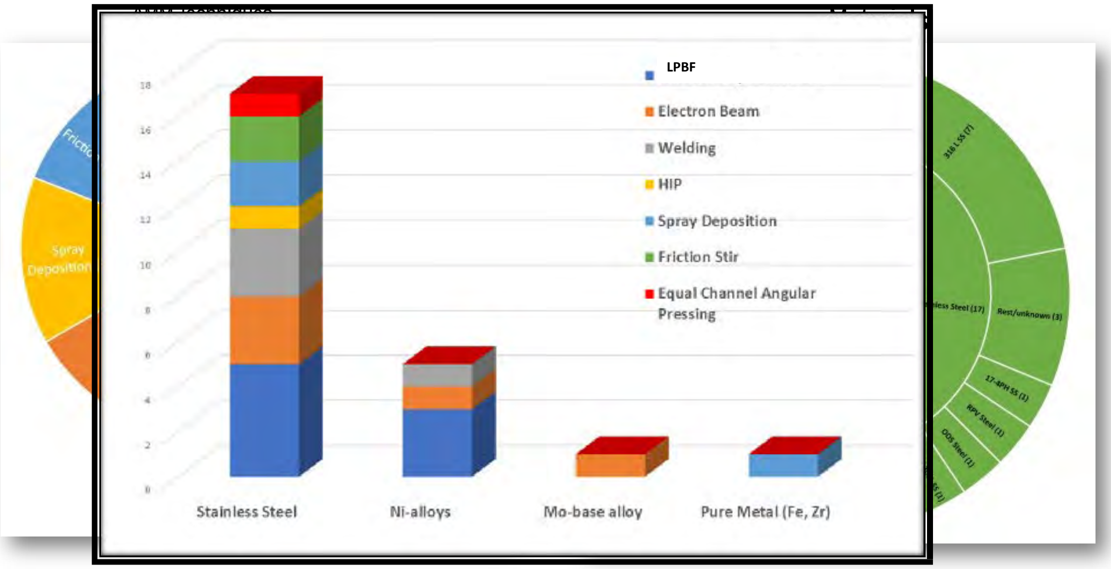


Materials

Courtesy Subhashish Meher

# Evaluate AMM Program Award Impact (NEET Awards 2011-2019)

DRAFT



Courtesy Subhashish Meher

# Gaps or Technology Challenges

**Prioritizing Methods and Materials**
**Complex set of needs**
**Risk reduction methods**
**Speed to industry deployment**
**Qualification Processes**
**Maturity Level**

- Performance data in "nuclear" environments
- How do we measure or gauge applications of new advanced manufacturing methods?
  - Technology readiness level
  - Qualification routes
  - Standards/Codes
  - Risks
- Determining requirement & performance specifications for different manufacturing process domains
- How do we measure & communicate the impact of our research (especially earlier TRL)?
- Cybersecurity in:
  - Digital Engineering
  - Machine Learning approaches
  - Big Data/Artificial Intelligence Applications
  - Automated Manufacturing
  - In-situ monitoring
  - Embedded sensor

## High Impact Materials & Manufacturing Technology Challenges

- Design approaches for manufacturing
  - More qualified materials are needed by reactor developers to allow for design flexibility and to meet performance targets.
  - Optimized process modeling and AI
  - Interface design
  - Residual stresses relationships to design features
  - Topology optimization
- Develop and qualify high strength, corrosion and radiation resistant materials for molten salt reactors
- Accelerate qualification (new paradigm?)
  - Verification of quality & validation of modeling tools: specific manufacturing process modeling
  - "New" material discovery (or is it adoption of lessons learned from other disciplines)
  - High-throughput testing and characterization
  - Verification of quality & validation of modeling tools: specific manufacturing process modeling
  - Acceptance protocols for high temperature reactor components fabricated by advanced manufacturing methods
  - Integrated shared databases
- Compact Heat Exchangers
  - Develop scientific understanding of processing-properties relation for enhanced diffusion bond properties
- Large component fabrication and welding, Size limitations (Scalability – size, volume)
- Sensors:
  - Radiation tolerant sensors
  - Miniaturization of sensors
  - Integrated manufacturing processes
- Thermal barrier coatings: Interface designs to prevent scaling, functional materials, isolation

## CURRENT AMM NEET PROJECTS

| | |
|---|---|
| HIP Cladding and Joining to Manufacture Large Dissimilar Metal Structures for Modular and GEN IV Reactors<br>*(Project awarded FY 21)* | Xiaoyuan Lou<br>*Auburn University* |
| Fiber Sensor Fused Additive Manufacturing for Smart Component Fabrication for Nuclear Energy<br>*(Project awarded FY 21)* | Kevin Chen<br>*University of Pittsburgh* |
| Diffuse Field Ultrasonics for In Situ Material Property Monitoring During Additive Manufacturing Using the SMART Platform<br>*(Project awarded FY 21)* | Christopher M. Kube<br>*Pennsylvania State University* |
| Machine Learning-based Processing of Thermal Tomography Images for Automated Quality Control of Additively Manufactured Stainless Steel and Inconel Structures | Alexander Heifetz<br>*Argonne National Laboratory* |
| Development of Innovative Manufacturing Approach for Oxide-Dispersion Strengthened (ODS) Steel Cladding Tubes using a Low Temperature Spray Process | Kumar Sridharan<br>*University of Wisconsin* |
| Integrated Computational Materials Engineering (ICME) and In-situ Process Monitoring for Rapid Qualification of Components Made by Laser-Based Powder Bed AM Processes for Nuclear Structural and Pressure Boundary Applications | David Gandy & Marc Albert<br>*Electric Power Research Institute* |
| Integrating Dissolvable Supports, Topology Optimization, and Microstructure Design to Drastically Reduce Costs in Developing and Post-Processing Nuclear Plant Components Produced by Laser-based Powder Bed Additive Manufacturing | Albert To<br>*University of Pittsburgh* |
| All-position Cladding by Friction Stir Additive Manufacturing | Zhili Feng<br>*Oak Ridge National Lab* |
| Laser Additive Manufacturing of Grade 91 Steel for Affordable Nuclear Reactor Components | Stuart Maloy<br>*Los Alamos National Lab* |

## Additive Manufacturing Projects – Code Case

### Integrated Computational Materials Engineering & In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder bed Additive Manufacturing Processes for Nuclear Structural

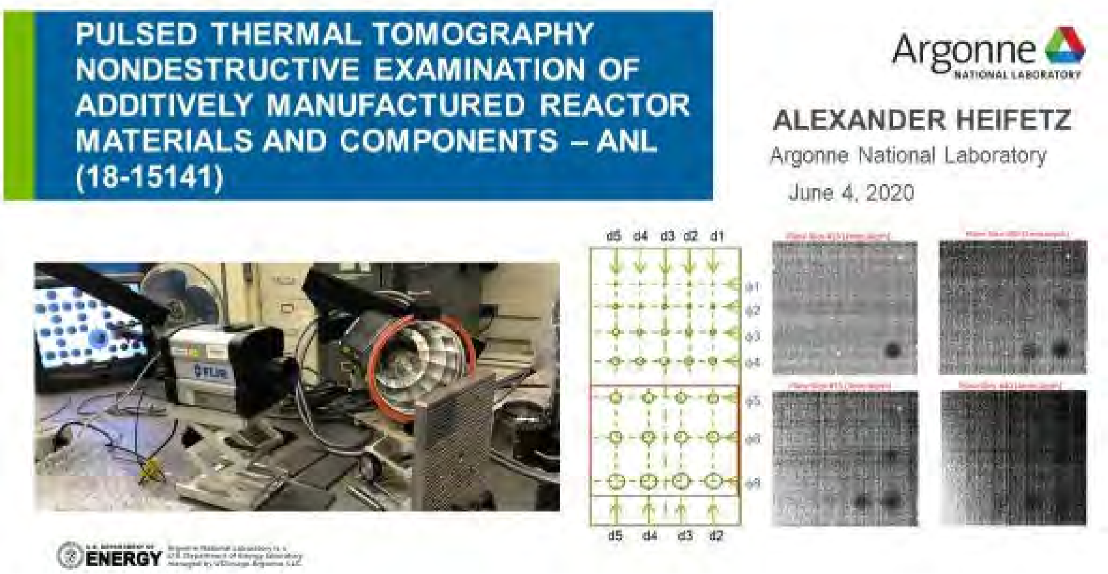
Award Number: DE-NE0008521
Award Dates : 10/2016 to 06/2020
PI: David Gandy
Team Members: ORNL, Westinghouse, Rolls-Royce

*Figure 1a. A 316L SS Pipe Tee fitting is being produced via LPB-AM.*

*Figure 1b. A 316L SS section of a valve body was produced via LPB-AM.*

- Working with ASME Special Committee on Additive Manufacturing and BPV-III to develop and submit Data Package and Code Case (with Westinghouse)
  - ASME Special Committee has drafted Guideline document for AM welding of 316L SS.
- Data Package finalized
- **Code Case submitted August 2020**

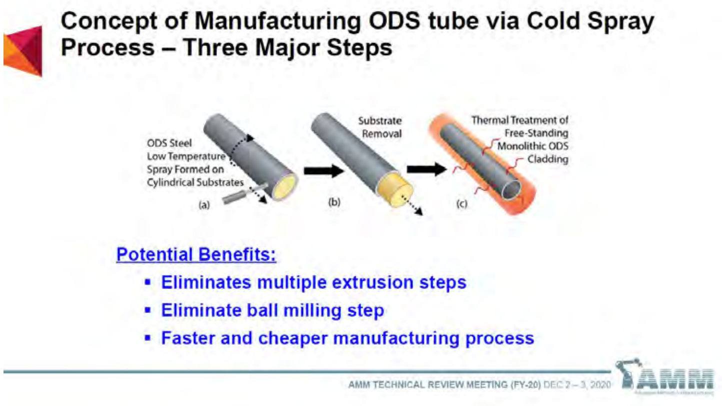
## Non-Destructive Testing



PULSED THERMAL TOMOGRAPHY NONDESTRUCTIVE EXAMINATION OF ADDITIVELY MANUFACTURED REACTOR MATERIALS AND COMPONENTS – ANL (18-15141)

ALEXANDER HEIFETZ
Argonne National Laboratory
June 4, 2020

## Development of Innovative Manufacturing Approach for ODS Steel Cladding Tubes using a Low Temperature Spray Process



**Concept of Manufacturing ODS tube via Cold Spray Process – Three Major Steps**

**Potential Benefits:**

- Eliminates multiple extrusion steps
- Eliminate ball milling step
- Faster and cheaper manufacturing process

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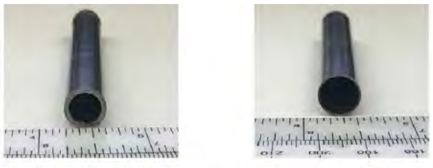
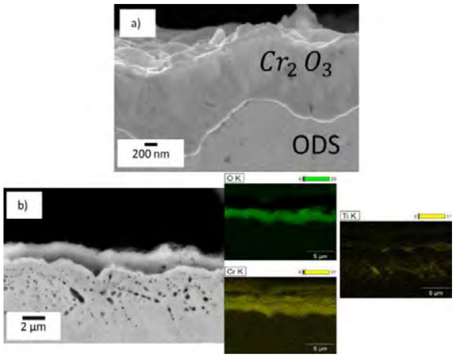


**ODS coated Al-alloy mandrel** **Removal of Al-alloy mandrel**



Kumar Sridharan
University of Wisconsin

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## CURRENT AMM INDUSTRY PROJECTS

**IFOA Scope**: Advanced manufacturing, fabrication and construction techniques for nuclear parts, components, and full-scale plants, or integrated efforts that could positively impact the domestic nuclear manufacturing enterprise

Representative Model of NuScale Power Reactor Vessel

| | |
|---|---|
| Establishment of an Integrated Advanced Manufacturing and Data Science Driven Paradigm for Advanced Reactor Systems | Scott Shargots<br>*BWXT* |
| Small Modular Reactor Pressure-vessel Manufacturing & Fabrication-technology Development (sole sourced) | David Gandy<br>*Electric Power Research Institute* |
| EPRI: Modular In-Chamber Electron Beam Welding Capability (Large Thick Section Components) | David Gandy<br>*Electric Power Research Institute* |
| Advancing and Commercializing Hybrid laser Arc Welding (HLAW) for Nuclear Vessel Fabrication, Including Small Modular Reactors (SMR) | Brian Farnsworth<br>*Holtec Manufacturing* |

# SMR RPV Manufacturing & Fabrication Technology Development

SMR Reactor Pressure Vessel Manufacturing & Fabrication Technology Development – EPRI (10/01/2017 – 09/30/2021)

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) 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

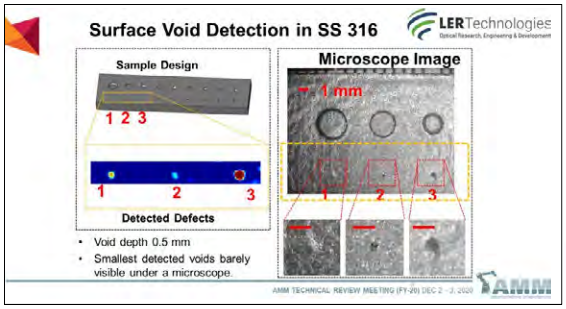
Mockup EB weld of lower head

Representative Model of NuScale Power Reactor Vessel

# CURRENT AMM SBIR PROJECTS

| | |
|---|---|
| Real Time NDE During 3D Manufacturing | Araz Yacoubian<br>*LER Technologies* |
| Additive Manufacturing of BWR Lower Tie Plates and other Fuel Assembly Components | Lauren Gramlich<br>*Novatech* |
| Additive Manufacturing of SMR Holddown Springs and Upper Nozzle Interfaces | George Pabis<br>*Novatech* |

NovaTech printed Lower Tie plate concept E, Inconel & SS



**Surface Void Detection in SS 316**

LERTechnologies
Optical Research, Engineering & Development

Sample Design

Detected Defects

Microscope Image

- Void depth 0.5 mm
- Smallest detected voids barely visible under a microscope.

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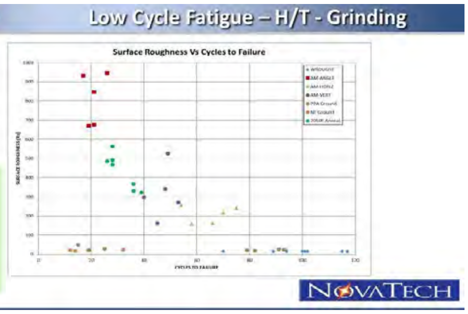
NovaTech design for a hold down spring that takes advantage of the capability of AM to produce complex geometries



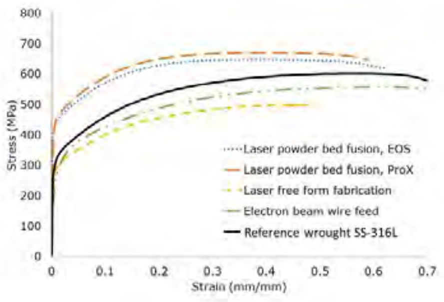
Low Cycle Fatigue – H/T - Grinding

# CURRENT AMM NEET NSUF PROJECTS

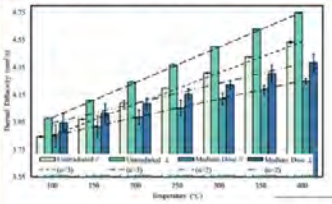
| | |
|---|---|
| Irradiation Studies on Electron Beam Welded PM-HIP Pressure Vessel | Janelle Wharry<br>*Purdue University* |
| Irradiation-Performance Testing of Specimens Produced by Commercially Available AM | Jeffrey King<br>*Colorado School of Mines* |
| Nanodispersion Strengthened Metallic Composites with Enhanced Neutron Irradiation Tolerance | Ju Li<br>*Massachusetts Institute of Technology* |
| Enhancing Irradiation Tolerance of Steels via Nanostructuring by Innovative Manufacturing Techniques | Mary Lou Dunzik-Gougar<br>*Idaho State University*<br>Haiming Wen<br>*Missouri University of Science and Technology* |
| Performance of SiC-SiC Cladding and Endplug Joints under Neutron Irradiation with a Thermal Gradient (Recap of Project) | Christian Deck<br>*General Atomics* |
| Irradiation Testing of Materials Produced by Additive Friction Stir Manufacturing (Recap of Project) | Chase Cox<br>*Aeroprobe Corporation* |

# Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

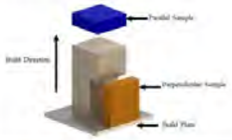
## Mechanical Test Results (SS-316L)



## Anisotropic Thermal Diffusivity?



SS-P2 (LPBF-vacuum)



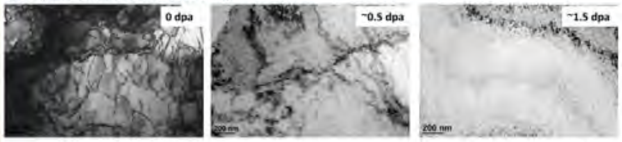
Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

| | Unirradiated SS-P1 (n=6) | | Unirradiated SS-P2 (n=6) | | Medium Dose SS-P2 (n=4) | | Unirradiated SS-P3 (n=6) | |
|---|---|---|---|---|---|---|---|---|
| Temperature | p-value | t-value* | p-value | t-value* | p-value | t-value* | p-value | t-value* |
| 100 °C | 0.450 | 1.169 | [illegible] | [illegible] | [illegible] | [illegible] | 0.857 | 0.197 |
| 150 °C | 0.453 | 1.161 | [illegible] | [illegible] | [illegible] | [illegible] | 0.323 | 1.126 |
| 200 °C | 0.459 | 1.137 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 250 °C | 0.455 | 1.152 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 300 °C | 0.451 | 1.167 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 350 °C | 0.453 | 1.162 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 400 °C | 0.454 | 1.155 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

*T-critical=1.728 (DOF=2, α=0.159)
+T-critical=1.833 (DOF=1, α=0.159)

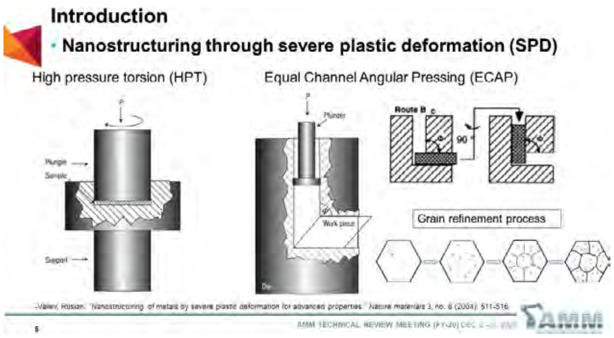
## Initial Post-Irradiation TEM Results

SS-P2 (Laser Powder Bed Fusion SS-316L)



Jeffrey King
Colorado School of Mines

# Enhancing irradiation tolerance of steels via nanostructuring by innovative manufacturing techniques



## Introduction

- Nanostructuring through severe plastic deformation (SPD)

High pressure torsion (HPT)

Equal Channel Angular Pressing (ECAP)

-Valiev, Ruslan. "Nanostructuring of metals by severe plastic deformation for advanced properties." Nature materials 3, no. 6 (2004): 511-516.

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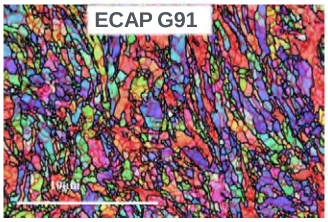
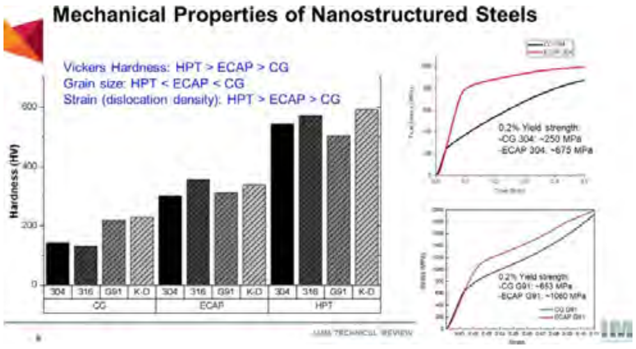


ECAP G91



## Mechanical Properties of Nanostructured Steels

Vickers Hardness: HPT > ECAP > CG
Grain size: HPT < ECAP < CG
Strain (dislocation density): HPT > ECAP > CG

0.2% Yield strength:
-CG 304: ~250 MPa
-ECAP 304: ~675 MPa

0.2% Yield strength:
-CG G91: ~653 MPa
-ECAP G91: ~1060 MPa

*Haiming Wen (Missouri S&T)*

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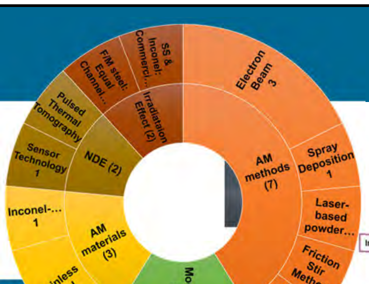
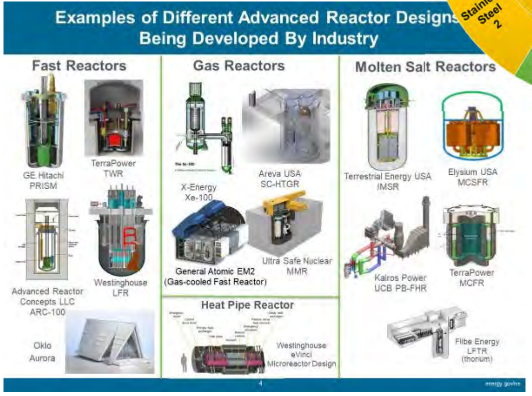
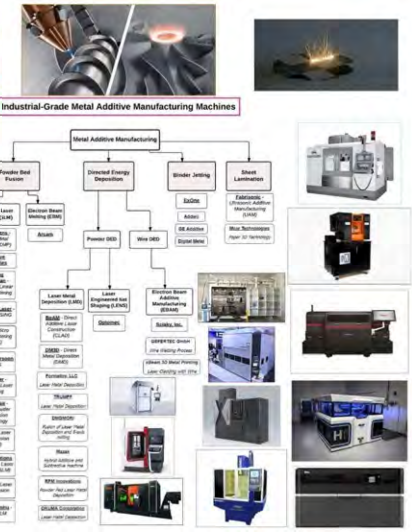
# What Next?

Update Strategic Plan
Mining previous awards
Implement FY21 priorities





## Examples of Different Advanced Reactor Designs Being Developed By Industry



Industrial-Grade Metal Additive Manufacturing Machines

# SAVE THE DATE

## GAIN-EPRI-NEI Advanced Methods for Manufacturing QUALIFICATION WORKSHOP

**AUGUST 24-26, 2021**

INL Meeting Center, 775 MK Simpson Blvd, Idaho Falls, ID 83401

**PURPOSE:**

Develop an integrated approach to the AMM qualification process for materials and components and identify current blind spots.

**OBJECTIVES:**

- Understand current qualification processes
- Create novel approaches to process qualification
- Identify "what" industry needs in product, properties, and performance
- Identify areas in the AMM Supply Chain qualification that are lacking
- Identify possible synergistic qualification needs from industry through performance requirements
- Identify opportunities to shorten qualification by using AMM techniques
- Identify opportunities to reduce project cost by using AMM techniques

*Check out the workshops tab at https://gain.inl.gov*

| FIRST NAME | LAST NAME | ORGANIZATION |
|---|---|---|
| Marc | Albert | EPRI/AMM |
| Marsha | Bala | INL/AMM Program |
| Lori | Braase | GAIN |
| Dirk | Cairns-Gallimore | DOE-NE |
| John | Carpenter | LANL/AMM Technical Team |
| Jason | Christensen | INL/AMM Regulatory |
| David | Gandy | EPRI/AMM |
| Ed | Herderick | OSU/AMM Technical Team |
| Ryan | deHoff | ORNL/Secure & Digital Manuf |
| Teresa | Krynicki | GAIN |
| Hillary | Lane | NEI/AMM |
| Kun | Mo | ANL/Adv Manuf |
| Everett | Redmond | NEI/GAIN |
| Sarah | Roberts | INL/AMM Support |
| Andrew | Sowder | EPRI/GAIN |
| Isabella | Van Rooyen | INL/AMM NTD |
| Ali | Zbib | PNNL/AMM Technical Team |

Industry input on needs and qualification approaches will form the basis for the AMM Roadmap in 2021 and Implementation Plan.

Lori.braase@inl.gov Program Manager GAIN

# Contact Information

Dirk Cairns-Gallimore: AMM DOE federal program manager
dirk.cairns-gallimore@nuclear.energy.gov

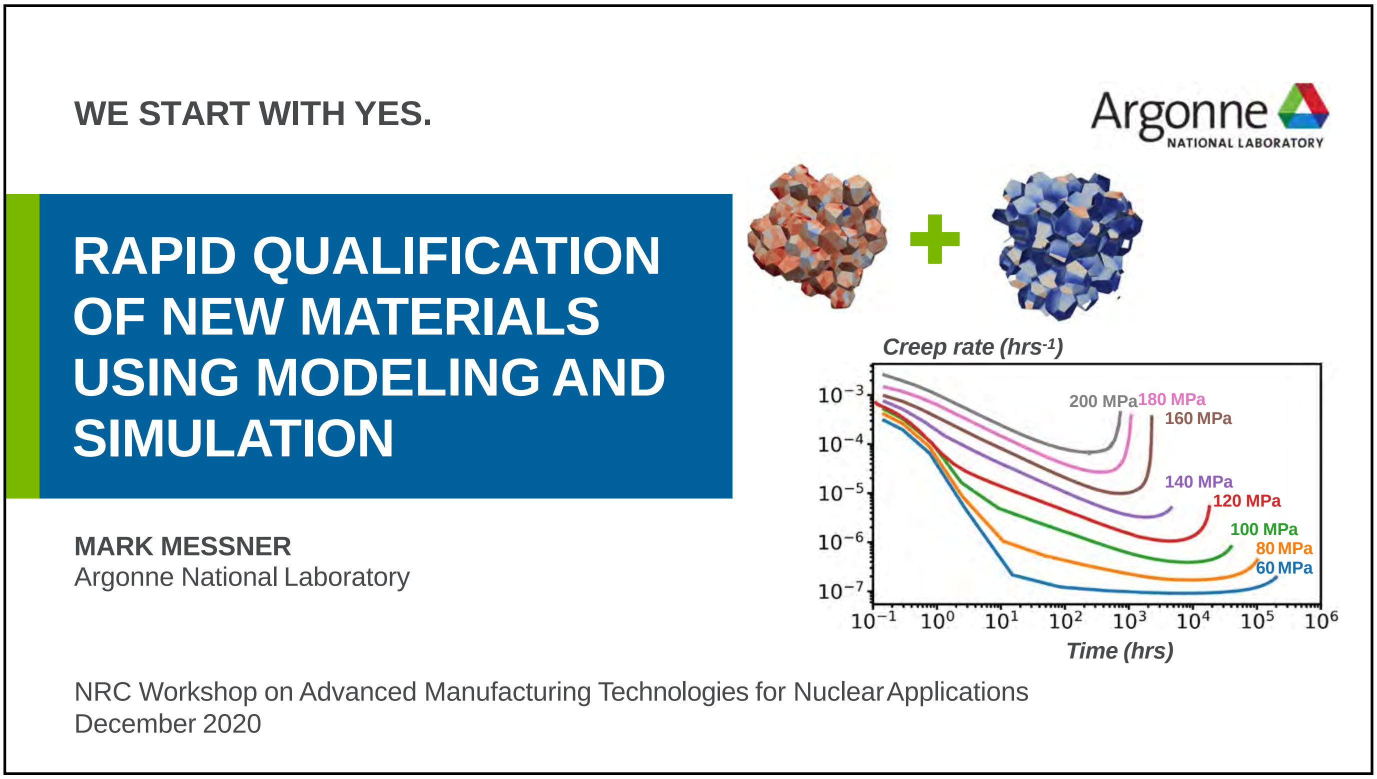
Dr. Isabella van Rooyen: AMM program National Technical Director
Isabella.vanrooyen@inl.gov

**For more program information, including recent publications:**
**www.energy.gov/ne**

SMR Reactor Pressure Vessel (EPRI)
One-half lower head: Forge and electron bean weld

## Questions?

Clean. Reliable. Nuclear.

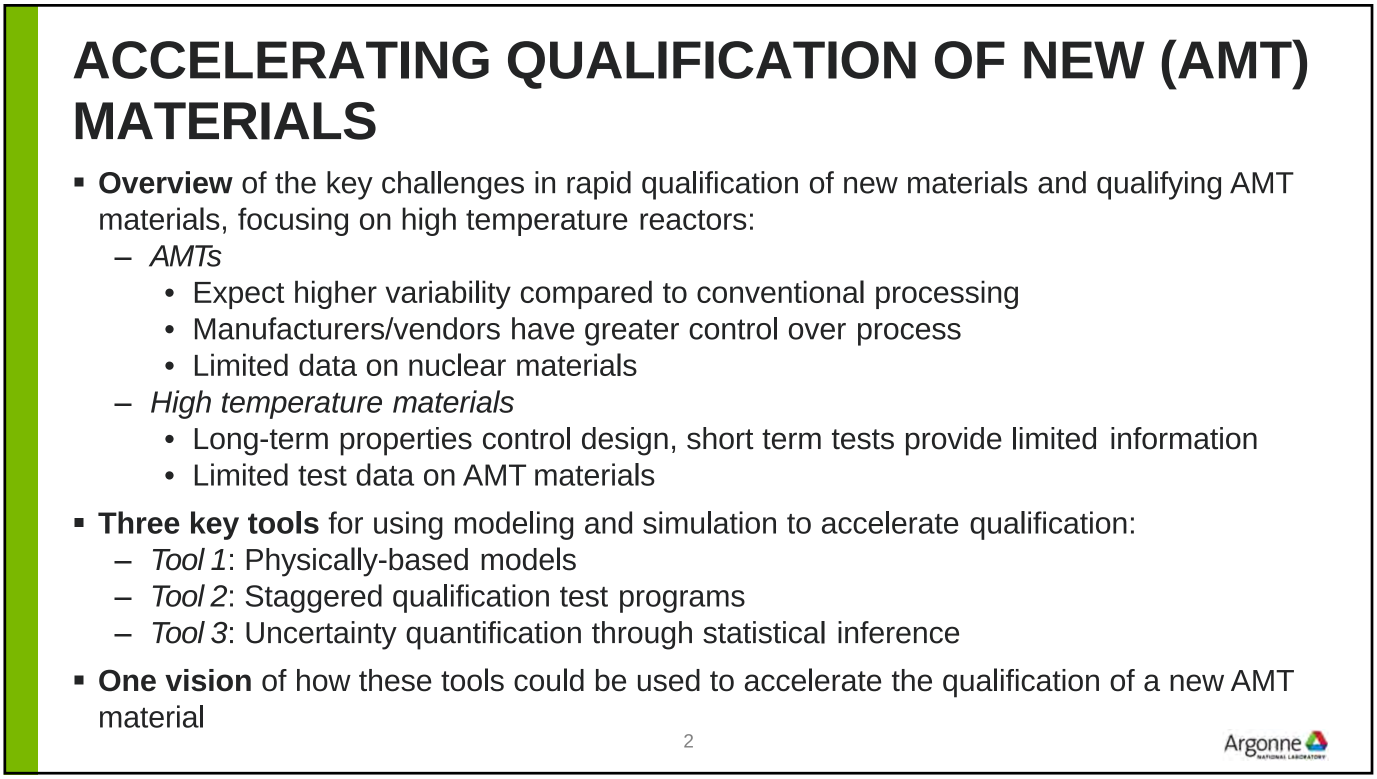


WE START WITH YES.

# RAPID QUALIFICATION OF NEW MATERIALS USING MODELING AND SIMULATION

**MARK MESSNER**
Argonne National Laboratory

NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications
December 2020

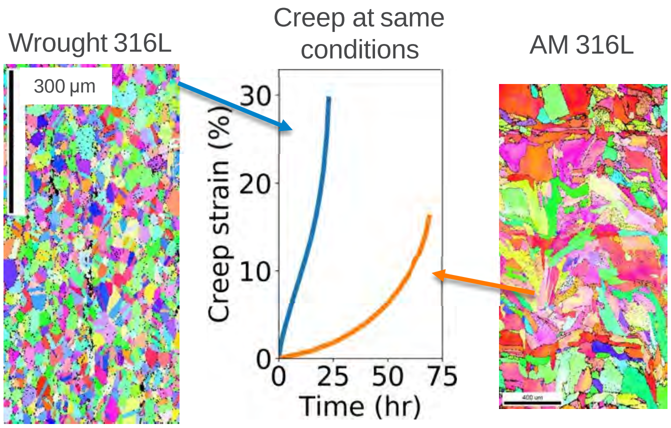


## ACCELERATING QUALIFICATION OF NEW (AMT) MATERIALS

- **Overview** of the key challenges in rapid qualification of new materials and qualifying AMT materials, focusing on high temperature reactors:
  - *AMTs*
    - Expect higher variability compared to conventional processing
    - Manufacturers/vendors have greater control over process
    - Limited data on nuclear materials
  - *High temperature materials*
    - Long-term properties control design, short term tests provide limited information
    - Limited test data on AMT materials
- **Three key tools** for using modeling and simulation to accelerate qualification:
  - *Tool 1*: Physically-based models
  - *Tool 2*: Staggered qualification test programs
  - *Tool 3*: Uncertainty quantification through statistical inference
- **One vision** of how these tools could be used to accelerate the qualification of a new AMT material

# WHAT ARE THE CHALLENGES QUALIFYING AM MATERIALS IN GENERAL?

- *Variability in AM material properties is much greater than for conventional wrought/cast material – more akin to welds*
  - Less understood processes
  - Many processing parameters controllable by users
  - Wide variety of technologies
  - Manufacturing likely to occur at a number of smaller sites, rather than at large, central production facilities
- *AM methods often result in significant material property variations within a single build*
- *We want a process that can take advantage of the flexibility of AM processes – not trying to simply 3D print conventional material*



AM material good, bad, or just different?

*AM creep specimens courtesy UW Madison*

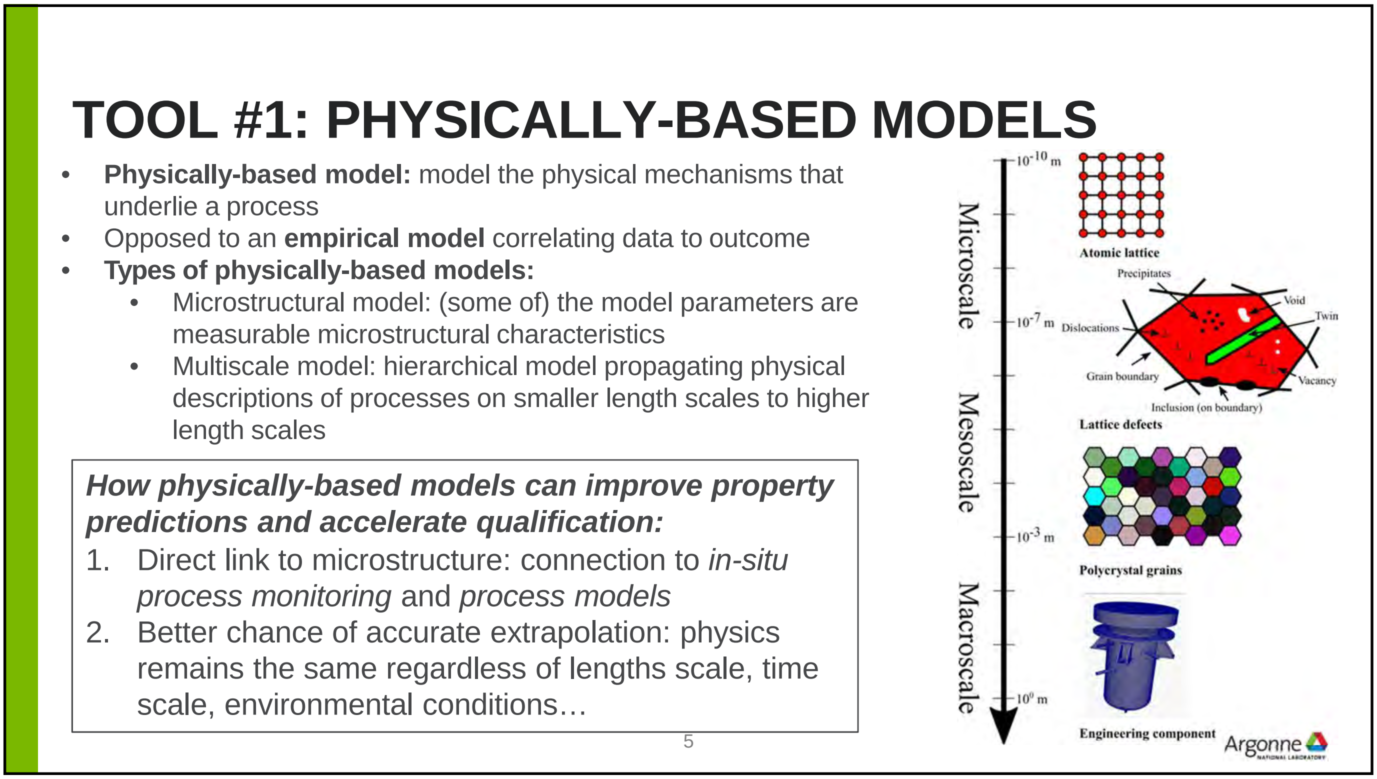
# WHAT ARE THE CHALLENGES QUALIFYING MATERIALS FOR HIGH TEMPERATURE SERVICE?

- At high temperatures long-term, time-dependent material properties control design:
  - Creep strength and ductility
  - Creep-fatigue life
  - Thermal aging characteristics
  - Environmental degradation
- Short-term tests might tell you very little about important long-term properties
- Statistical variation in mechanical properties tends to be high, even for well-controlled traditional wrought material processes
- Weld resilience can be challenging
- Very little long-term mechanical test data on AM material for properties relevant to high temperature design

Seam pipe failure at coal power station (Viswanathan and Stringer, 2000)

Creep cavitation (INL)

HRSG tube failure (EPRI, 2005)

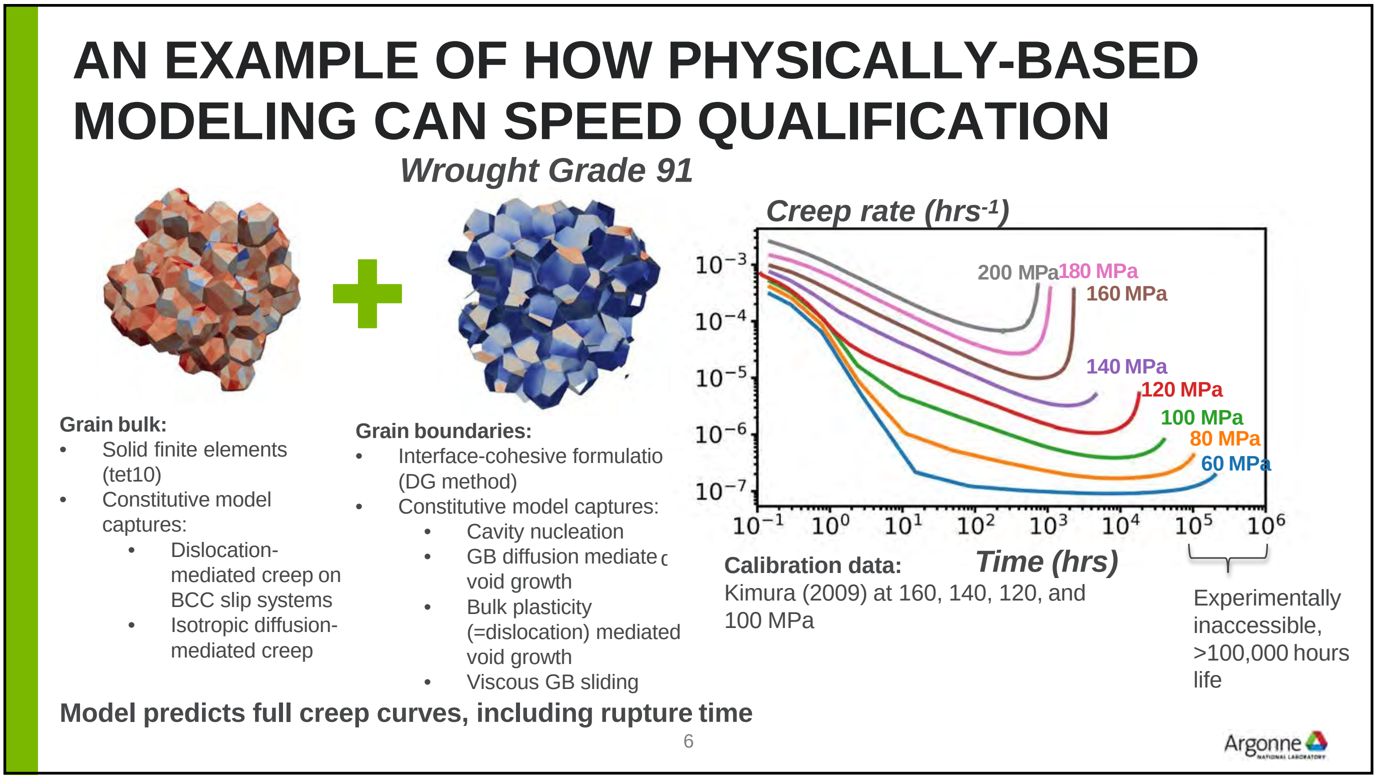


# TOOL #1: PHYSICALLY-BASED MODELS

- **Physically-based model:** model the physical mechanisms that underlie a process
- Opposed to an **empirical model** correlating data to outcome
- **Types of physically-based models:**
    - Microstructural model: (some of) the model parameters are measurable microstructural characteristics
    - Multiscale model: hierarchical model propagating physical descriptions of processes on smaller length scales to higher length scales

***How physically-based models can improve property predictions and accelerate qualification:***

1. Direct link to microstructure: connection to *in-situ process monitoring* and *process models*
2. Better chance of accurate extrapolation: physics remains the same regardless of lengths scale, time scale, environmental conditions…



# AN EXAMPLE OF HOW PHYSICALLY-BASED MODELING CAN SPEED QUALIFICATION

***Wrought Grade 91***

**Grain bulk:**
- Solid finite elements (tet10)
- Constitutive model captures:
    - Dislocation-mediated creep on BCC slip systems
    - Isotropic diffusion-mediated creep

**Grain boundaries:**
- Interface-cohesive formulatio (DG method)
- Constitutive model captures:
    - Cavity nucleation
    - GB diffusion mediate void growth
    - Bulk plasticity (=dislocation) mediated void growth
    - Viscous GB sliding

**Calibration data:** Kimura (2009) at 160, 140, 120, and 100 MPa

Experimentally inaccessible, >100,000 hours life

**Model predicts full creep curves, including rupture time**

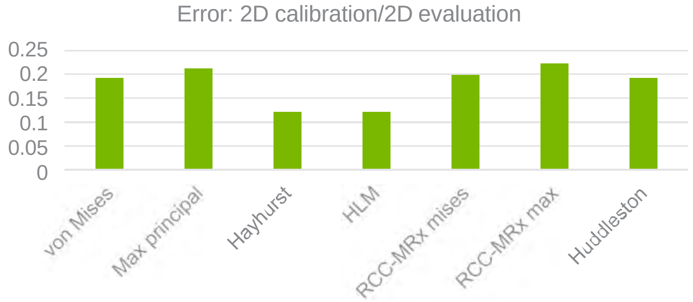
3

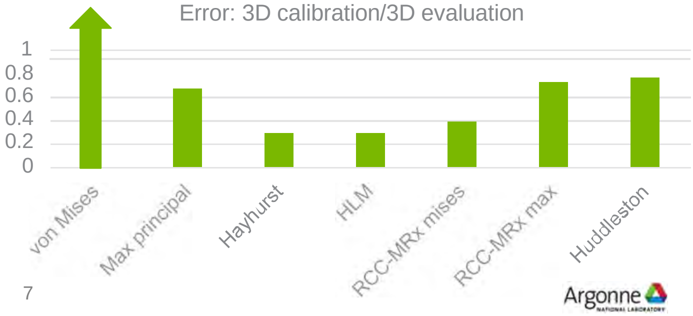
# EVALUATING CREEP UNDER TRIAXIAL LOAD

- We typically test creep specimens with uniaxial stresses
  - Occasionally we have biaxial test data (pressure tubes)
  - Notched tests are difficult to interpret
- **Key question: how to extrapolate this data to realistic 3D states of stress?**
- Usual engineering approach: find an effective stress measure that converts 3D → 1D so that the 1D rupture correlation predicts 3D rupture
- But we don't have 3D creep test data or long-term 2D data
- We can use the physical model to predict triaxial rupture and assess different engineering models (or develop new ones!)

**Key outcomes of study:**

- All the effective stress measures are about equally accurate when calibrated and compared to biaxial rupture data
- ***Some are much better than others when calibrated and evaluated against 3D data***





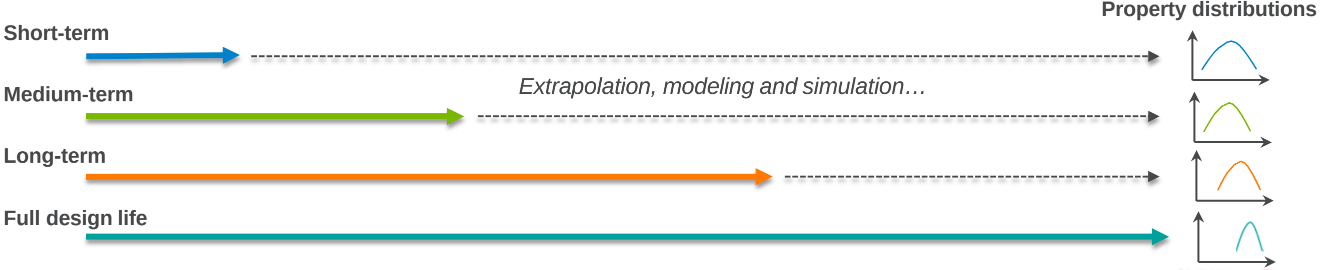
# TOOL #2 STAGGERED QUALIFICATION APPROACHES

**How would this work?**

1. Initiate long-term property tests on many candidate materials (you can terminate the tests for the materials that don't pan out)
2. Use the short-term test results, the best available processing information (in-situ process monitoring, advanced characterization), and material simulations to predict long-term properties *with uncertainty*
3. As tests from #1 conclude, updated models in #2 to provide new best estimates and uncertainties

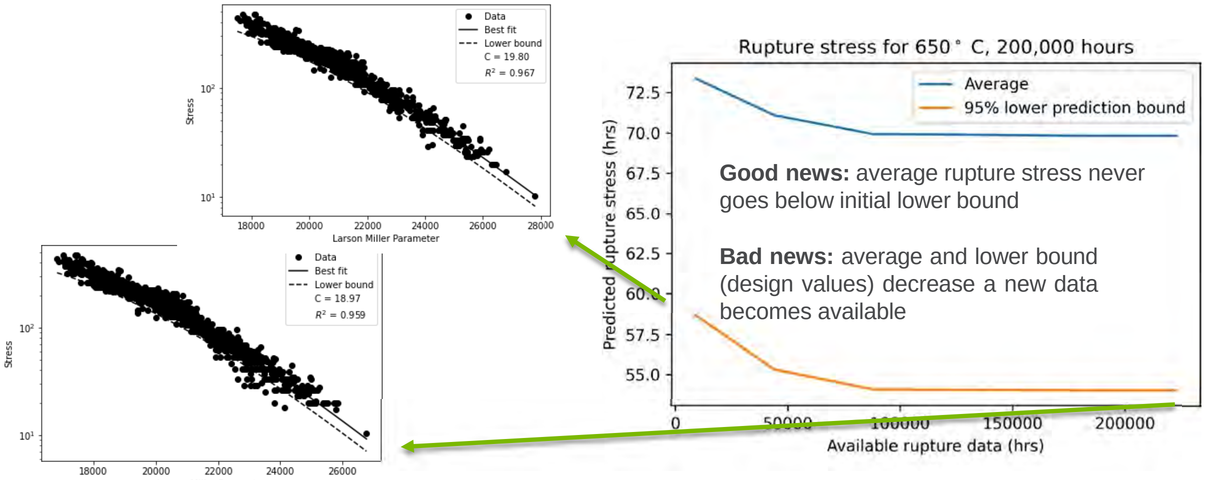
**Key questions**

1. Can vendors/designers work like this? You won't have "certain" design data in the beginning and the mean of the property distribution might change.
2. Can regulators work like this? You'll be asked to assess designs with uncertain design data and/or accept designs configured for alterations if long-term testing results change the design assumptions.
3. Can codes and standards bodies work like this? It may require a move towards probabilistic design.



# ARE STAGGERED QUALIFICATION APPROACHES FEASIBLE?

*"What if" analysis pretending that 316H is a new material. Targets 200,000 hours life because we have actual rupture data for this time*



**Good news:** average rupture stress never goes below initial lower bound

**Bad news:** average and lower bound (design values) decrease a new data becomes available

***We need a better way to quantify uncertainty***

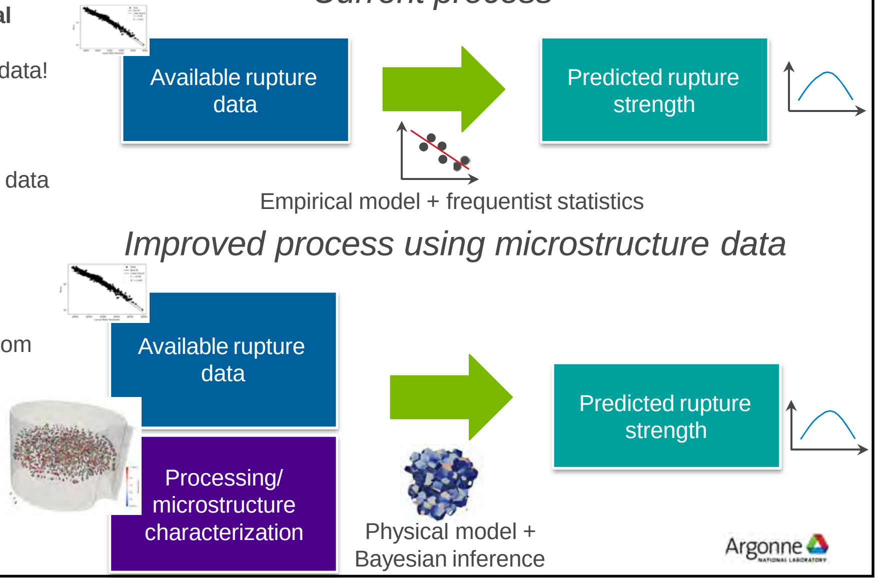
# TOOL #3: UNCERTAINTY QUANTIFICATION THROUGH BAYESIAN INFERENCE

**Challenges applying staggered, probabilistic approach with conventional modeling:**

- Mechanisms not present in short-term data!
- Little opportunity to take advantage of improved processing (data stays in database…)
- Doesn't take advantage of all available data to narrow/improve statistical estimates
  - Processing data
  - Microstructural characterization

Physical models have a better chance of accurately capturing long-term properties from short term data

Bayesian inference provides a framework feeding in *incomplete* processing and microstructure information to yield better predictions



*Current process*

Available rupture data

Predicted rupture strength

Empirical model + frequentist statistics

*Improved process using microstructure data*

Available rupture data

Processing/ microstructure characterization

Predicted rupture strength

Physical model + Bayesian inference

# A HIGH LEVEL DESCRIPTION OF BAYESIAN INFERENCE

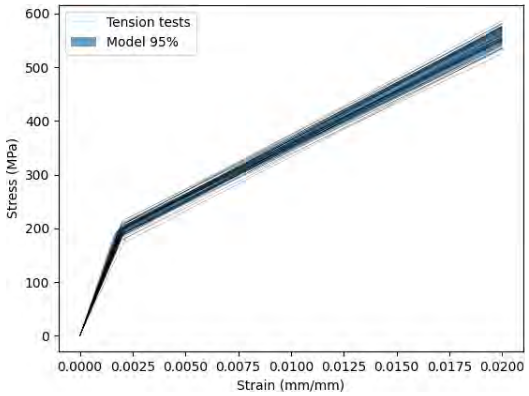
**Statistical inference**: deduce properties of a underlying probability distribution, often one that is difficult to sample directly

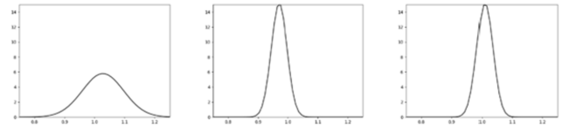
**Example:**

- Traditional approach: fit a deterministic model to the average response of several tension tests
- Inference: infer the distribution of the model parameters that explains the variation in the test data

**Importance:**

- Quantify uncertainty in model predictions – not just a predicted material property + a confidence interval, but an understanding of what causes the variation in the property
- A method for understanding microstructural variation from limited characterization data, but lots of high throughput property measurements





Young’s modulus Yield stress Hardening modulus

# COMBINING INFERENCE WITH PHYSICALLY-BASED MODELS

*Linking microstructural statistics to the corresponding material property statistics*

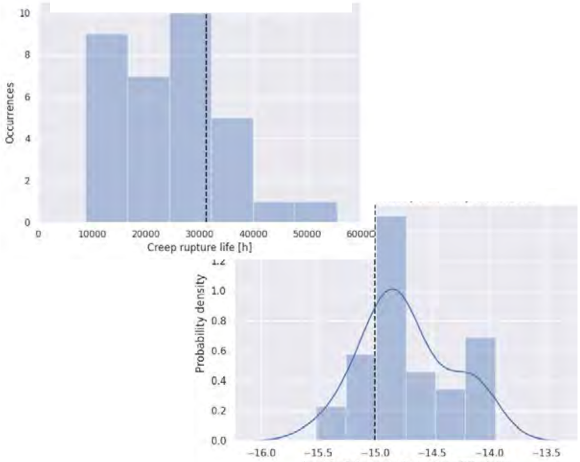
**Why?**

- If we can characterize the microstructure coming out of the process we can translate that directly to (long-term?) property predictions
- We can tune the process (via experimentation or process modeling) to produce better materials

**Example**

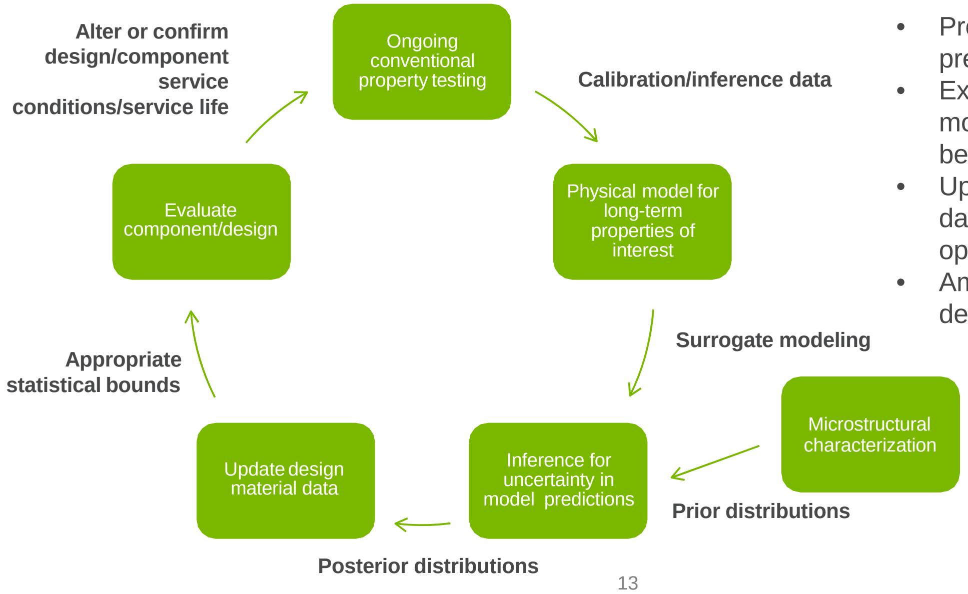
- Back to wrought Grade 91
- Grain boundary diffusivity is a key property controlling rupture life
    - What distribution of GB diffusivity explains distribution of Grade 91 rupture life?
    - How could we control GB diffusivity (via GB energy) to improve the rupture life of the material?

**Experimental rupture distribution**



**Inferred GB diffusivity distribution**

# *ONE* ROUTE TOWARDS RAPID QUALIFICATION



- Provides initial, uncertain predictions for initial design
- Extrapolates with physical model, hopefully providing better long-term design data
- Updates design material data to ensure ongoing safe operation
- Amenable to probabilistic design methods

Argonne

# SUMMARY

- **Modeling and simulation can play a role in accelerating the qualification of new AMT materials**
- **Key gaps:**
  - Building regular, owner, and codes/standards confidence in new approaches
  - Benchmark studies to test out rapid qualification approaches
    - Low hanging fruit: try with well-characterized wrought material
    - Round robin benchmarks for nuclear materials + AMTs
  - Improved data-driven methods for material science problems and ways to combine data-driven and physically-based modeling
    - Comparatively sparse datasets
    - Physical constraints on model predictions
  - Better ways to bridge length scales and time scales in multiscale modeling

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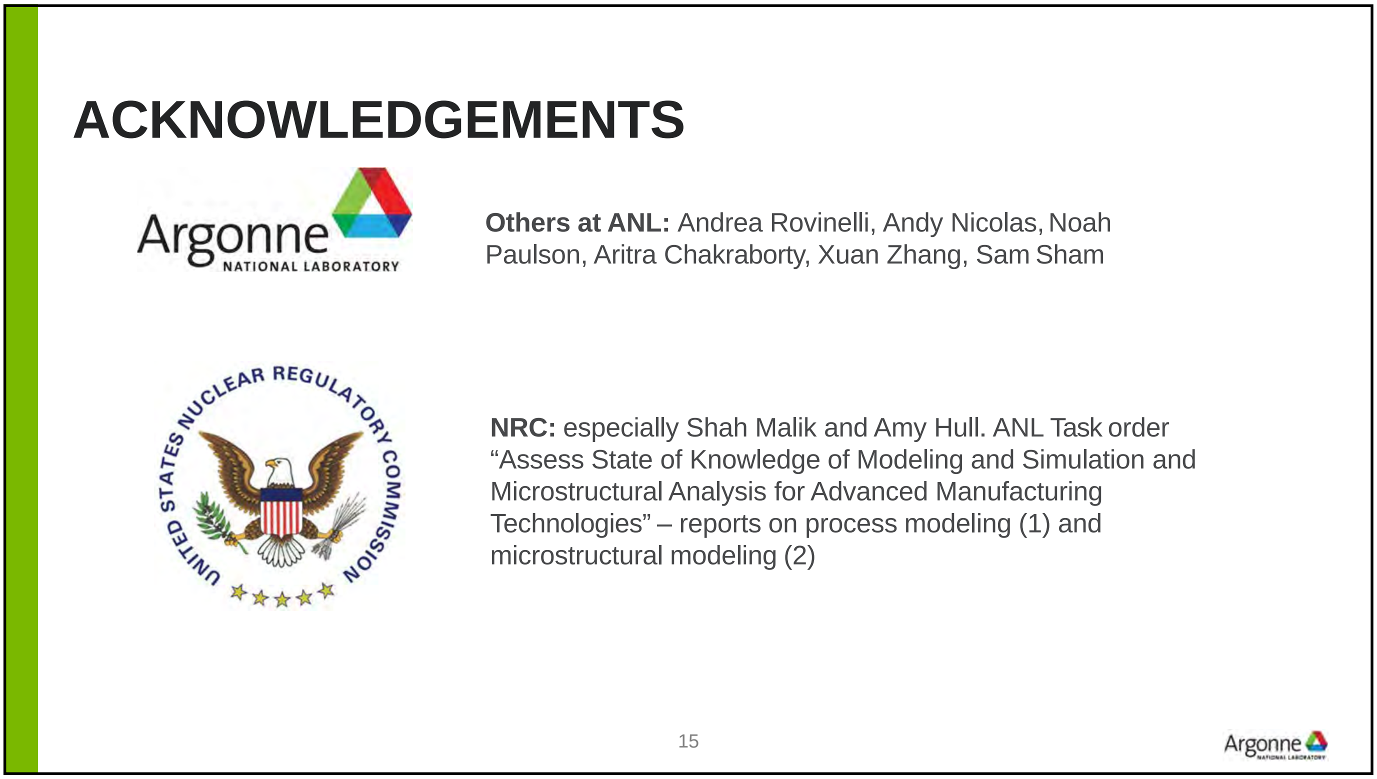


# ACKNOWLEDGEMENTS

**Others at ANL:** Andrea Rovinelli, Andy Nicolas, Noah Paulson, Aritra Chakraborty, Xuan Zhang, Sam Sham

**NRC:** especially Shah Malik and Amy Hull. ANL Task order "Assess State of Knowledge of Modeling and Simulation and Microstructural Analysis for Advanced Manufacturing Technologies" – reports on process modeling (1) and microstructural modeling (2)

# Cold Spray Development for Coatings

Kumar Sridharan (University of Wisconsin, Madison)
George Young (Kairos Power, Alameda, CA)

NRC Workshop on Advanced Manufacturing
December 7th to 10th, 2020

## Other Members of the Team

### University of Wisconsin

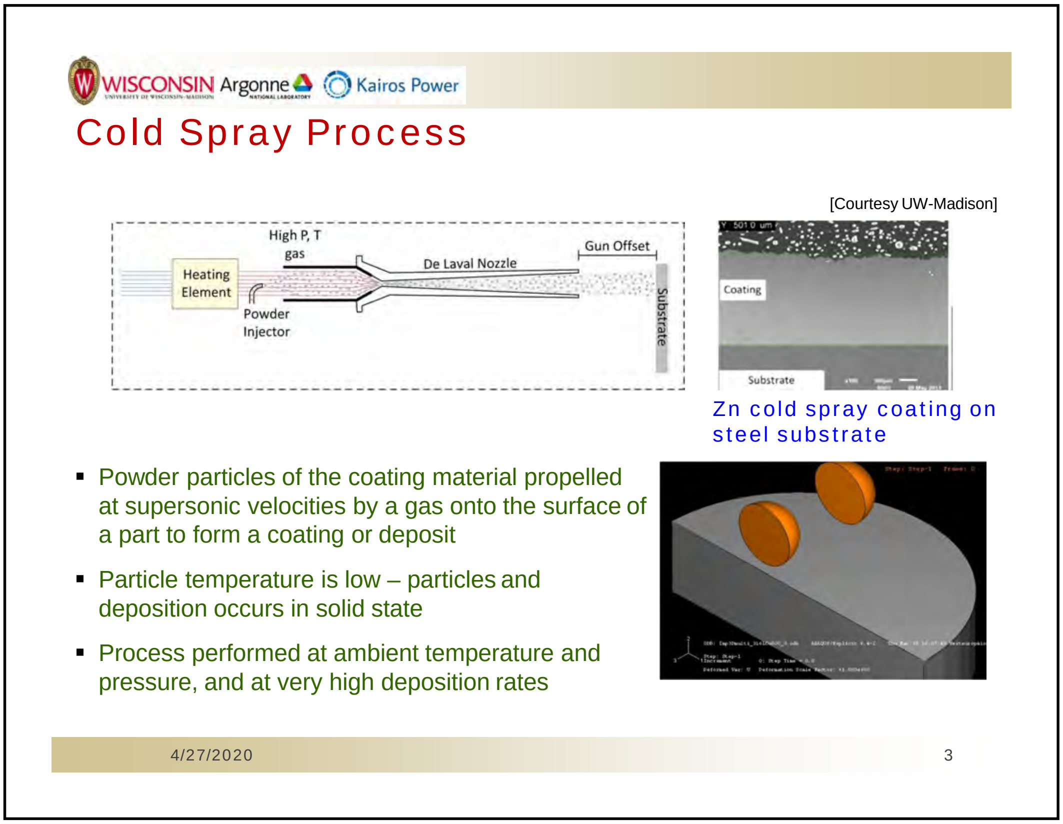
Hwasung (Sung) Yeom
Kyle Quillin
Evan Willing
Mia Lenling
Tyler Dabney
Nicholas Pocquette

### Kairos Power

Steven Huang
Micah Hackett

### Argonne National Laboratory

Sam Sham
Mark Messner

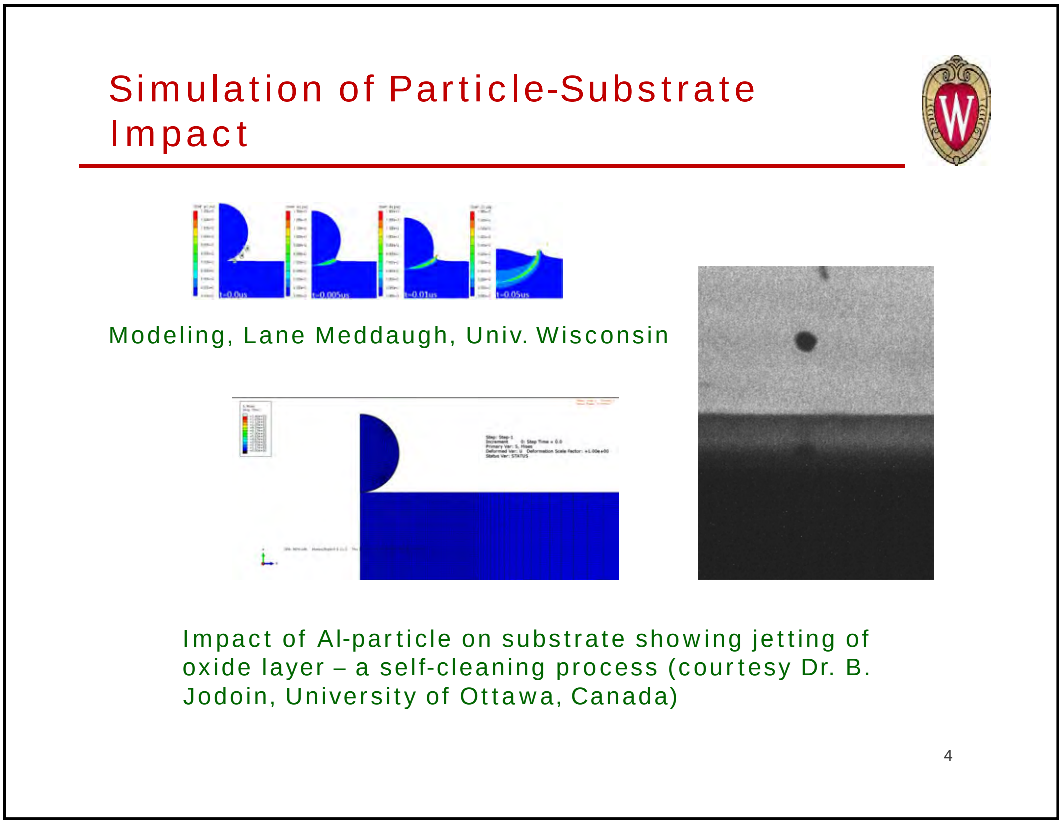


## Cold Spray Process

[Courtesy UW-Madison]

Zn cold spray coating on steel substrate

- Powder particles of the coating material propelled at supersonic velocities by a gas onto the surface of a part to form a coating or deposit
- Particle temperature is low – particles and deposition occurs in solid state
- Process performed at ambient temperature and pressure, and at very high deposition rates

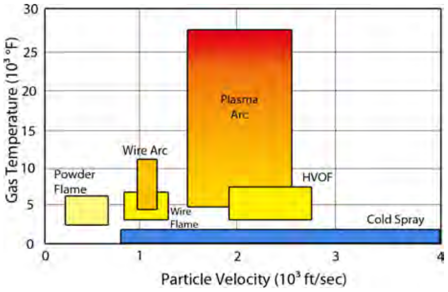


## Simulation of Particle-Substrate Impact

Modeling, Lane Meddaugh, Univ. Wisconsin

Impact of Al-particle on substrate showing jetting of oxide layer – a self-cleaning process (courtesy Dr. B. Jodoin, University of Ottawa, Canada)

# Low Powder Particle Temperature

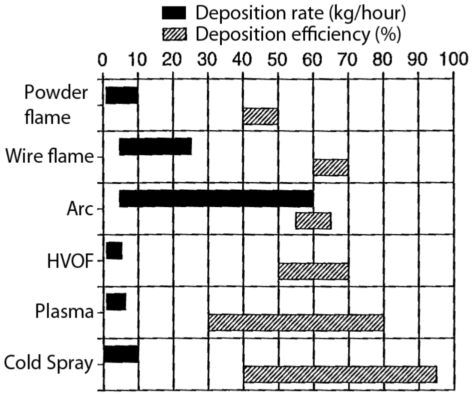


Low temperature, high particle velocity process

Low particle temperature confers several advantages:

- Little or no oxide inclusions in the coating/deposited material
- Ideally suited for spraying metallic materials (e.g., Al, Cu, Ni, alloys, reactive (Ti) and refractory metals (Ta), cermets, e,g, Al/$Al_2O_3$, WC-Co)
- Recently ceramics as well, $TiO_2$ (Japan), Ti-Al-C (UW-Madison)

# High Deposition Efficiency



High deposition efficiencies allow for:

- Manufacture of near-net shape products
- Additive manufacturing, 3D-printing
- Repair and dimensional restoration

# Cold Spray Laboratory at University of Wisconsin, Madison (est. 2012)

Robot for pre-programmed movement of spray gun

Sample stage and dust collector (below that)

Sound-proof spray booth

- 4000-34 KINETIK System, from ASB Industries/CGT-GmBH
- Spray booth from Noise Barriers
- Robot controlled (Nachi system, from Antennen)

Nitrogen/helium gas cylinders

Robot controls (left) and spray gun control (right)

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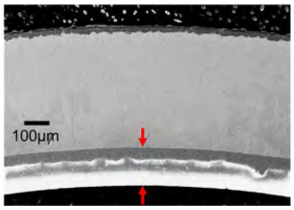
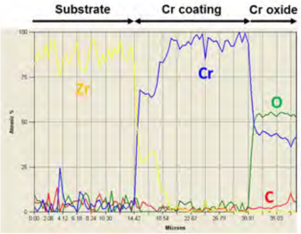
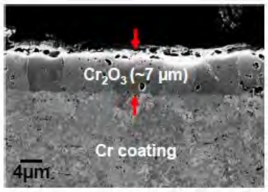
# Applications of Cold Spray for Nuclear Energy Systems – ATF (with Westinghouse)

- 1300°C exposure:

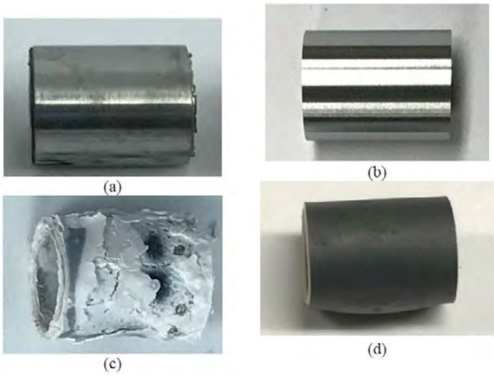






- **Very thin oxide layer (~ 7μm)**
- **Very thin interdiffusion layer (2~3 μm)**
- **No interface spallation observed**
- **Zr-alloy side almost 200μm**

# Cold Spray Cr Exposure at 1300°C (with Westinghouse)



Optimized Zirlo (before test)

Optimized Zirlo coated with Cr (before test)

Optimized Zirlo (after test)

Optimized Zirlo coated with Cr (after test)

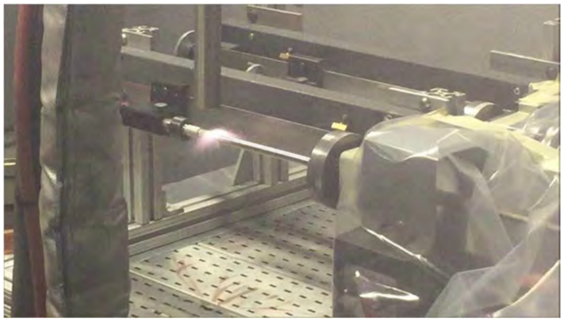
**Cr coating provides good protection against oxidation**

---

# Applications of Cold Spray for Nuclear Energy Systems – ATF (with Westinghouse)

- Cr-Coating developed at UW-Madison (< 3 yrs)
- Part of WECs EnCore™ ATF program
- Joint UW-WEC patent, 2020
- Technology transfer for full-length (12') coated cladding (called lead test rods, LTR)
- In-reactor testing of LTR underway at a Utility Reactor, started in 2019

# Cold Spray Coating of Zr-alloy Cladding Tubes



*"High Temperature Oxidation and Microstructural Evolution of Cold Spray Chromium Coatings on Zircaloy-4 in Steam Environments", H. Yeom, B. Maier, G. Johnson, T. Dabney, M. Lenling, and K. Sridharan,* ***Journal of Nuclear Materials****, 526, 2019, 151737.*

*"Development of Cold Spray Chromium Coatings for Improved Accident Tolerant Zirconium-alloy Cladding", B. Maier, H. Yeom, G. Johnson, T. Dabney, J. Walters, P. Xu, J. Romero, H. Shah, and K. Sridharan,* ***Journal of Nuclear Materials****, 519, 2019, p. 247.*

*"Improving Deposition Efficiency in Cold Spraying Chromium Coatings by Powder Annealing", H. Yeom, T. Dabney, G. Johnson, B. Maier, M. Lenling, and K. Sridharan,* ***The International Journal of Advanced Manufacturing Technology****, 100(5), 2019, p. 1373.*

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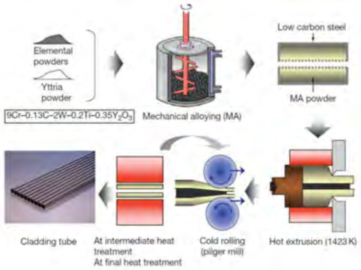
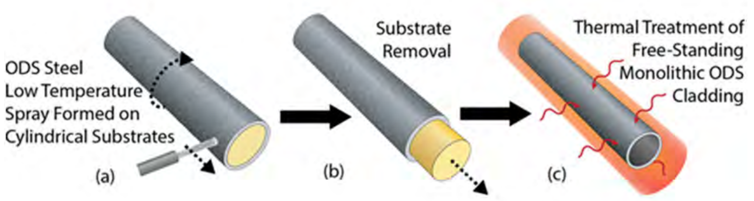
# Conventional Manufacturing of ODS Steel Tubes – Slow and Expensive Process

- Milled powders -> canned and degassed at 400 °C -> multiple hot/ warm extrusion steps (8 -10 steps) at temperatures > 1000 °C and annealing.
- Low strain rate extrusion
- May lead to grain anisotropy, and anisotropy in mechanical properties
- Melting processes cannot be used as they lead to upward stratification of oxide nanoparticles (heterogeneous dispersion)



Conventional fabrication of ODS steel tubes requires mechanical alloying and multiple extrusion steps [G. Odette et al, Ann. Rev. Mater Res., 2008]

## Particle Size Distributions for Ni and W Powders

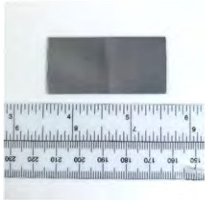


**Potential Benefits:**

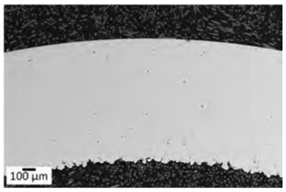
- **Eliminates multiple extrusion steps**
- **Eliminate ball milling step**
- **Faster and cheaper manufacturing process**

## Free-Standing ODS Cladding Tube Manufactured Using Gas Atomized Powder using Cold Spray

ODS Steel Flat



Cross-section of ODS cladding tube

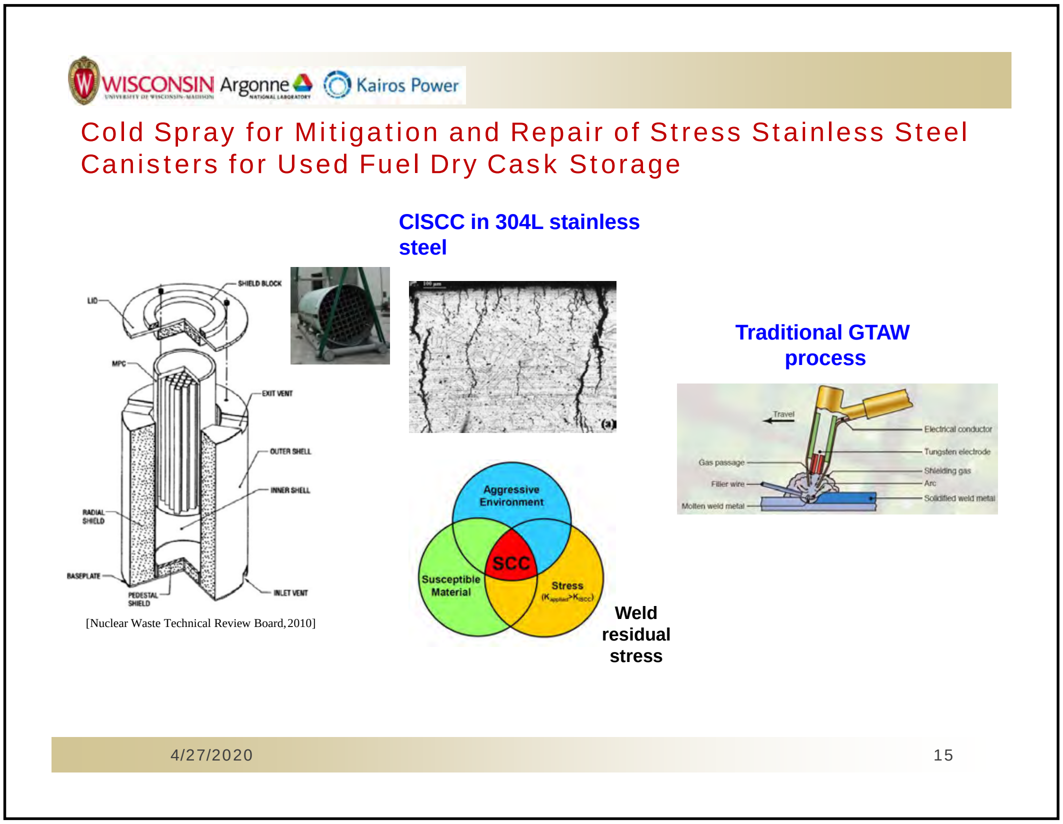


Free-standing ODS cladding tube

Length: 204 mm (8”) cladding tube
O.D.: 11.5 mm
Wall Thickness: ~ 1 mm

*“Improving Deposition Efficiency in Cold Spraying Chromium Coatings by Powder Annealing”, H. Yeom, T. Dabney, G. Johnson, B. Maier, M. Lenling, and K. Sridharan,* ***The International Journal of Advanced Manufacturing Technology****, 100(5), 2019, p. 1373.*

*“A Novel Approach for Manufacturing Oxide Dispersion Strengthened (ODS) Steel Cladding Tubes using Cold Spray Technology”, B. Maier, M.Lenling, H. Yeom, G. Johnson, S. Maloy, and Kumar Sridharan,* ***Nuclear Engineering and Technology****, 51, 4, 2019, p. 1069.*



## Cold Spray for Mitigation and Repair of Stress Stainless Steel Canisters for Used Fuel Dry Cask Storage

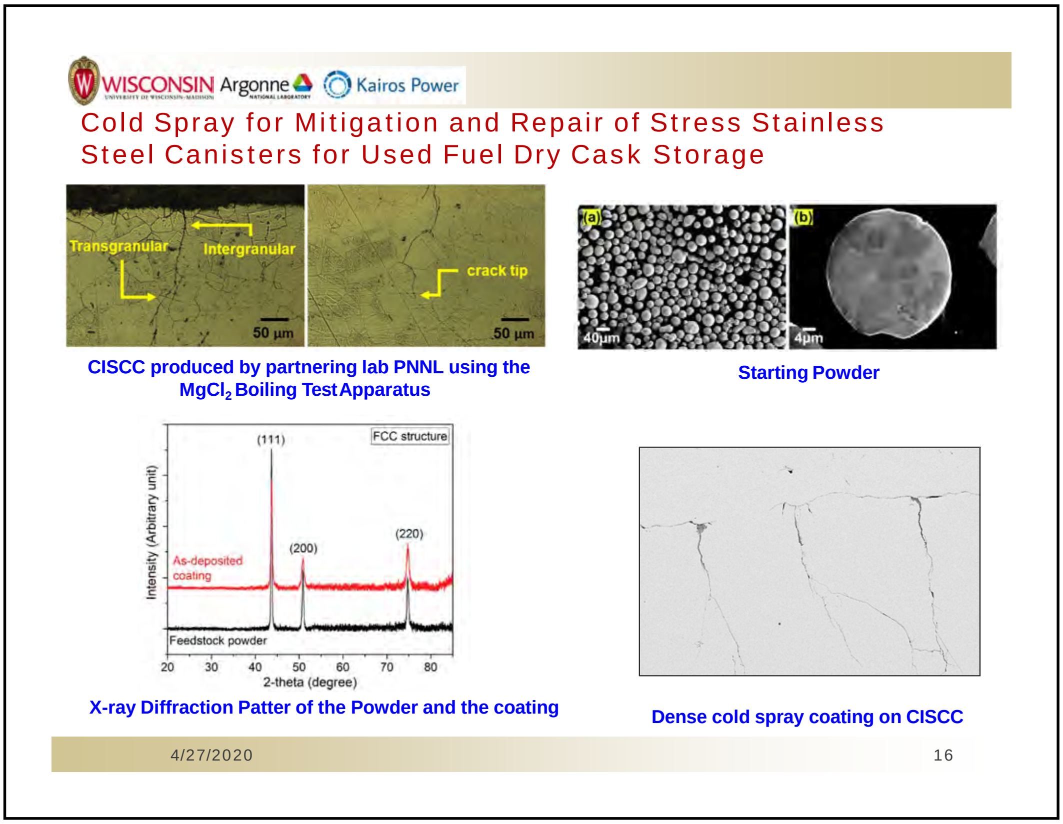
[Nuclear Waste Technical Review Board,2010]

**CISCC in 304L stainless steel**

**Weld residual stress**

**Traditional GTAW process**

15



## Cold Spray for Mitigation and Repair of Stress Stainless Steel Canisters for Used Fuel Dry Cask Storage

**CISCC produced by partnering lab PNNL using the $MgCl_2$ Boiling Test Apparatus**

**Starting Powder**

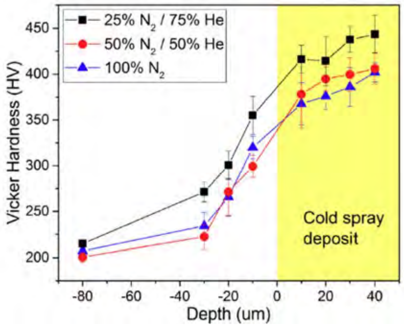
**X-ray Diffraction Patter of the Powder and the coating**

**Dense cold spray coating on CISCC**

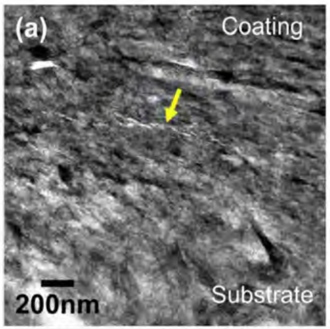
16

## Cold Spray for Mitigation and Repair of Stress Stainless Steel Canisters for Used Fuel Dry Cask Storage

| Propellant gas condition | Surface residual stress (MPa) | | |
|---|---|---|---|
| | Parallel to spray direction | 45° direction | Perpendicular to spray direction |
| 700 °C $N_2$ gas | −207 (−30.0 psi) | −216 (−31.3 psi) | −252 (−36.5 psi) |
| 550 °C $N_2$/He (50/50) | −246 (−35.7 psi) | −314 (−45.6 psi) | −350 (−50.8 psi) |
| 550 °C $N_2$/He (25/75) | −350 (−50.8 psi) | −396 (−57.5 psi) | −452 (−65.5 psi) |



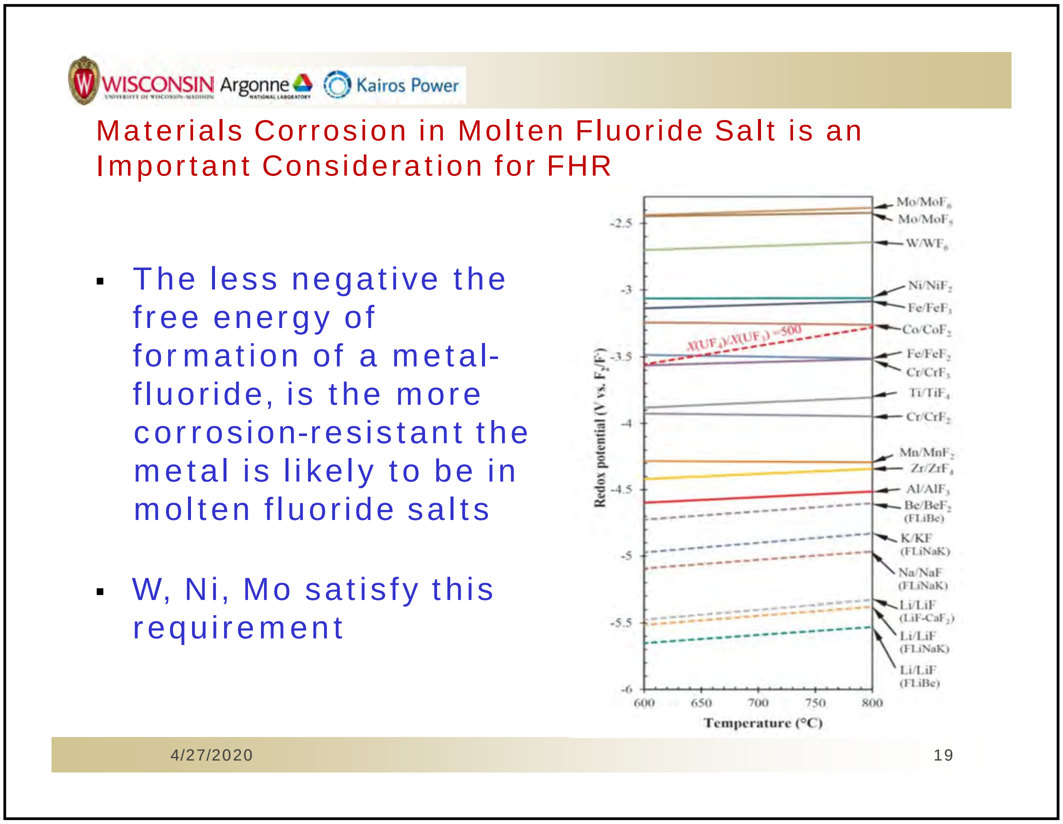
**Microhardness the cold spray coating and substrate**



**TEM image of cold spray coating and substrate**

*"Cold Spray Deposition of 304L Stainless Steel to Mitigate Chloride-Induced Stress Corrosion Cracking in Canisters for Used Nuclear Fuel Storage", H. Yeom, T. Dabney, N. Pocquette, K. Ross, F. E. Pfefferkorn, and K. Sridharan, **Journal of Nuclear Materials**, vol. 538, 2020,152254.*

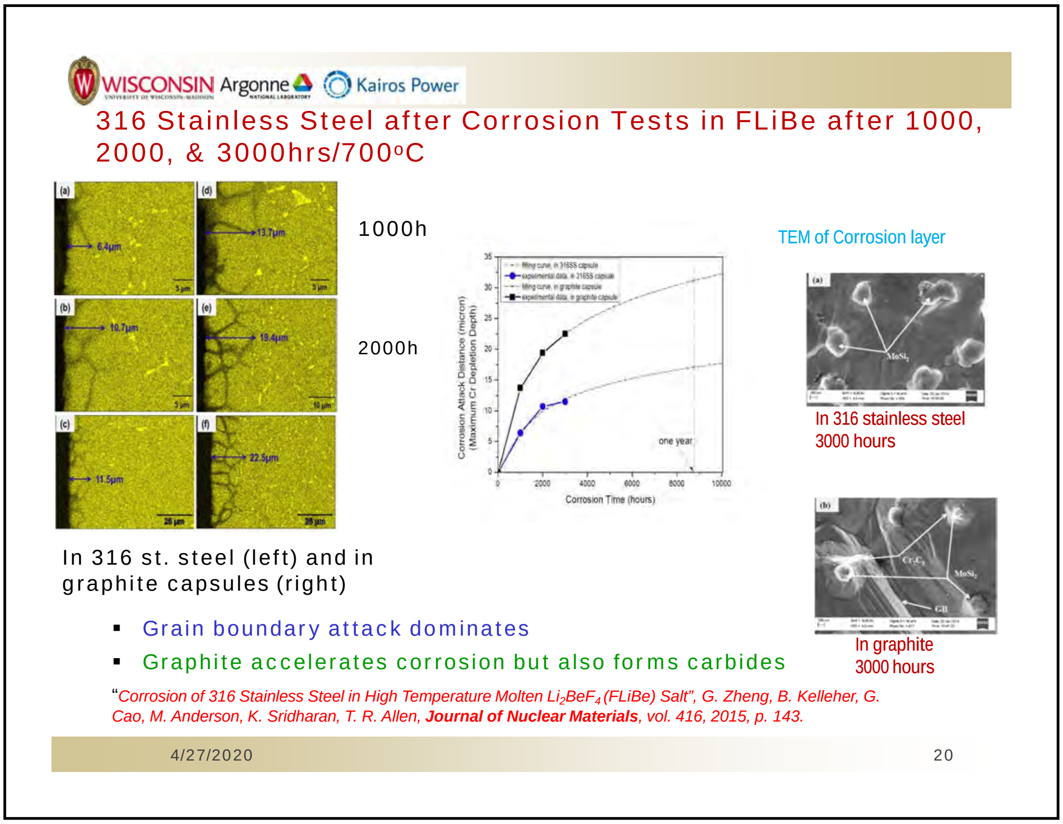
## Corrosion and Tritium Diffusion Barrier Coatings for Fluoride Salt-Cooled High Temperature Reactor (FHR) – Preliminary Studies



WISCONSIN Argonne Kairos Power

## Materials Corrosion in Molten Fluoride Salt is an Important Consideration for FHR

- The less negative the free energy of formation of a metal-fluoride, is the more corrosion-resistant the metal is likely to be in molten fluoride salts
- W, Ni, Mo satisfy this requirement



WISCONSIN Argonne Kairos Power

## 316 Stainless Steel after Corrosion Tests in FLiBe after 1000, 2000, & 3000hrs/700°C

In 316 st. steel (left) and in graphite capsules (right)

TEM of Corrosion layer

In 316 stainless steel 3000 hours

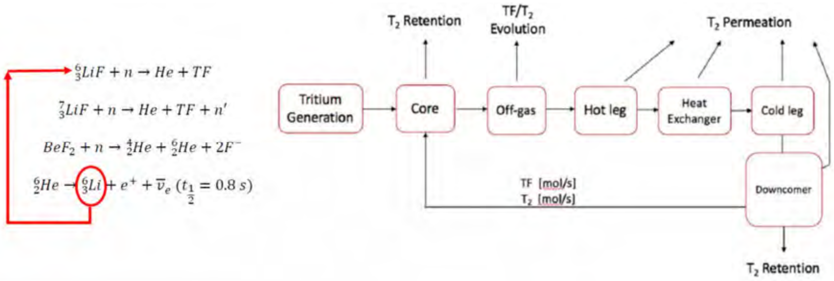
In graphite 3000 hours

- Grain boundary attack dominates
- Graphite accelerates corrosion but also forms carbides

"*Corrosion of 316 Stainless Steel in High Temperature Molten $Li_2BeF_4$ (FLiBe) Salt*", *G. Zheng, B. Kelleher, G. Cao, M. Anderson, K. Sridharan, T. R. Allen,* ***Journal of Nuclear Materials****, vol. 416, 2015, p. 143.*

## Tritium Diffusion Through Materials

- Tritium will be generated due to neutron reaction with FliBe (coolant for FHR)
- KP-FHR's Tritium Management Strategy is to assure that all environmental releases are monitored and comply with licensed pathways and limits
- The formation of tritium fluoride will be mitigated through reactions with beryllium metal to avoid corrosion
- Kairos Power is developing several methods by which tritium transport will be controlled, e.g. low permeability cladding



$$^{6}_{3}LiF + n \rightarrow He + TF$$

$$^{7}_{3}LiF + n \rightarrow He + TF + n'$$

$$BeF_2 + n \rightarrow {}^{4}_{2}He + {}^{6}_{2}He + 2F^-$$

$$^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^+ + \overline{\nu}_e \ (t_{\frac{1}{2}} = 0.8\ s)$$

## Tritium Diffusion Through Materials

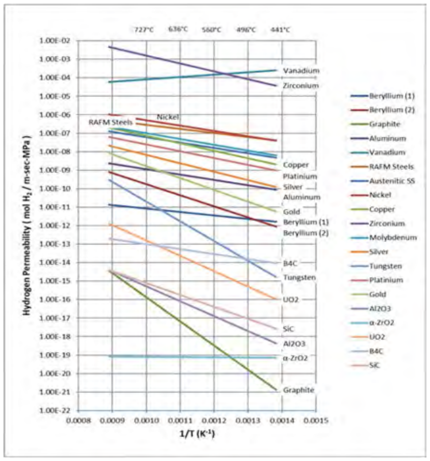


Table 1. Recommended diffusivity and solubility relationships for protium in various metals and classes of alloys in the absence of trapping.

| Alloy | Diffusivity $D = D_o \exp(-E_D/RT)$ $D_o$ $\left(\frac{m^2}{s}\right)$ | $E_D$ $\left(\frac{kJ}{mol}\right)$ | Solubility, $\Phi/D$ $K = K_o \exp(-\Delta H_s/RT)$ $K_o$ $\left(\frac{mol\ H_2}{m^3 \cdot \sqrt{MPa}}\right)$ | $\Delta H_s$ $\left(\frac{kJ}{mol}\right)$ | Ref. |
|---|---|---|---|---|---|
| Beryllium | $3 \times 10^{-11}$ | 18.3 | 18.9 *<br>$5.9 \times 10^{6}$ * | 16.8 *<br>96.6 * | [73]<br>[43]<br>[78] |
| Graphite | $9 \times 10^{-5}$ | 270 | 19 | -19.2 | [43] |
| Aluminum | $2 \times 10^{-8}$ | 16 | 46 | 39.7 | [220]<br>[150] |
| Vanadium | $3 \times 10^{-8}$ † | 4.3 † | 138 | -29 | [127]<br>[197] |
| RAFM steels ‡ | $1 \times 10^{-7}$ | 13.2 | 436 | 28.6 | |
| Austenitic stainless steel | $2 \times 10^{-7}$ | 49.3 | 266 | 6.9 | [95] |
| Nickel | $7 \times 10^{-7}$ | 39.5 | 564 | 15.8 | [153] |
| Copper | $1 \times 10^{-6}$ | 38.5 | 792 | 38.9 | [154] |
| Zirconium | $8 \times 10^{-7}$ | 45.3 | $3.4 \times 10^{7}$ | 35.8 | [143]<br>[221] |
| Molybdenum | $4 \times 10^{-8}$ | 22.3 | 3300 | 37.4 | [198] |
| Silver | $9 \times 10^{-7}$ | 30.1 | 258 | 56.7 | [199]<br>[200] |
| Tungsten | $6 \times 10^{-4}$ | 103.1 | 1490 | 100.8 | [53] |
| Platinum | $6 \times 10^{-7}$ | 24.7 | 207 | 46.0 | [202] |
| Gold | $5.6 \times 10^{-8}$ | 23.6 | 77900 § | 99.4 § | [205] |

* per the text, the solubility of hydrogen in beryllium is very low and there is not good agreement between the few studies of the material

† data for isotopes other than protium does not scale as the square root of mass

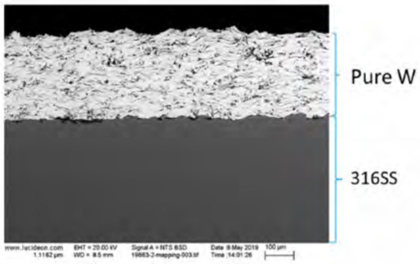
‡ values are averaged over the data presented in Figure 12 and Figure 13

§ estimated using the permeability from Ref. [203] and the quoted diffusivity.

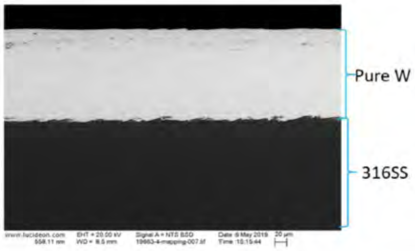
*From [Causey]*

# Tritium Diffusion Through Materials

- W coatings are desirable for both corrosion resistance and low tritium permeability
- Currently evaluating several coatings (carbide, oxide, metallic) and methods (thermal spray, cold spray, explosion bonding, etc.)
- Note Kairos / ANL (Messner & Sham) GAIN to develop ASME rules for corrosion resistant cladding



Thermal Sprayed W



Explosion Bonded W

*Work performed by Kairos Power*

# Investigating Ni-W Composite for a Combination of Corrosion and Tritium Diffusion

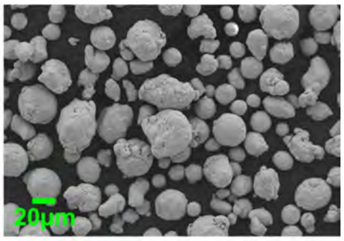
| Powder Type | Sample ID | Substrate Dimension (Quantity) |
|---|---|---|
| Pure Ni | 20190625n01/n02 | 1.25” × 6” (2) |
| Mixture of Ni and W (~16 wt.% Ni) | 20190711n01/n02 | 1.25” × 6” (2) |
| Mixture of Ni and W (~10 wt.% Ni) | 20190719n01/n02 | 1.25” × 6” (2) |
| Mixture of Ni and W (~5 wt.% Ni) | 20190725n01/n02 | 1.25” × 6” (2) |
| Ni-coated W | 20190731n01/n02 | 1.25” × 6” (2) |
| Mixture of Ni and W (~2 wt.% Ni) | 20191029n01/n02 | 1.25” × 6” (2) |
| Mixture of Ni and W (~1 wt.% Ni) | 20191031n01/n02 | 1.25” × 6” (2) |

- Two 1.25” × 6” samples of each coating type produced for testing at Kairos
- One 1.25” × 2” sample produced for cross-section characterization at UW
- Atlantic Equipment Engineers provided the gas atomized 99.9% Ni-powder
- Tekna provided the 99.7% W-powder
- Global Tungsten and Powder provided 6% Ni-coated powder
- SS316H substrate was provided by McMaster-Carr.

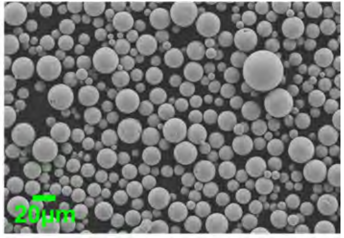
# Particle Size Distributions for Ni and W Powders

- Both powders sieved to -25μm before spraying
- Average Ni particle size ~20μm
- Average W particle size ~12μm
- Ni-coated W powder sizes range from 5-32μm

As-received Ni powder



As-received W powder



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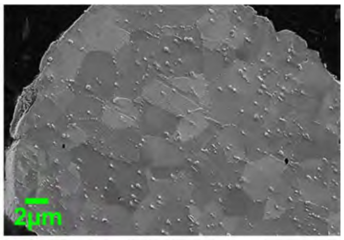
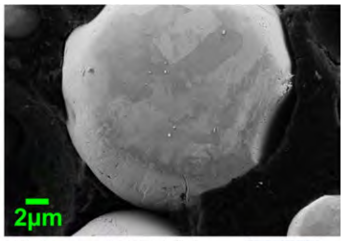
# Microstructure of Ni and W Powder

- Both powders showed equiaxed and micron-scale grained microstructure
- Fine Ni-oxide particulates were detected in Ni matrix as an impurity – generally shown in gas atomized powders

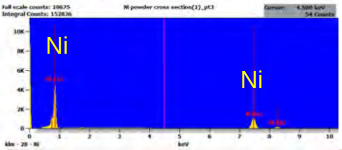
Ni powder (cross-section)

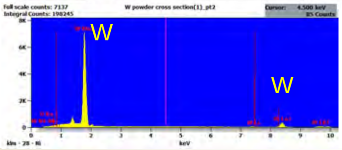


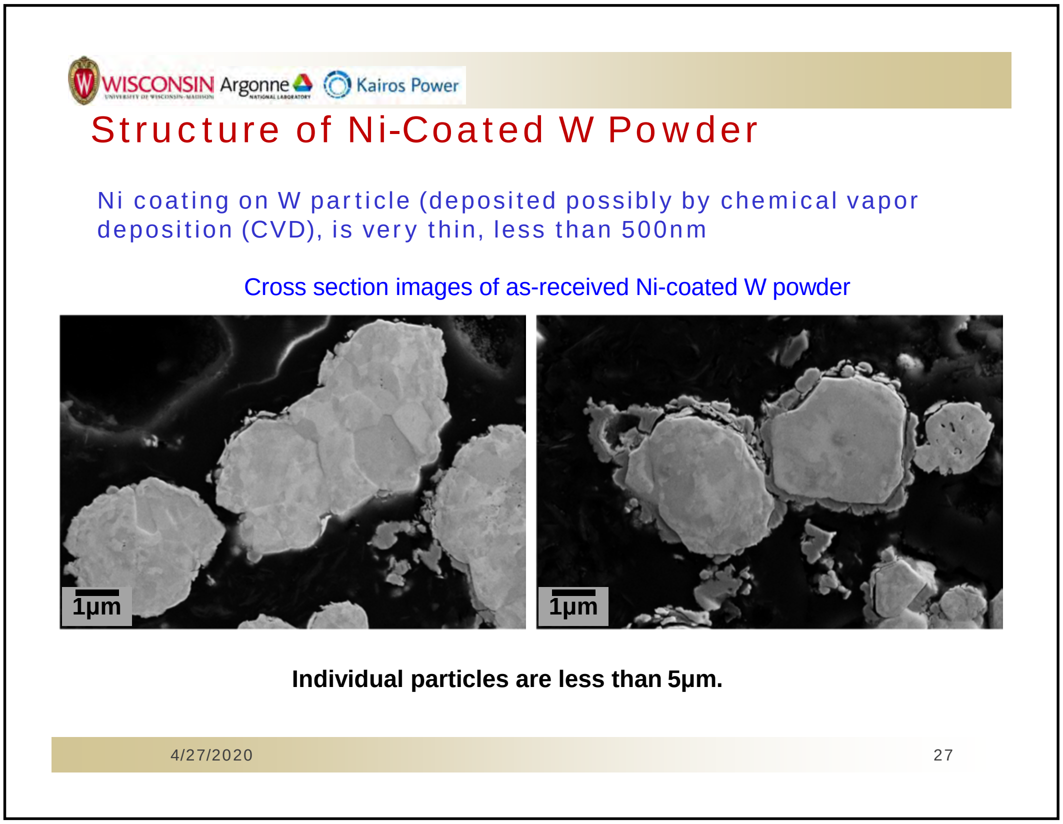
W powder (cross-section)



EDS analysis







## Structure of Ni-Coated W Powder

Ni coating on W particle (deposited possibly by chemical vapor deposition (CVD), is very thin, less than 500nm

Cross section images of as-received Ni-coated W powder

**Individual particles are less than 5µm.**

4/27/2020 27

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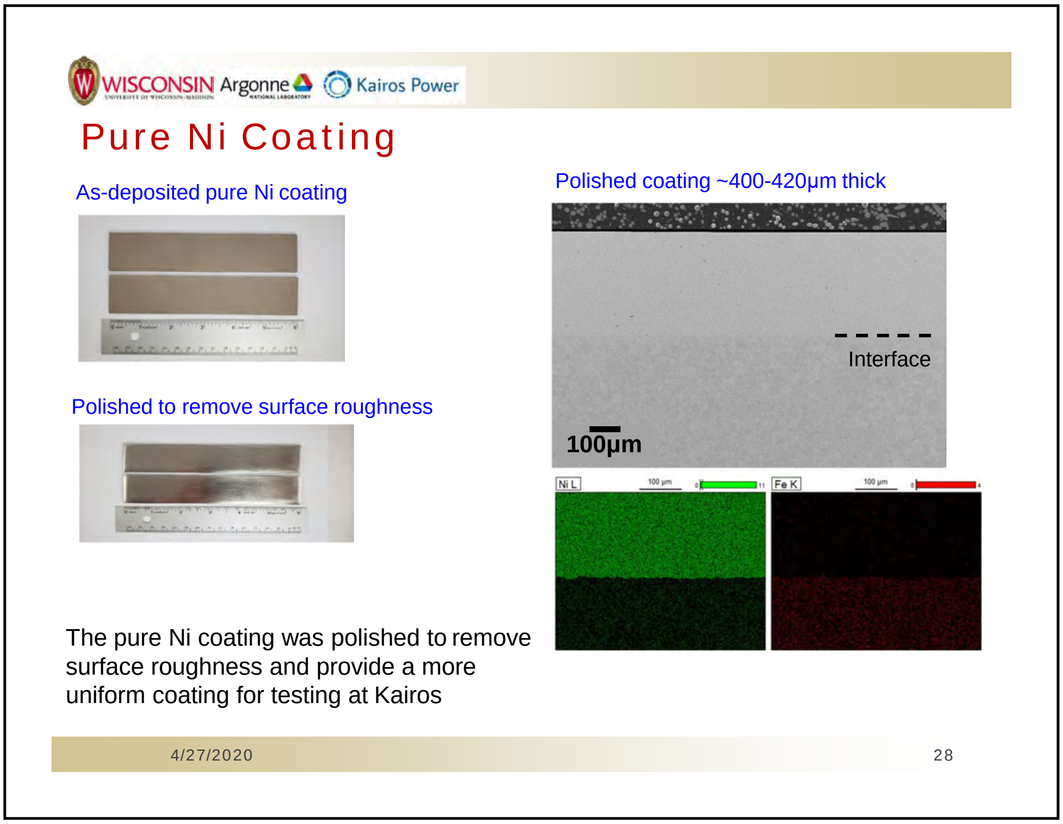

## Pure Ni Coating

As-deposited pure Ni coating

Polished to remove surface roughness

Polished coating ~400-420µm thick

The pure Ni coating was polished to remove surface roughness and provide a more uniform coating for testing at Kairos

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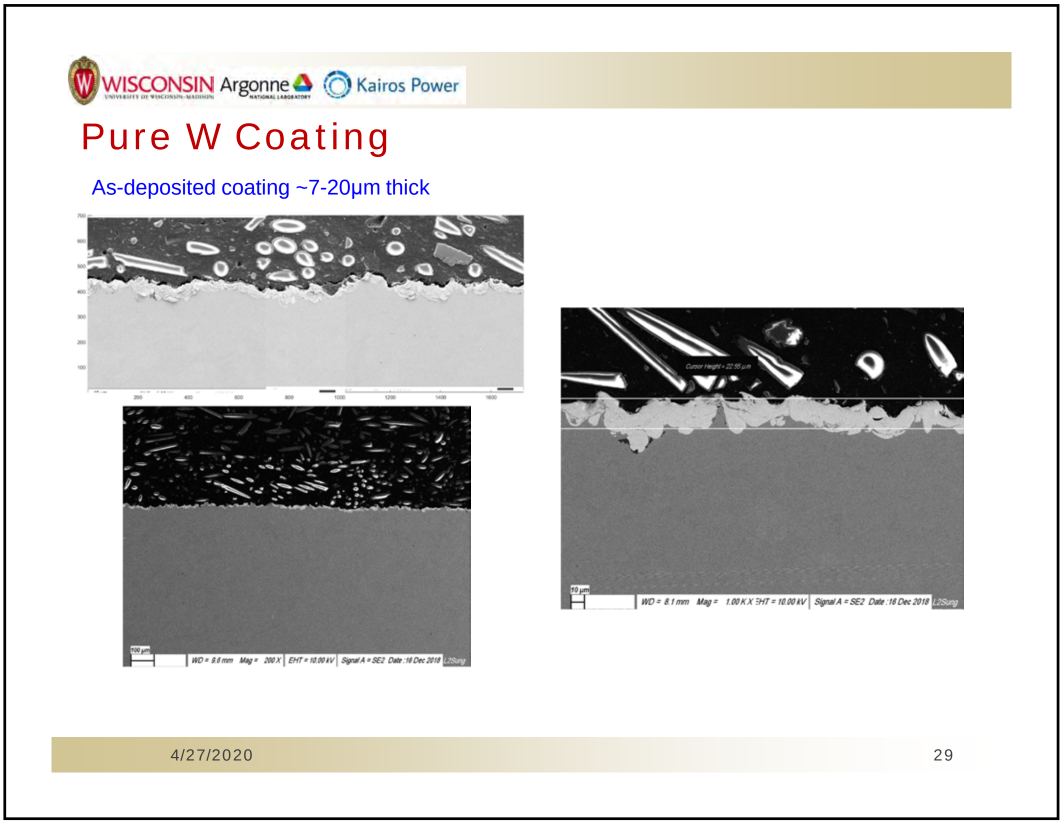
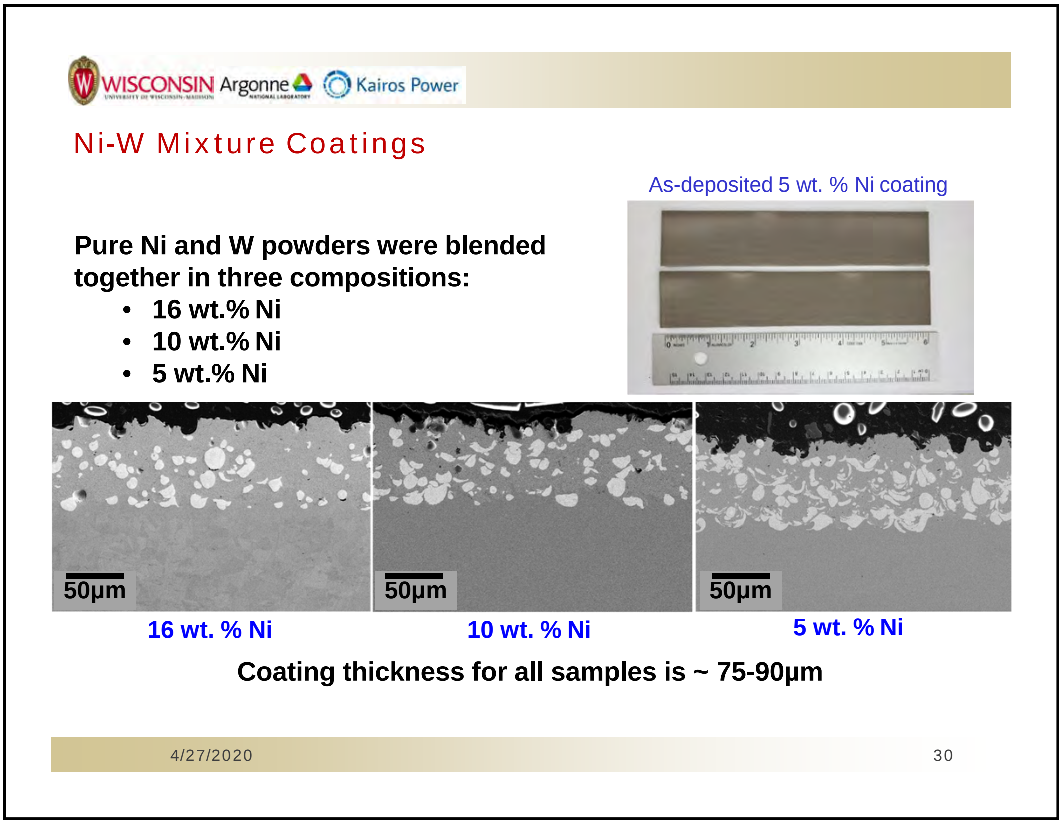


## Pure W Coating

As-deposited coating ~7-20µm thick



## Ni-W Mixture Coatings

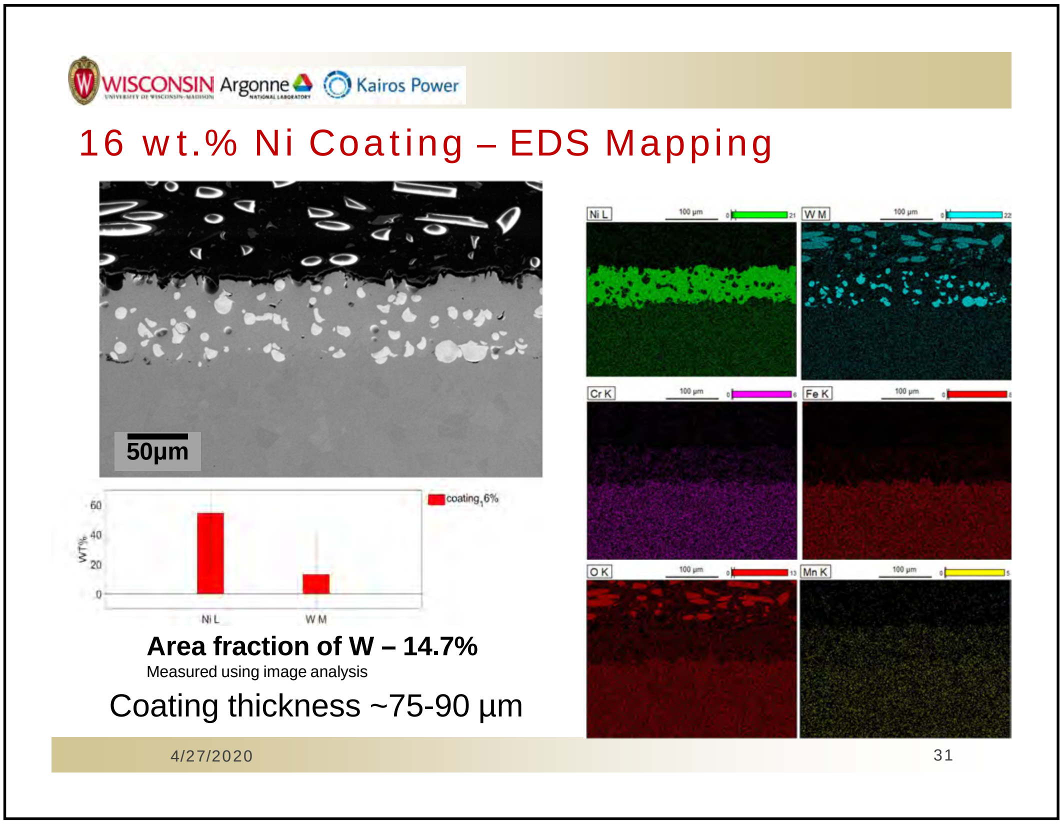
As-deposited 5 wt. % Ni coating

**Pure Ni and W powders were blended together in three compositions:**

- **16 wt.% Ni**
- **10 wt.% Ni**
- **5 wt.% Ni**

**16 wt. % Ni** **10 wt. % Ni** **5 wt. % Ni**

**Coating thickness for all samples is ~ 75-90µm**



## 16 wt.% Ni Coating – EDS Mapping

**Area fraction of W – 14.7%**

Measured using image analysis

Coating thickness ~75-90 µm

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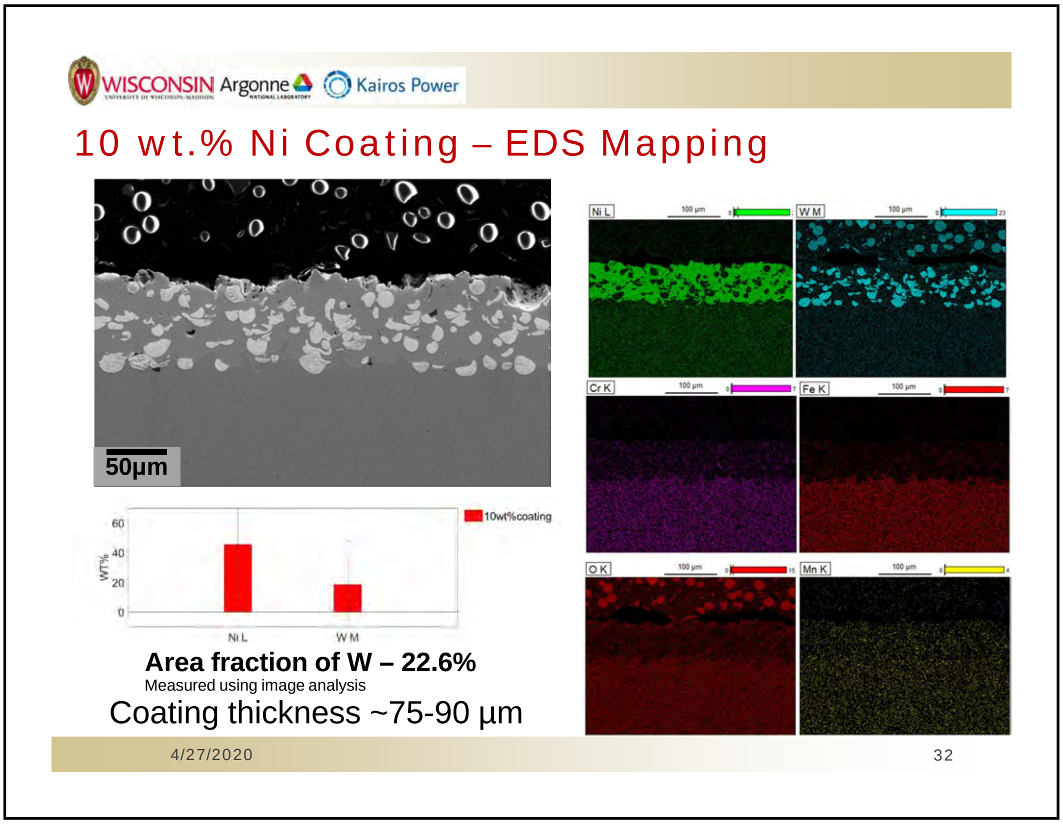

## 10 wt.% Ni Coating – EDS Mapping

**Area fraction of W – 22.6%**

Measured using image analysis

Coating thickness ~75-90 µm

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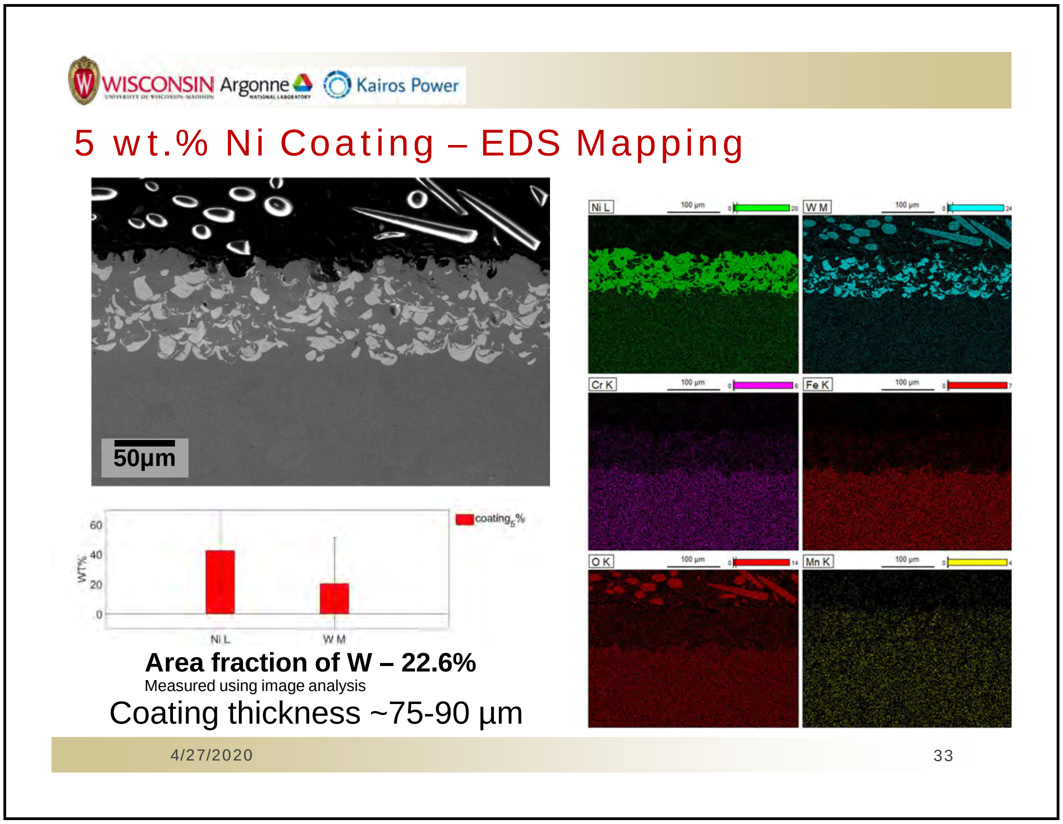
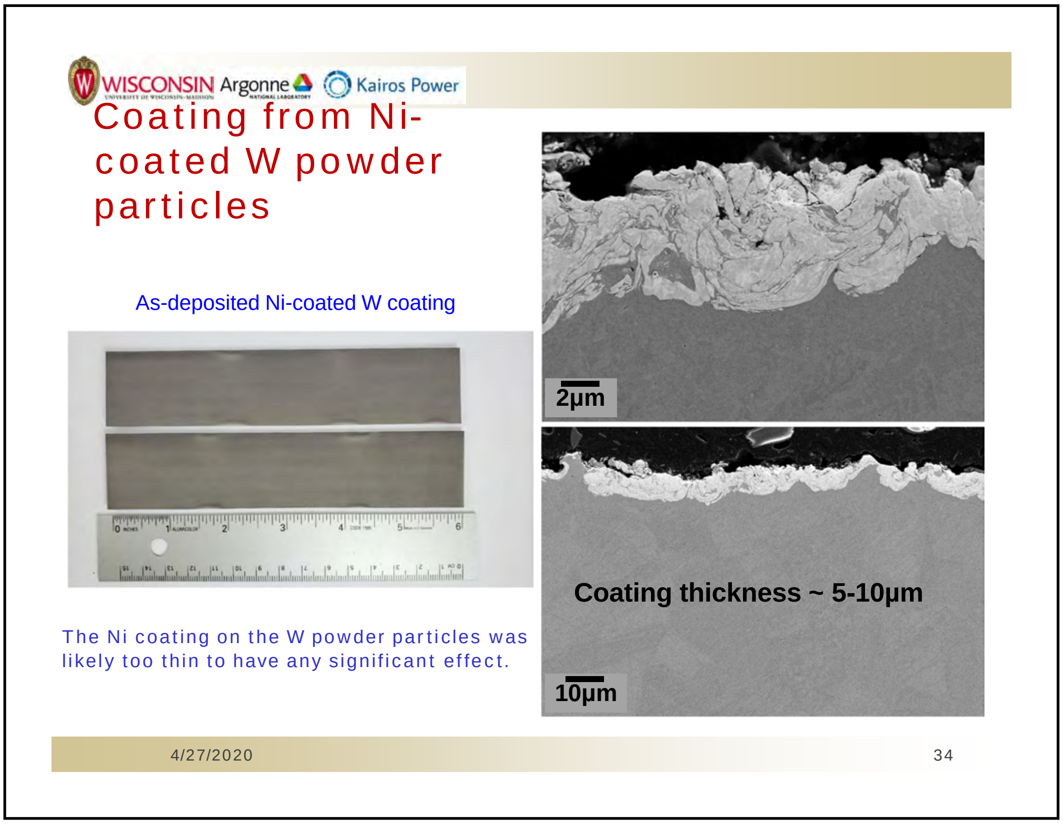


## 5 wt.% Ni Coating – EDS Mapping

**Area fraction of W – 22.6%**
Measured using image analysis

Coating thickness ~75-90 µm

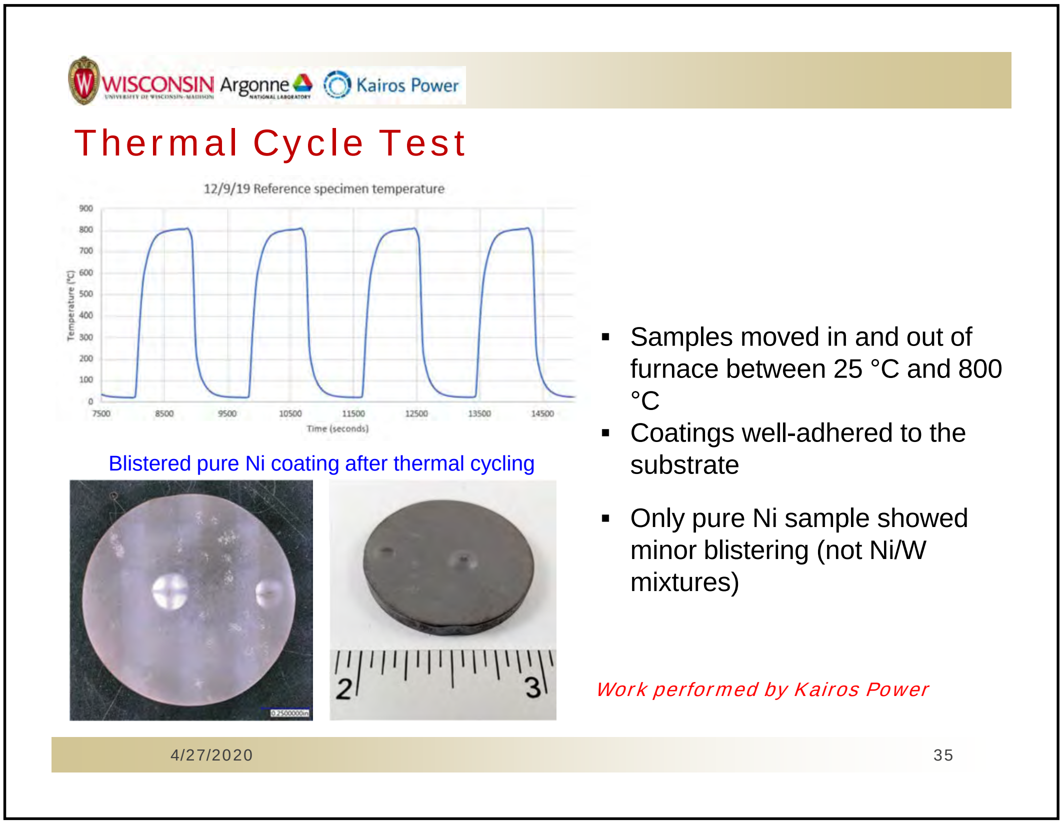


## Coating from Ni-coated W powder particles

As-deposited Ni-coated W coating

**Coating thickness ~ 5-10µm**

The Ni coating on the W powder particles was likely too thin to have any significant effect.



## Thermal Cycle Test

- Samples moved in and out of furnace between 25 °C and 800 °C
- Coatings well-adhered to the substrate
- Only pure Ni sample showed minor blistering (not Ni/W mixtures)

*Work performed by Kairos Power*

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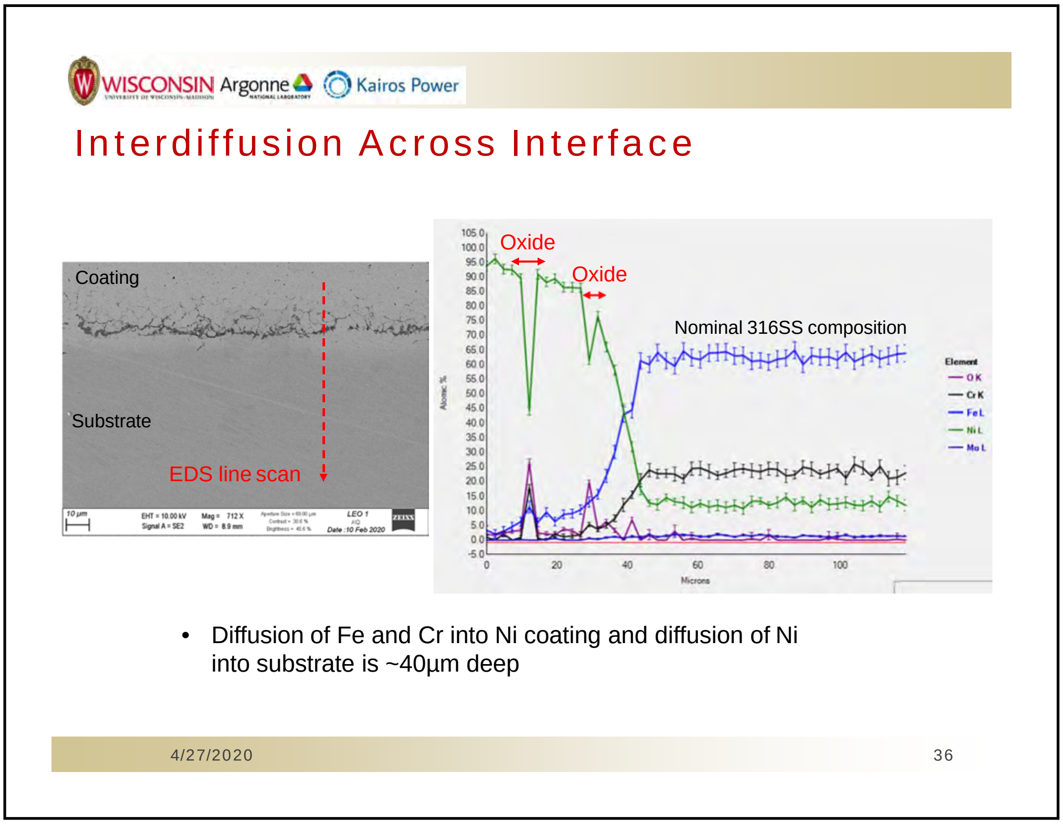

## Interdiffusion Across Interface

- Diffusion of Fe and Cr into Ni coating and diffusion of Ni into substrate is ~40µm deep

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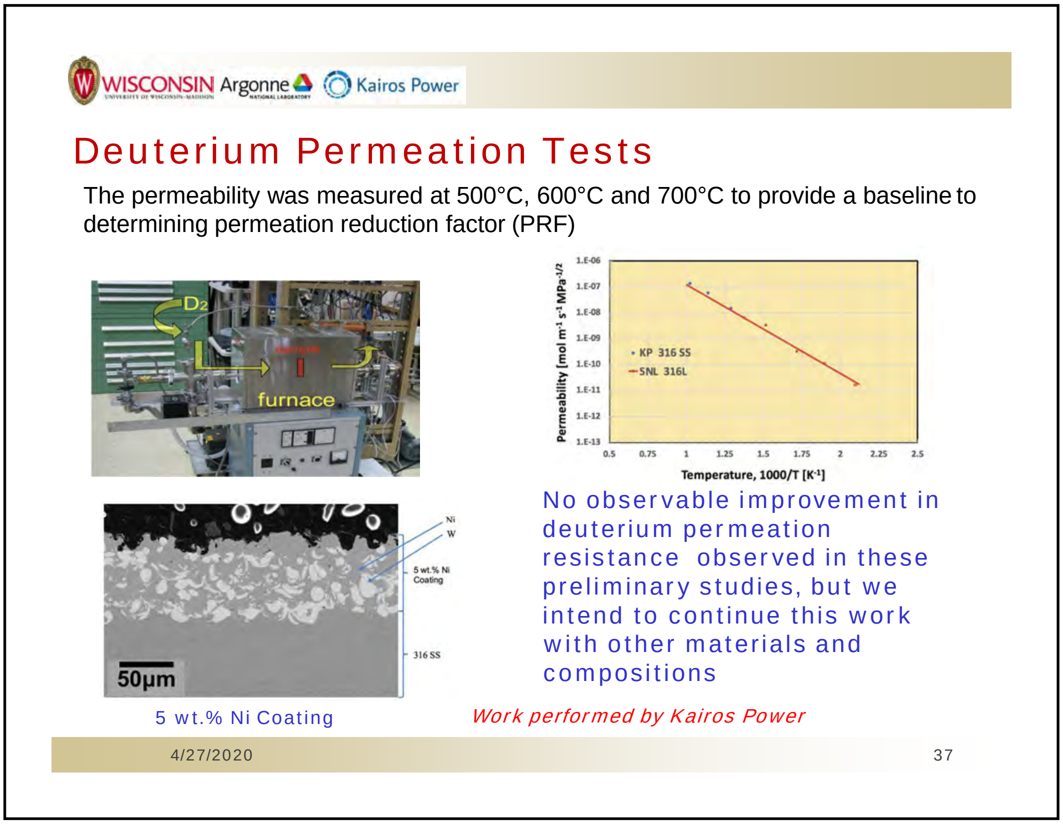

## Deuterium Permeation Tests

The permeability was measured at 500°C, 600°C and 700°C to provide a baseline to determining permeation reduction factor (PRF)

No observable improvement in deuterium permeation resistance observed in these preliminary studies, but we intend to continue this work with other materials and compositions

5 wt.% Ni Coating

*Work performed by Kairos Power*

4/27/2020

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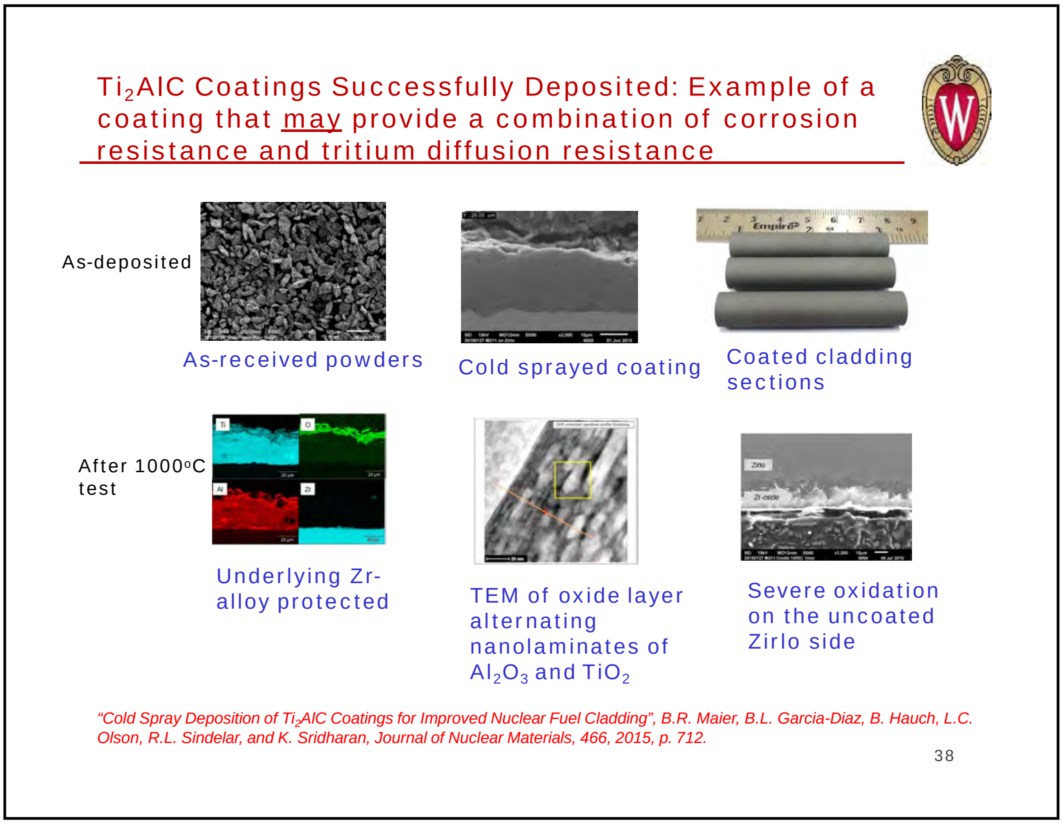

## $Ti_2AlC$ Coatings Successfully Deposited: Example of a coating that may provide a combination of corrosion resistance and tritium diffusion resistance

As-deposited

As-received powders

Cold sprayed coating

Coated cladding sections

After 1000°C test

Underlying Zr-alloy protected

TEM of oxide layer alternating nanolaminates of $Al_2O_3$ and $TiO_2$

Severe oxidation on the uncoated Zirlo side

*"Cold Spray Deposition of $Ti_2AlC$ Coatings for Improved Nuclear Fuel Cladding", B.R. Maier, B.L. Garcia-Diaz, B. Hauch, L.C. Olson, R.L. Sindelar, and K. Sridharan, Journal of Nuclear Materials, 466, 2015, p. 712.*

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WISCONSIN Argonne Kairos Power

# Contact Information and Questions

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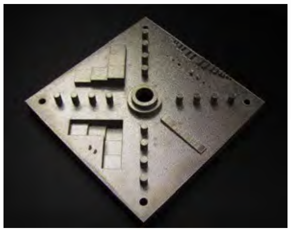
Tel: 608-263-4789


University of Wisconsin
Cold Spray Laboratory

# In–situ Process Measurements for Monitoring, Control, and Simulation of AM

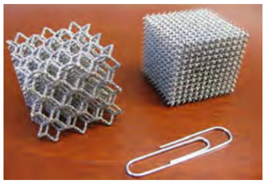


Brandon Lane, Ph.D.

Intelligent Systems Division

Engineering Laboratory

National Institute of Standards and Technology



NIST
National Institute of Standards and Technology
U.S. Department of Commerce

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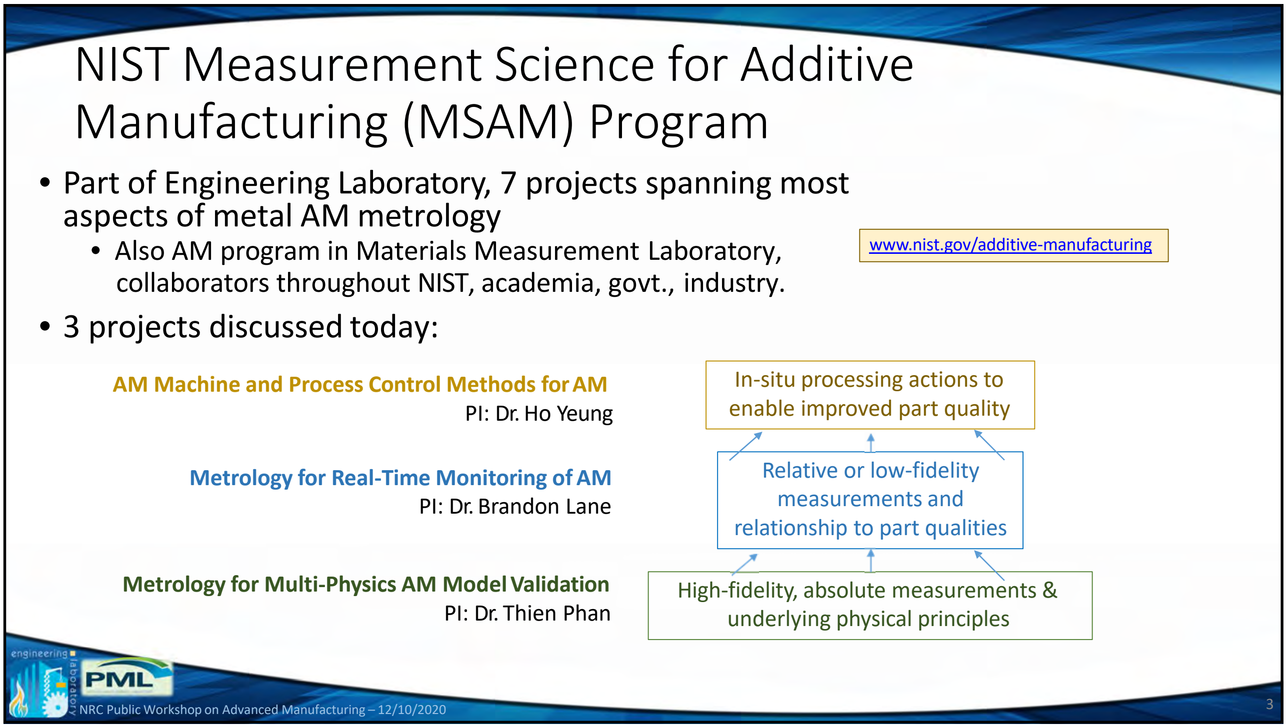
## Outline

- NIST Measurement Science for AM (MSAM)
- EOS M270 Thermography
- Additive Manufacturing Metrology Testbed
  - Industrially-relevant process monitoring
  - Model-based feed-forward controls
  - Absolute thermometry
  - Other fun measurements!
- Laser Processing Diffraction Testbed (LPDT)
- Dissemination and use of measurements



# NIST Measurement Science for Additive Manufacturing (MSAM) Program

- Part of Engineering Laboratory, 7 projects spanning most aspects of metal AM metrology
  - Also AM program in Materials Measurement Laboratory, collaborators throughout NIST, academia, govt., industry.
- 3 projects discussed today:

www.nist.gov/additive-manufacturing

**AM Machine and Process Control Methods for AM**
PI: Dr. Ho Yeung

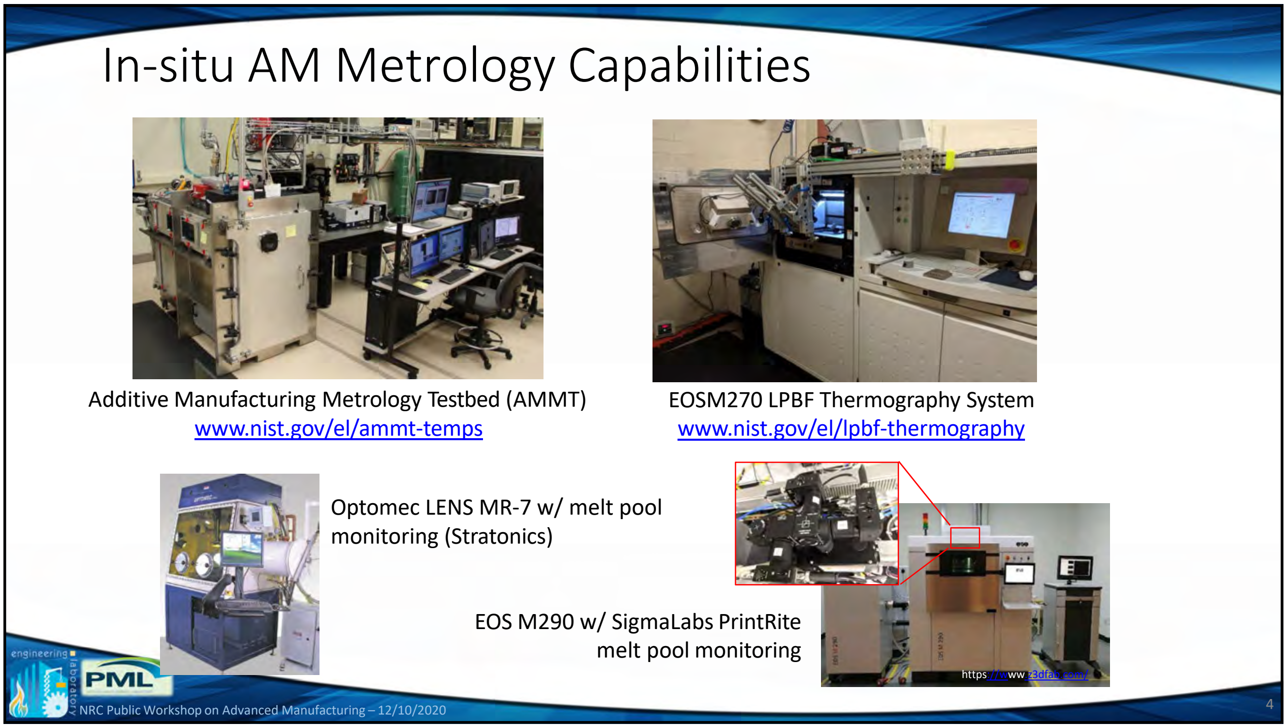
**Metrology for Real-Time Monitoring of AM**
PI: Dr. Brandon Lane

**Metrology for Multi-Physics AM Model Validation**
PI: Dr. Thien Phan

In-situ processing actions to enable improved part quality

Relative or low-fidelity measurements and relationship to part qualities

High-fidelity, absolute measurements & underlying physical principles



# In-situ AM Metrology Capabilities

Additive Manufacturing Metrology Testbed (AMMT)
www.nist.gov/el/ammt-temps

EOSM270 LPBF Thermography System
www.nist.gov/el/lpbf-thermography

Optomec LENS MR-7 w/ melt pool monitoring (Stratonics)

EOS M290 w/ SigmaLabs PrintRite melt pool monitoring

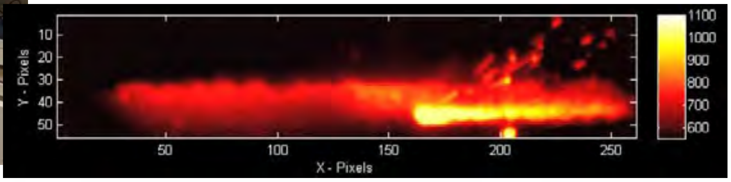
https://www.z3dfab.com/

# EOS M270 + Thermography System

Part-scale **radiance** temperature and cooling rate measurements during 3D part builds
Rapid testing of different geometries in standard materials

Camera information -> New camera

| | |
|---|---|
| 1800 frames per second | -> 2400+ fps |
| 40 µs integration time (shutter speed) | -> HDR capabilities |
| 360 pixel wide, 128 mm tall field of view | -> 320x256 pixels |
| 44° viewing angle | |
| Viewable area on baseplate, 12 mm x 6 mm | -> Variable |
| iFOV – 54 µm x 36 µm | -> min 45x30 µm |



https://www.nist.gov/el/lpbf-thermography

PIs: Jordan Weaver, Brandon Lane

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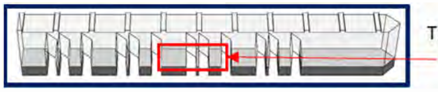
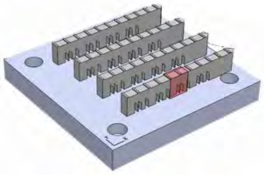
# EOS M270 + Thermography System

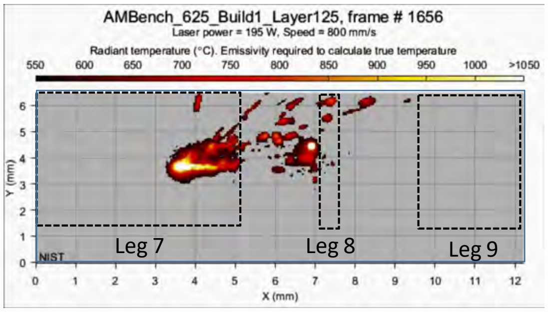
Mapped MP Length and Cooling rates in 3D build

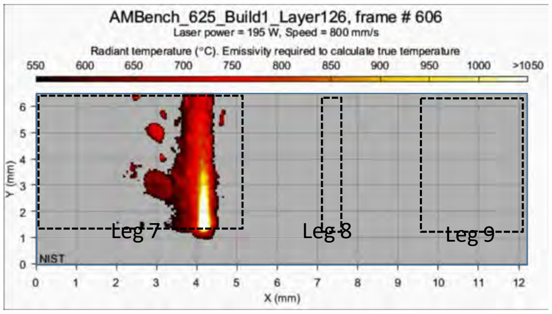




- X-orientation scans
- Odd layer (#125)

- Y-orientation scans
- Even layer (#126)





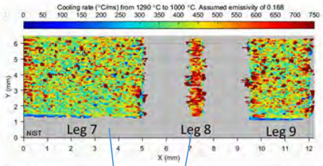
Heigel et al. (2020) *Integrating Materials and Manufacturing Innovation.* https://doi.org/10.1007/s40192-020-00170-8
Data: Heigel et al. (2020) *J. Research NIST.* https://doi.org/10.6028/jres.125.005

# EOS M270 + Thermography System

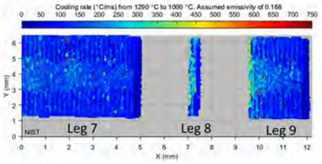
Mapped MP Length and Cooling rates in 3D build

Thermal camera
field of view

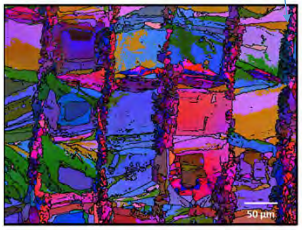
**X-orientation scans**
**Odd layer (#125)**



**Y-orientation scans**
**Even layer (#126)**

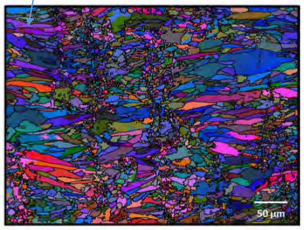


AMB2018-01-625-B2-P1-L4 Thick



Slower Cooling Rate

AMB2018-01-625-B2-P1-L8 Thin



Faster Cooling Rate

EBSD images from
Stoudt et al. (2020) *Integrating Materials and Manufacturing Innovation*.
https://doi.org/10.1007/s40192-020-00172-6

All data available at www.nist.gov/ambench/

AM BENCH 2022

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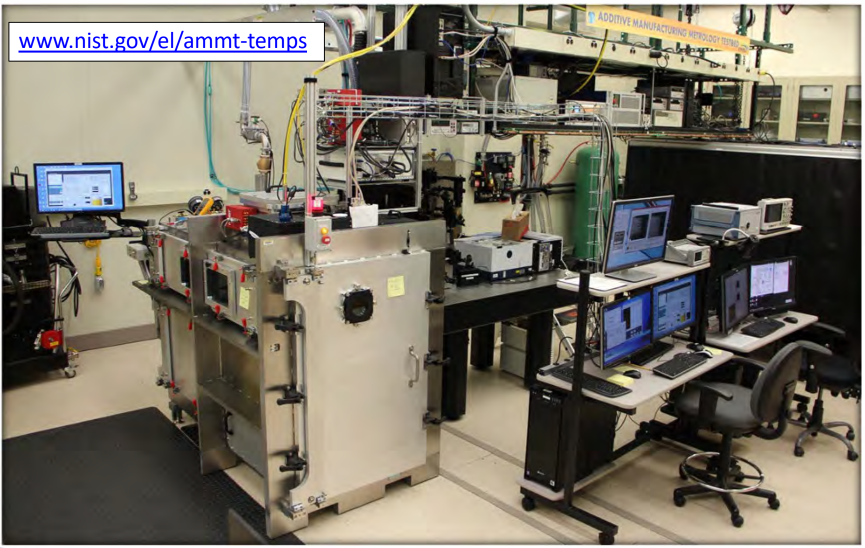
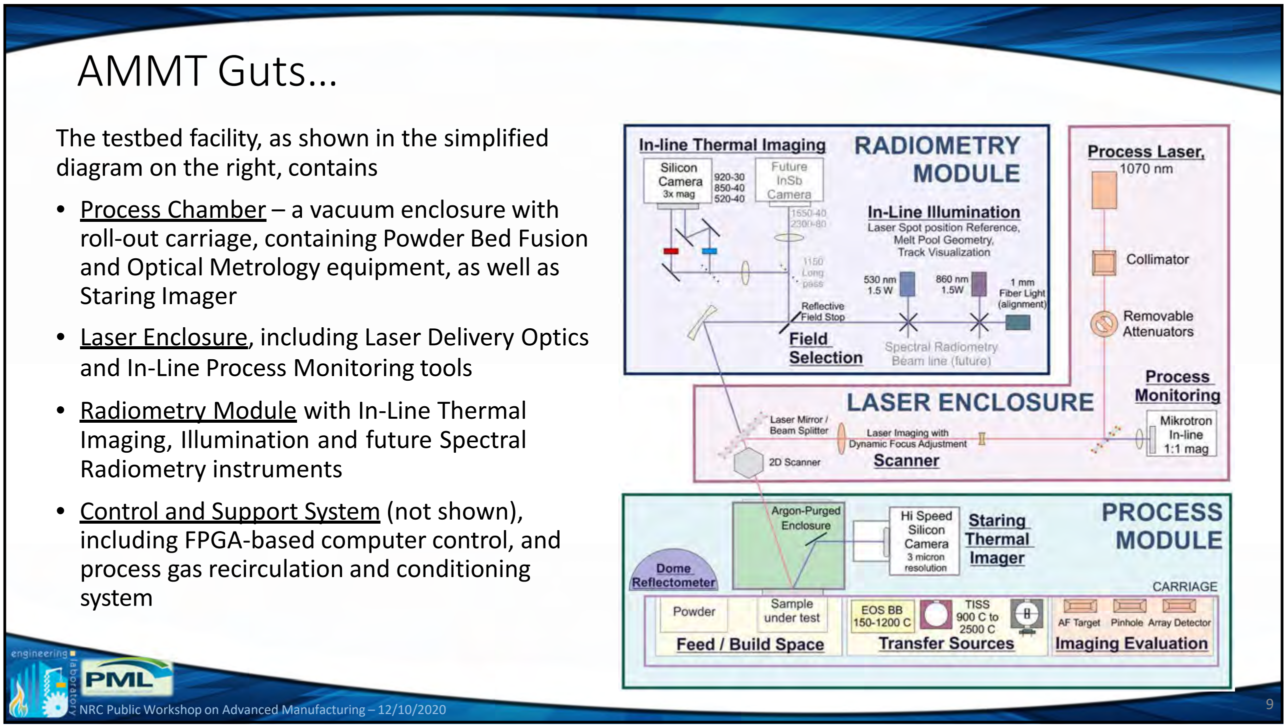
# Additive Manufacturing Metrology Testbed (AMMT)



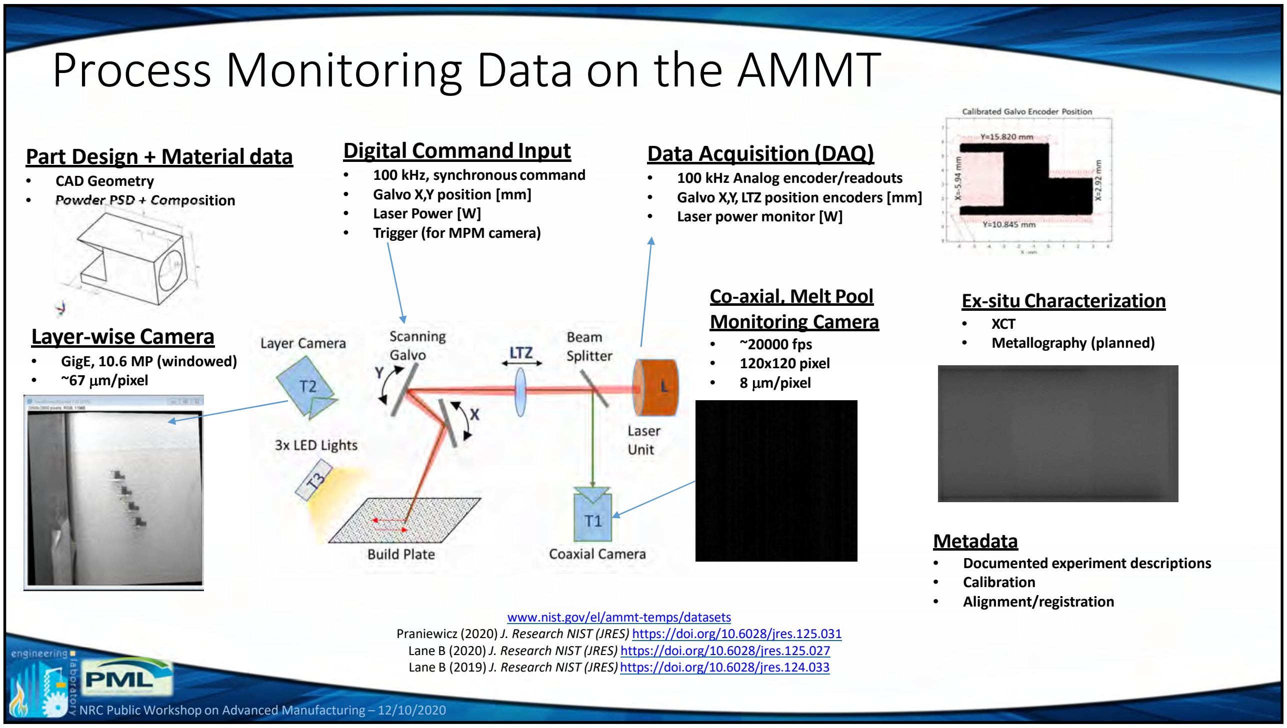
www.nist.gov/el/ammt-temps



# AMMT Guts…

The testbed facility, as shown in the simplified diagram on the right, contains

- Process Chamber – a vacuum enclosure with roll-out carriage, containing Powder Bed Fusion and Optical Metrology equipment, as well as Staring Imager
- Laser Enclosure, including Laser Delivery Optics and In-Line Process Monitoring tools
- Radiometry Module with In-Line Thermal Imaging, Illumination and future Spectral Radiometry instruments
- Control and Support System (not shown), including FPGA-based computer control, and process gas recirculation and conditioning system



# Process Monitoring Data on the AMMT

**Part Design + Material data**
- CAD Geometry
- *Powder PSD + Composition*

**Digital Command Input**
- 100 kHz, synchronous command
- Galvo X,Y position [mm]
- Laser Power [W]
- Trigger (for MPM camera)

**Data Acquisition (DAQ)**
- 100 kHz Analog encoder/readouts
- Galvo X,Y, LTZ position encoders [mm]
- Laser power monitor [W]

**Layer-wise Camera**
- GigE, 10.6 MP (windowed)
- ~67 µm/pixel

**Co-axial, Melt Pool Monitoring Camera**
- ~20000 fps
- 120x120 pixel
- 8 µm/pixel

**Ex-situ Characterization**
- XCT
- Metallography (planned)

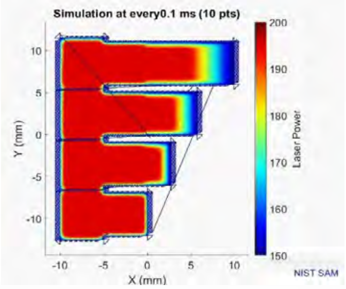
**Metadata**
- Documented experiment descriptions
- Calibration
- Alignment/registration

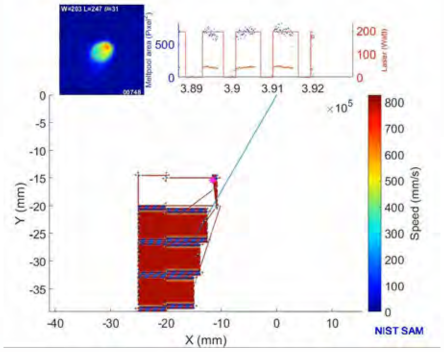
www.nist.gov/el/ammt-temps/datasets
Praniewicz (2020) *J. Research NIST (JRES)* https://doi.org/10.6028/jres.125.031
Lane B (2020) *J. Research NIST (JRES)* https://doi.org/10.6028/jres.125.027
Lane B (2019) *J. Research NIST (JRES)* https://doi.org/10.6028/jres.124.033

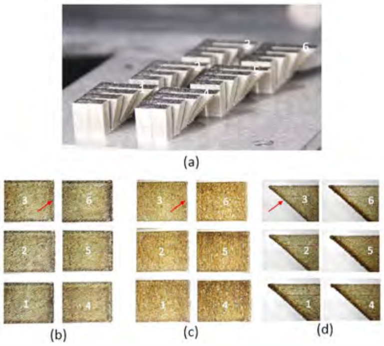
# AMMT – Geometry/Thermal Model-based Control

- Geometric Conductivity Factor (GCF) – solid vs. powder in vicinity of melt pool
- Residual Heat Factor (RHF) – time & distance from previous melt pool locations
- Control: Laser power = f[GCF, RHF]

Part 1: No thermal control
Part 3: Highest thermal control





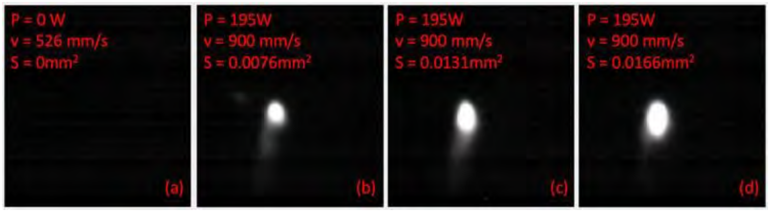


RHF: Yeung H et al. (2020) *Manufacturing Letters* https://doi.org/10.1016/j.mfglet.2020.07.005
GCF: Yeung et al. (2019) *Additive Manufacturing* https://doi.org/10.1016/j.addma.2019.100844

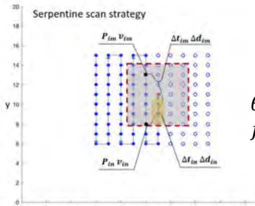
# Example Use: Machine Learning-based Control

AMMT scan strategy digital command

Execute on AMMT, measure MP image features (area)



Neighboring-effect model (NBEM)
(Similar to RHF)

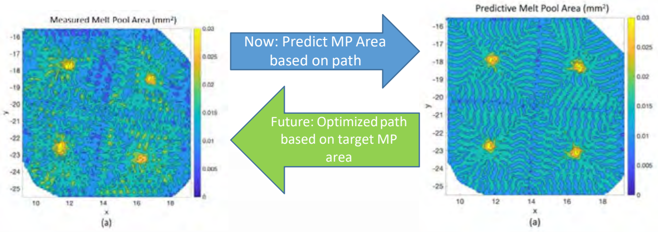


$$\theta_i^{\Delta t} = \sum_{j=1}^{n} f_{\Delta t}(\Delta t_{ij}) \frac{P_{ij}}{v_{ij}}$$

$$\theta_i^{\Delta d} = \sum_{j=1}^{n} f_{\Delta d}(\Delta d_{ij}) \frac{P_{ij}}{v_{ij}}$$

$$S_i = f\left(P_i, v_i, \theta_i^{\Delta t}, \theta_i^{\Delta d}\right)$$

Build data-driven model, predicting MP image area as function of scan strategy



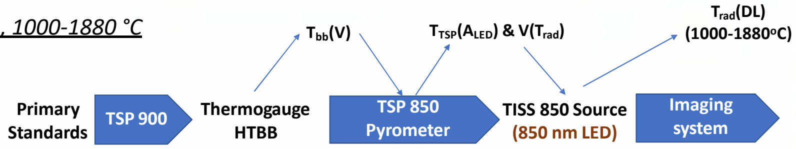
Now: Predict MP Area based on path

Future: Optimized path based on target MP area

**Papers:** Yeung et al (2020) *Additive Manufacturing* https://doi.org/10.1016/j.addma.2020.101383[2]
Yang et al. (2020 *J. Comp. Inf. Sci. Eng.* https://doi.org/10.1115/1.4046335
**Dataset:** Lane B (2019) https://doi.org/10.6028/jres.124.033

# AMMT – Radiance Temperature Calibration

*Example: 850 nm, 1000-1880 °C*

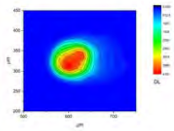


$T_{bb}$(V)

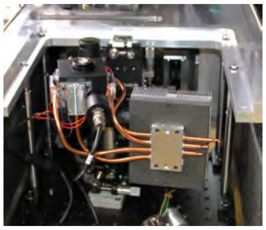
$T_{TSP}$($A_{LED}$) & V($T_{rad}$)

$T_{rad}$(DL)
(1000-1880°C)

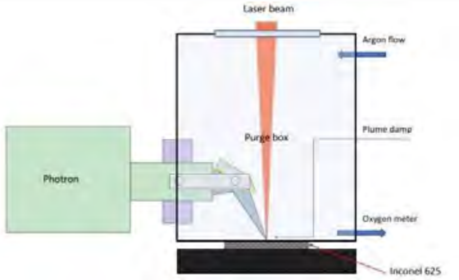
**Primary Standards** → **TSP 900** → **Thermogauge HTBB** → **TSP 850 Pyrometer** → **TISS 850 Source (850 nm LED)** → **Imaging system**



**Melt Pool Source**



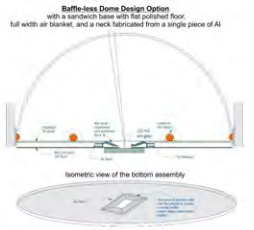
Custom designed TISS 850 LED-driven source for in-situ calibration



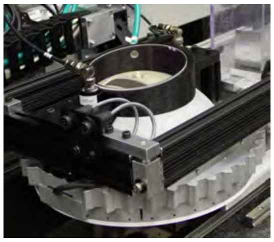
Staring Imager in a measurement configuration, with a high magnification lens and folding mirror

Staring Imager in calibration position (outside of the purge enclosure)

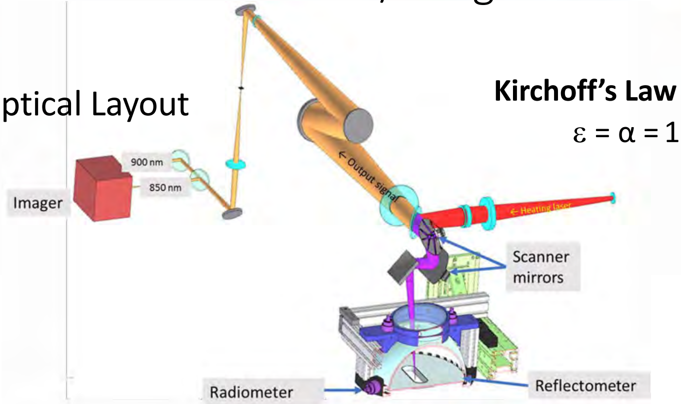
# AMMT – Hemispherical Reflectometer/Integrator



**Dome Reflectometer Design**



Optical Layout

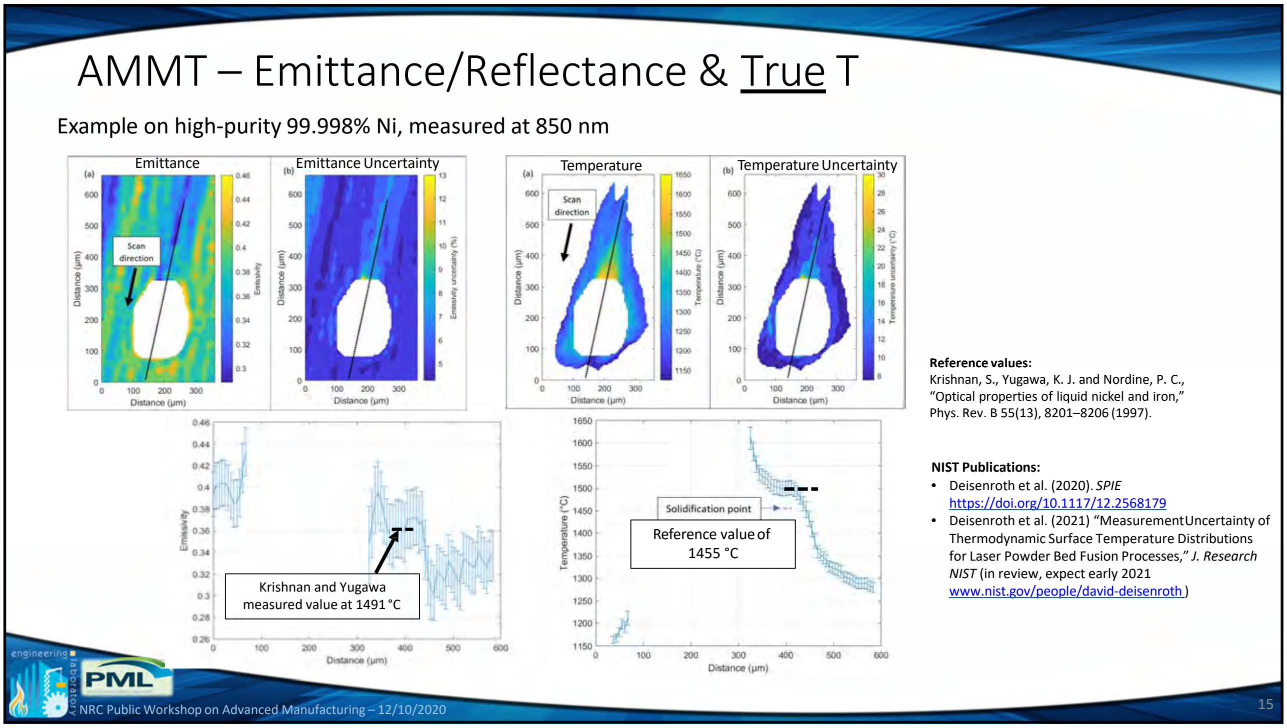


**Kirchoff's Law**

$\varepsilon = \alpha = 1 - \rho$

- Designed to provide uniform hemispherical illumination in the sample position
- Hemispherical-Directional Reflectance Factor (HDRF) -> surface emittance

Deisenroth et al. (2020). *Reflection, Scattering, and Diffraction from Surfaces VII* (SPIE) https://doi.org/10.1117/12.2568179
Deisenroth et al. (2021) "Measurement Uncertainty of Thermodynamic Surface Temperature Distributions for Laser Powder Bed Fusion Processes," *J. Research NIST* (in review, expect early 2021 www.nist.gov/people/david-deisenroth)



# AMMT – Emittance/Reflectance & True T

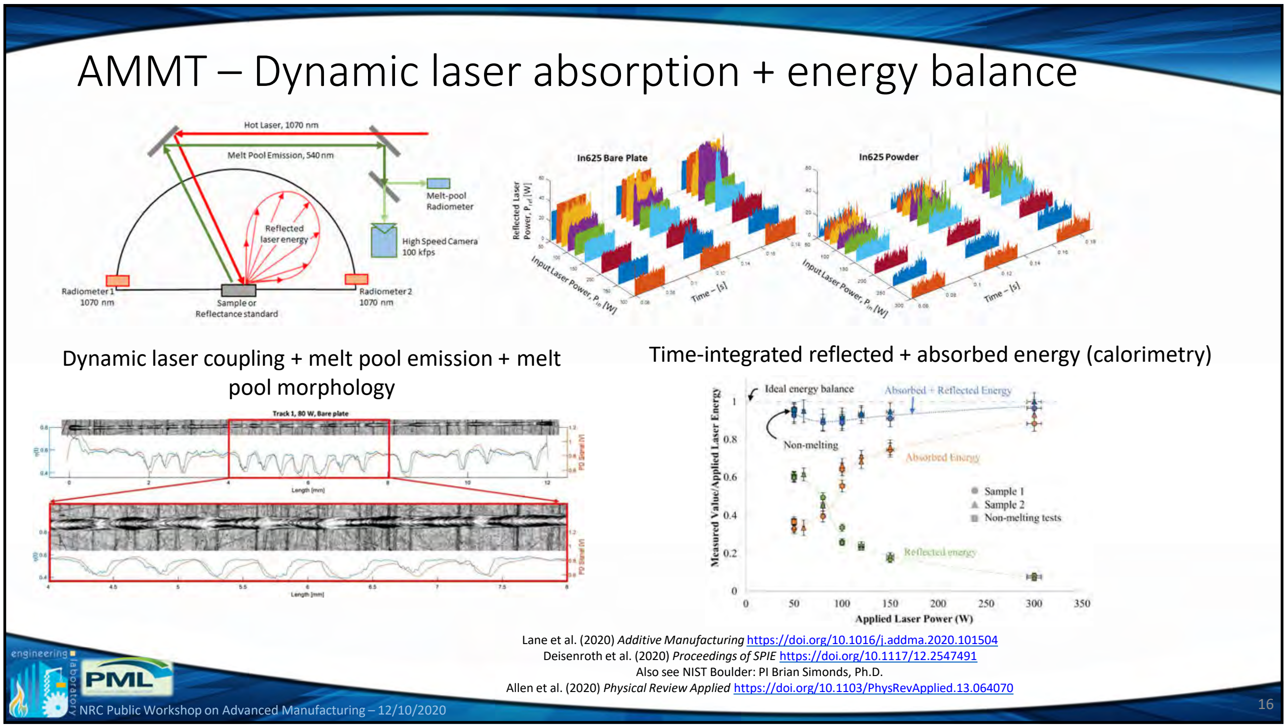
Example on high-purity 99.998% Ni, measured at 850 nm

**Reference values:**
Krishnan, S., Yugawa, K. J. and Nordine, P. C., "Optical properties of liquid nickel and iron," Phys. Rev. B 55(13), 8201–8206 (1997).

**NIST Publications:**

- Deisenroth et al. (2020). *SPIE* https://doi.org/10.1117/12.2568179
- Deisenroth et al. (2021) "MeasurementUncertainty of Thermodynamic Surface Temperature Distributions for Laser Powder Bed Fusion Processes," *J. Research NIST* (in review, expect early 2021 www.nist.gov/people/david-deisenroth )

NRC Public Workshop on Advanced Manufacturing – 12/10/2020



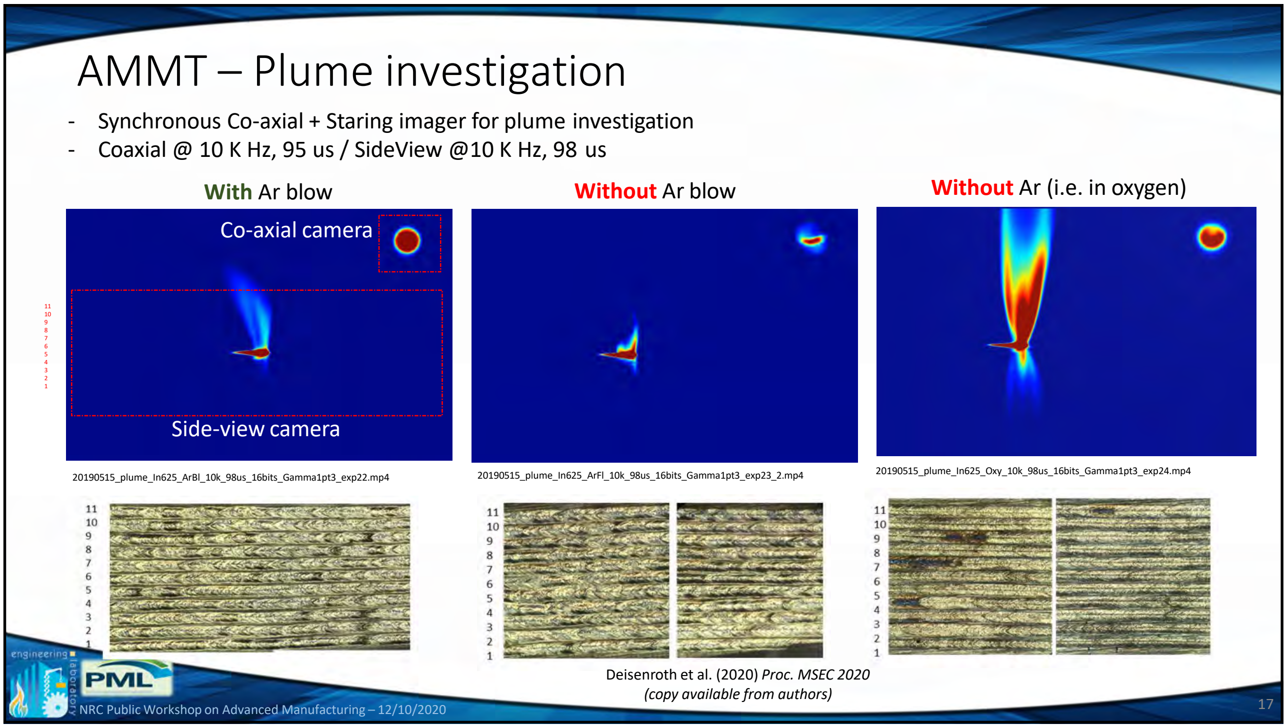
# AMMT – Dynamic laser absorption + energy balance

Dynamic laser coupling + melt pool emission + melt pool morphology

Time-integrated reflected + absorbed energy (calorimetry)

Lane et al. (2020) *Additive Manufacturing* https://doi.org/10.1016/j.addma.2020.101504
Deisenroth et al. (2020) *Proceedings of SPIE* https://doi.org/10.1117/12.2547491
Also see NIST Boulder: PI Brian Simonds, Ph.D.
Allen et al. (2020) *Physical Review Applied* https://doi.org/10.1103/PhysRevApplied.13.064070

NRC Public Workshop on Advanced Manufacturing – 12/10/2020



# AMMT – Plume investigation

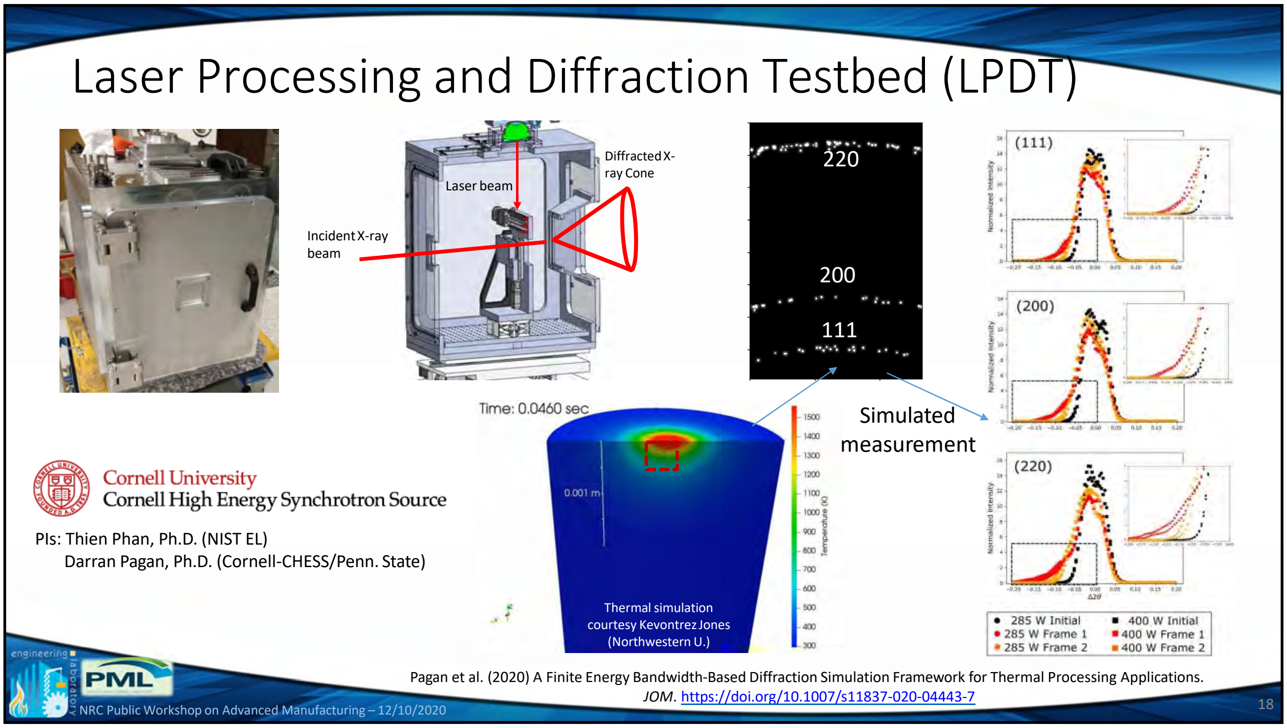
- Synchronous Co-axial + Staring imager for plume investigation
- Coaxial @ 10 K Hz, 95 us / SideView @10 K Hz, 98 us

20190515_plume_In625_ArBl_10k_98us_16bits_Gamma1pt3_exp22.mp4

20190515_plume_In625_ArFl_10k_98us_16bits_Gamma1pt3_exp23_2.mp4

20190515_plume_In625_Oxy_10k_98us_16bits_Gamma1pt3_exp24.mp4

Deisenroth et al. (2020) *Proc. MSEC 2020*
*(copy available from authors)*



# Laser Processing and Diffraction Testbed (LPDT)

Thermal simulation courtesy Kevontrez Jones (Northwestern U.)

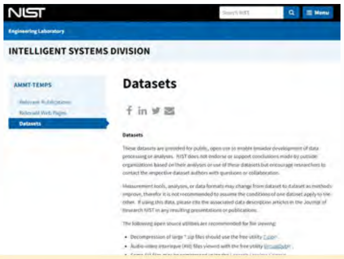
Cornell University
Cornell High Energy Synchrotron Source

PIs: Thien Phan, Ph.D. (NIST EL)
Darran Pagan, Ph.D. (Cornell-CHESS/Penn. State)

Pagan et al. (2020) A Finite Energy Bandwidth-Based Diffraction Simulation Framework for Thermal Processing Applications. *JOM*. https://doi.org/10.1007/s11837-020-04443-7

# NIST AM In-situ Data & Dissemination

AMMT Website
https://www.nist.gov/el/ammt-temps/datasets



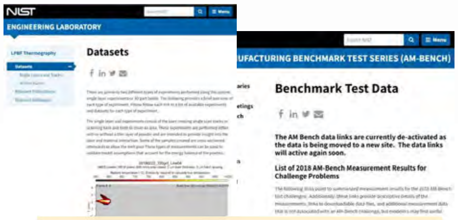
Updated in-situ process monitoring datasets from the AMMT

NIST AMMD
https://ammd.nist.gov/

Incorporation of AMMT data into database
Data visualization tools

NIST LPBF Thermography Website
+ AM-Bench Website

https://www.nist.gov/el/lpbf-thermography/datasets
https://www.nist.gov/ambench/benchmark-test-data



Staring thermography system on EOS M270
AM-Bench has myriad ex-situ data (res. strain, μ-structure, etc.)

ASME® 2020 HACKATHON
COMPUTER / INFORMATION / ENGINEERING

IDETC-CIE Conference, August 15-16, 2020
https://event.asme.org/IDETC-CIE-2020/Program/Hackathon
IMECE Conference, November 14-15 2020
https://event.asme.org/IMECE/Program/Hackathon

# Acknowledgements:

AMMT Team *
EOS Thermography Team +
LPDT Team o

$^{o}$Thien Phan (NIST EL)
$^{+}$Jordan Weaver (NIST EL)
+Benjamin Molnar (NIST EL)
*$^{o}$Steven Grantham (NIST PML)
*Sergey Mekhontsev (NIST PML)
*Leonard Hanssen (NIST PML)
*$^{o}$Ho Yeung (NIST EL)
*David Deisenroth (NIST EL)
*Jorge Neira (NIST PML)
*Vladimir Khromchenko (NIST PML)
*Clarence Zarobila (NIST PML)
*Jarred Tarr (NIST EL)
*$^{o+}$Alkan Donmez (NIST EL)

$^{+}$Jarred Heigel (ThirdWave Systems, U.S.)
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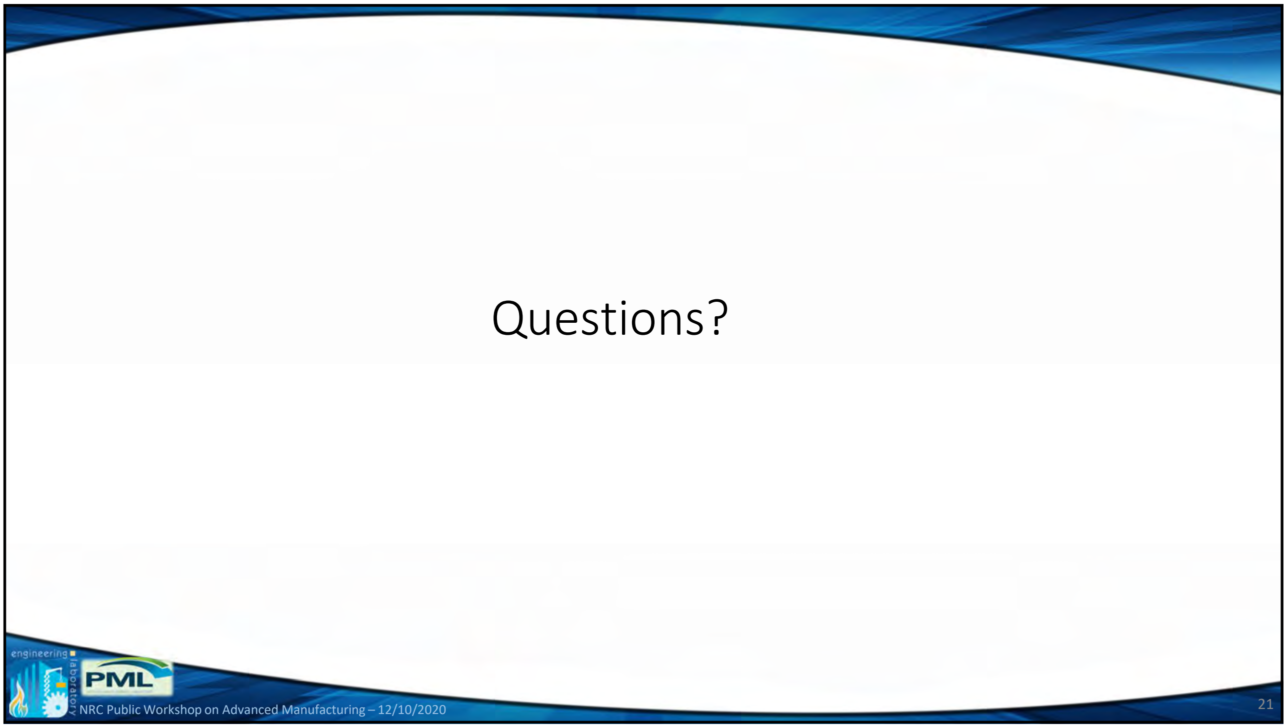
*Igor Yadroitsev (Central U. Tech, South Africa)
$^{o}$Darren Pagan (Cornell / Penn. State)
$^{o}$Kevontrez Jones (Northwestern U.)



Questions?

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**Mark Barfoot**
Director, AM Programs
mbarfoot@ewi.org
716.710.5597

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# EWI OVERVIEW

- **History**
  - Founded in 1984, EWI's comprehensive engineering services help companies identify, develop and implement the best options for their specific applications.
- **Our Mission**
  - Break through our customers' technical barriers, solve their manufacturing challenges, and further their success.
- **Expertise**
  - Industry experts in materials joining, forming, testing, modeling and additive manufacturing
- **Locations**
  - Headquartered in Columbus Ohio with technology centers in Buffalo, NY and Loveland, CO.

# EWI - AM Capabilities

- EWI leads way in AM by evaluating new processes, developing material property data, and helping our clients adopt and implement state-of-the-art technology to build their products.
  - Recognized expertise in metal AM
  - All 7 ASTM Additive technologies in house
  - Extensive laboratory and testing capabilities
  - Non profit
  - Technology and vendor agnostic neutral party
- Founded Additive Manufacturing Consortium (AMC) in 2009

Additive Manufacturing Consortium

# Additive Manufacturing Consortium

**Mission: Accelerate and advance the manufacturing readiness of additive manufacturing technologies**

- Goals:
  - Platform for ***collaboration*** across global industry, academia and government entities.
  - Execute group sponsored projects focused on addressing ***pre-competitive*** AM challenges
  - ***Partner*** on government funding opportunities
  - ***Forum*** for discussion/shaping AM roadmaps

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# "Direct Quotes" from our members

"We can't do this alone"

"Leveraging membership fees and time to develop low TRL (Technology Readiness Level)"

"Technical Interchange with like minded AM professionals"

"Keep our company updated in terms of challenging solutions for metal AM issues"

"Sharing of R&D Costs "

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# Industries & Organizations & Partners


Aerospace


Defense


Ship Building


Automotive


Medical


Oil & Gas


Consumer Products


Government


Universities


Powder/Material Mfg


Service Bureau's


OEM's


Software

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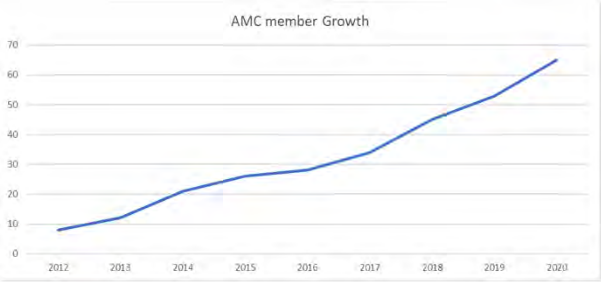
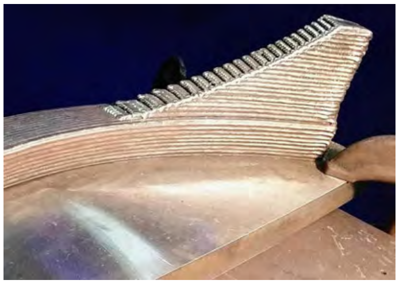
# Growth of AMC Members



**Increasing membership…**
- 65 Total Members
- Increasing by 5-8 full members/year.
- 90% + retention rate

# AMC Project Portfolio

**Total current project portfolio is:**
- +$4.5M in past project work
- Over $2M cash/in-kind per year of project work
- Currently 6 -8 projects/year



# Benefits Summary

- **Network** with **like minded** additive professionals
- **Technical discussions** on latest AM work
- Leverage your membership fees for **combined project work**
- Allowances for foreground IP and confidentiality *
- Ongoing Technical Communication
  - Biweekly project teleconferences
  - Quarterly technical meetings including tours of AM facilities

**per membership and sponsorship agreement terms*

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# Quarterly Meetings

- AMC holds Quarterly Meetings at partner sites

- Average attendance is 80-140 people
  - Includes AMC members and invited guests.*

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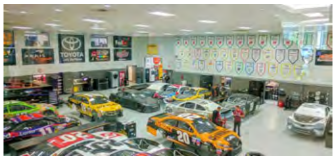
## Typical Quarterly Meetings & Tours

Desktop Metal

OERLIKON

Joe Gibbs Racing



NASA Marshall Space Flight Center

Honeywell

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## Typical Quarterly Meeting Agenda

- **Day 1 – Members only meeting**
  - Update on current AMC projects
- **Day 2 – General Session – latest AM news**
  - Evaluation of Laser Powder Bed Fusion AM to Produce replacement legacy aircraft components
  - Additive Manufacturing – A User's Perspective
  - Advanced Finishing Methods in Additive Processes
  - High Speed Thermography results on EOS M270
  - High throughput Testing reveals rare, catastrophic defects

LOCKHEED MARTIN

SSL

EXTRUDE HONE AFM

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

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## AMC 2021 Down Selected Projects

**To be voted on Feb 3-4,2020**

- Materials
  - Continue Testing for IN625 & 718
  - Phase 2 – Material Characterization for high strength AL alloys
  - Microstructure evaluation of joint interfaces between additive & convention methods
- AM Machines & Tests
  - Continuation of NEW AM Technologies
  - Assessment of new metal AM technologies – Hybrid Systems
  - Materials Testing in AM – Does your coupon size, shape & surface condition matter?
  - Phase 2 – Evaluate correlation between powder analysis techniques in relation to the printed part quality (surface roughness, mechanical properties and dimensional accuracy)
  - Deeper dive into Velo System including distortion in support free geometries
  - Phase 2 – Factors affecting as build surface finish
- Technology Advancement
  - AM for tooling study
  - Continuation of Investigation into multi-laser systems
  - Deeper Dive into LPBF Process restarts – what's really happening at microstructure level, and are we allowed to do process restarts?
- Post Processing & Finishing
  - Post Processing of AM Parts
- Simulation
  - AM Process simulation for parameter development

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## AMC 2020 Projects

- Phase 6 - Continuation of IN625/IN718 – Effect of thickness on microstructure
- Phase 4 - Material Characterization & Testing for high strength aluminum alloys (7075)
- Phase 2a – Continuation of evaluating new AM technologies
- Factors affecting AS built surfaces (vertical, upskin, downskin)
- How to qualify machine performance across various manufacturers
- Investigation into multi-laser systems
- Phase 3 – Evaluation of NDE techniques

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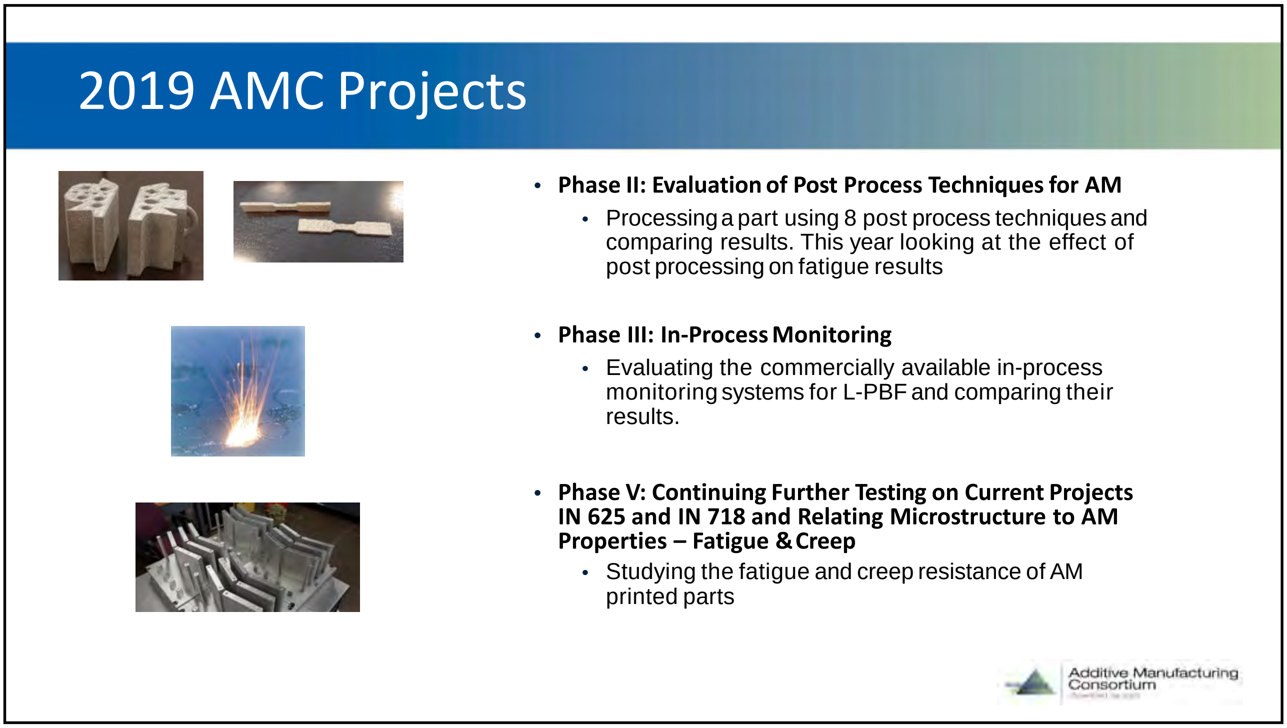
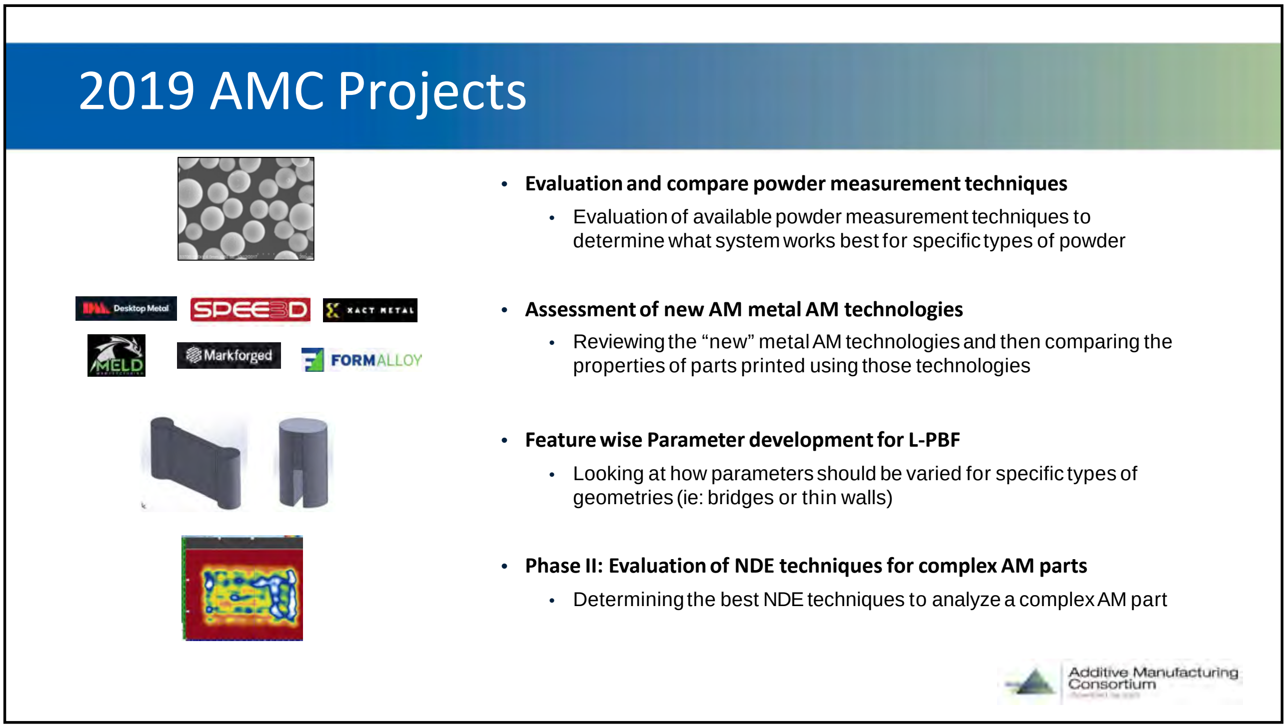


# 2019 AMC Projects

- **Phase II: Evaluation of Post Process Techniques for AM**
  - Processing a part using 8 post process techniques and comparing results. This year looking at the effect of post processing on fatigue results
- **Phase III: In-Process Monitoring**
  - Evaluating the commercially available in-process monitoring systems for L-PBF and comparing their results.
- **Phase V: Continuing Further Testing on Current Projects IN 625 and IN 718 and Relating Microstructure to AM Properties – Fatigue & Creep**
  - Studying the fatigue and creep resistance of AM printed parts



# 2019 AMC Projects

- **Evaluation and compare powder measurement techniques**
  - Evaluation of available powder measurement techniques to determine what system works best for specific types of powder
- **Assessment of new AM metal AM technologies**
  - Reviewing the "new" metal AM technologies and then comparing the properties of parts printed using those technologies
- **Feature wise Parameter development for L-PBF**
  - Looking at how parameters should be varied for specific types of geometries (ie: bridges or thin walls)
- **Phase II: Evaluation of NDE techniques for complex AM parts**
  - Determining the best NDE techniques to analyze a complex AM part

## How do I Join?

- Complete Membership agreement
    - Current term is 2018-2021
    - Dues payable annually
- Contact Mark Barfoot, Director of AM Programs
    - Email at mbarfoot@ewi.org
    - Phone at 716.710.5597

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## Next Meeting

Feb 3-4th, 2020 – VIRTUAL

- tours and topics TBA shortly

Contact me if you are interested in coming as a guest

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# WHY JOIN AMC

“Develop strategic relationships/networks and advance AM technology in a pre-competitive, collective manner that could provide value to our company and accelerate the introduction of AM-built parts into aerospace applications”

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Appendix: Past AMC Projects

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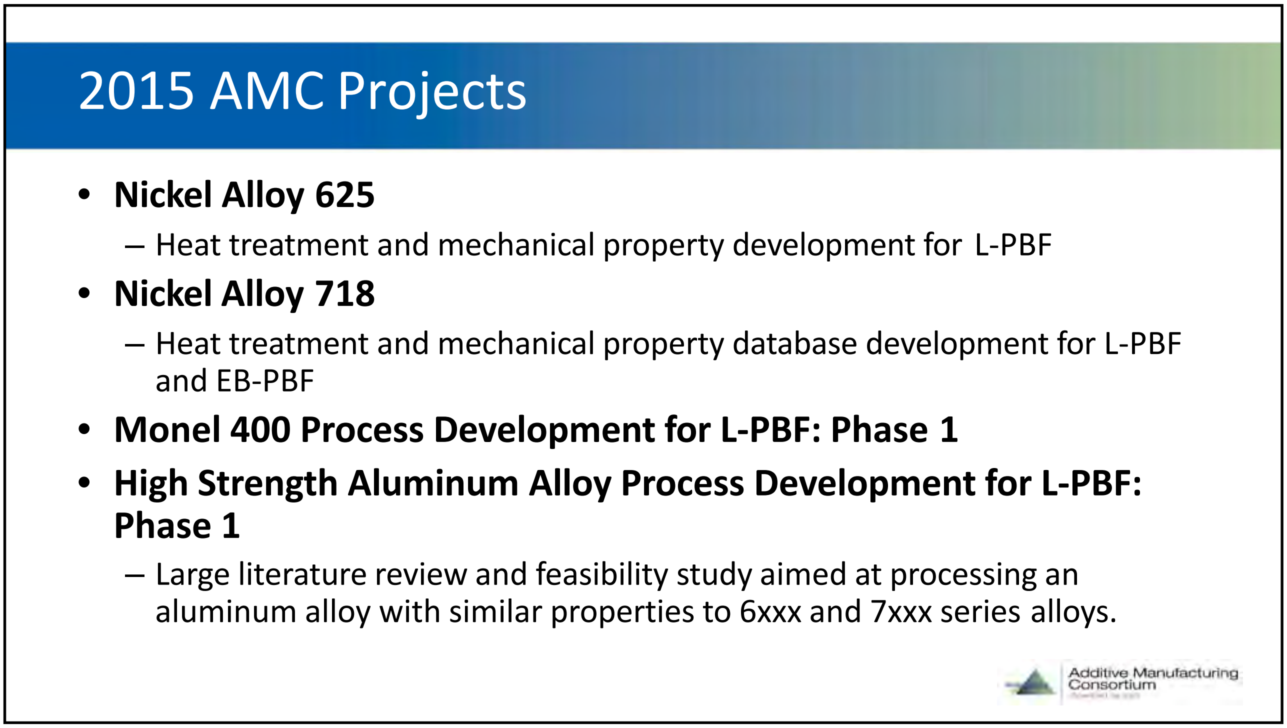

# 2015 AMC Projects

- **Nickel Alloy 625**
  - Heat treatment and mechanical property development for L-PBF
- **Nickel Alloy 718**
  - Heat treatment and mechanical property database development for L-PBF and EB-PBF
- **Monel 400 Process Development for L-PBF: Phase 1**
- **High Strength Aluminum Alloy Process Development for L-PBF: Phase 1**
  - Large literature review and feasibility study aimed at processing an aluminum alloy with similar properties to 6xxx and 7xxx series alloys.

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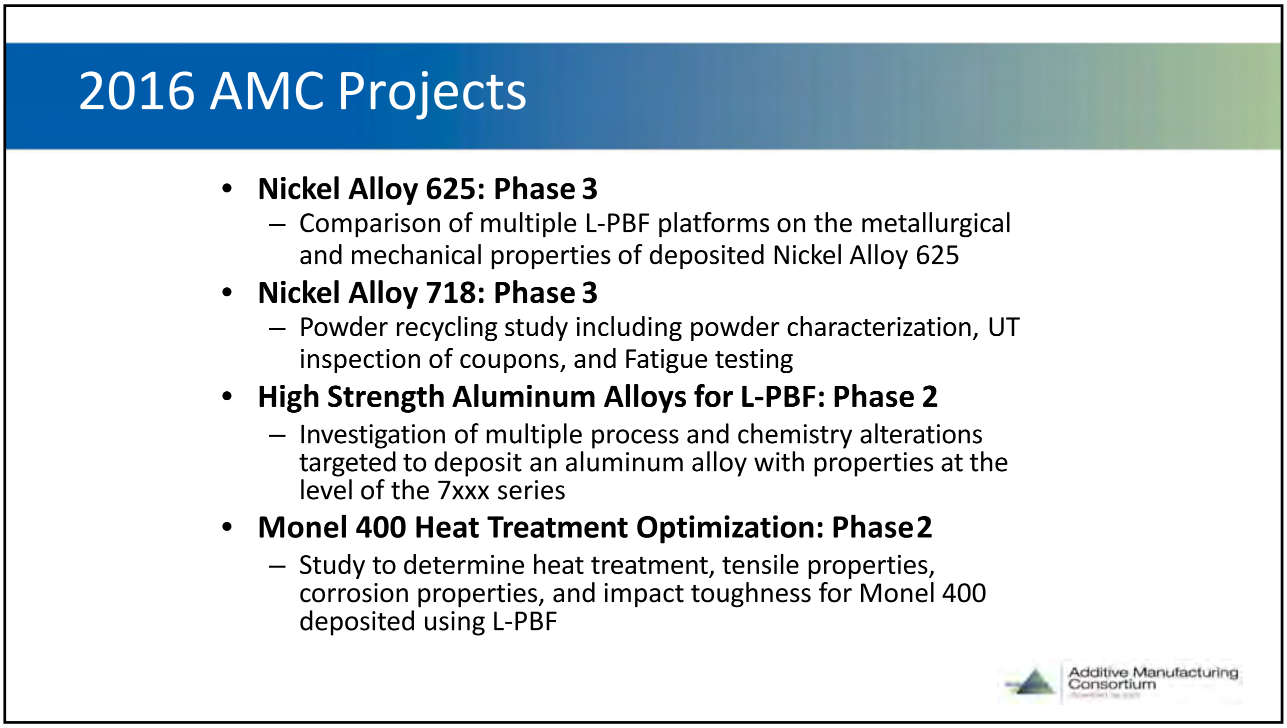

# 2016 AMC Projects

- **Nickel Alloy 625: Phase 3**
  - Comparison of multiple L-PBF platforms on the metallurgical and mechanical properties of deposited Nickel Alloy 625
- **Nickel Alloy 718: Phase 3**
  - Powder recycling study including powder characterization, UT inspection of coupons, and Fatigue testing
- **High Strength Aluminum Alloys for L-PBF: Phase 2**
  - Investigation of multiple process and chemistry alterations targeted to deposit an aluminum alloy with properties at the level of the 7xxx series
- **Monel 400 Heat Treatment Optimization: Phase 2**
  - Study to determine heat treatment, tensile properties, corrosion properties, and impact toughness for Monel 400 deposited using L-PBF

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## 2017 AMC Projects

- **In-Process Monitoring of Defects in L-PBF: Phase 1**
  - In-process monitoring and defect rectification study utilizing multiple sensors
- **High Strength Aluminum Alloys for L-PBF: Phase 3**
  - Heat treatment optimization through metallurgical and mechanical property evaluation for two high strength aluminum alloys
- **AM Powder Recycling and Reconditioning for L-PBF: Phase 1**
  - Investigation of powder recycling and reconditioning through mixing and plasma spheroidization
- **Nondestructive Post-Process Evaluation of AM Components: Phase 1**
  - Evaluation of NDE techniques and their applicability to multiple types of L-PBF defects

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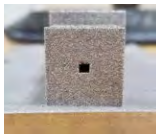
## 2018 AMC Projects

- **Evaluation of Post Process Techniques for AM**
  - Processing a part using 8 post process techniques and comparing results



- **Phase II: In-Process Monitoring & Defect Rectification**
  - Evaluate performance of different repair strategies over varying L-PBF defect modes and levels

- **Continuing Further Testing on Current Projects IN 625 and IN 718 and Relating Microstructure to AM Properties**
  - Effective of chemistry changes from different powder suppliers on microstructure and material properties

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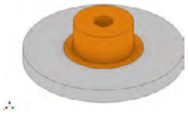
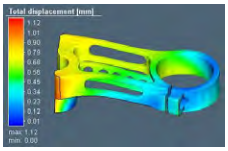
# 2018 AMC Projects



- **DED Multi-material/ Repair**
  - Review of QuesTek Innovations for CALPHAD simulation and then produce a Swagelok component using DED



- **Comparison of Commercially Available AM Simulation Tool**
  - Evaluate software simulation capabilities and performance comparisons. Build a part and compare prediction to actuals

- **Stainless Steel Multi-Process AM**
  - Evaluating microstructure and results of stainless steel parts printed using L-PBF and DED process

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EWI

We Manufacture Innovation

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EWI is the leading engineering and technology organization in North America dedicated to developing, testing, and implementing advanced manufacturing technologies for industry. Since 1984, EWI has offered applied research, manufacturing support, and strategic services to leaders in the aerospace, automotive, consumer electronic, medical, energy, government and defense, and heavy manufacturing sectors. By matching our expertise to the needs of forward-thinking manufacturers, our technology team serves as a valuable extension of our clients' innovation and R&D teams to provide premium, game-changing solutions that deliver a competitive advantage in the global marketplace.

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