U.S. DEPARTMENT OF **ENERGY** | *Office of* **NUCLEAR ENERGY**

# Advanced Materials & Manufacturing Technologies (AMMT) Program on Demonstration of Advanced Manufactured Components in Nuclear Applications

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Ryan Dehoff (ORNL), Andrea Jokisaari (INL), Isabella van Rooyen (PNNL), TALs;

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*2023 NRC Workshop on AMTs for Nuclear Applications*
October 24-26, 2023

**MDF**

# AMMT and ORNL has a demonstrated track record of working with industry to facilitate nuclear demonstrations

- AMMT, like its predecessor at ORNL the TCR program, has and will continue to find tangible scenarios to help and enable developers with its advanced technologies.
  - Working with advanced reactor developers to enhance the design and manufacturing of their components
  - Working with the current fleet of reactors and their vendors to adopt new cost-effective approaches to manufacturing
  - Working with the supply chain to adopt and commercialize TCR manufacturing procedures
  - Teaming to deliver a new accelerated and cost-effective approach to quality certification of additively manufacture components
  - Licensing technology to reactor developers

# AMMT will continue the demonstration of additive manufacturing technologies for nuclear components

**AMMT Nuclear Capabilities:**

- Material Testing

- Component Build & Testing

- Regulatory/Standards Updates

- Qualification Program

- In-situ Monitoring & Digital Qualification

- Modeling

- Industry Partner Demonstrations
    - Framatome
    - Kairos Power
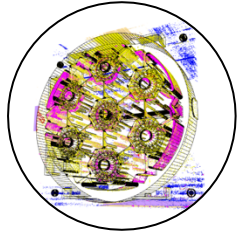    - Westinghouse
    - Future Demonstrations?
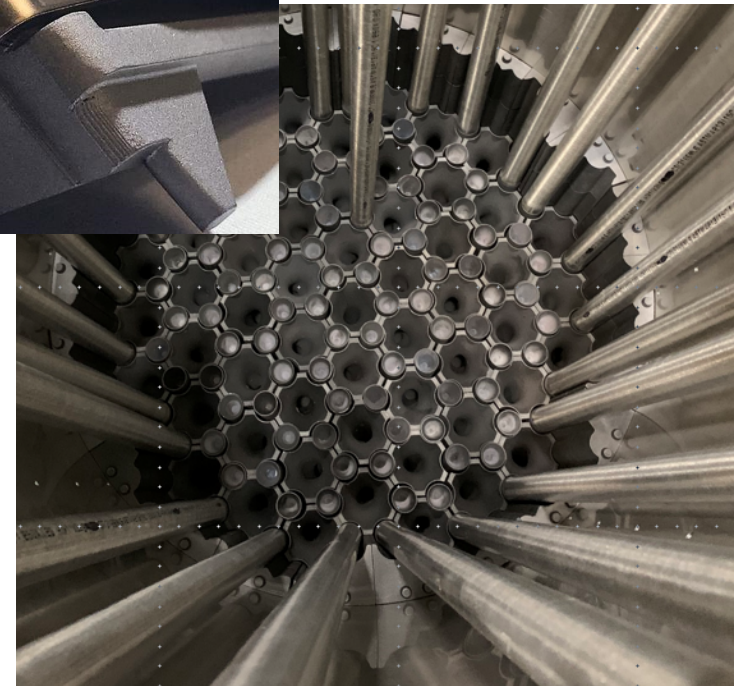
# Framatome Channel Fasteners inserted into TVA's Browns Ferry Unit 2 reactor April 26th, 2021
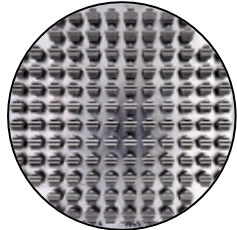


Powder Bed Laser Printing Expertise → MDF Process and Process Understanding from
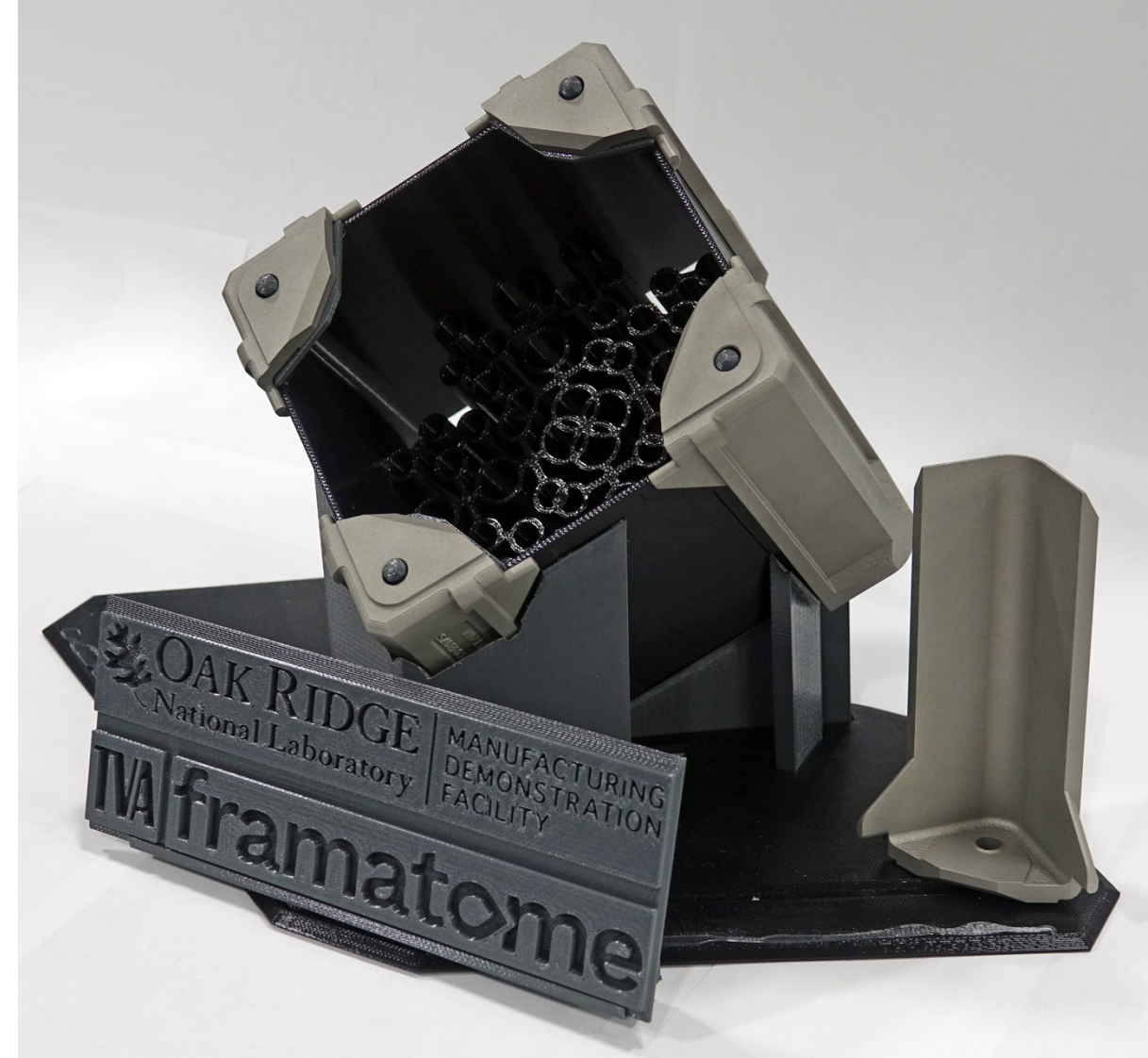
Peregrine → In-Situ Process Monitoring of builds to determine defects
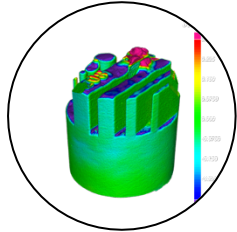
3D Characterization → Leveraged the Zeiss CRADA and ORNL Equipment for full component inspection

*"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."*
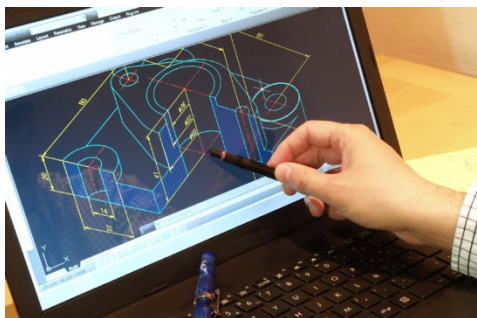
Framatome website (Dec 2020)
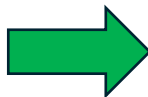
# Challenges:

- Geometric Accuracy
  - Build layout effects accuracy
  - Surface Finish, Machining Required
  - Conversation between design and manufacturing

- Process Optimization
  - Material Testing
  - In-situ Monitoring & Digital Qualification

- Regulatory/Standards Updates

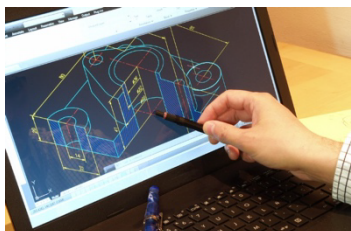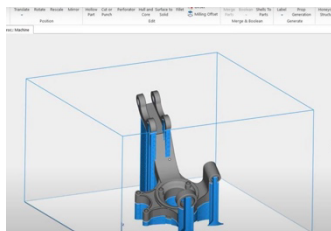- Qualification Program
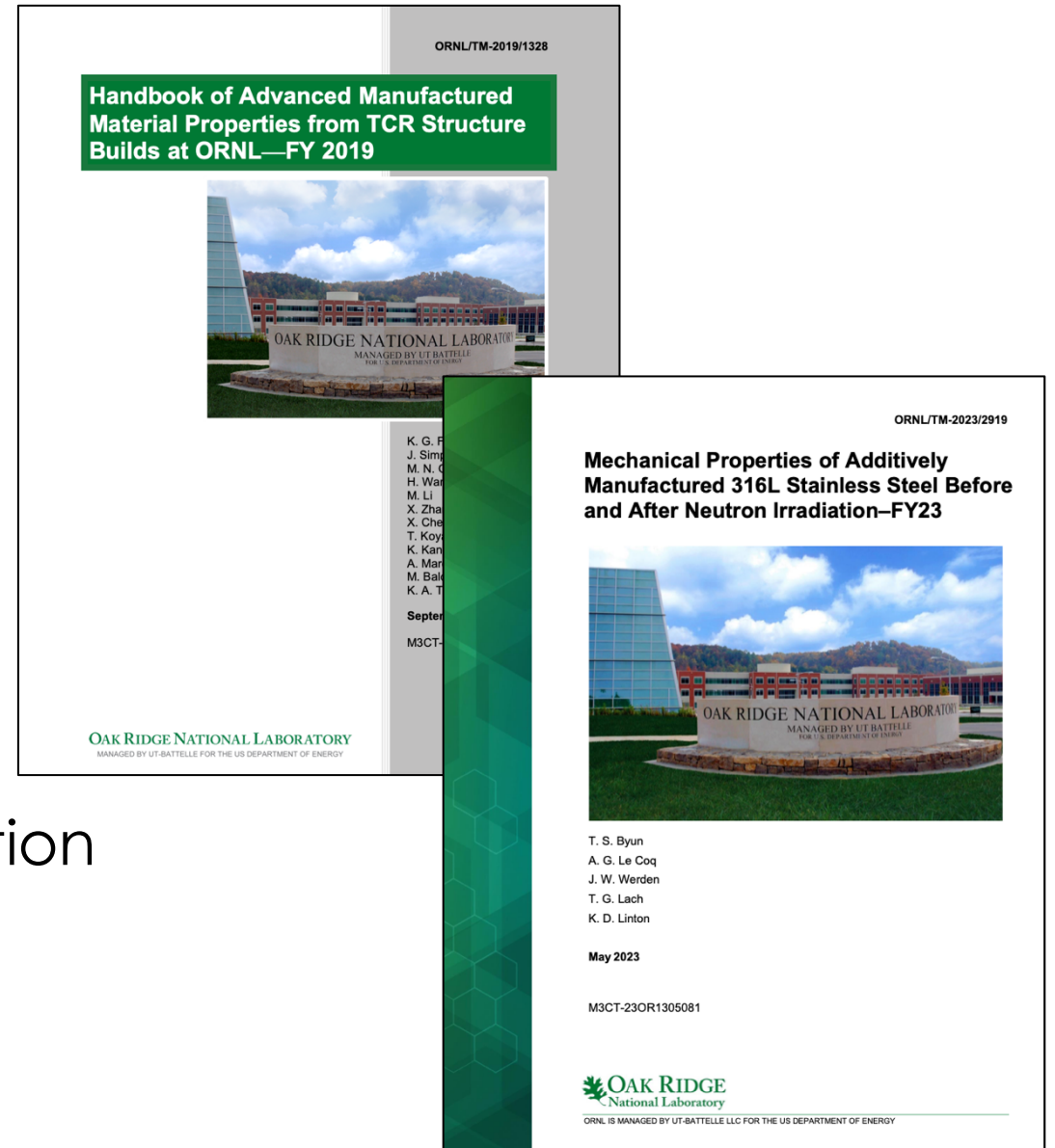
**What You See**
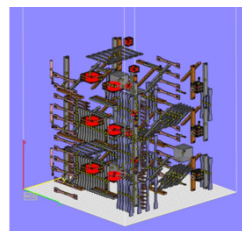
Design → Plug & Play → Final Part
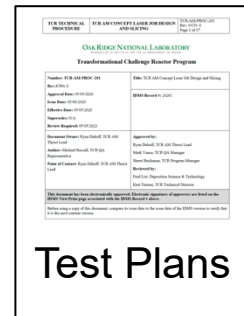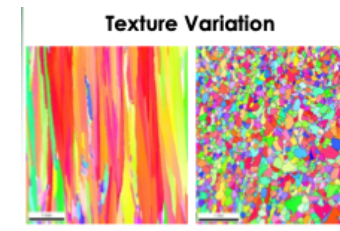
**Reality**

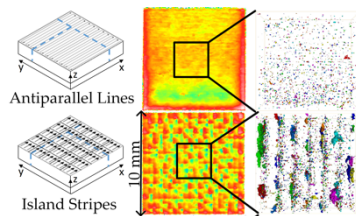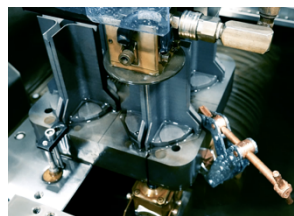Design · Supports · Additional Samples · Test Plans · Feedstock Variability · Microstructure Variability

Process Parameters · Post Heat Treatment · Machining · Inspection · Cleaning & Packing · Insertion
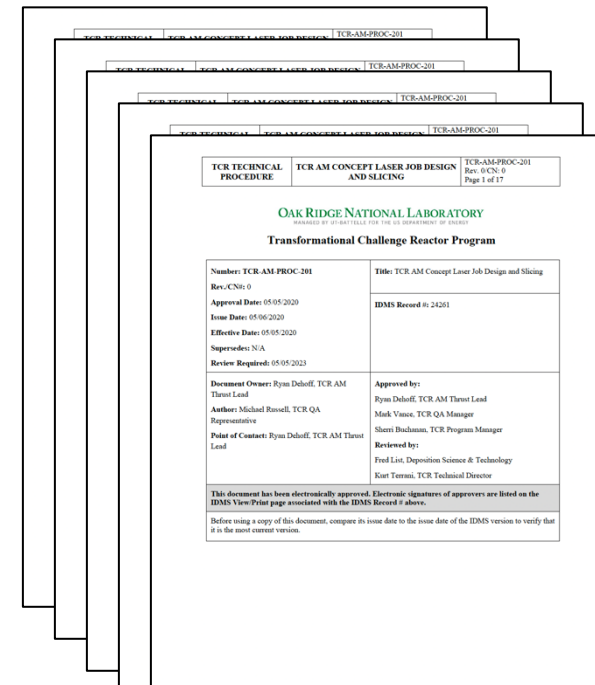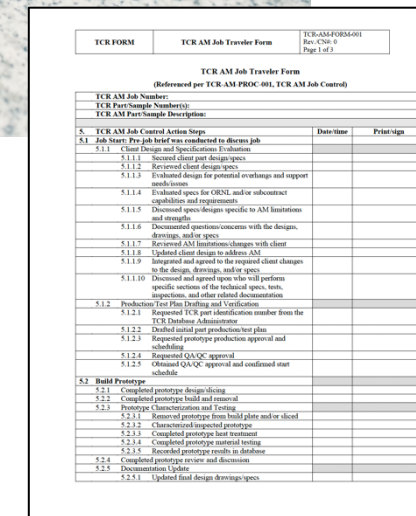
# AMMT Updates to TCR AM Qualification Program:

## AMMT Nuclear Qualification Program:

- ASME NQA-1 Quality Program
  - TCR Version used to Qualify Framatome Part

- NQA-1 Quality Assurance Plan
  - Update published in September 2023

- NQA-1 AMMT Specific – Procedure Set
  - Technical & Administrative
  - AM Machine & Process Specific
  - Powder Management
  - Post-Processing
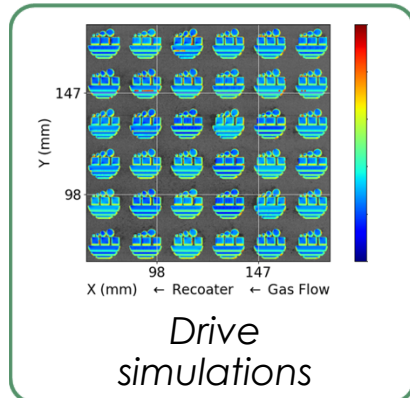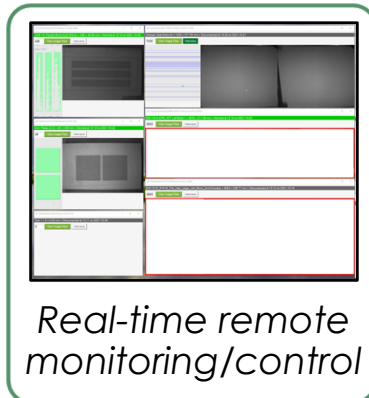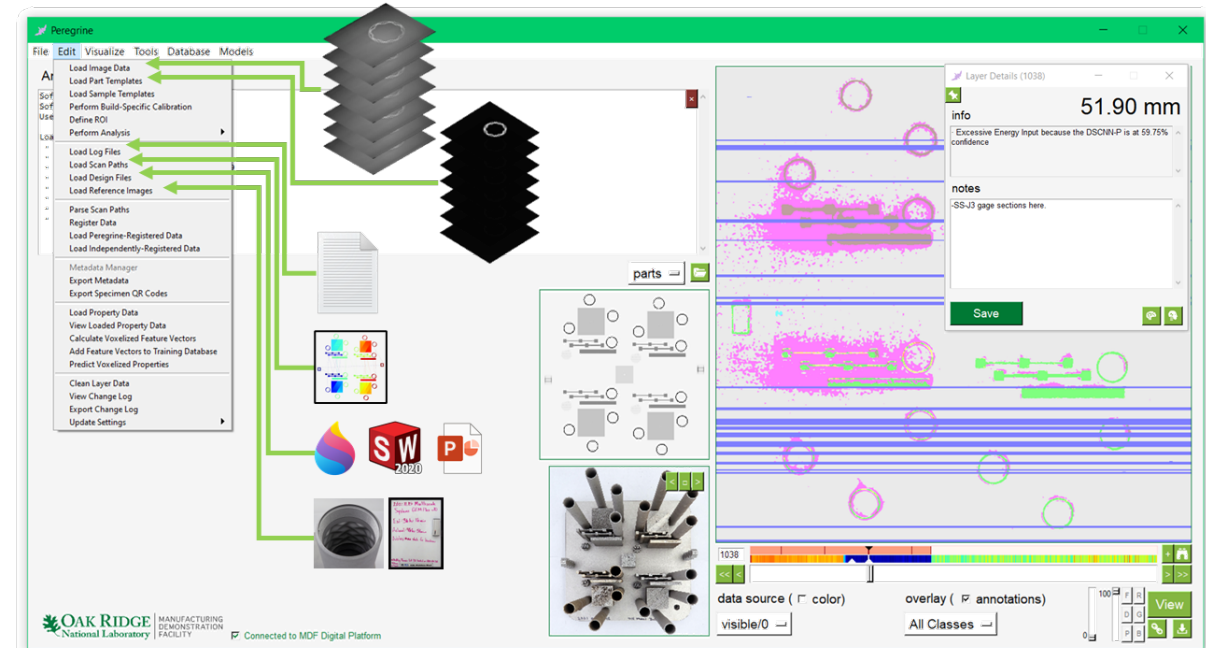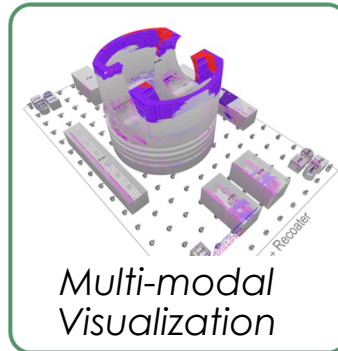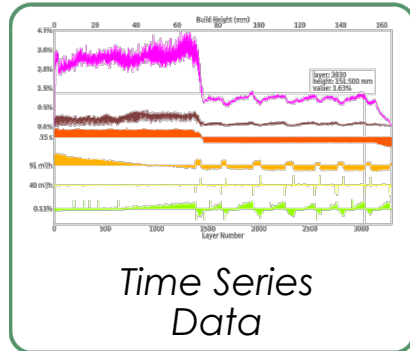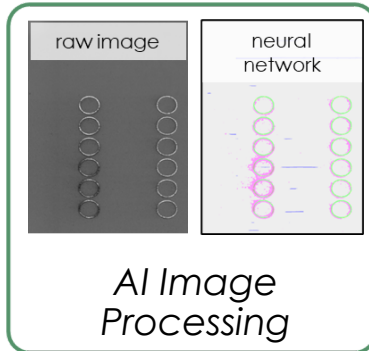  - Production & Test Planning
  - Conformance
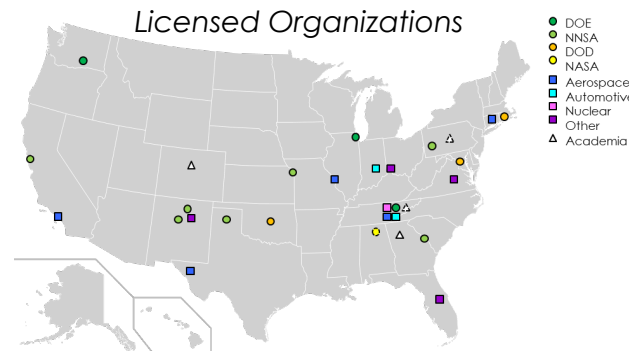
# MDF Digital Factory: Peregrine

## A software platform for collecting, annotating, analyzing, and visualizing AM data

- Utilizes artificial intelligence to classify process data

- Correlations with location specific testing and characterization data

- Enables simulation of AM processes


AI Image Processing


Time Series Data


Multi-modal Visualization


Real-time remote monitoring/control


Drive simulations



## Peregrine Usage Impacting the U.S.


Licensed Organizations

- DOE
- NNSA
- DOD
- NASA
- Aerospace
- Automotive
- Nuclear
- Other
- Academia

**13** U.S. government labs using and developing

**12** R&D licenses granted

**3** CRADAs have leveraged *Peregrine*

**2** universities using Peregrine for R&D

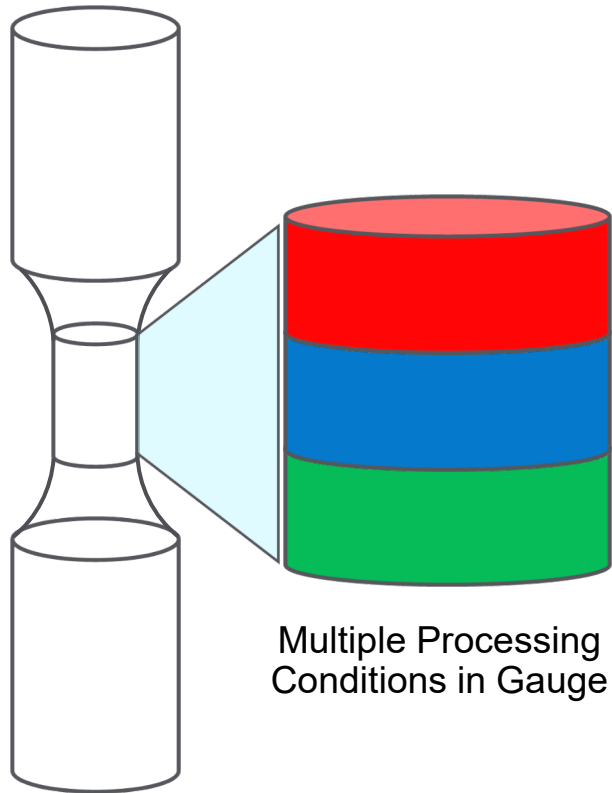**15+** organizations using **100+ GB** of in-situ data

**5** journal papers and **1** U.S. patent

# Peregrine used for Build/Process Optimization
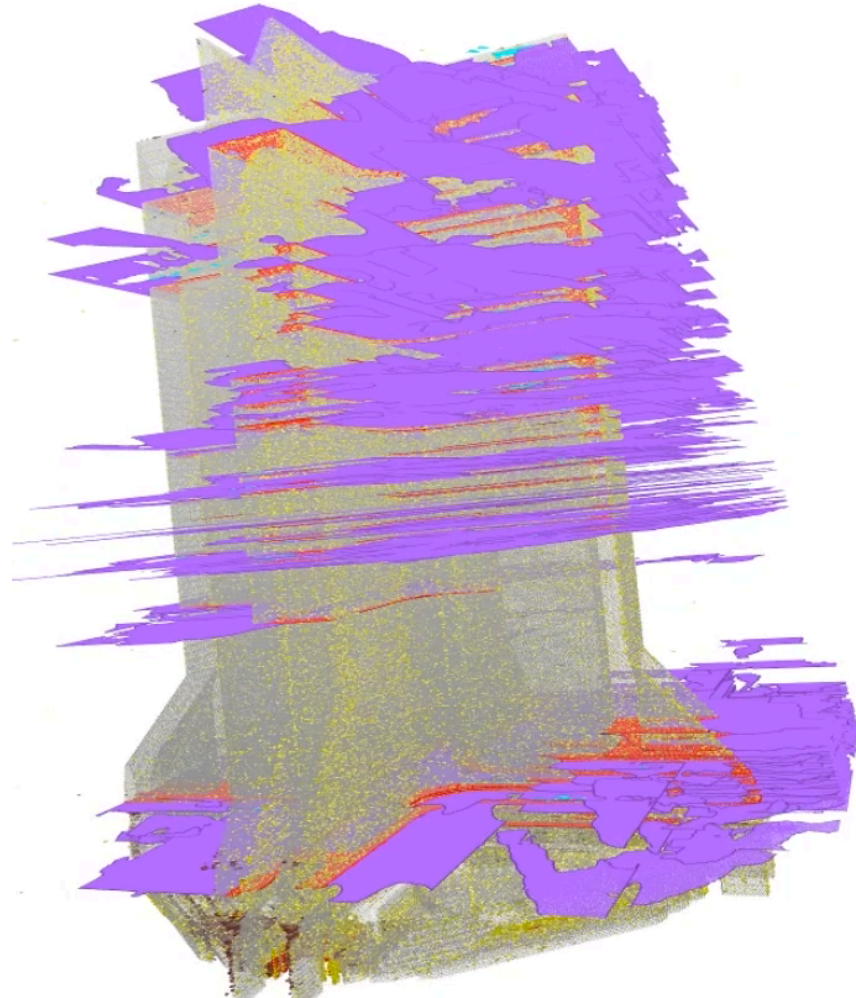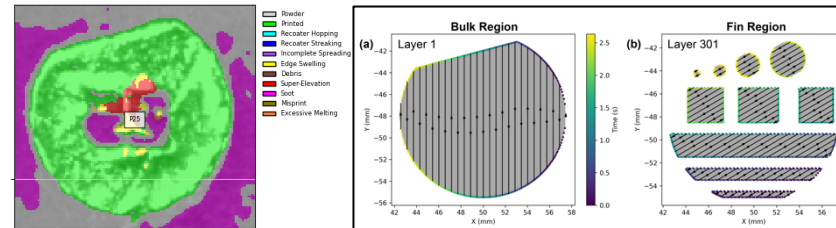
# AMMT Challenge Problem: Rapid Qualification

Understand our ability to predict the creep performance for a coupon with spatially varying microstructure and identify shortcomings of rapid qualification of 316H

**Multiple Processing Conditions in Gauge**

**Digital Image Correlation AM Creep Specimen**

### Data Captured During Build

### Post Inspection: Destructive & NDE
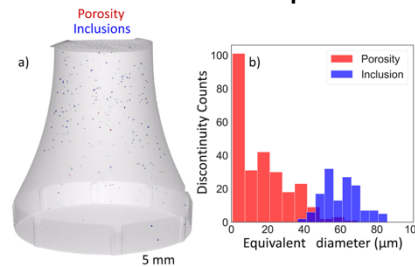
1. Computed Tomography
2. Ultrasonic Investigation
3. Microstructure Evaluation

### Models for Microstructure Prediction Across Scales
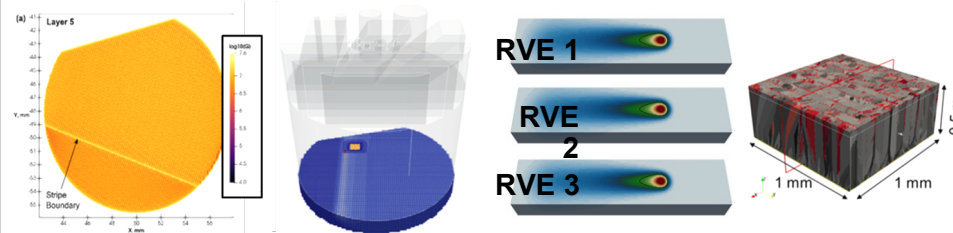
### Creep Performance Prediction

- Crystal plasticity finite element discretization
- Microscale deformation and stress
- Macroscale predicted creep anisotropy

**How Close are We?**
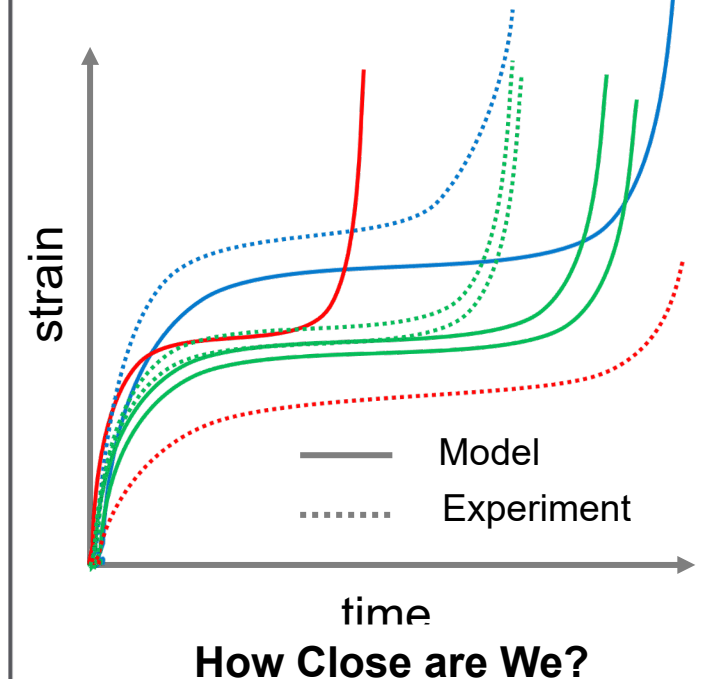
# Powder Metallurgy via Hot Isostatic Pressing
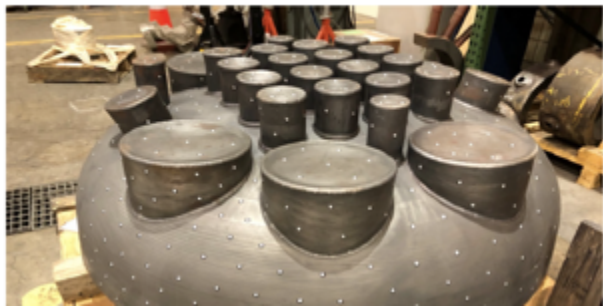


**The Pressure Vessel**
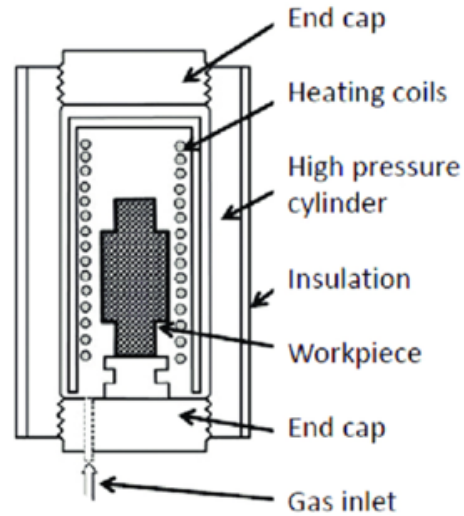


**HIP CAN**



**Typical Pressure-Temp-time cycle**

# Large-scale Metal Capabilities

OAK RIDGE
National Laboratory
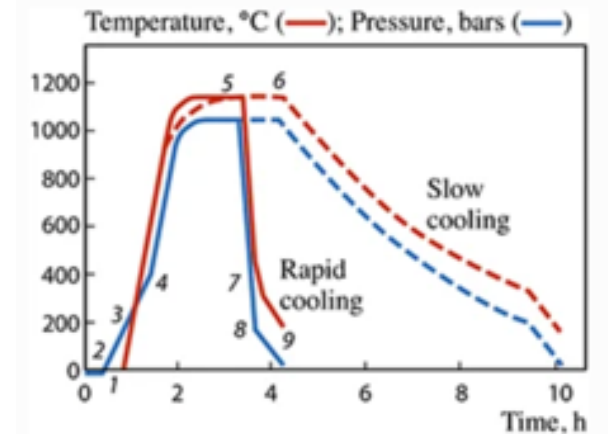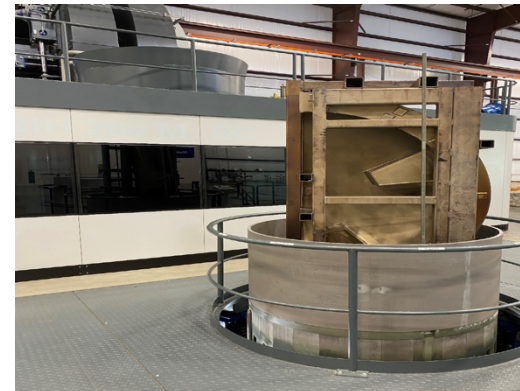
## Lincoln Wire Arc

- ABB 6DOF arms and 2DOF positioners
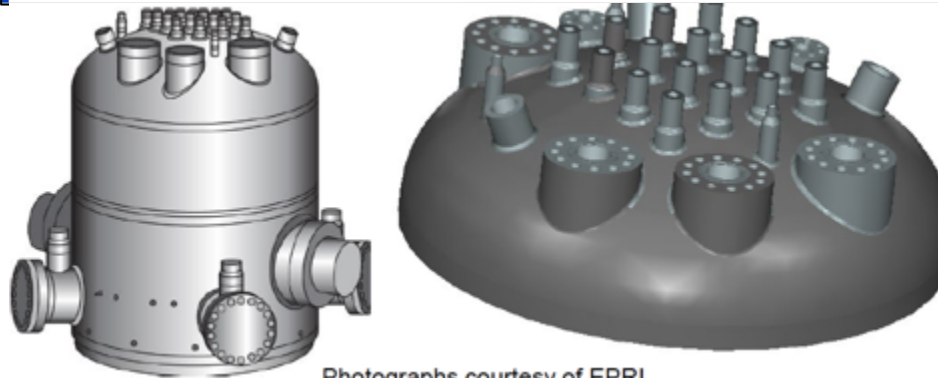- Lincoln Electric Welders
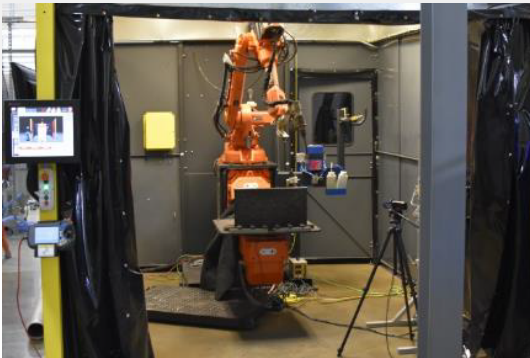
## GKN Cells 1 and 2

- Kuka 6DOF arms and 2DOF positioner
- Laser-wire
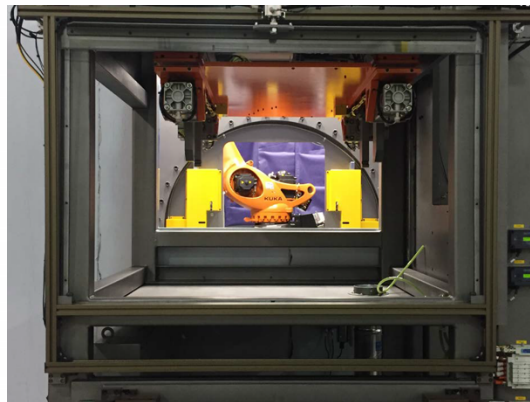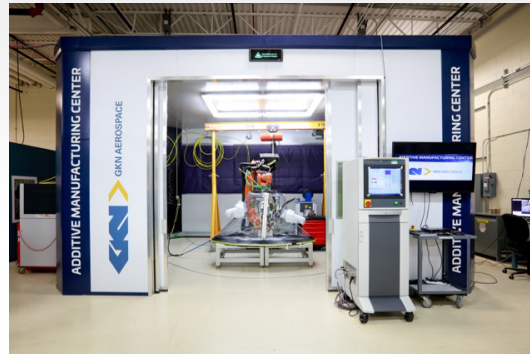
## Hybrid Systems

VC500A/5X AM HWD
　Laser Hot-Wire
　Serial #1
MU-8000V LASER EX
　Blown-Powder
　TRUMPF Laser

OKUMA
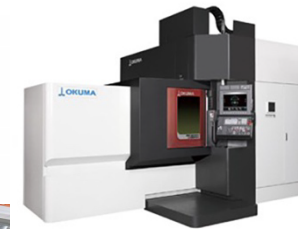
Mazak

## Custom Systems

- MedUSA: Multi-agent, coordinated deposition
  - 3x ABB 6DOF arms and1DOF table
  - 3x Lincoln Electric welders
- Operando Neutron Deposition
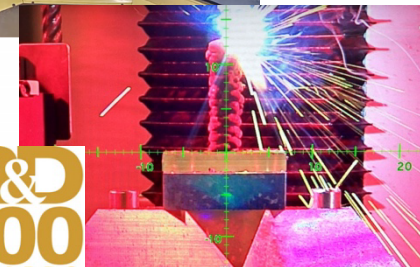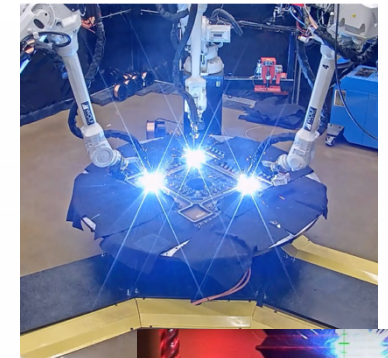
# Laser-Wire DED Background at MDF

- Replacement technology for custom forgings and billet
- **Drivers:** Lead time, cost, and buy-to-fly ratio (10:1 to 2:1)


Printed Preform


½ Machined Demo Part


Notional Spar Demonstrator
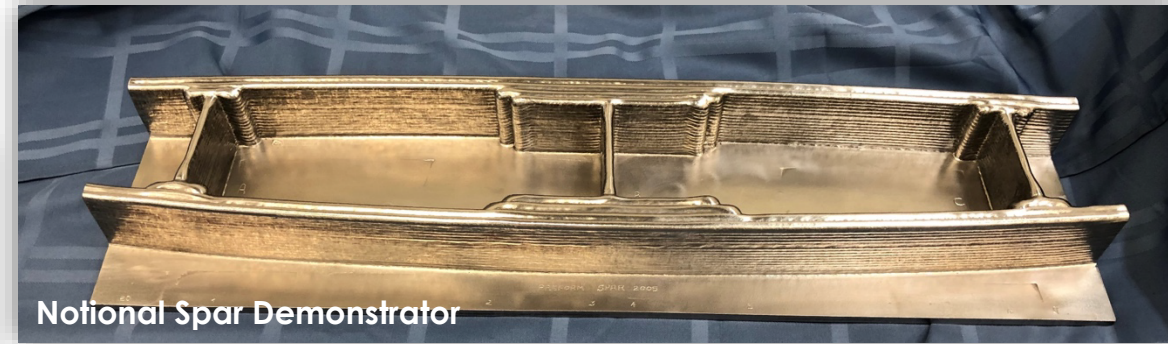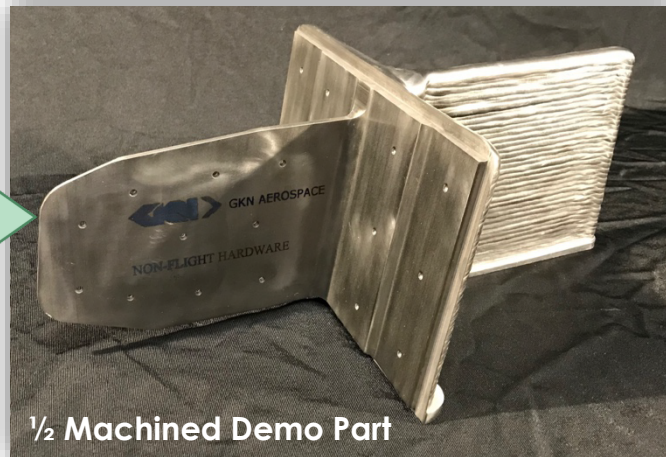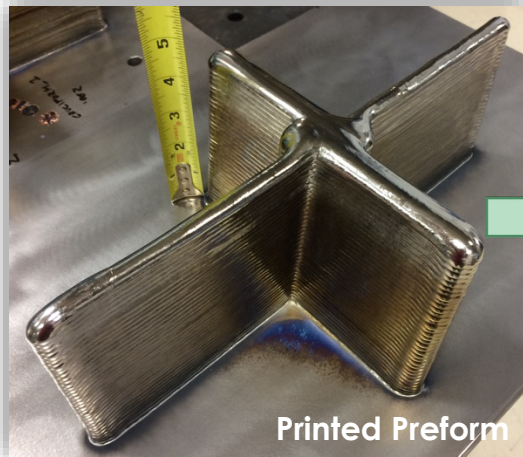
## Why Laser-Wire?

- Highly controllable (heat source ← → feedstock)
- Excellent surface finish for post-print machining
- Medium system cost

## System Specs:

- 20 kW laser power
- 8 DOF motion
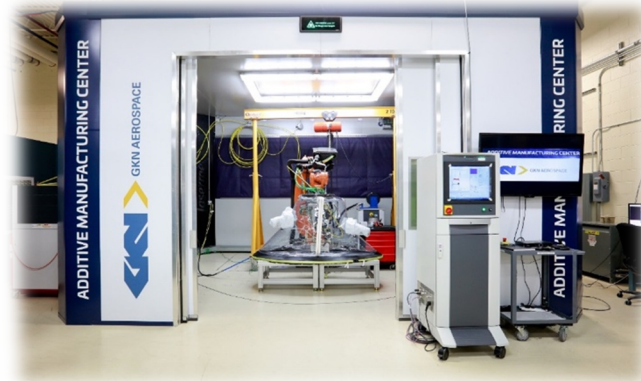

**Cell 1: R&D**


**Cell 2: Pilot Production**

OAK RIDGE
National Laboratory

Open slide master to edit

# Large Scale Aerostructure Demonstrator, ~96" long, >100 lbs Ti64
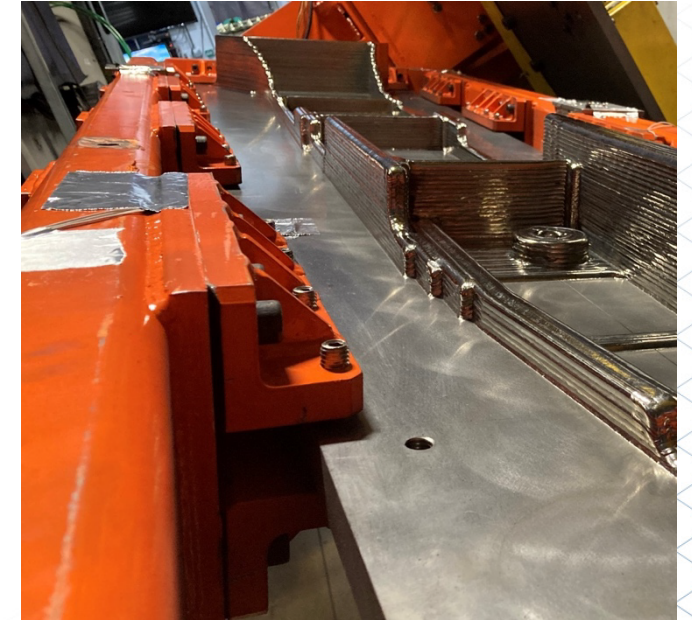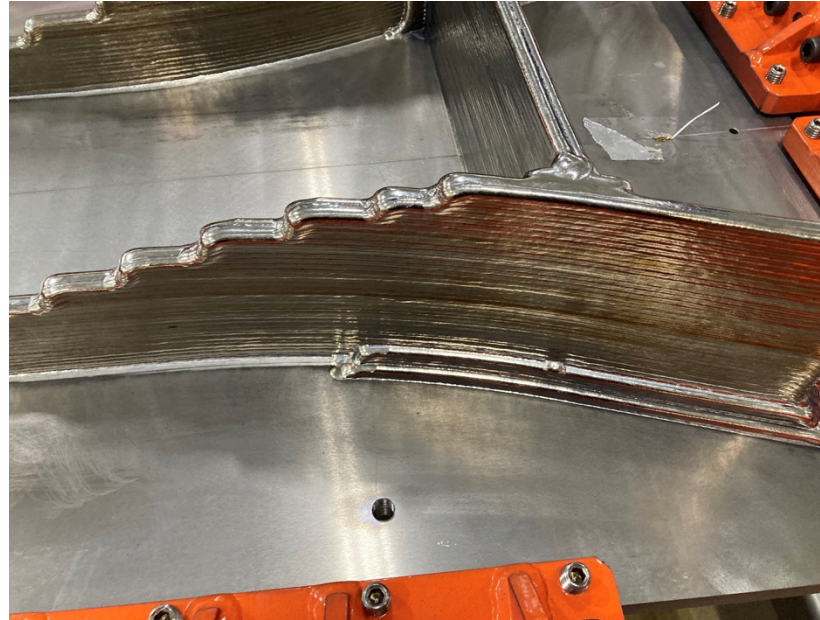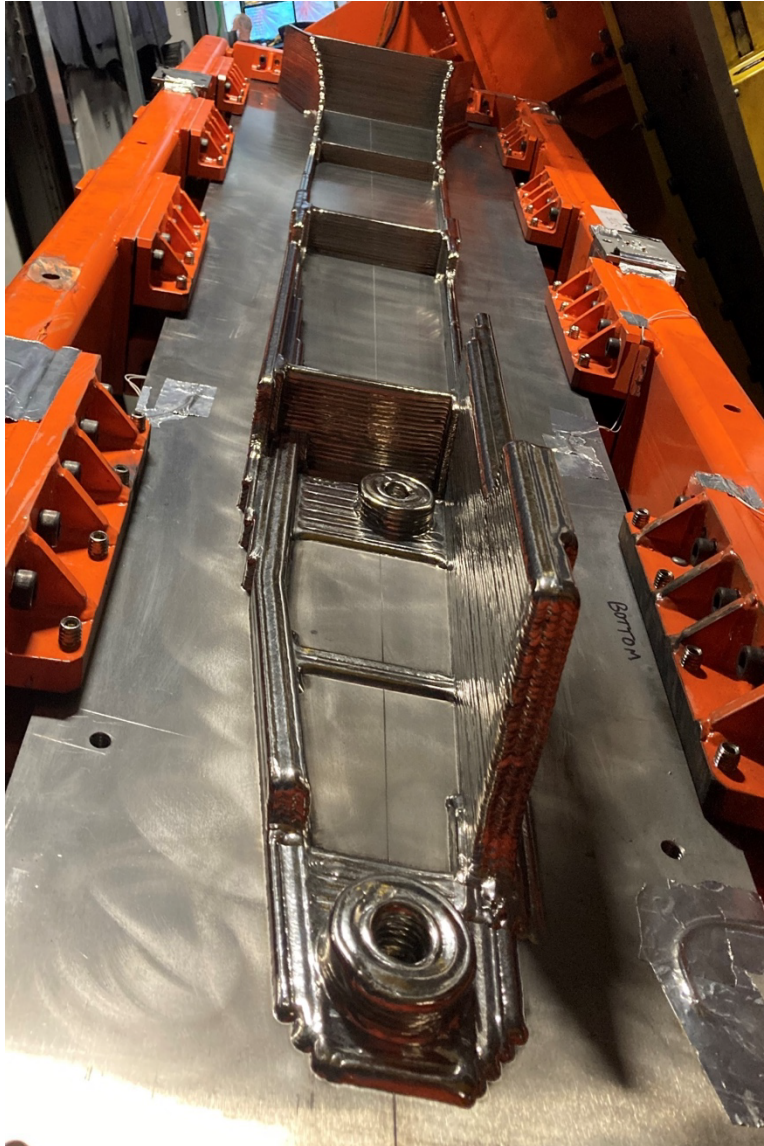
# Monitoring Snapshot: Laser-Wire Cell 1

In-Axis Visible Melt Pool Camera

In-Axis NIR Melt Pool Camera

ISO View IR Camera

Stereo-Vision DIC Cameras

Interlayer IR Camera

2D Laser Line Scanner

Thermocouple Array

OAK RIDGE
National Laboratory
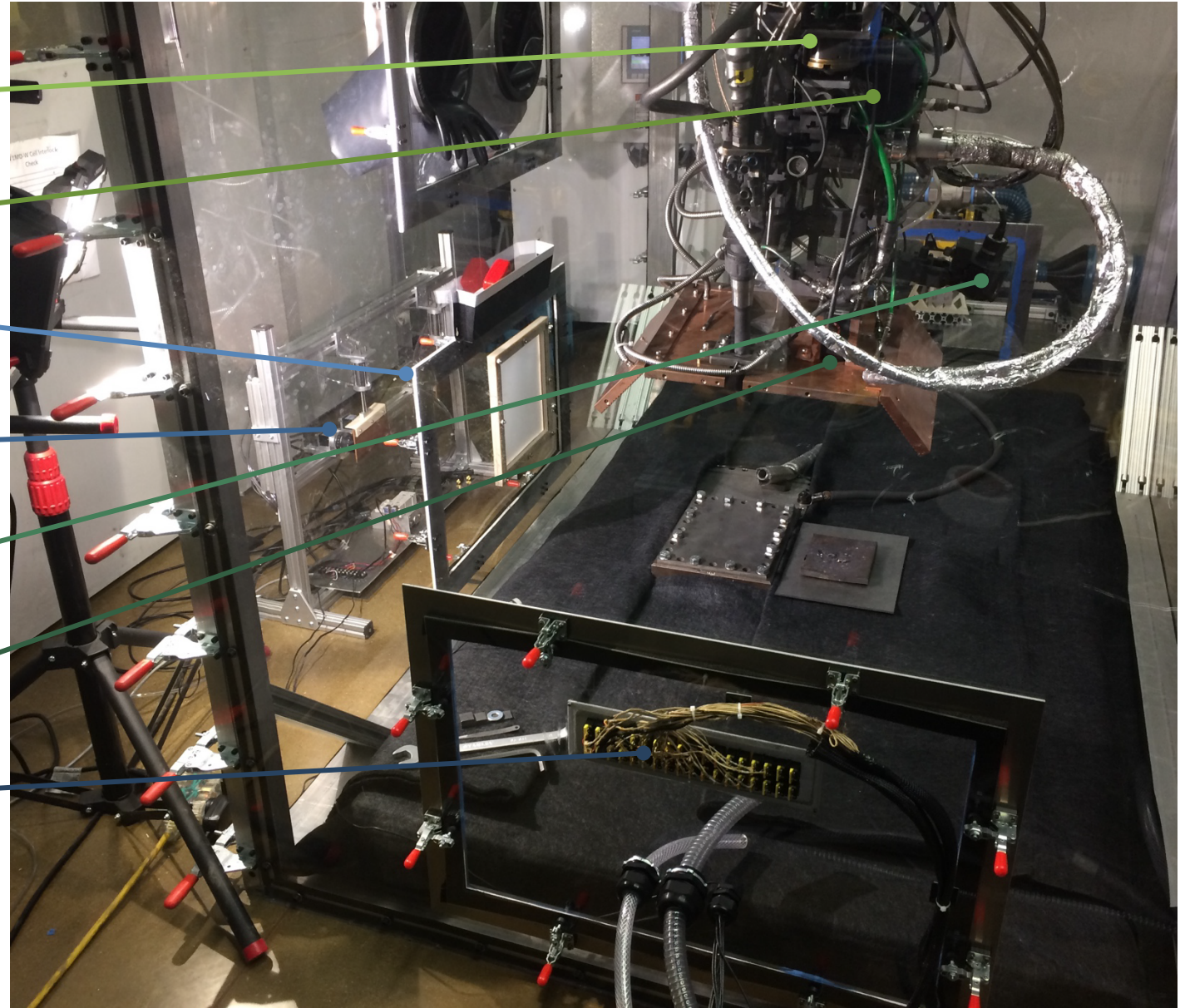
# Laser-Wire Process Control

*"Heartbeat" Toolpath*



Robot Position Within Toolpath



Thermal Control Response



Overview Camera
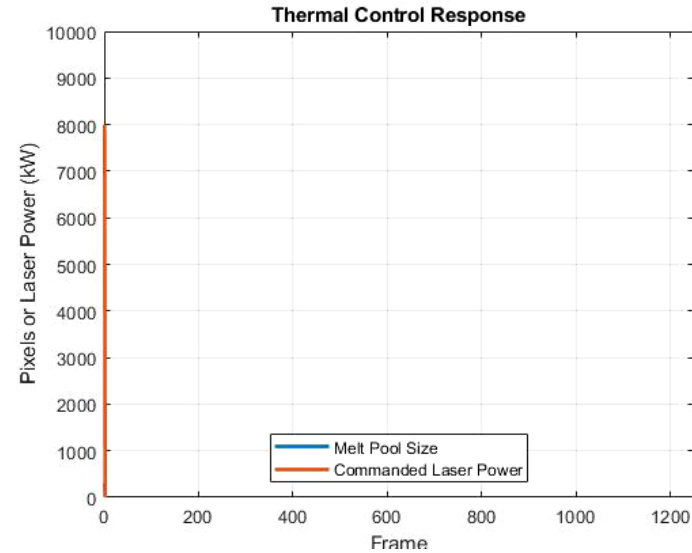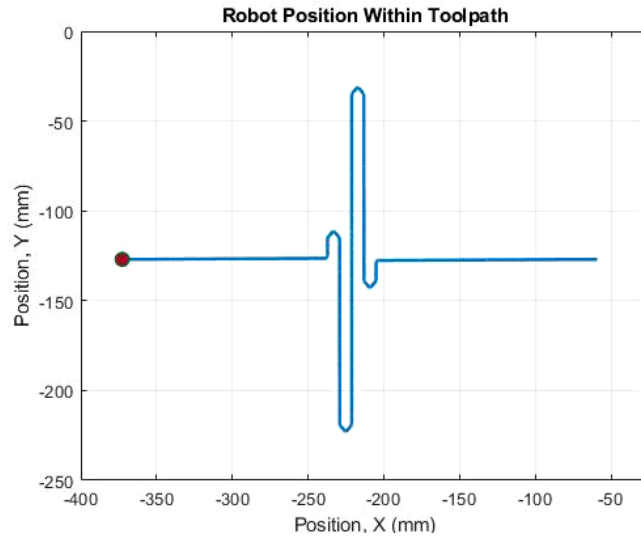


**Process Camera**



**Thermal Camera**
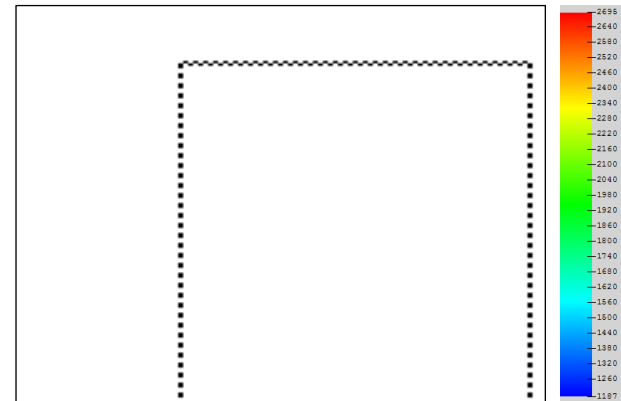
Outside Melt Pool Definition

Outside Measurement Window

Melt Pool Definition

16

Open slide master to edit
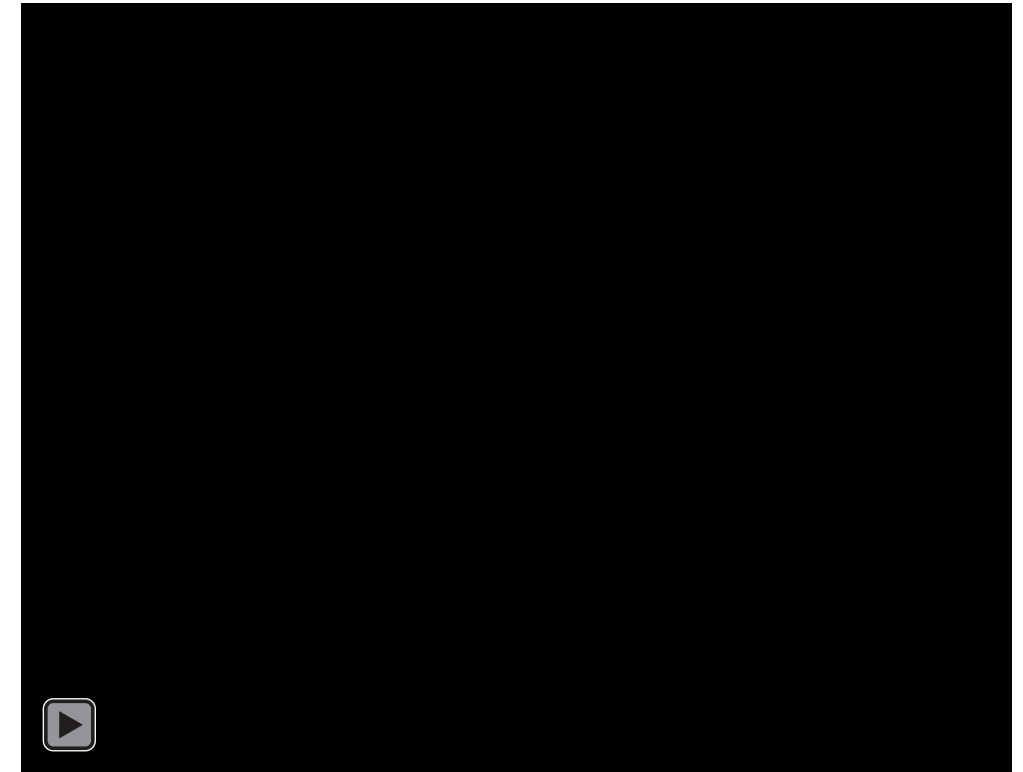
# In-situ Monitoring Assisted Large-Scale AM of Mild Steel and 316L Alloys For Nuclear Application

*Hybrid AM and WAAM, In-situ Monitoring and Largescale distortion modeling teams*

**Objective:** Feasibility Demonstration and Post-HIP Assessment of AM Pressure Vessels

## Scientific Achievement

- Successful Fabrication of HIP Cans via 3 unique AM modalities – Processing data collected
- Completion of full-scale HIP trial for WAAM can

## Impact & Potential Application Space

- Large Scale Nuclear Comp- SMR head, t- Valves
- Other Energy applications – Renewables, O&G

## Details

- Learning as we build – Hybrid AM vs WAAM vs Blown Powder DED
- Data acquisition – melt pool, IR + visual camera, thermocouple
- Metallurgical and Mechanical assessment is key



*CAD to Part (Non-Symmetric) via Hybrid AM (Laser Hot Wire)*



*Successful HIP-ing of Concentric WAAM HIP can*

# Interdisciplinary Multi-Process Challenge
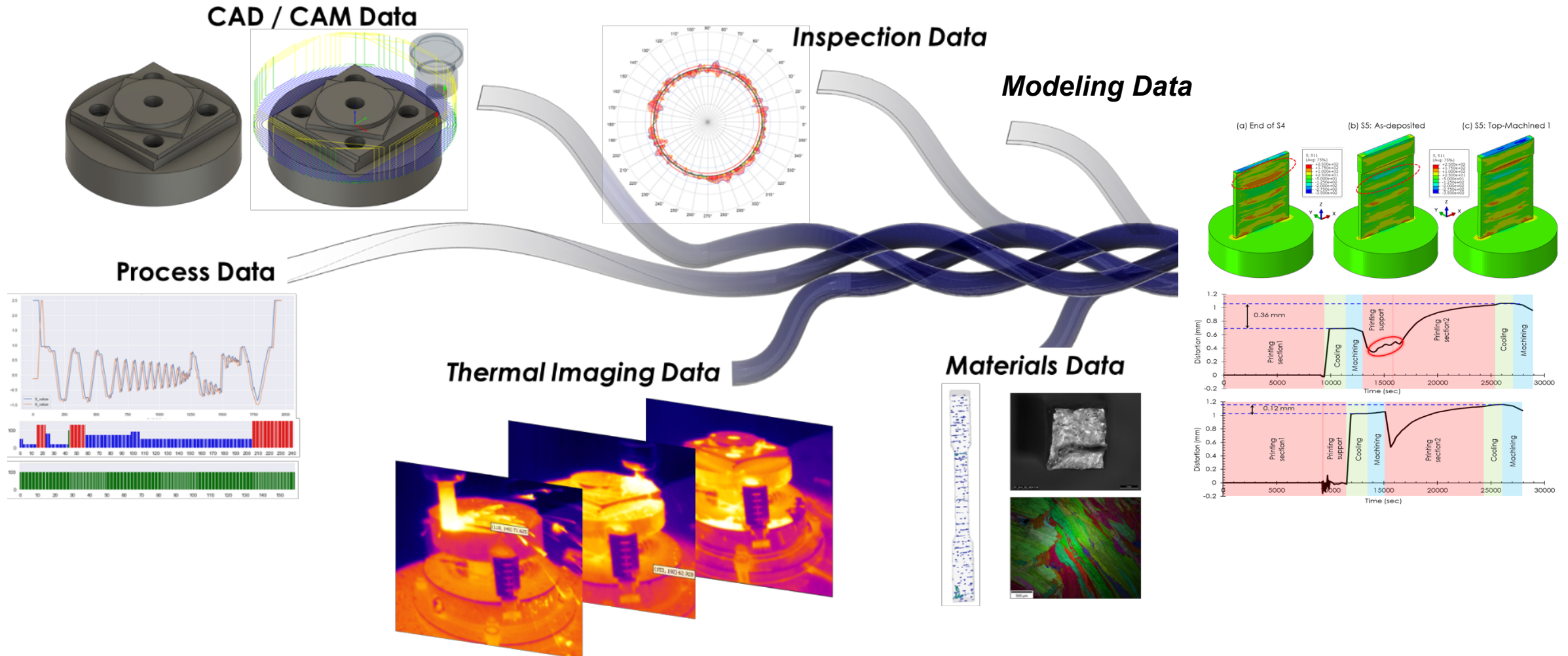


Feldhausen, Thomas, Kyle Saleeby, and Thomas Kurfess. "Spinning the digital thread with hybrid manufacturing." *Manufacturing Letters* 29 (2021): 15-18.

# Nuclear Part Demonstration Process:

- Program Planning
  - Is Part Right for AM Demonstration?
  - Schedule for Development/Licensing
  - Production/Qualification Plan

- Design/Engineering
  - Design for AM Optimization
  - Fabrication Demonstration
  - Finalize Design & Specifications

- Fabrication/Qualification Plan
  - AMMT Specific
  - Customer Developed



TVA
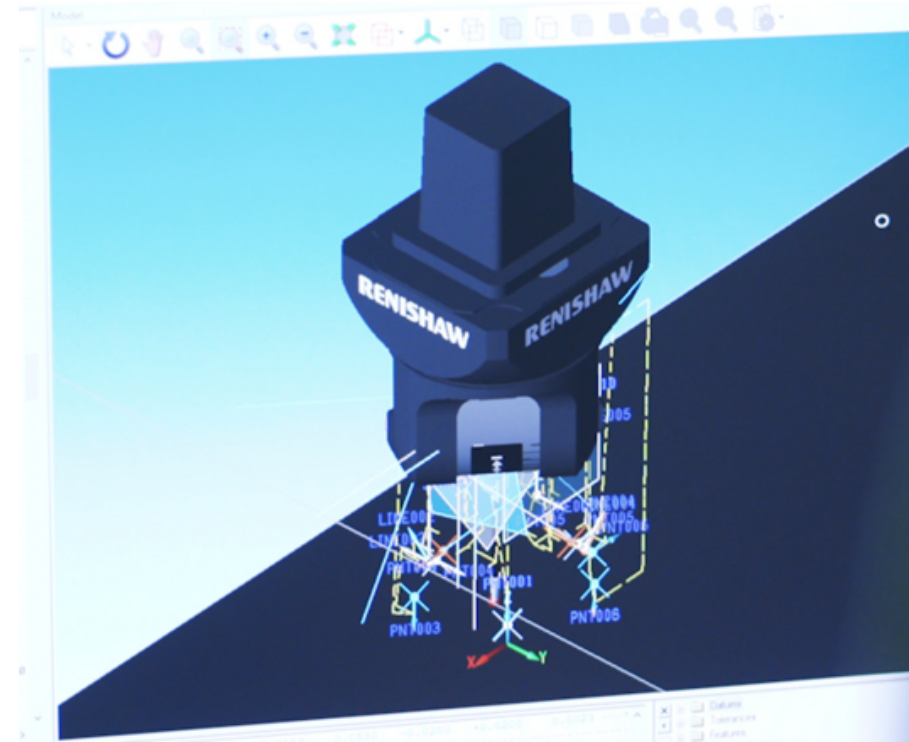
framat○me

# Nuclear Part Demonstration Process (cont'd):

- **AMMT Fabrication/Qualification Plan:**
  - Material Acquisition/Controls (powder/wire)
  - Part Fabrication
  - Post Processing
  - Testing (in-situ, destructive, NDE)
  - Qualification (built into every step)
    - Fabrication/Quality Traveler
    - Quality Hold-points
  - Packaging & Shipping
  - Certification of Conformance
- **Customer Licensing/Qualification Plan:**
  - Inputs to Customer Qualification Plan/Report
  - Licensing/Regulatory Support
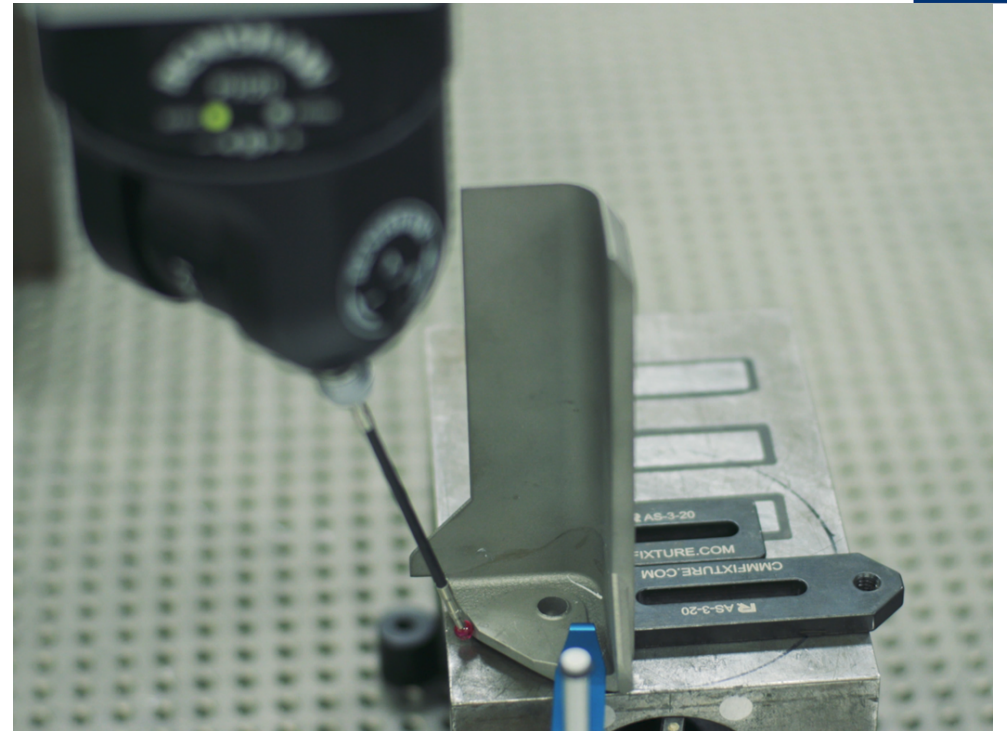
# Nuclear Part Demonstration Process (cont'd):

- **Demonstration Part Fabrication:**
  - Fabrication Team Training & Qualification
  - Pre-job Brief – Review of Fab/Qual Plan
  - Part Fabrication
  - Post-Processing (heat treat/machining)
  - Quality Checks/Inspections (integrated)
  - Testing
  - Customer Observation/Integration in process
  - Certificate of Compliance

- **Customer Licensing/Qualification Plan:**
  - Inputs to Customer Qualification Plan/Report
  - Licensing/Regulatory Support



TVA
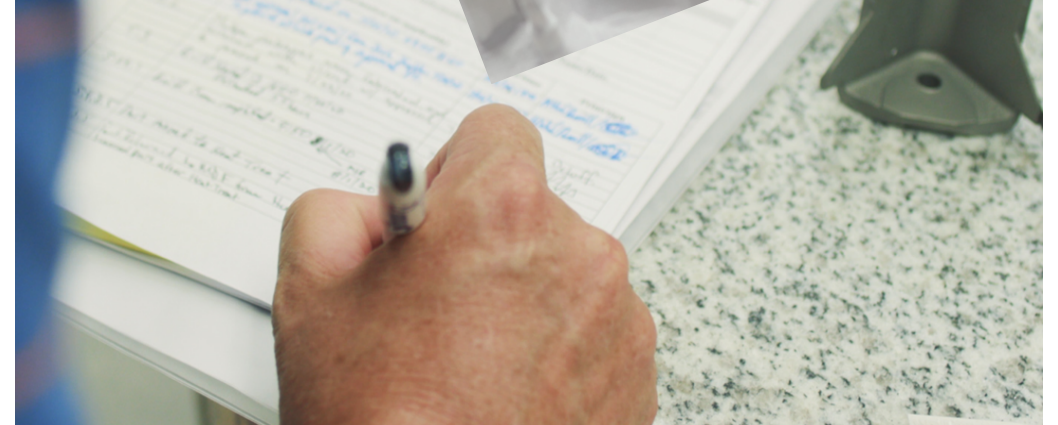
framatome

# Questions

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# Rapid Pedigree X-ray CT Data Pipeline



364-19 (Keyhole)   365-23 (Optimum)   365-41 (LOF)

Porosity (%)

Power(W)

Velocity(mm/s)

Hatch(mm)
- 0.05
- 0.1
- 0.15
- 0.2
- 0.25
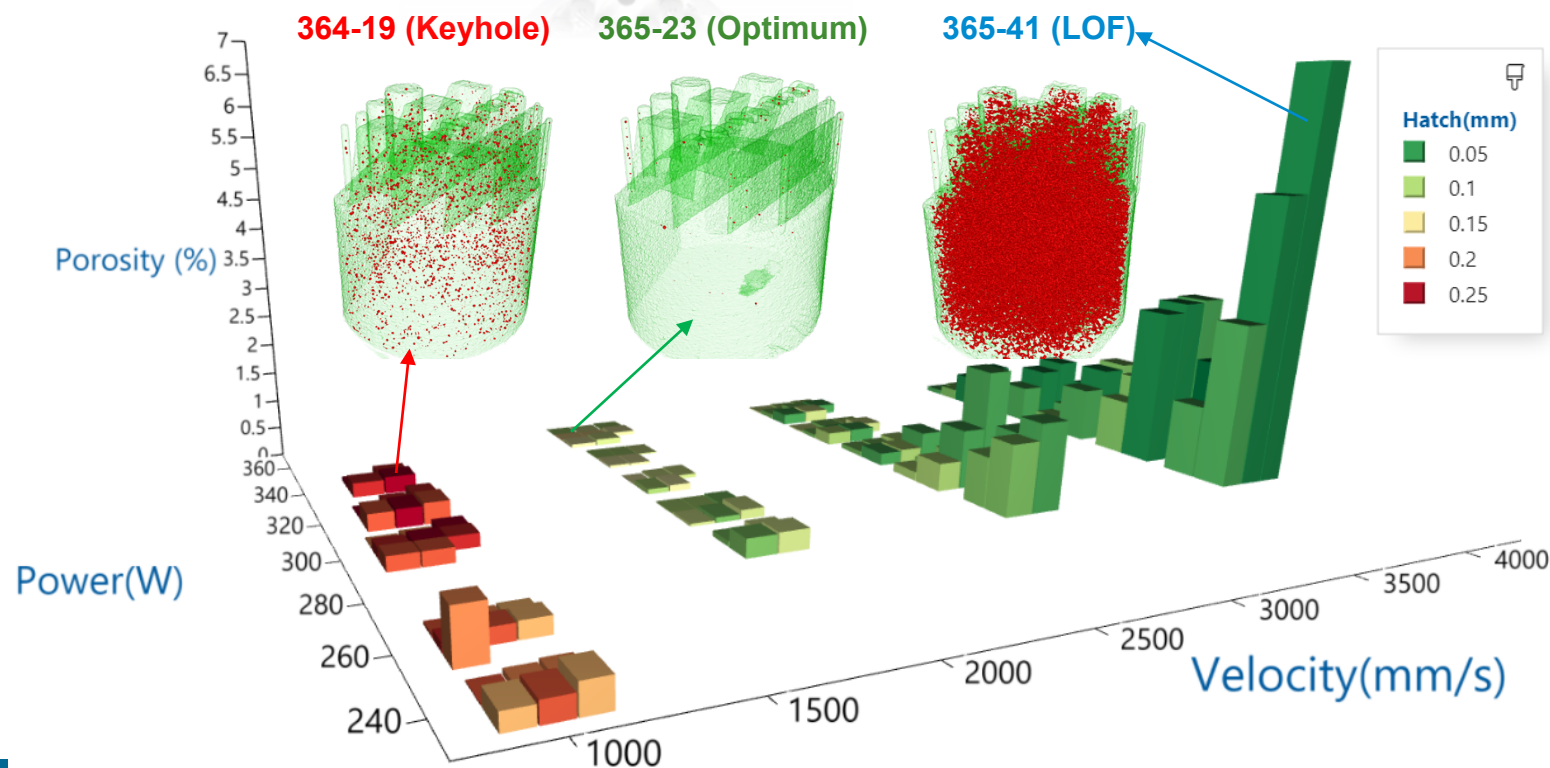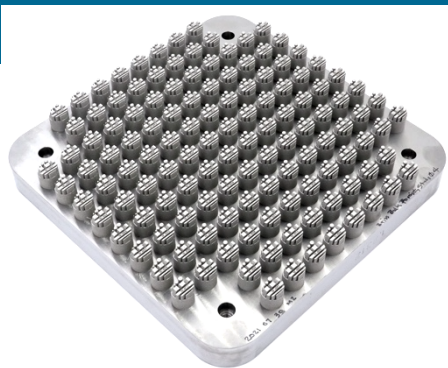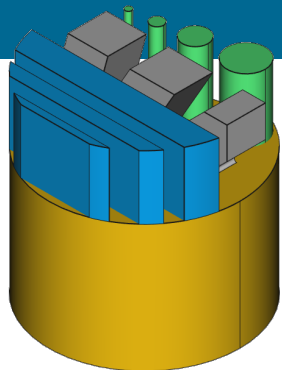
Pedigree Data for Visualization, AI & ML & Validated Informatics

365-41 (LOF)   364-19 (Keyhole)   365-23 (Optimum)

Velocity(mm/s)
- 1000
- 1500
- 2000
- 2500
- 3000
- 3500
- 4000

Visualization of Data
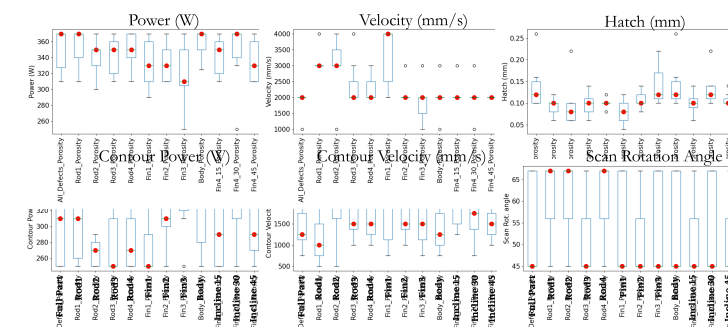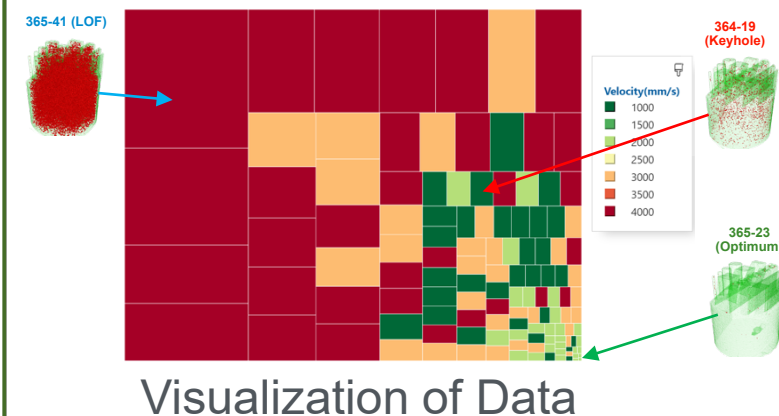
Preliminary Correlation

# Using ML to Classify Simulated Process Data

**Alex Plotkowski**, Gerry Knapp, Jamie Stump, John Coleman, Matt Rolchigo
*Process Modeling and Variability in AM 316 SS (CR-22OR040304)*

## Scientific Achievement

- Used unsupervised machine learning methods to classify simulation data for AM melt pools.
- Experimentally validated model and ML predictions.

## Impact & Potential Application Space

- Enables rapid determination of variability in AM components.
- Relevant for accelerated qualification of AM nuclear components.

## Details

- Solidification predictions as a function of scan path made using 3DThesis.
- Multi-level classification to relate sub- and inter-melt pool behavior to anticipated solidification microstructures.
- Extensive EBSD for a representative 316 SS sample used for validation.
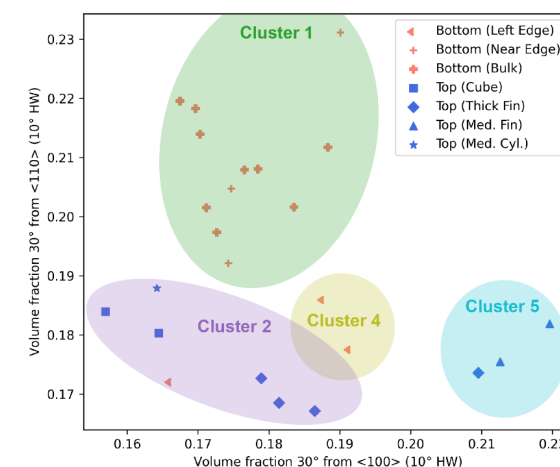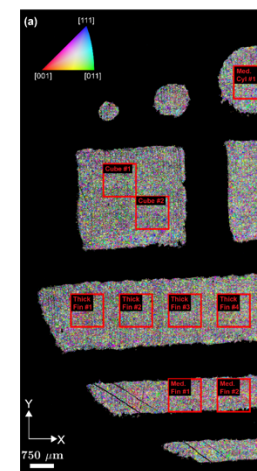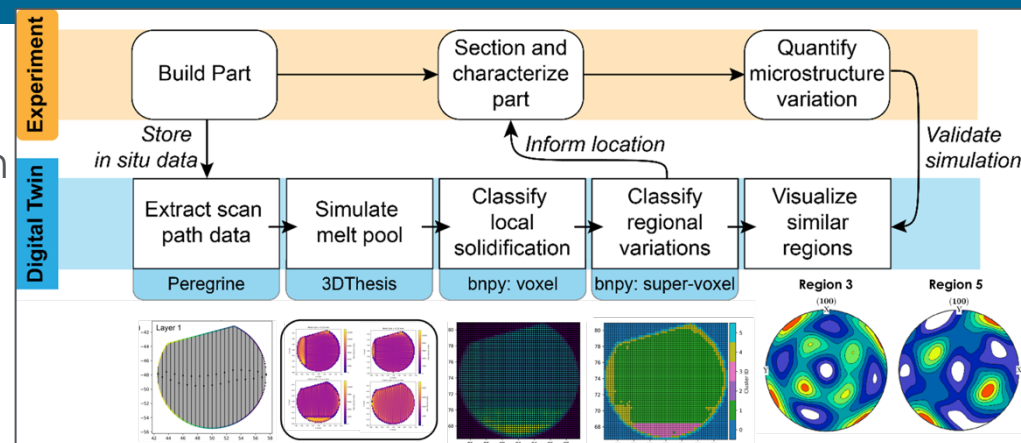


*Workflow developed to generate and classify simulated thermal data for AM processing. Classification was experimentally validated for SS316L*

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# Using ML for Rapid Automated Characterization of 316L/H

**Amir Ziabari**, Andres Marquez Rossy, et al.
*Automated, High Throughput Materials Characterization Techniques* (CR-22OR040601)



Design of Experiment

WP-CM, WP-PN

Metrotom XCT System Procured under AMMT

1. Loads 10 coupons at a time
2. Quickly scan a coupon
3. Output the data

Rapid Characterization Process

SEM Procured under AMMT

1. Receive the data (after each scan)
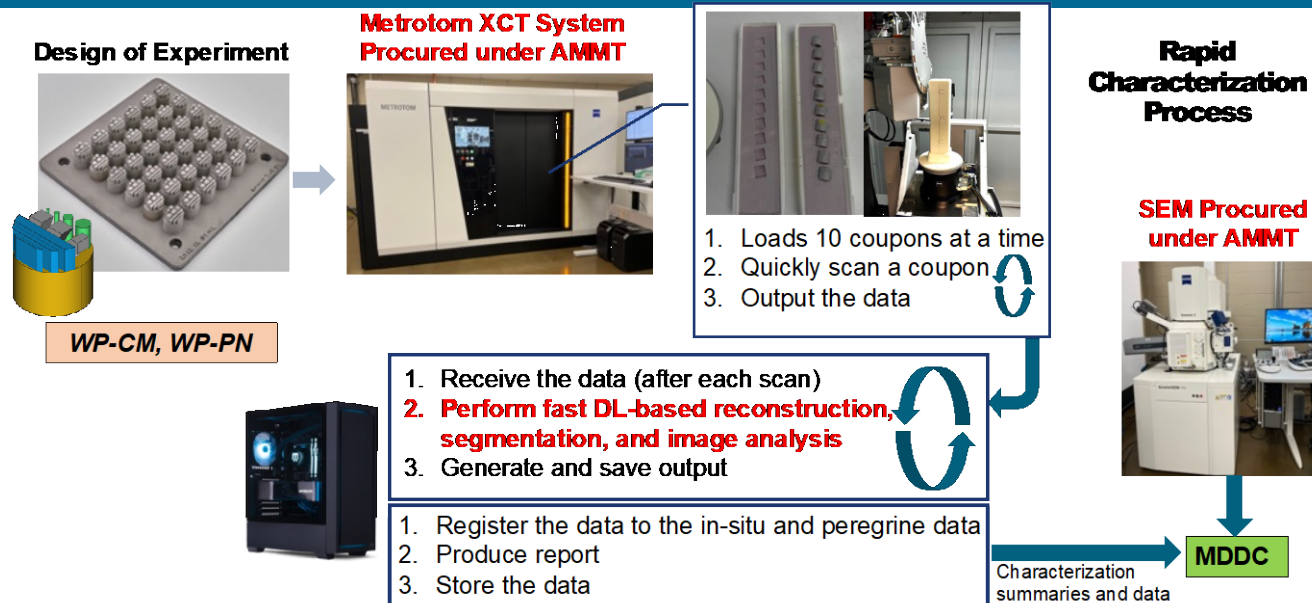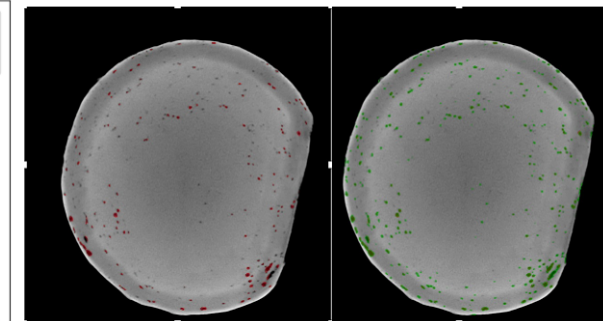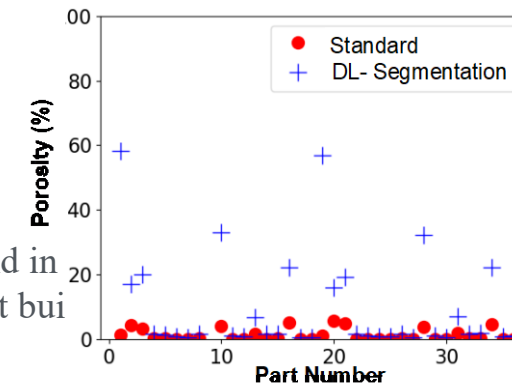2. **Perform fast DL-based reconstruction, segmentation, and image analysis**
3. Generate and save output

1. Register the data to the in-situ and peregrine data
2. Produce report
3. Store the data

Characterization summaries and data

MDDC

Standard                ORNL

**DL-reconstruction allows for resolving the flaws using 6X faster scans in thick dense 316L/H**

## Scientific Achievement

- Used ML methods for fast ex-situ characterization of dense metal components.

## Impact & Potential Application Space

- Aid in understanding of process-structure-property-performance relationships, and in determining optimum printing process window for fully densified 316 component bui

## Details

- Deep Learning based reconstruction and segmentations allowed for rapid and high-quality characterization of the parts (both verified through high resolution XCT and microscopy).

- More than 700 316L/H coupons XCT scanned and characterized allowing multiple teams to study impact of process parameters on porosity and dimensionality of different components.

Red: Standard; Green: ORNL DL- Segmentation

**DL-Segmentation demonstrates that true porosity can be underestimated by 60X! with standard algorithms**

# Highlights

➢ High throughput data mining based CALPHAD on 316L and 316H shows $\delta$ phase variation of 63% and 70% respectively, for compositions within ASTM specifications

➢ In 316H, the equilibrium carbide volume fraction varies from 0.8% to 2% for ASTM spec. composition

➢ Preliminary builds conducted using a multi-factor design of experiments to understand the impact of processing on heterogeneity