# Advanced Manufacturing Supporting Gen IV Reactor Systems

Dr. Isabella Van Rooyen

15 April 2025

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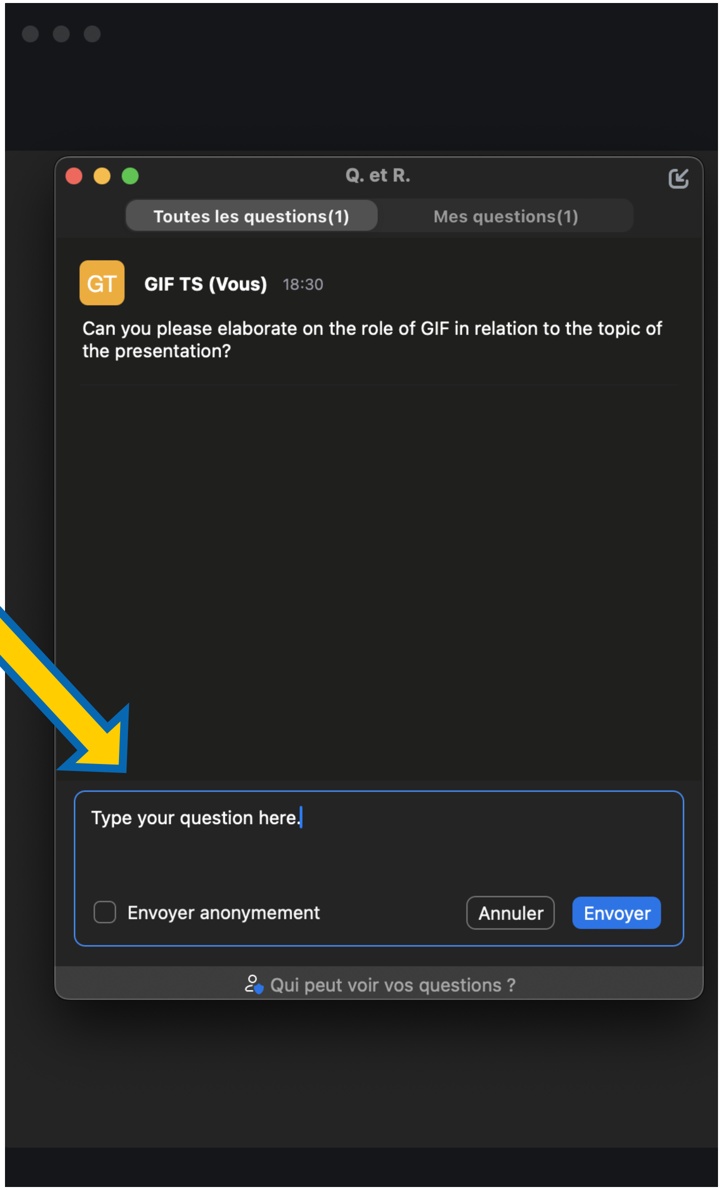

# Advanced Manufacturing Supporting Gen IV Reactor Systems

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15 April 2025

# Meet the Presenter

Dr. Isabella J. van Rooyen is a Senior Technical Advisor for Advanced Material Systems at Pacific Northwest National Laboratory (PNNL), following 10.5 years at Idaho National Laboratory (INL) as a Distinguished Staff Scientist.

Dr. van Rooyen supports the Department of Energy, Office of Nuclear Energy as (1) United States representative and co-chair on the International Advanced Manufacturing and Materials Engineering Working Group for Generation IV reactors (GIF AMME WG); (2) Advanced Material and Manufacturing technical area lead for Advanced Materials and Manufacturing Technologies (AMMT) program; and (3) previously as National Technical Director for the “Advanced Methods for Manufacturing” (AMM) program.

Experience spans nuclear, aerospace, and automotive industries for high temperature materials development (e.g., SiC, Zircaloy, beryllium, titanium, nickel alloys, tungsten-copper, composite materials, Fe-based alloys, Ni-based alloys, HEA), nuclear fuels (e.g., $UO_2$, UCO, $U_3Si_2$, TRISO) and advanced manufacturing techniques such as laser materials processing (joining, welding, cladding, etc.), casting processes, powder metallurgy (sintering, hot isostatic pressing (HIP), etc.), and additive manufacturing (AM) processes.

Dr. van Rooyen has more than 60 journal publications, 40 conference contributions, 7 granted patents and holds a PhD (physics), MSc (metallurgy), and MBA.



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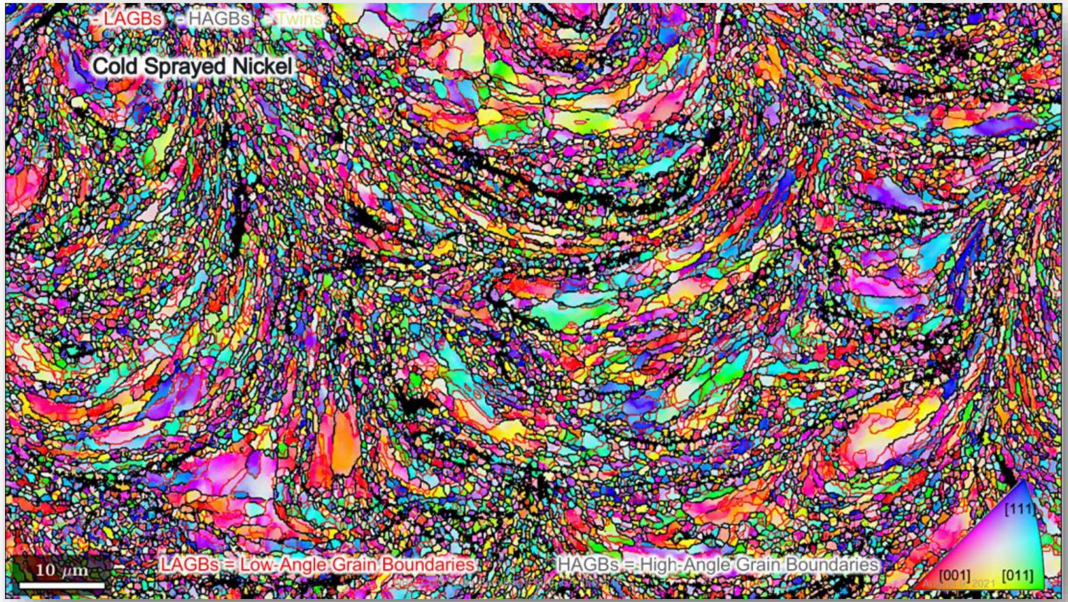
# Overview

- What is Advanced Manufacturing?
- GIF Advanced Manufacturing and Materials Engineering Working Group (AMME WG) and Surveys
- Selected examples of current works:
  - Additive Manufacturing – Overview of Framatome's Application Perspective
  - Joining and Welding Techniques
  - Large Scale Manufacturing
  - Profile Forming Processes
  - Cold Spray Processing for Nuclear Energy Applications
  - New Techniques or Applications
  - Non-Destructive Examination
- Supply Chain Challenges and Opportunities
- Advanced Manufacturing Acceptance in ASME
- US Advanced Materials and Manufacturing Technologies Program
- Final Remarks



# Contribution Acknowledgments

- AMME WG co-chairs and members
- AMMT Leadership & Researchers
- Marc Albert (EPRI)
- Charles Carpenter (AMRC)
- Kumar Sridharan (Wisconsin-Madison)
- Didier BARDEL and Chris Wiltz (Framatome)
- Adrian Wagner (INL)
- Aninda Dutta Ray (IAEA)
- Eric MacDonald, Pedro Cortes (UTEP)
- Xiaoyuan Lou (Purdue University)
- Soumya Nag (ORNL)
- Priyanka Agrawal (North Texas University)
- Subhashish Meher, Ankit Roy, Mohan Sai Kiran Kumar Yadav Nartu, Chinthaka Silva, Thomas Hartman, Mageshwari Komarasamy, Matthew Olszta, Julian Escobar Atehortua, Ramprashad Prabhakaran, Carolyne Burns, Zachary Kennedy, Amrita Lall, Michelle Fern, Saumyadeep Jana, David Garcia, Mayur Pole, Ken Ross, Jorge Dos Santos, Robert Montgomery, Praveen Thallapy, Pratikshya Meher, Cindy Powell, Jorge F. dos Santos, Glenn Grant, Scott Whalen; Saumyadeep Jana, Dalong Zhang, David W. Gotthold, Kenneth Ross, Robert Montgomery, Jack Lareau, Asif Mahut, Daniel Yoon, David Garcia, Tian Wang, Ankit Roy, Pratikshya Meher (PNNL)

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# What is Advanced Manufacturing?

- Advanced manufacturing encompasses the use of innovative technologies to **improve and optimize all aspects** of the manufacturing process, from product conception to end-of-life, with the goal of **enhancing efficiency, productivity, and competitiveness**. It involves integrating advanced technologies like robotics, automation, and data analytics into traditional manufacturing processes.
- The US NRC is currently evaluating 5 advanced manufacturing techniques:
  - "Mature" Technologies: Powder metallurgy hot isostatic pressing (PM-HIP), Electron beam welding (EBW) & Cold Spray
  - New Technologies: Additive manufacturing (Laser powder bed fusion (L-PBF) and Direct energy deposition (DED)
- Nuclear Energy Institute (NEI) identified 16 advanced manufacturing methods that are of the most interest to fabricate components for nuclear power plants.

Interest in collaborative activities remains high

# GIF Advanced Manufacturing and Materials Engineering Working Group (AMME WG)

- Started in 2018 as a task force, converted to a working group in October 2023

- A publicly accessible website:

**https://www.gen-4.org/gif-activities/working-groups/advanced-manufacturing-and-materials-engineering-working-group**

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# Advanced Manufacturing and Materials Engineering Working Group (AMME WG)

## Objectives

The overarching main objective of the AMME-WG is to promote the use of advanced manufacturing and materials engineering technology ***to reduce the time to deployment*** of advanced reactor systems.

Specifically, the WG aims to ***promote international collaboration on the qualification*** of advanced materials and manufacturing processes for use in Generation IV reactors.

## Members

| Two Country Representatives | One Representative |
|---|---|
| Canada | Australia |
| France (+ additional substitute) | China |
| Korea | Japan |
| US | Switzerland |
| | UK |

**5 Observers (Industry) and Ad hoc Observers: IAEA**

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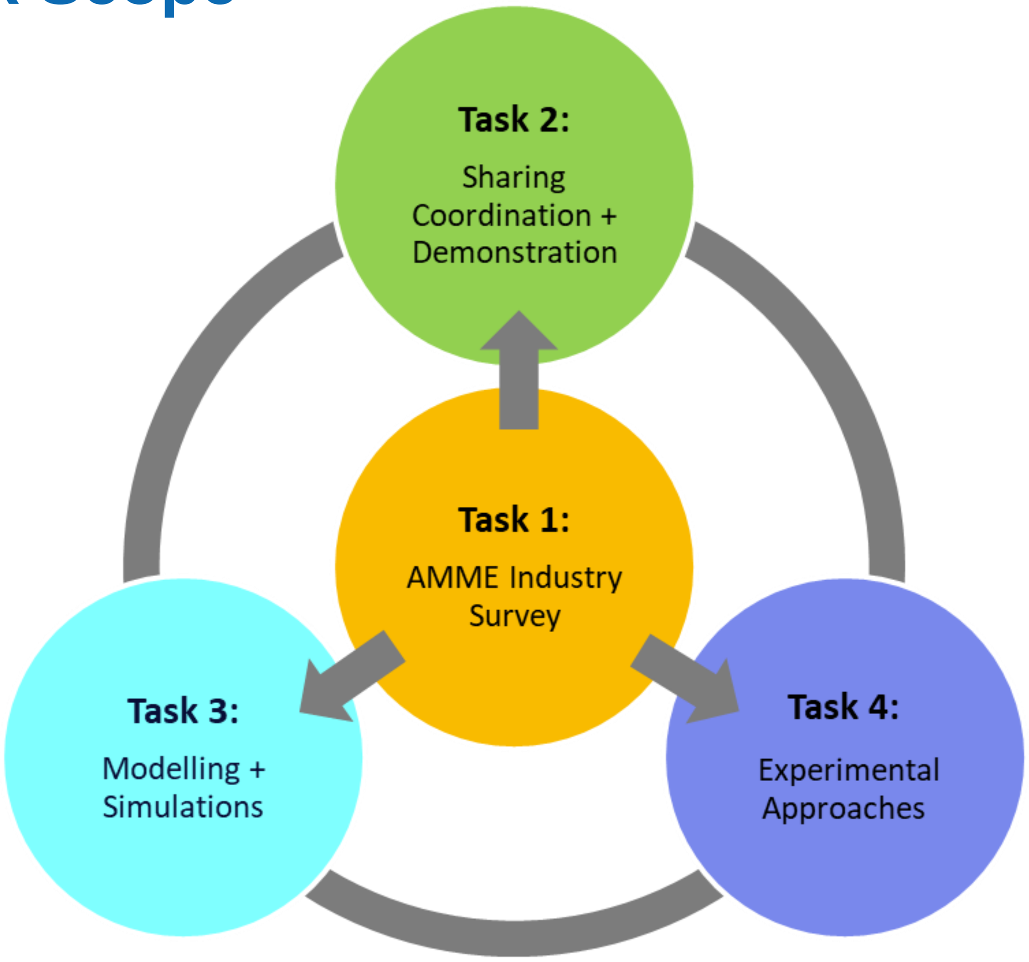
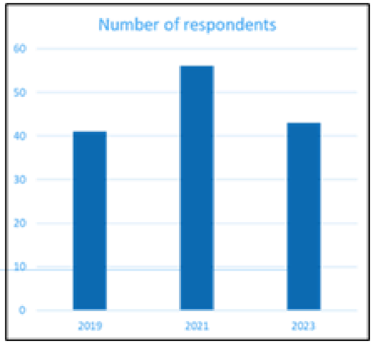
# Description of AMME WG Technical Work Scope

**Three Co-Chairs:**
**I. van Rooyen (US), M. Messner (US), L. Edwards (AU)**

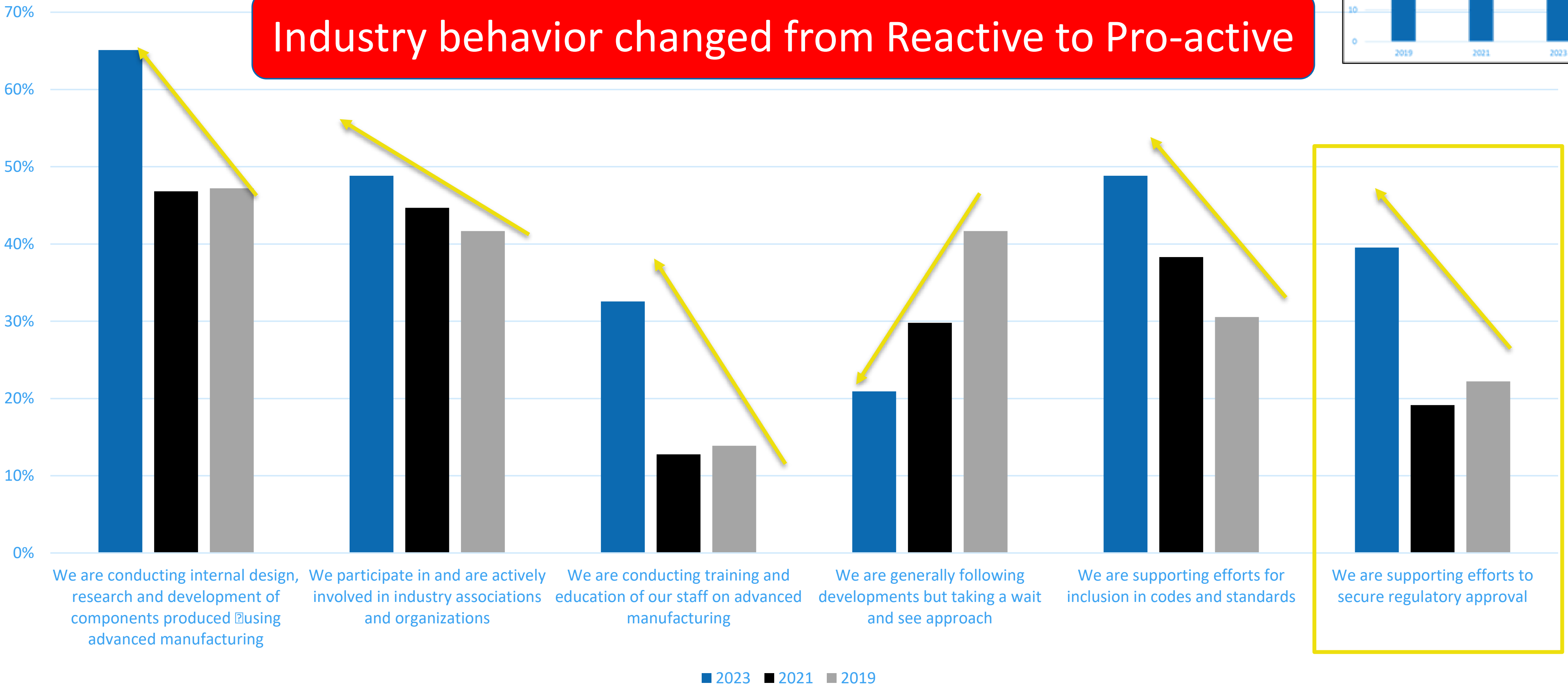
| TG #1: Survey on AM Applications in Industry | TG #2: Sharing, Coordination, and Demonstration of Work on the Qualification of AMMT | TG #3: Modelling and Simulation Approaches for the Qualification of AM Applications | TG #4: Experimental Approaches for the Qualification of AM Applications |
|---|---|---|---|
| **Lead: Messner (US)** | **Lead: Van Rooyen (US)**<br>**Co-Lead: Nilsson (EU)** | **Lead: Ivan (CA)** | **Lead: Teysseyre (CA)** |



# AMME WG Task 1: Engagement: trends over time




**Industry behavior changed from Reactive to Pro-active**




- **Uniform increase in general engagement with AMTs**
- **Large recent increase in regulatory engagement**

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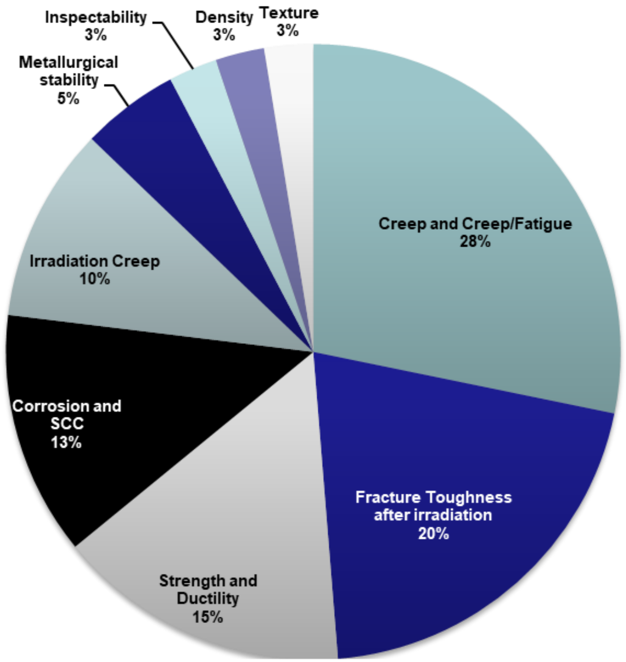
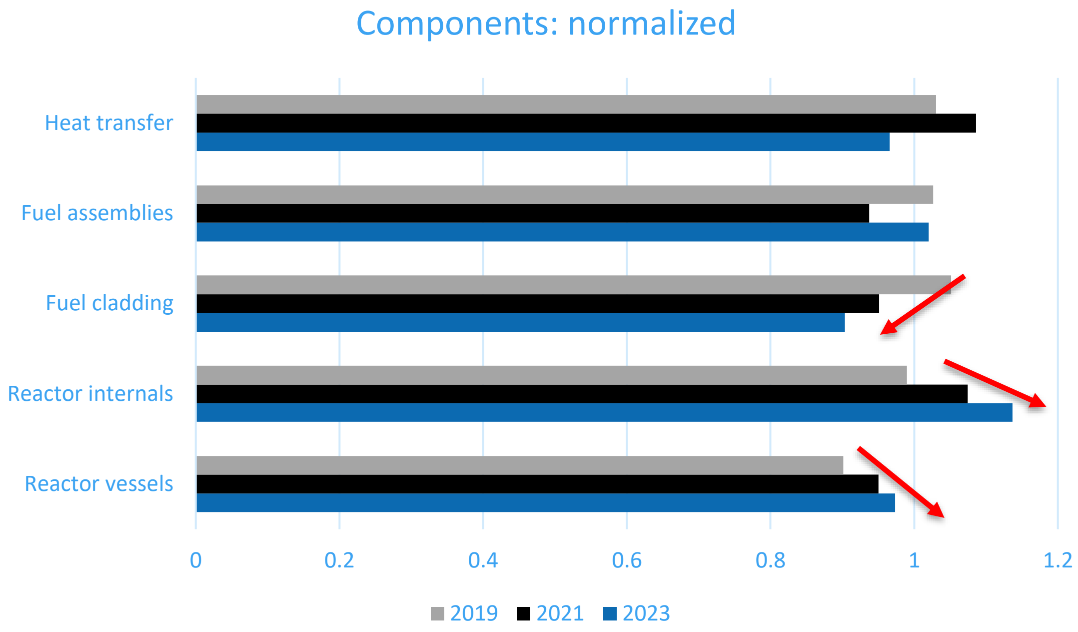
# AMME WG Task 1: Components & Properties trends over time




| | 2023 | 2021 | 2019 |
|---|---|---|---|
| Steels | 1 | 1 | 1 |
| Nickel alloys | 2 | 2 | 2 |
| Ceramics | 3 | 3 | 4 |
| Other | 4 | 4 | 3 |

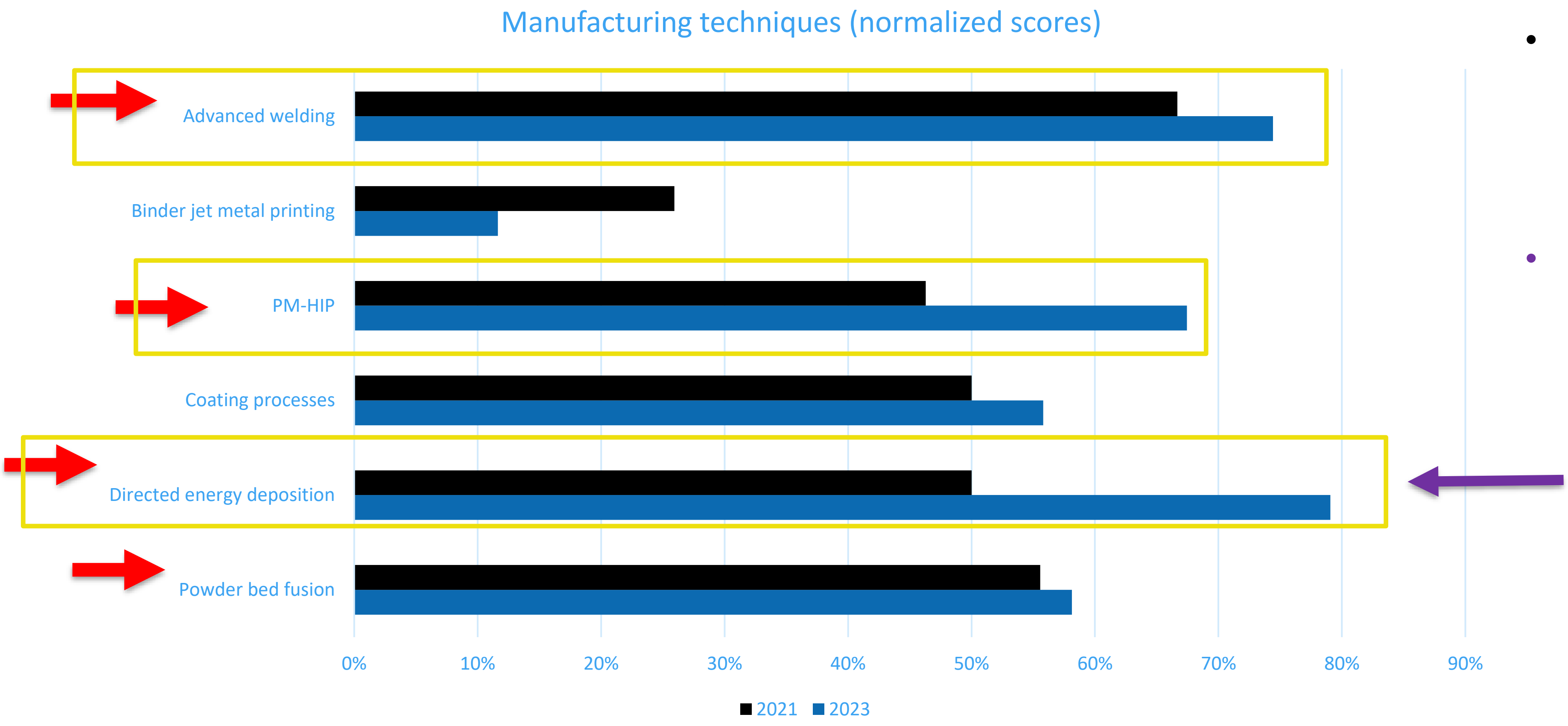
- Steels still highest interest, focus on traditional engineering materials
- Interest in ceramics seems to be increasing relative to metals




- High temperature properties (e.g. creep & creep/fatigue)
- Irradiated properties
  (e.g., Irradiation affected toughness, creep, SSC etc.)

- Interest in cladding decreased
- **Interest in reactor internals increased**
- Interest in reactor vessels slightly increased

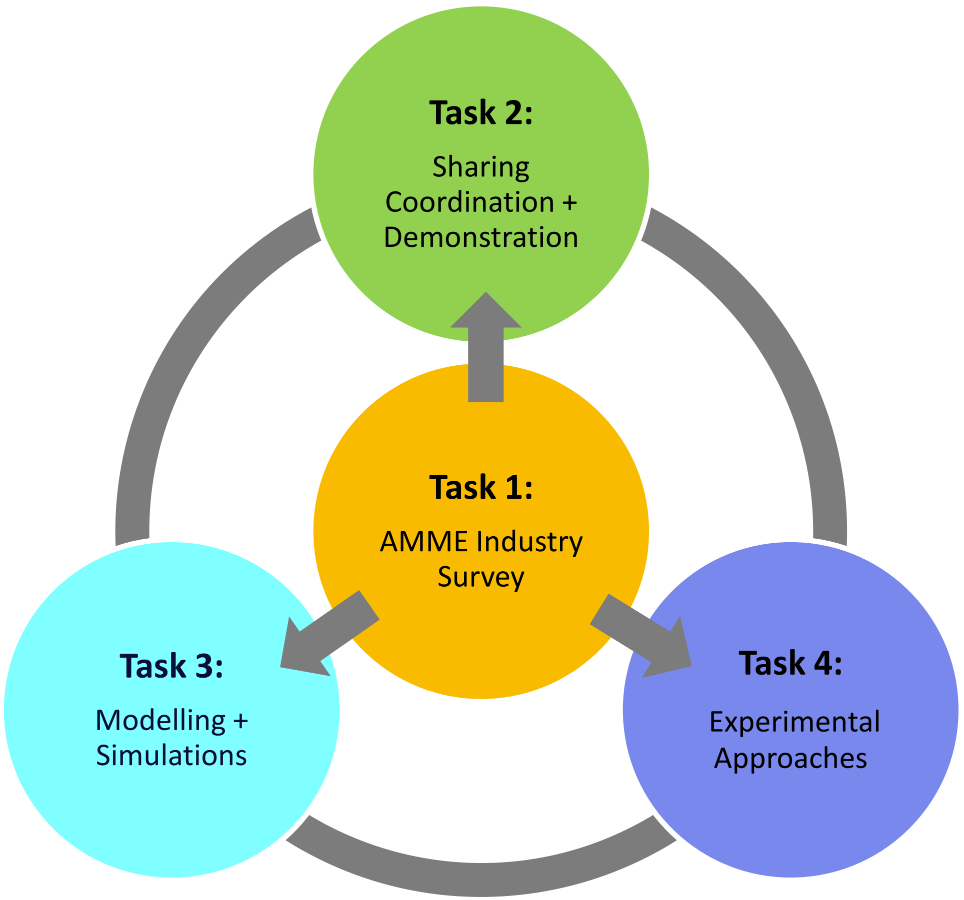
# AMME WG Task 1: Manufacturing Techniques Interest: Comparison to 2021




- Significant that advanced welding (better ways of doing existing manufacturing) continues to be one of the top listed
- **Significant increased interest in DED**
  - Slightly more interest in wire fed DED (19) compared to powder fed (15), but close

**Possible Trend to Large Scale Manufacturing and Integration of Systems??**

# AMME-WG Planned Activities




## Task 2: Sharing, Coordination, and Demonstration of Work on the Qualification of AMM Techniques

- Current nuclear industry qualification efforts/methodology & acceleration activities — Activity 2.1
- Identify complimentary activities between counties and learn from each other — Activity 2.2
- Establish a plenary session at international conference — Activity 2.3 Completed March 2025
- Protocol for communication and database linkage tool for GIF members — Activity 2.4 Completed Oct 2024
- Workshop to disseminate the information collected by the WG — Activity 2.5
- Develop activities aimed at feedstock powder — Activity 2.6

Activities 2.1; 2.2 and 2.5: In progress

Activities 2.3; 2.4: Completed

Activity 2.6: Not started

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Preliminary, survey still open

# Activities 2.1 and 2.2: Current Nuclear Industry Qualification Efforts

- Survey distributed among AMME WG members for contacting the industry partners in their countries
  - 81 Questions
  - 16 respondents from R&D private organizations, suppliers, reactor designers and regulator
- AMME WG will continue working on the Survey


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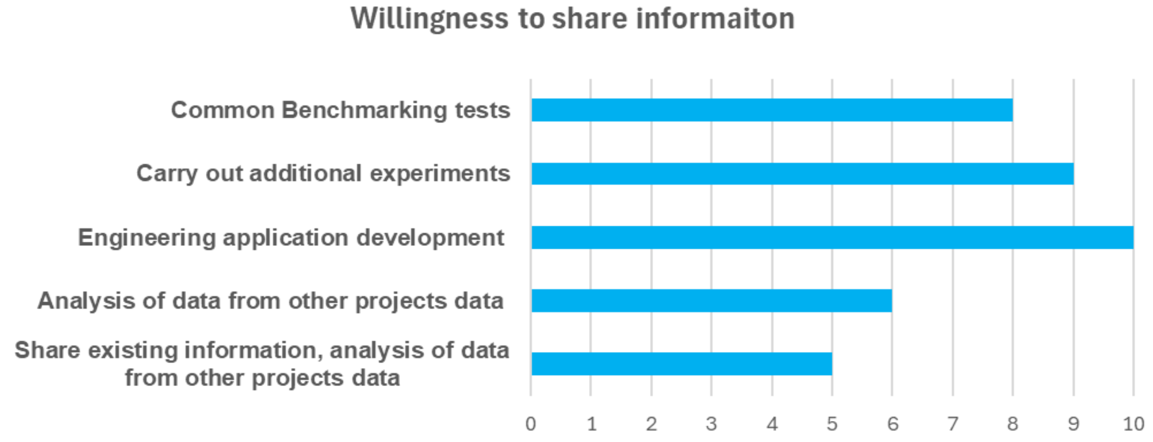
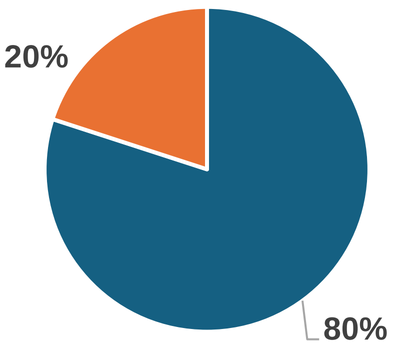
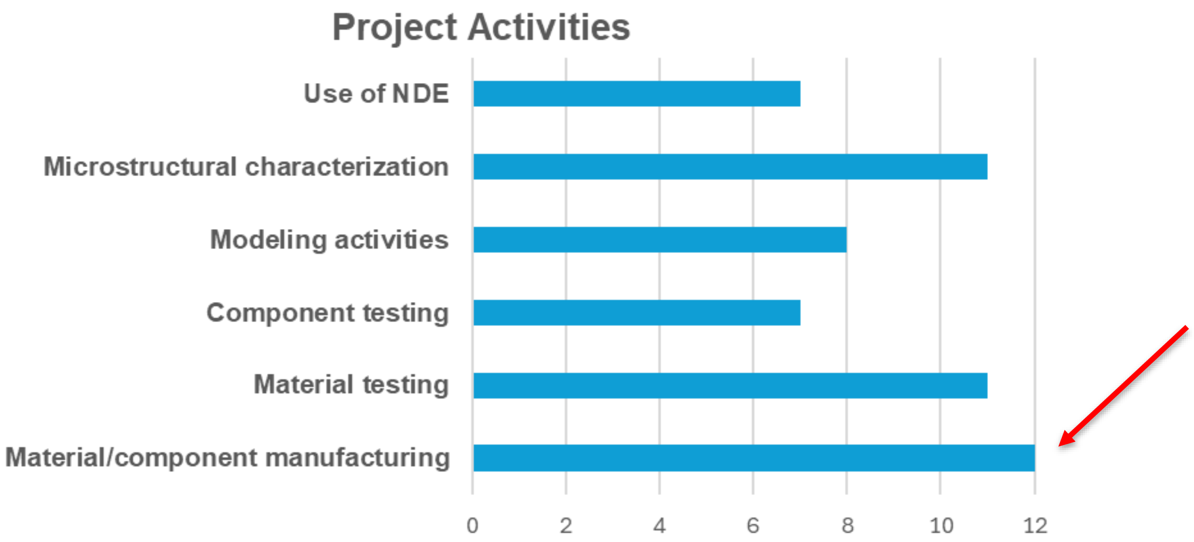


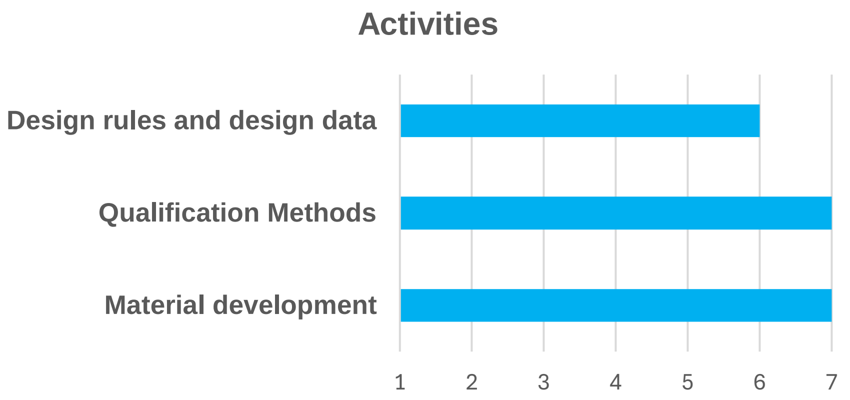



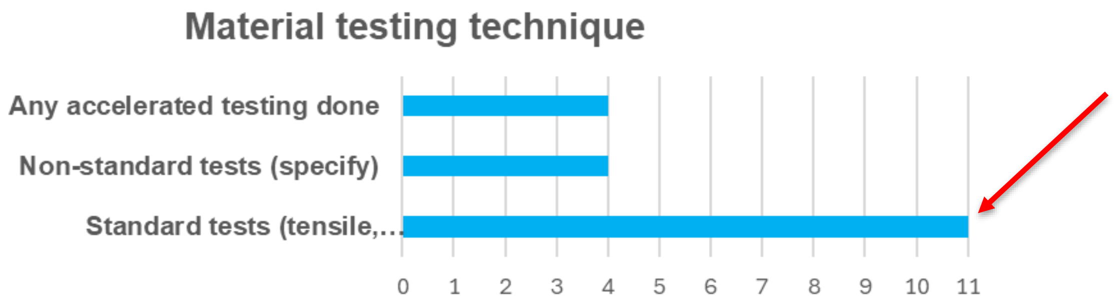

- Willingness and readiness for working together but with some caveat.....

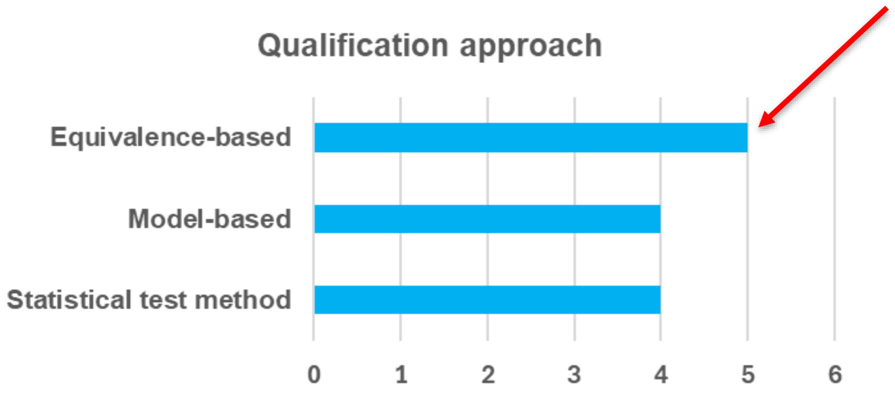
Preliminary, survey still open

# Activities 2.1 and 2.2: Current Nuclear Industry Qualification Efforts




- Broad range of integrated activities
- Standard tests dominate

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# Activity 2.3: Additive Manufacturing Industry Perspective Panel Session


TMS2025
154th Annual Meeting & Exhibition

**Panel Discussion Questionnaire Topics**

- Introduction and panelists' role in Additive Manufacturing
- Technological Advancements
- Industrial Adoption and Economic Impact
- Sustainability and Environmental Impact

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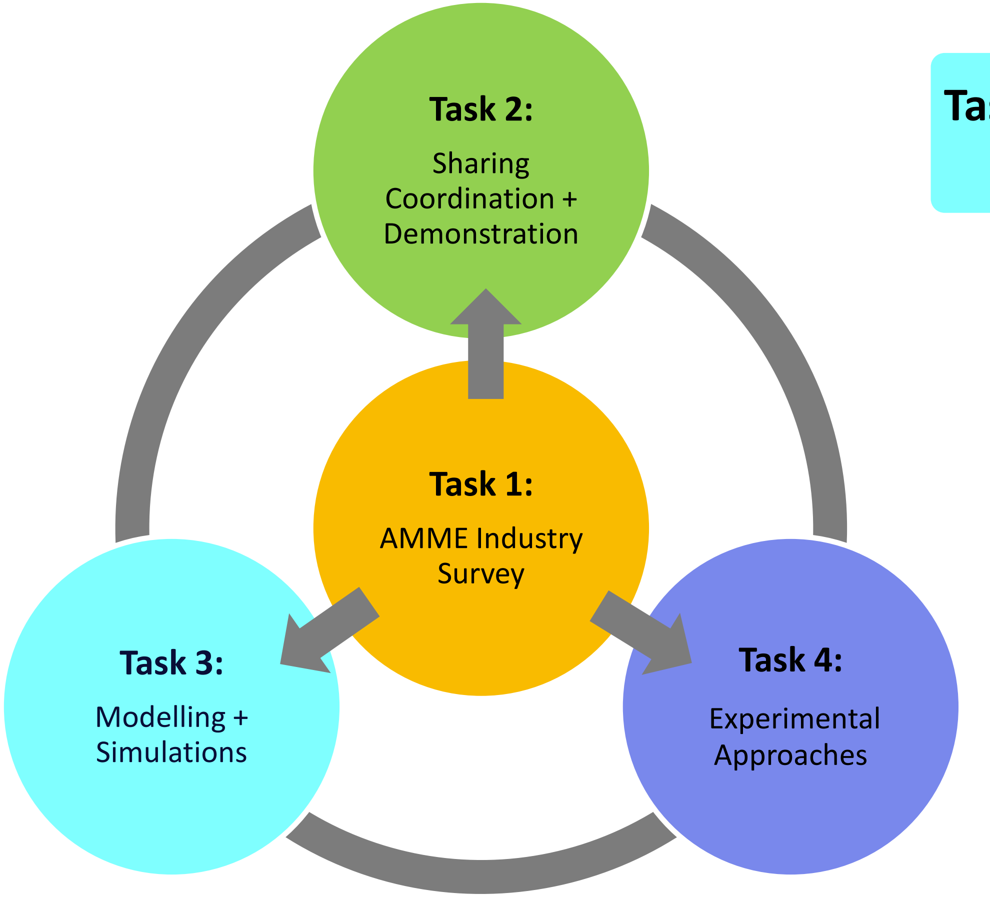
Providing Industry Solutions

# AMME-WG M&S Task Group: Planned Activities




**Task 3: Modelling and Simulation Approaches for the Qualification of AM Applications**

- Demonstrate machine learning and correlate processing history to material structure — Activity 3.1
- Identify and promote common and/or open-source software — Activity 3.2
- Develop and disseminate benchmark problems for applying models to accelerate material qualification — Activity 3.3
- Identify key ranges of operating parameters for models to target temperature, time, fluence — Activity 3.4

Activity 3.3: In progress

Activity 3.2: Completed

# AMME-WG Task 3: Excel-Based Database of AM Codes

Query: Which codes can model certain Processes and provide certain Outputs?

| 1 | Software Tool | References | Link | Process | Use | Simulation Method | Availability |
|---|---|---|---|---|---|---|---|
| 45 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Direct Energy Deposition | Thermal history | Phase field | Open Source Software |
| 46 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Direct Energy Deposition | Thermal history | | Open Source Software |
| 47 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Direct Energy Deposition | Microstructural Pre | | Open Source Software |
| 48 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Direct Energy Deposition | Microstructural Pre | | Open Source Software |
| 49 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Powder Bed Fusion | Thermal history | | Open Source Software |
| 50 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Powder Bed Fusion | Thermal history | | Open Source Software |
| 51 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Powder Bed Fusion | Microstructural Prediction | Phase field | Open Source Software |
| 52 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Powder Bed Fusion | Microstructural Prediction | Transient Heat Transfer | Open Source Software |
| 53 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Electron Beam Welding | Thermal history | Phase field | Open Source Software |
| 54 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Electron Beam Welding | Thermal history | Transient Heat Transfer | Open Source Software |
| 55 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Electron Beam Welding | Microstructural Prediction | Phase field | Open Source Software |
| 56 | MOOSE | inomaa, T., Yashchuk, I., Lindroos, M., | https://mooseframework.org/ | Electron Beam Welding | Microstructural Prediction | Transient Heat Transfer | Open Source Software |
| 63 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Powder Bed Fusion | Microstructural Prediction | Phase field | Commercial |
| 64 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Powder Bed Fusion | Microstructural Prediction | Phase field | Open Source Software |
| 65 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Powder Bed Fusion | Microstructural Prediction | Solid Mechnics | Commercial |
| 66 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Powder Bed Fusion | Microstructural Pre | | Open Source Software |
| 71 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Direct Energy Deposition | Microstructural Pre | | Commercial |
| 72 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Direct Energy Deposition | Microstructural Pre | | Open Source Software |
| 73 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Direct Energy Deposition | Microstructural Pre | | Commercial |
| 74 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Direct Energy Deposition | Microstructural Pre | | Open Source Software |
| 79 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Electron Beam Welding | Microstructural Prediction | Phase field | Commercial |
| 80 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Electron Beam Welding | Microstructural Prediction | Phase field | Open Source Software |
| 81 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Electron Beam Welding | Microstructural Prediction | Solid Mechnics | Commercial |
| 82 | OpenPhase Studio | iu, D. and Wang, Y.,2017 | http://openphase-solutions.com/ | Electron Beam Welding | Microstructural Prediction | Solid Mechnics | Open Source Software |
| 83 | PRISMS | agesen, L.K., Adams, J.F., Allison, J.E., | http://www.prisms-center.org/ | Powder Bed Fusion | M | | Open Source Software |
| 84 | PRISMS | agesen, L.K., Adams, J.F., Allison, J.E. | http://www.prisms-center.org/ | Powder Bed Fusion | M | | Open Source Software |

**Process**
- Direct Energy Deposition
- Electron Beam Welding
- Friction Welding
- Powder Bed Fusion
- Sintering
- Fused Deposition

**Use**
- Distortion
- Microstructural Prediction
- Molten Pool
- Porosity
- Residual stress
- Thermal history

**Availability**
- Commercial
- Open Source Software
- Limited
- Proprietary

Apply Process Filter

Apply Use Filter

Automatically Determine Availability Options

References and Live URL to Access More Info

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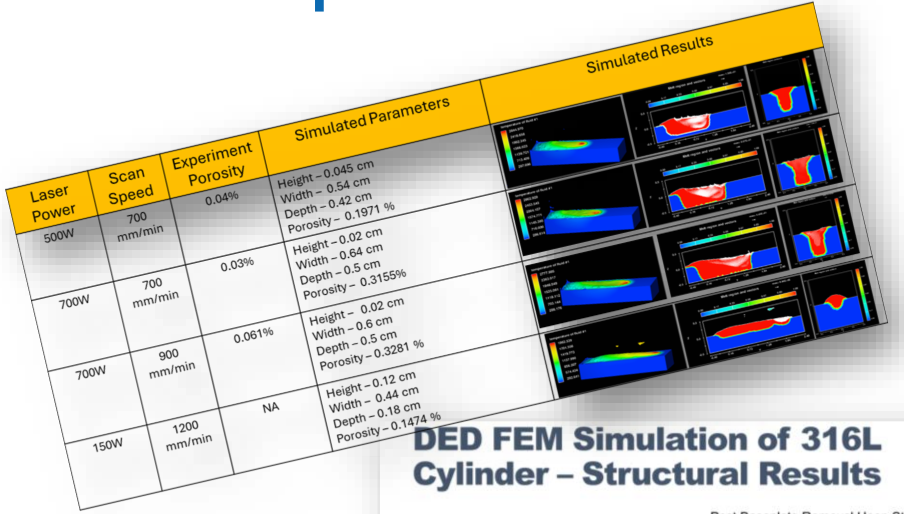
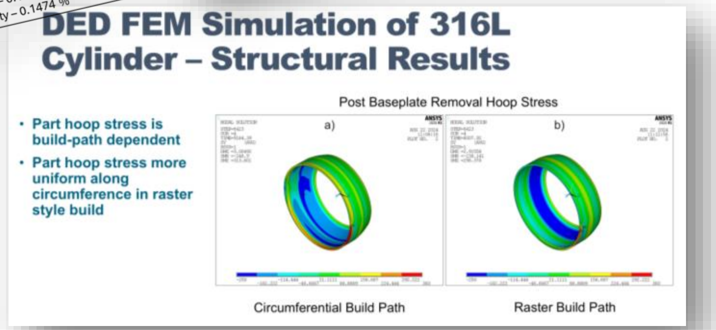
# NEA Workshop on Regulatory Frameworks and Technical Approaches for Qualification and Through-Life Performance of Materials in Advanced Reactors: June 3-5, 2025, U.S. Nuclear Regulatory Commission's Headquarters in Rockville, MD.



| Laser Power | Scan Speed | Experiment Porosity | Simulated Parameters | Simulated Results |
|---|---|---|---|---|
| 500W | 700 mm/min | 0.04% | Height – 0.045 cm<br>Width – 0.54 cm<br>Depth – 0.42 cm<br>Porosity – 0.1971 % | |
| 700W | 700 mm/min | 0.03% | Height – 0.02 cm<br>Width – 0.64 cm<br>Depth – 0.5 cm<br>Porosity – 0.3155% | |
| 700W | 900 mm/min | 0.061% | Height – 0.02 cm<br>Width – 0.6 cm<br>Depth – 0.5 cm<br>Porosity – 0.3281 % | |
| 150W | 1200 mm/min | NA | Height – 0.12 cm<br>Width – 0.44 cm<br>Depth – 0.18 cm<br>Porosity – 0.1474 % | |




Pacific Northwest NATIONAL LABORATORY

DED FEM & Flow3D Simulation of 316L Cylinder – Methodology

**Title:** A case study assessment of qualification acceleration informed by physics-based modelling

**Authors:** Lucian Ivan (CNL), Mark Messner (ANL), Daniel Yoon (PNNL), Taylor Mason (PNNL), Karl-Fredrik Nilsson (JRC), Celine CABET (CEA), Isabella J van Rooyen (PNNL)

Qualifying new advanced manufacturing technologies (AMTs) for use with nuclear design codes can be a long and complex process, thereby hindering their wider adoption. The Generation IV International Forum (GIF) Advanced Manufacturing Materials Engineering Working Group (AMME-WG) has engaged in several collaborative initiatives to support the nuclear industry in decreasing time to deployment of Gen-IV advanced reactors. A particular effort is to investigate how modelling and simulation (M&S) approaches could help accelerate the material and process qualification for industrial applications using AMTs. Through advancements in M&S methodologies, industrial users of AMTs could develop and produce critical information that could lead to the adoption of the technology as an essential and integral part in the qualification process. However, open questions remain about the requirements in terms of modelling capabilities and computational cost for a cost-effective M&S approach to ensure accurate builds and repeatable components.

To facilitate the wider adoption of such M&S techniques in the nuclear industry, the goal of the WG is to identify and maintain an inventory of current state-of-the-art computational methods and codes that are instrumental in informing and assessing the properties (e.g., microstructure) of the materials and the components resulting from AMTs. To this end, the WG has started the development of a database of available M&S methods and software packages that have already been applied to AMT and could support the qualification of advanced manufactured materials and processes of interest to nuclear systems. The codes consider physics-based, data-driven, and hybrid approaches which vary in modelling and computational complexity. By filtering the information in the database, an industrial user would be able to identify suitable M&S tools that could assist in the qualification of AMT.

To assess the feasibility of the approach and establish modelling requirements, this work considers a case study in which predictions obtained with several selected codes in the database are evaluated against experimental testing data for a geometry-agnostic component made of 316 stainless steels. The talk will present the outcome of the assessment and discuss some of the challenges in applying M&S methods for performance testing related to the qualification of AMT applications.

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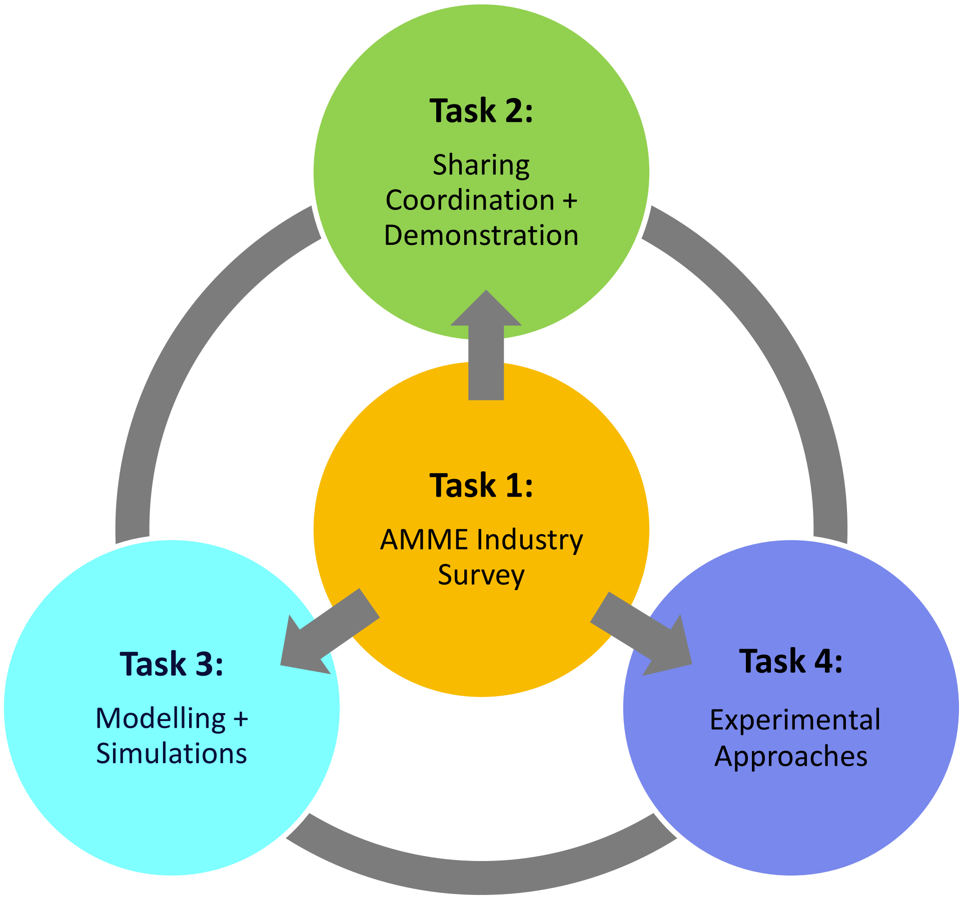
# AMME-WG Planned Activities

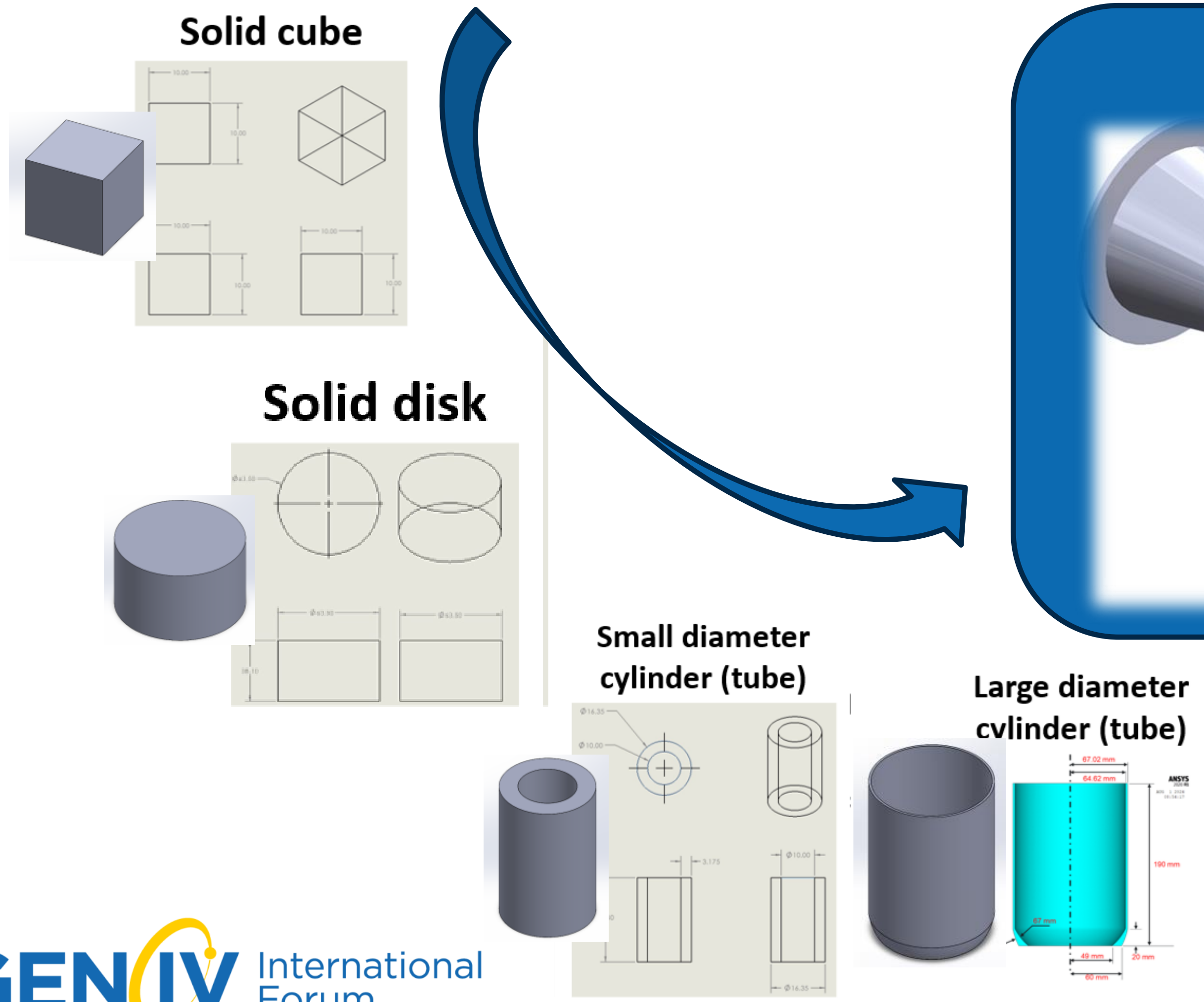


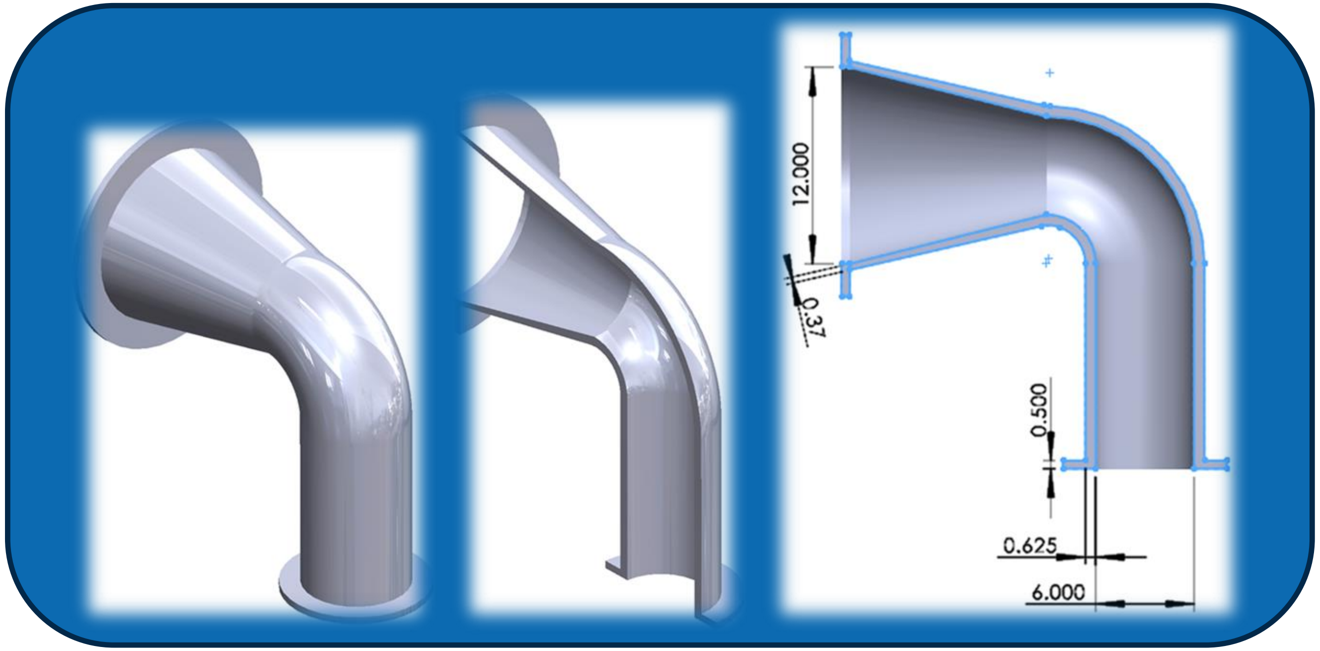

## Task 4: Experimental Approaches for the Qualification of AM Applications

- Development of a benchmark study to include manufacturing and performance measurement of reactor relevant geometries (tee, elbow, etc.) — Activity 4.1
- Identification and acquisition of data on environmental effects on AM materials. — Activity 4.2
- Identify existing datasets for use in training/validating machine learning models — Activity 4.3
- Exploration of accelerated testing methodologies — Activity 4.4
- Post process NDE techniques — Activity 4.5

Activities 4.1; 4.4 and 4.5: In progress

# Task 4.1: Expanded Elbow Geometry Benchmark Design



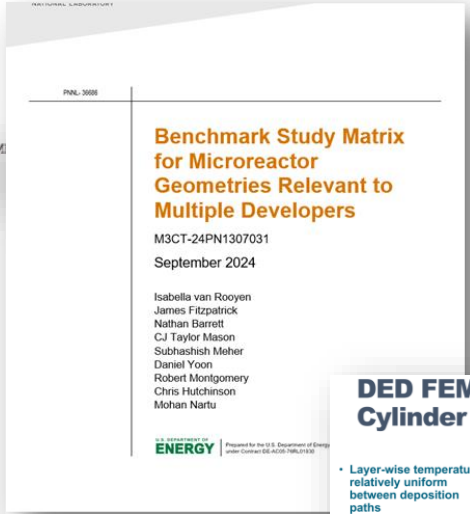

316L
316LN
316H
Possible In 617/625?

Powder-DED
LPBF
Wire DED

[Isabella van Rooyen, James Fitzpatrick, Nathan Barrett, CJ Taylor Mason, Subhashish Meher, Daniel Yoon, Robert Montgomery, Chris Hutchinson, Mohan Nartu, Benchmark Study Matrix for Microreactor Geometries Relevant to Multiple Developers, M3CT-24PN1307031, PNNL- 36686, September 2024]

# Geometry Benchmark– Highlights

## 316L DED



PNNL-36686

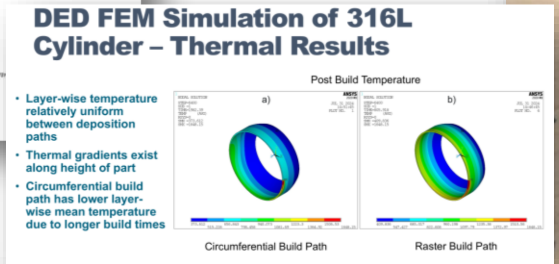
Benchmark Study Matrix for Microreactor Geometries Relevant to Multiple Developers

M3CT-24PN1307031

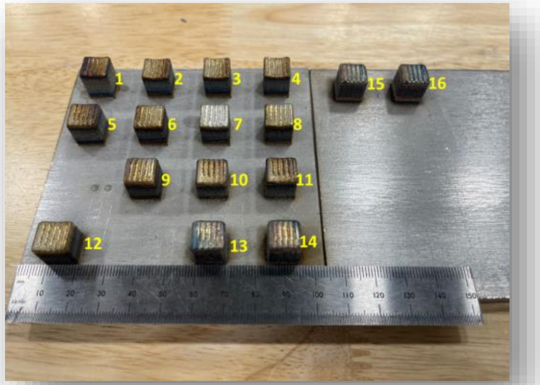
September 2024

Isabella van Rooyen
James Fitzpatrick
Nathan Barrett
CJ Taylor Mason
Subhashish Meher
Daniel Yoon
Robert Montgomery
Chris Hutchinson
Mohan Nartu

U.S. DEPARTMENT OF ENERGY




## 316H DED





Draft 1

### Characterization Benchmark Studies: Material 316 H (low N) Stainless Steel

(This should be developed for each Material Type)

| | Cube | Solid Disk | Tube/Small Diameter Cylinder | Large Cylinder | PNNL Non-Proprietary Design | Full Scale Micro Reactor Heat Exchanger Liner |
|---|---|---|---|---|---|---|
| Powder Characterization | X | X | X | X | n/A | X |
| Dimensional examination | X | X | X | X | N/A | X |
| Optical Microscopy - Porosity | A, X | A, X | A, X | A, X | A | A |
| Density | A, X | A, X | A, X | A, X | A | A ? X TBD |
| SEM - EBSD GBC, KAM, Orientation | A, X | A, X | A, X | A, X | A | A ? X TBD |
| XRD<br>-Phases<br>-Residual Stresses | A, X | A, X | A, X | A, X | A | A ? X TBD |
| Hardness<br>RT→800°C | A, X | A, X | A, X | A, X | A | A ? X TBD |
| Mechanical properties<br>Tensile & Yield Strength<br>RT →800°C | B | N/A | A | A | A | A ? X TBD |
| Creep and/or Creep - Fatigue<br>RT → 800°C | ? B TBD | N/A | A | A | A | A ? X TBD |
| NDE* | C | C | C | C | C | C ? X TBD |
| Environmental Testing | ? B TBD | ? B TBD | ? B TBD | ? B TBD | ? B TBD | ? X TBD |

A: Small sample from actual part  B: Separately Standard Size fabricated Sample  C: Full actual part  X: PNNL planned or completed

* Stand alone benchmark to be developed

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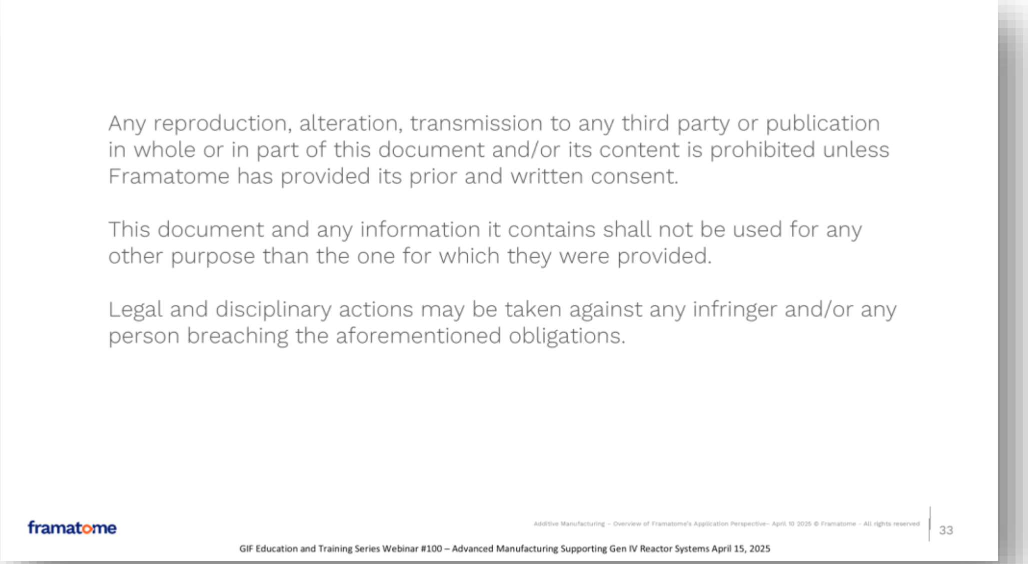
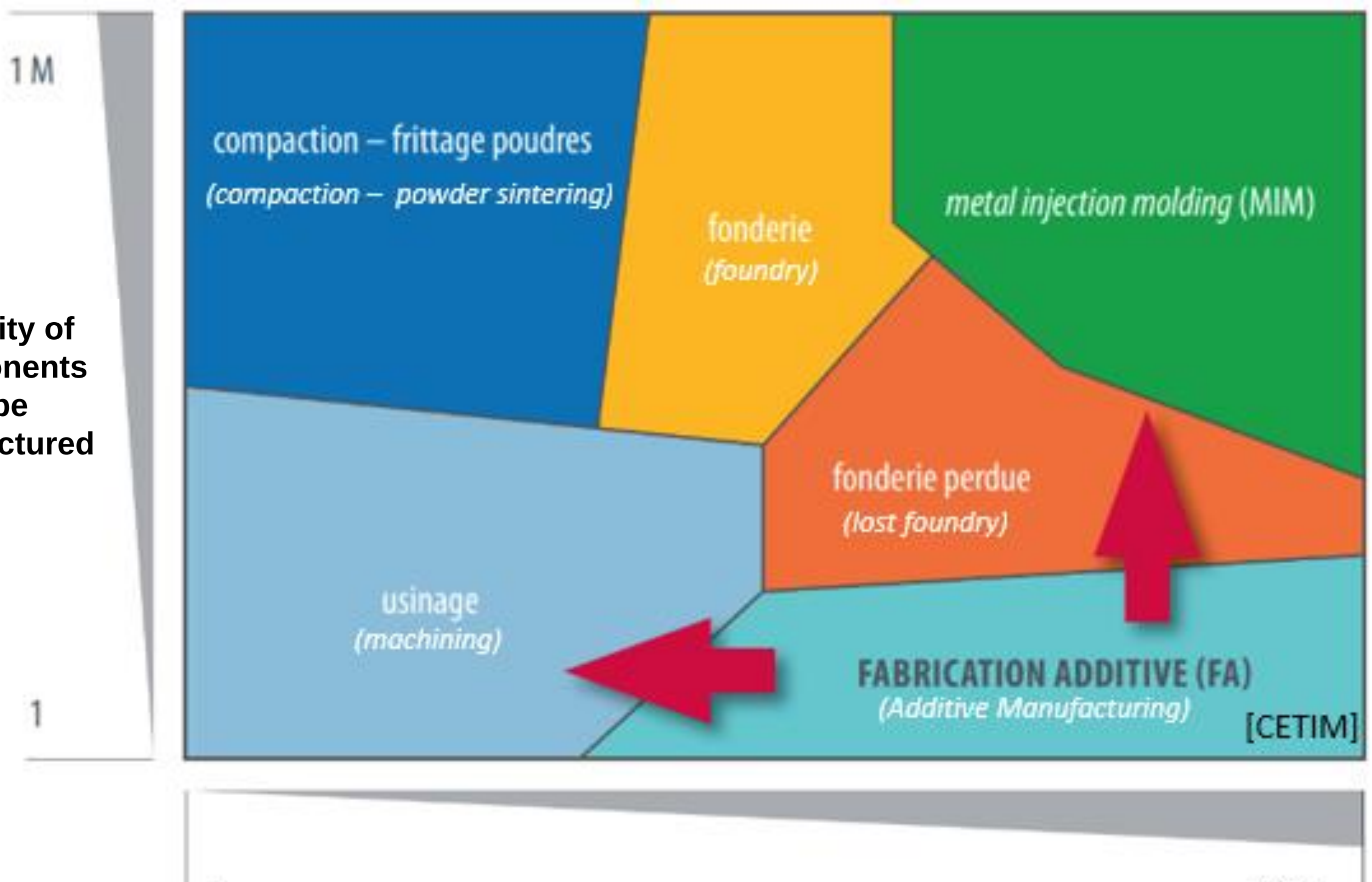
# Additive Manufacturing – Overview of Framatome's Application Perspective

# Where Does Additive Manufacturing Fit in Comparison with Other Manufacturing Processes ?

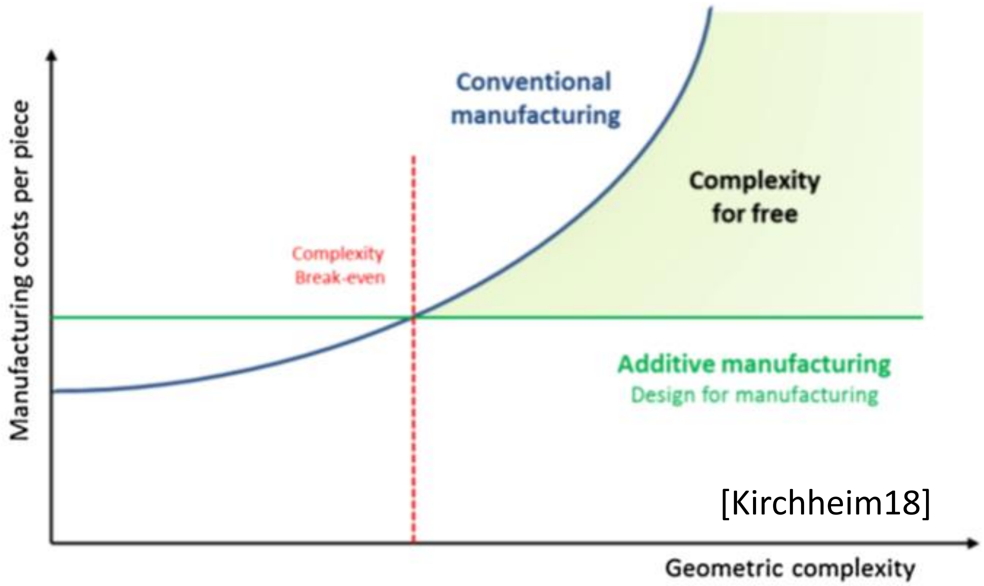
- AM brings strong advantages for complex components and tends to extend its impact as a serial production technology

**Quantity of Components to be Manufactured**



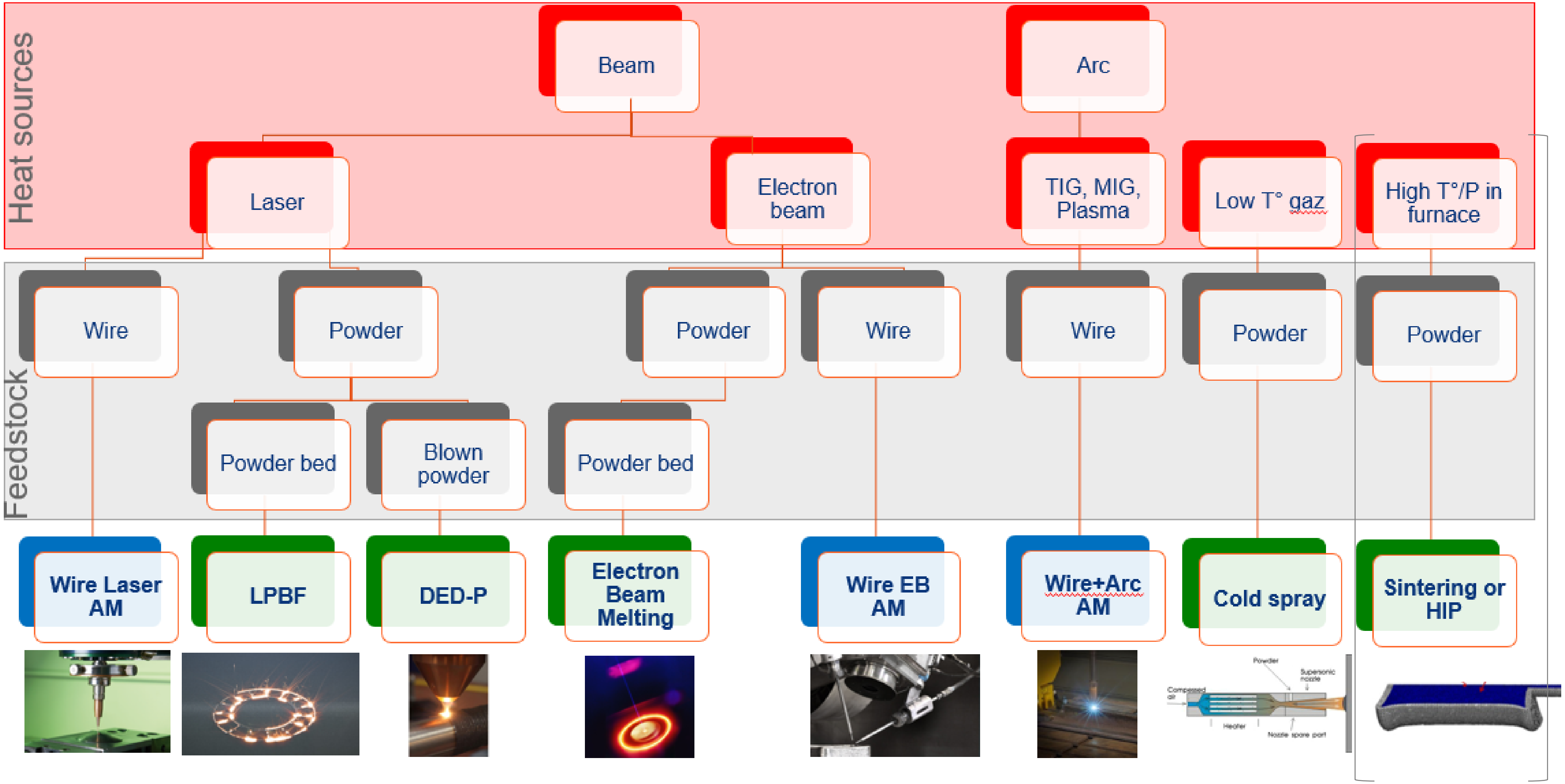

**Complexity of Component**

**Selection of Additive Manufacturing When Relevant**

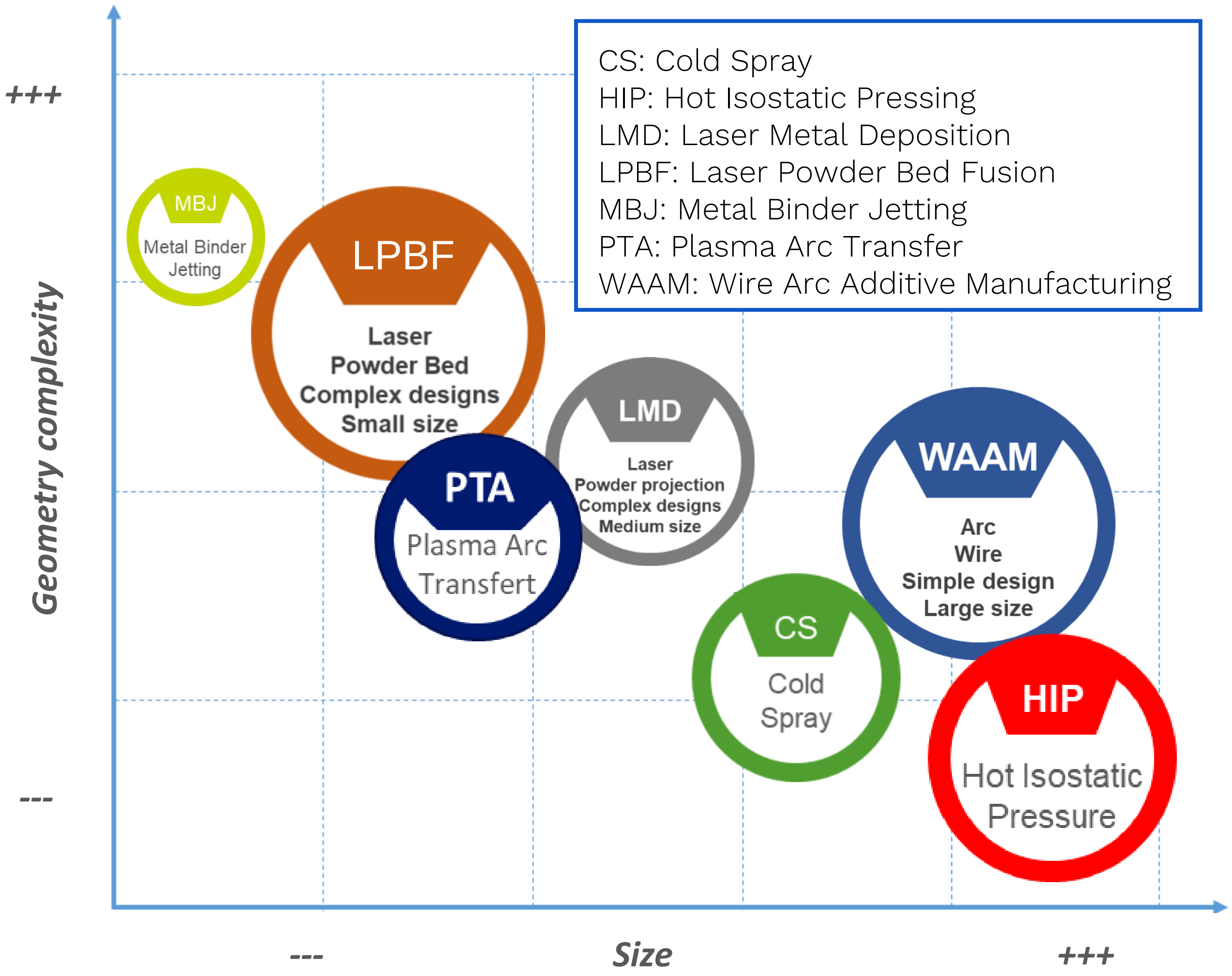



➔ The additive manufacturing process is not always the right answer (simple geometries, very high quantity, etc.)

# Overview of Metallic Additive Manufacturing – Various Processes



# Several Processes to Address Different Component Size and Complexities – Each Process with its Advantages




LPBF


Fuel or small components


Machining Tool


Fuel Assembly Upper Tape Plate

LMD

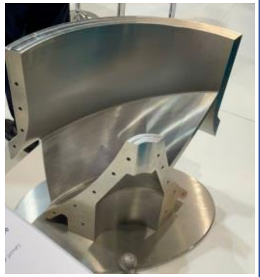
Could be hybride process with substractive steps

Or material gradients


Exemple of use on a core internal

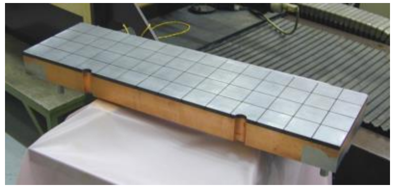
WAAM

Add functions or Heavy component building

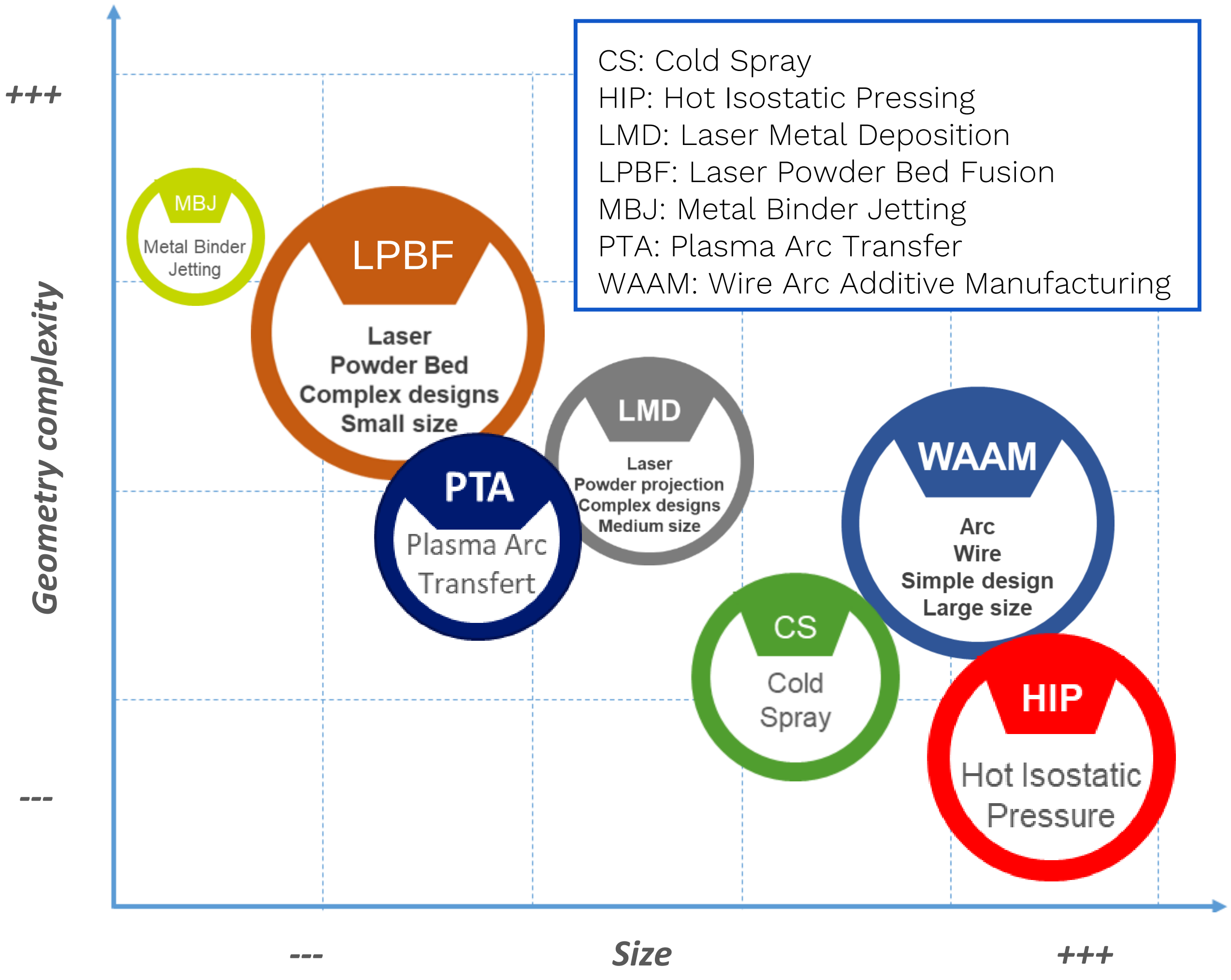


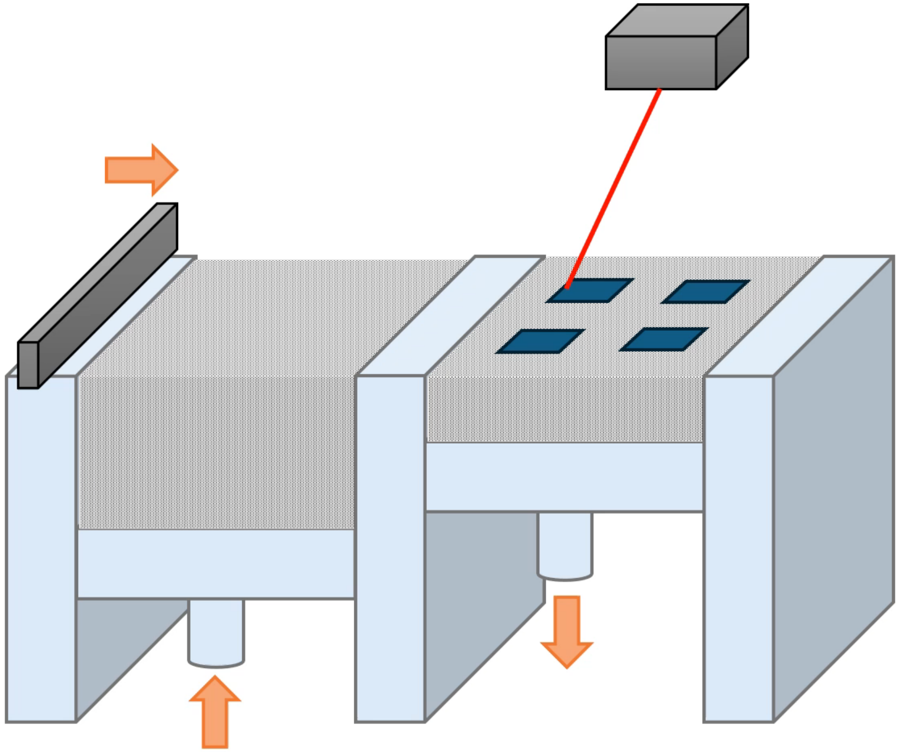
HIP


Primary Circuit Elbow


Multi-material assembly

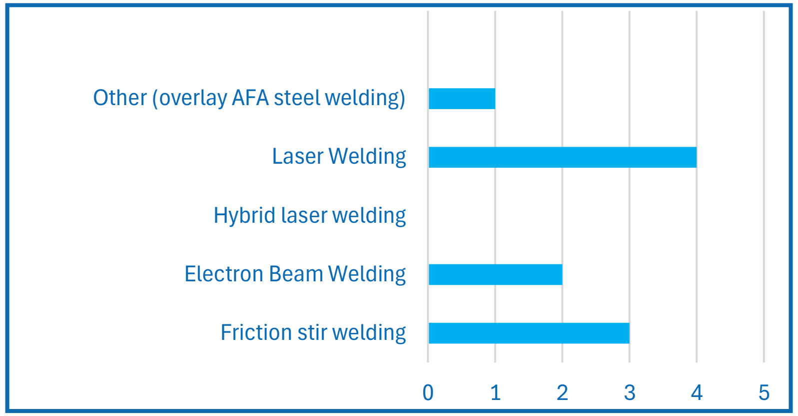
# Laser Power Bed Fusion Main Interest for Framatome Regarding Nuclear Fuel Components



[M. Chauche et al. 2025]

Preliminary, survey still open




# Joining and Welding Techniques

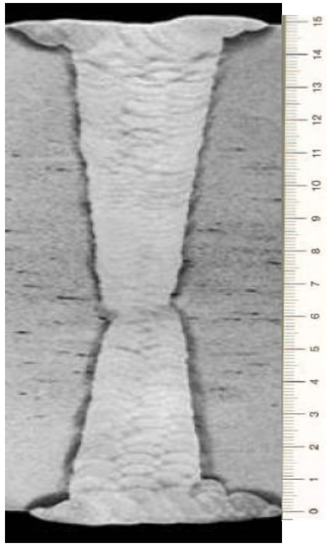
- Electron Beam Welding (EBW)
- Friction Stir Welding
- HIP Joining
- Laser Welding

Friction stir @ PNNL

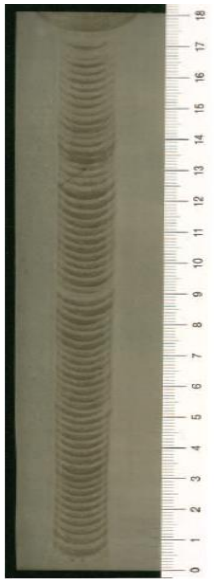
# EBW for high integrity components

- Autogenous welding method (no welding wire)
- Typically, square butt joints / lap joints
- Reduced heat input (reduced distortion)
- Keyhole welding process (thick sections in a single pass)

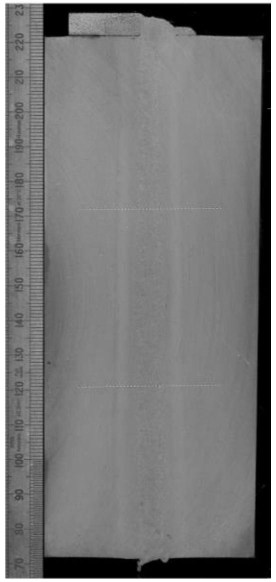
GMAW, 15 layers
150 mm thick



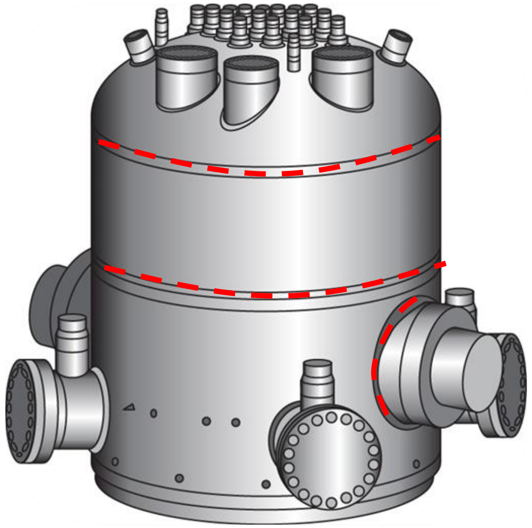
NG GTAW, 78 layers
180 mm thick



EBW, 1 pass
150 mm thick

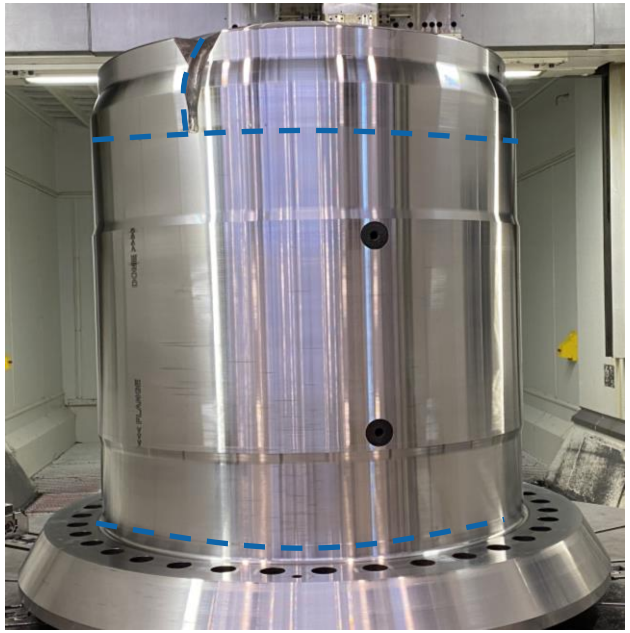


***Review of Advanced Manufacturing Techniques and Qualification Processes for Light Water Reactors – Electron Beam Welding (ORNL)***
https://www.nrc.gov/docs/ML2214/ML22143A928.pdf



Presentative model of NuScale Power Reactor Pressure Vessel Copyright NuScale Power.
US DOE Project: DE-NE0008629

***Deployment of Heavy Section Electron Beam Welding (EBW) Technologies***
https://www.epri.com/research/products/3002027860
***Review of Advanced Manufacturing Techniques and Qualification Processes for Light Water Reactors – Electron Beam Welding***
https://www.nrc.gov/docs/ML2214/ML22143A928.pdf
***Nondestructive Evaluation of Electron Beam Welds***
https://www.nrc.gov/docs/ML2432/ML24327A005.pdf



**Challenges for deployment of EBW for high integrity components**

- Elimination of preheat for welding of vessel steels (ASME)
- Slope-out method for circumferential welds
- Repair methods
- Non-destructive evaluation of welds
- Surface preparation methods (demagnetization methods)

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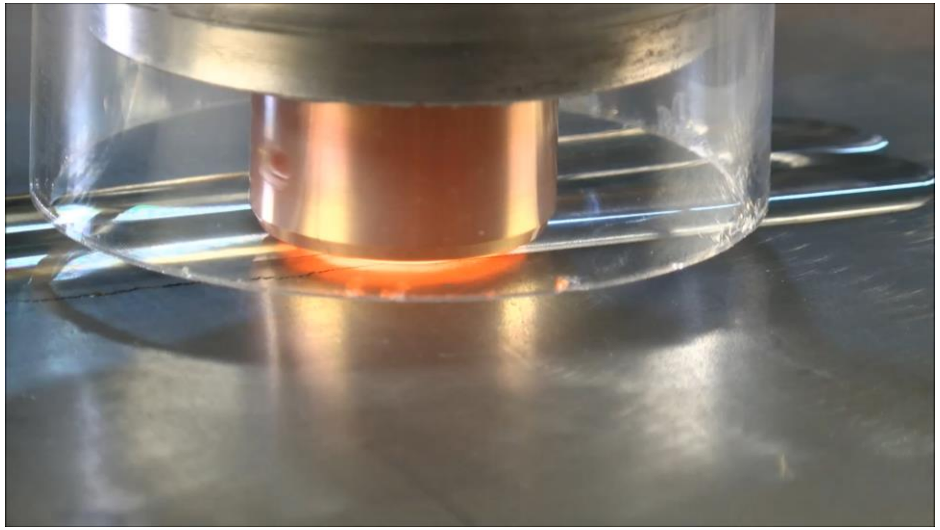
University of Sheffield AMRC

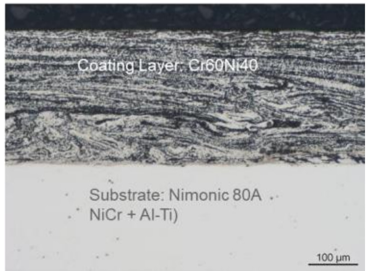
# Friction Stir Welding

**Advantages:**

- Mechanical properties are **overmatched** (full structural repair)
- Fully repairs physical defects (cracks, pitting) and microstructural damage (sensitization)
- Green Process (no harmful fumes generated, low energy consumption)
- Weld or repairs can be done in a single pass
- Fully automated, Temperature controlled FSP
- **FSP** has the potential to process various microstructures, improved corrosion resistance

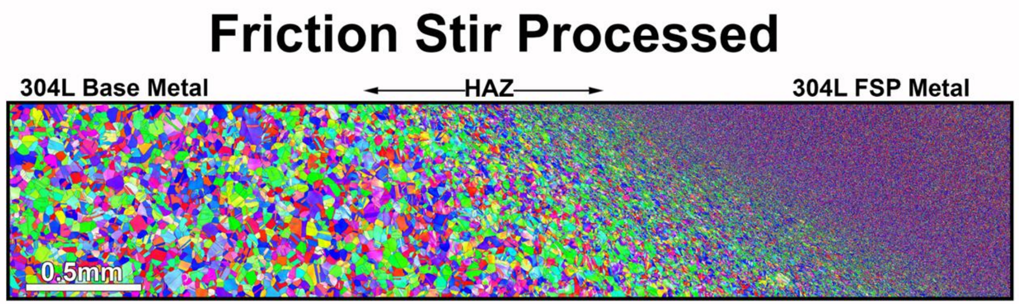


- Repair of Tooling

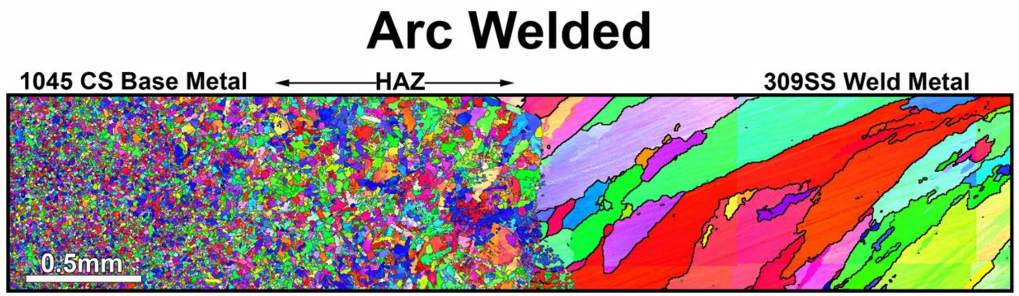



Bi-metallic pipe for offshore Oil & Gas applications

- No harm to base metal
- Improved properties




- Harmful HAZ
- Reduced properties and performance

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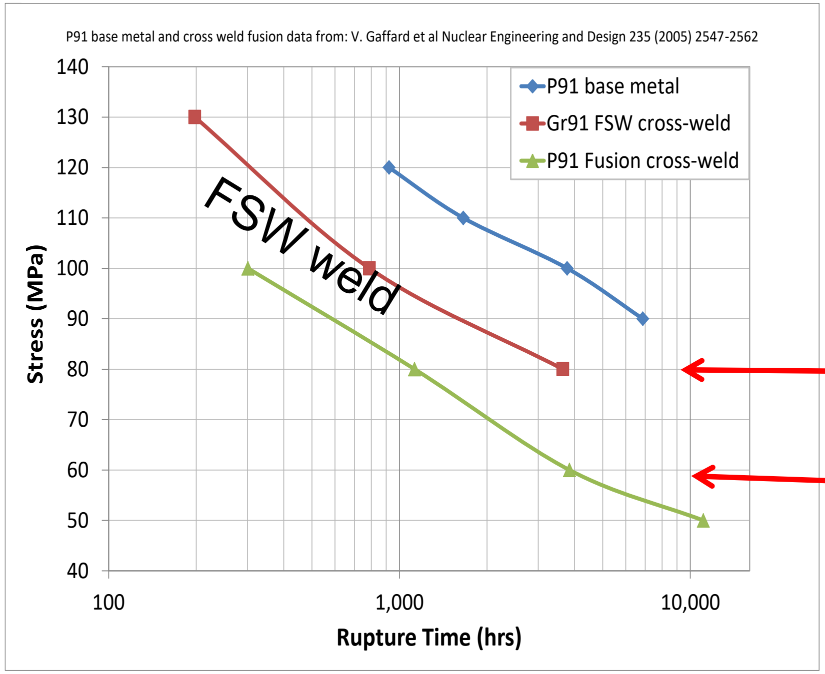
# Creep Rupture Testing of Friction Stir Welds

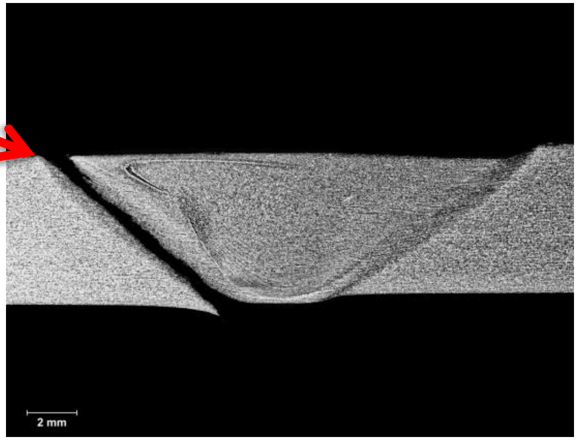
**First observation**: Welds fail in the heat affected zone in a similar way to fusion welds

Gr91 Friction Stir Welds vs Fusion Welds in cross weld tensional creep at 625C




P91 base metal – normalized and tempered

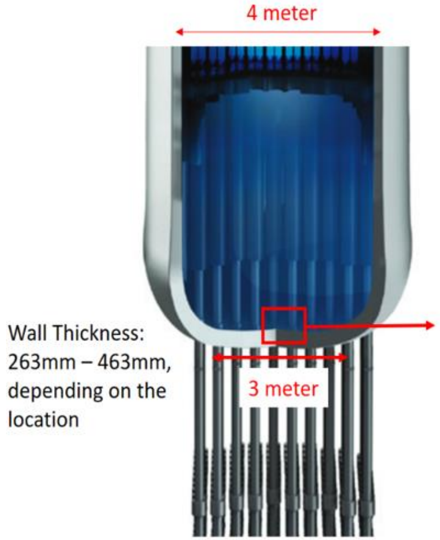
P91 welded by submerged arc then PWHT 2 hr 760C

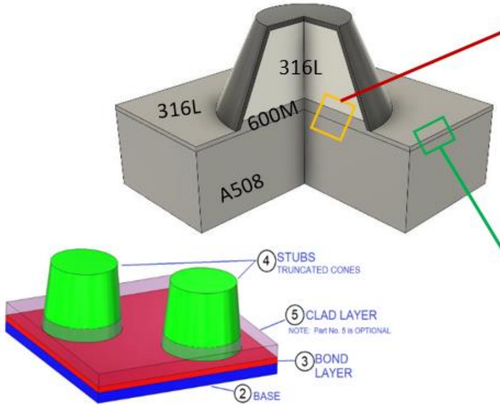



- FSW weld in Gr91 shows ~3X improvement in creep life over PWHTed fusion weld
- Design knockdown in strength is 32% for SMAW with PWHT (WSRF 0.68) vs. 18% for FSW (WSRF 0.82)

# Convergent PM-HIP Manufacturing for Multi-material Structure of Reactor Pressure Vessel

PI: Xiaoyuan Lou, Purdue University




Clad thickness: 1/8 inch

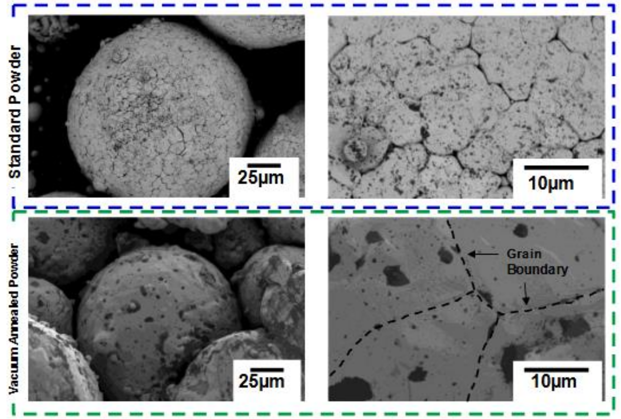
## Joining Technology

- HIP direct joint
- HIP transitional joint (600M, 82)
- Functionally graded joint

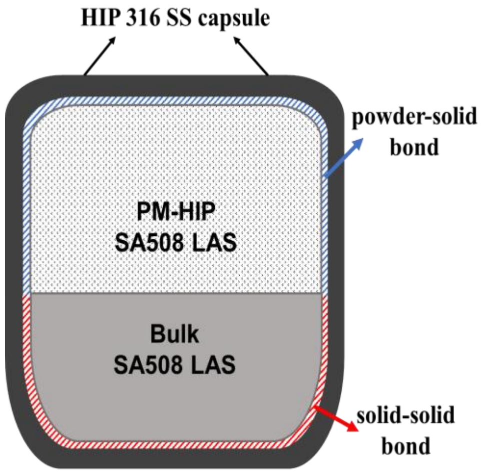
## Cladding Technology

- Cold spray clad
- HIP capsule diffusion bond (solid-to-solid, solid-to-powder)

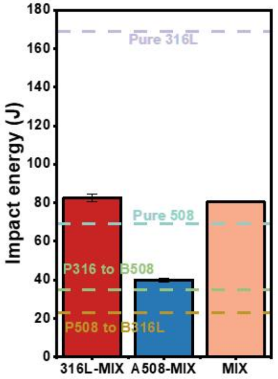
## Vacuum Annealing Powder Deoxygen Process

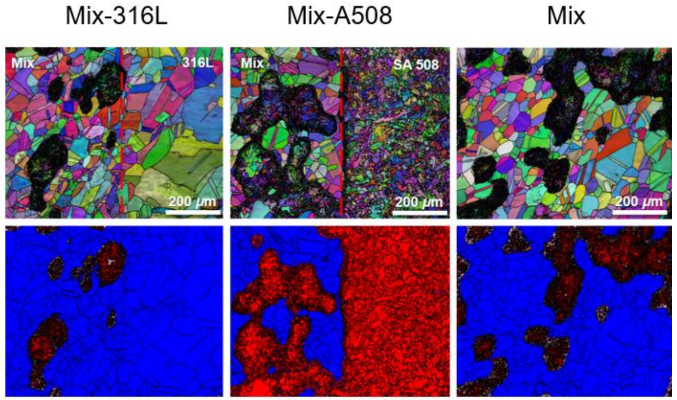



## HIP Cladding

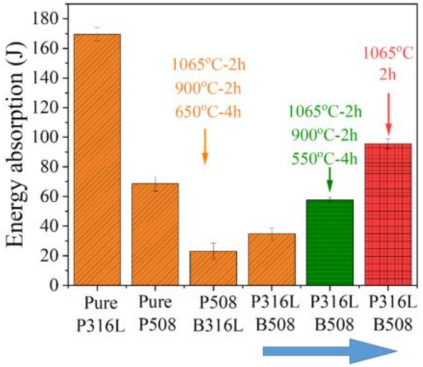



## Graded Joining by HIP

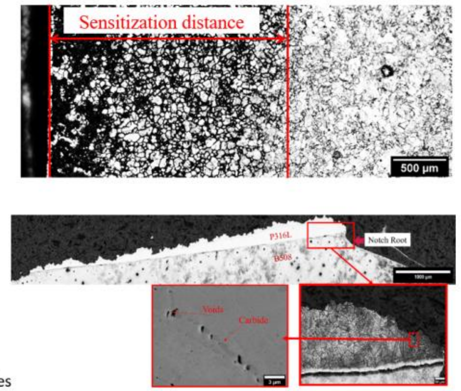



## Direct and Transitional Joining of dissimilar metal by HIP




Heat Treatment Minimizing Carbides

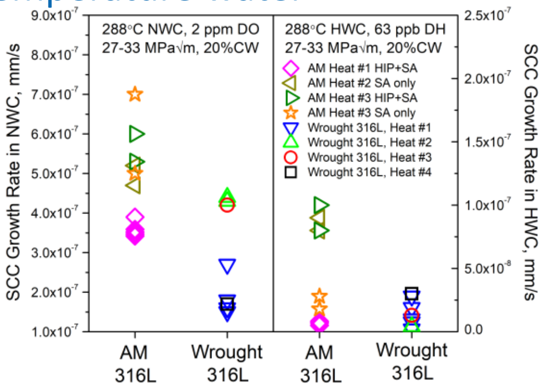


# Nuclear Qualification for Laser Additive Manufacturing

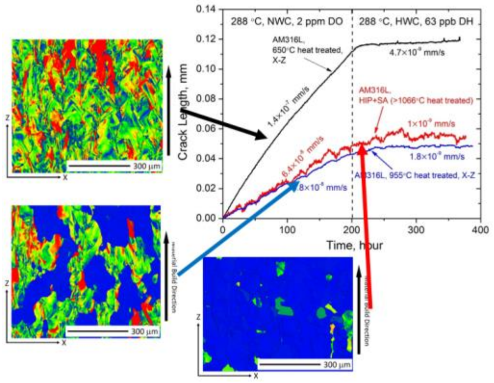
PI: Xiaoyuan Lou, Purdue University

## Environmental Cracking of AM 316L Stainless Steel

Comparable crack growth rate to cold worked wrought 316L in high temperature water

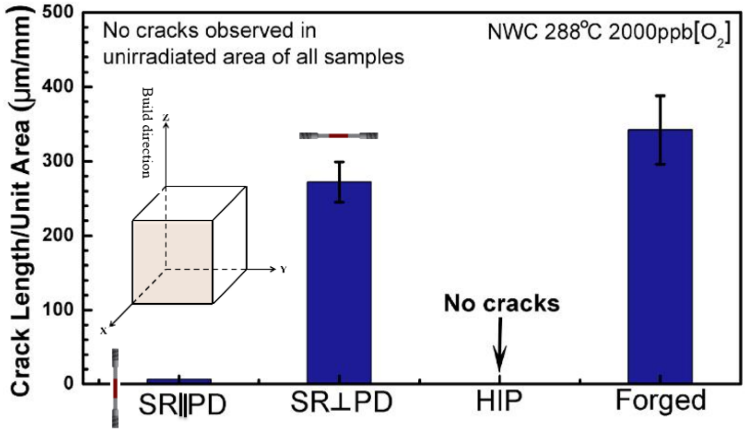



High-temperature treatment is necessary to reduce crack growth rate

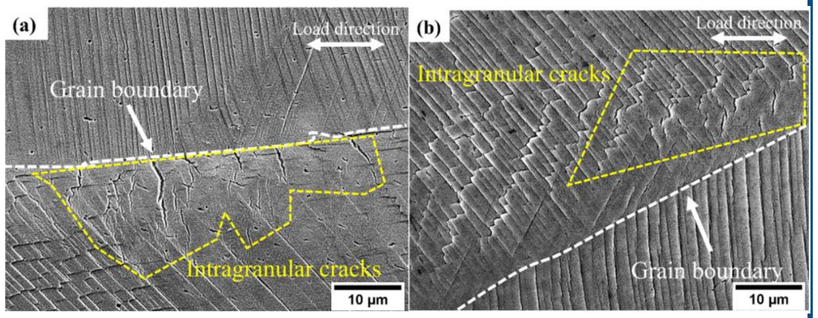



## Irradiation Assisted Stress Corrosion Cracking of AM 316L Stainless Steel

IASCC Susceptibility of Different Material Conditions

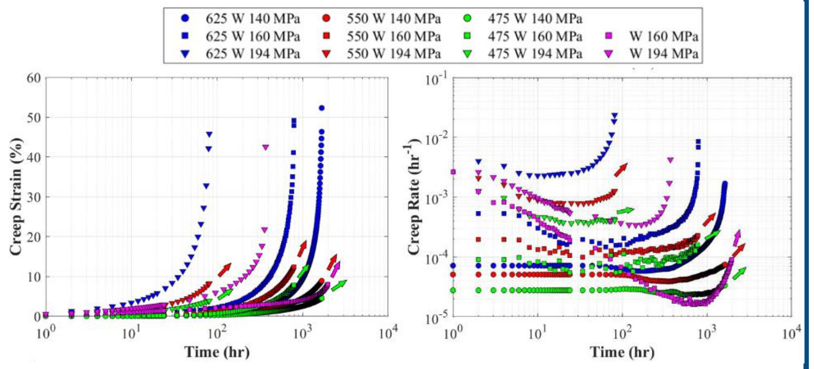



Unique Cracking Mode

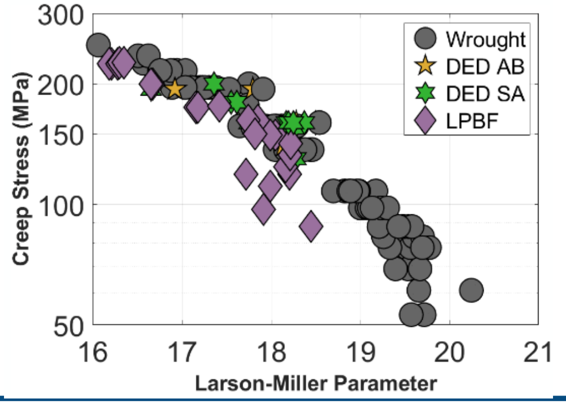



## High Temperature Creep Behavior of AM 316H Stainless Steel

Strong Dependency on Laser Parameters




DED 316H falls within the scatter bound and LPBF 316H is slightly below.



# Large Scale Manufacturing

- Electric Field Assisted Sintering (EFAS)
- HIP
- Wire DED
- Solid State Manufacturing: Friction Stir Additive / Layer Deposition

## Electric Field Assisted Sintering

*INL capabilities help industry optimize advanced materials manufacturing*

Idaho National Laboratory has a long history of helping U.S. companies remain competitive in advanced manufacturing. Researchers are constantly innovating new processes and technologies to reduce the life cycle energy consumption of manufactured goods, and ensure critical material supplies meet high-performance standards.

As a result, INL has developed an array of core capabilities that are ideally suited to solve advanced manufacturing challenges. Over the past two decades, INL has expanded those capabilities to include Electric Field Assisted Sintering (EFAS), an approach that dramatically improves the manufacturing of high-performance components.

**WHAT IS EFAS?**
EFAS supports the decarbonization of metals, ceramics and composite material manufacturing through process electrification. EFAS enables distributed manufacturing activities that connect with regional supply chains and raw materials to deliver high-performance products.

Many of today's high-performance technologies, including nuclear reactors, spacecraft, concentrated solar plants and hydrogen cells, require advanced materials made of metals and ceramics that can withstand extreme conditions or meet exacting specifications.

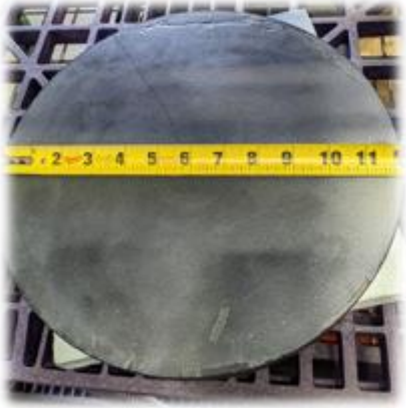
In the past, these advanced materials were typically manufactured from powder that was poured into a die, subjected to high pressure, and slowly heated in a process called hot pressing. However, hot pressing results in limited performance and wastes a lot of energy, contributing to high costs that have limited the widespread use of advanced materials in industries that manufacture more everyday items such as automobiles.

Advances in EFAS, including "brand specific" process names such as Spark Plasma Sintering, or Direct Current Sintering and Flash Sintering, now make it possible to

INL Idaho National Laboratory

# DCS-800: Large format EFAS system

- 800 ton press
- 150 kA
- Chamber:
  - 64 $ft^3$
  - 24” Ø rams
  - Sample size:8” to 24” Ø



# Large-scale Component Manufacturing

*(Soumya Nag, et al. ORNL)*

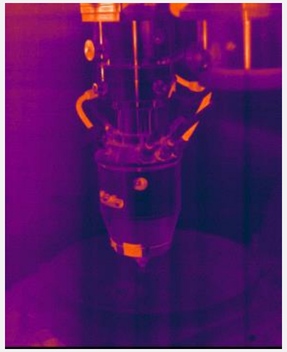
- Feasibility demonstration of additive and hybrid manufacturing of large-scale nuclear components (e.g. vessel, valves).
- Smart Manufacturing: incorporate *in-situ* monitoring data into component qualification and certification.

## Test Case 1: HIP Valve Geometry

- State: Post HIP-ed; AM Platform: Hybrid AM
- Material for AM can: 316L SS;
- Material for PM: 316L SS
- Time to Print/Machine: 20 hr/25 hr
- Weight: 25lbs; Volume: 53 in$^3$


Actual AM Build

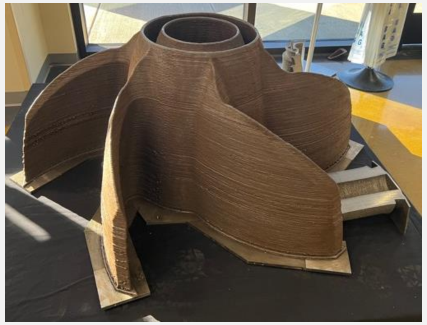
Digital Image Correlation (DIC)

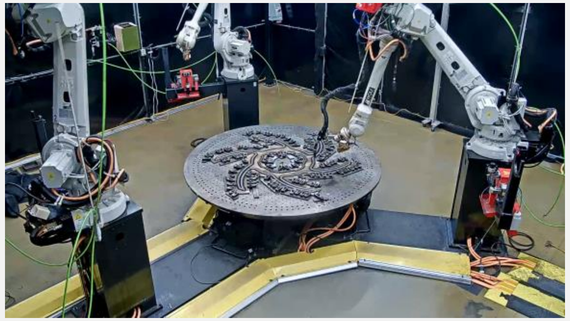


IR camera

## Test Case 2: Impeller Prototype

- State: As Built; AM Platform: WAAM/MedUsa
- Material for AM can: 410 Ni Mo SS;
- Material for PM: TBD
- Time to print: 46 hr @ 20lb/hr
- Weight: 900lbs; Volume: 6889 in$^3$ (5ft dia, 25” ht)

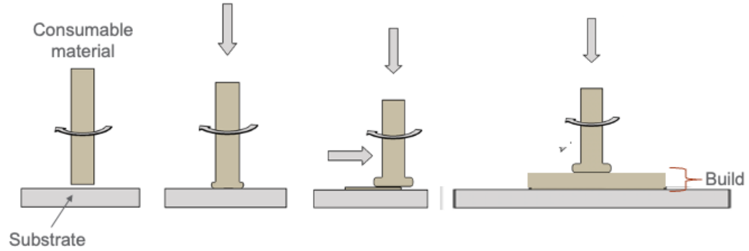


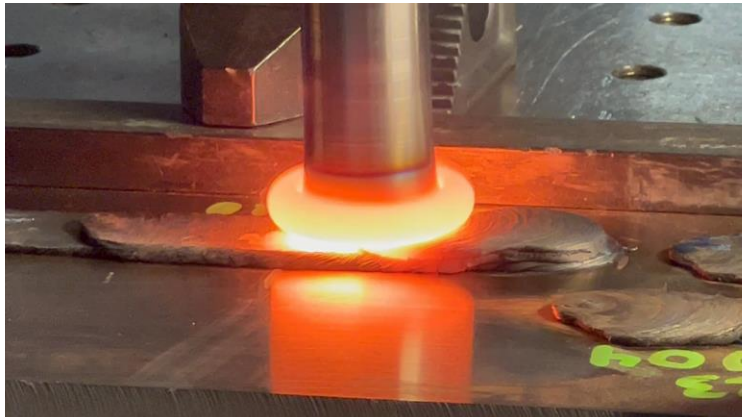


# Friction Stir Additive Manufacturing

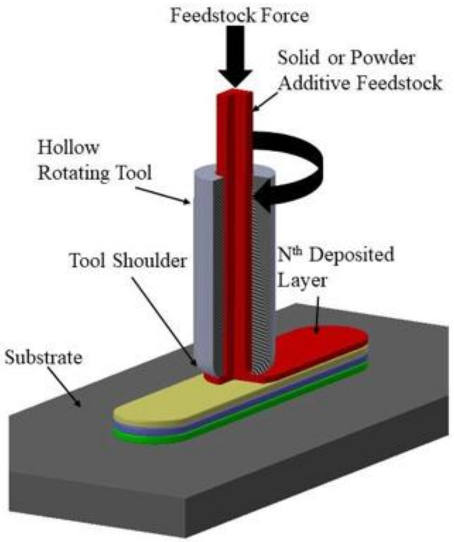
- Application of high shear strain during metals synthesis or fabrication, to produce high-performance microstructures in alloys, semi-finished products and engineered assemblies, without bulk melting the constitutive materials.
  - can facilitate diffusional processes and phase transformations, offering the potential of a scalable route to the production of metastable, or far-from-equilibrium materials
- Additive Solid Phase Manufacturing is **focused on three solid phase deposition technologies**:

## Friction Surfacing (Additive)

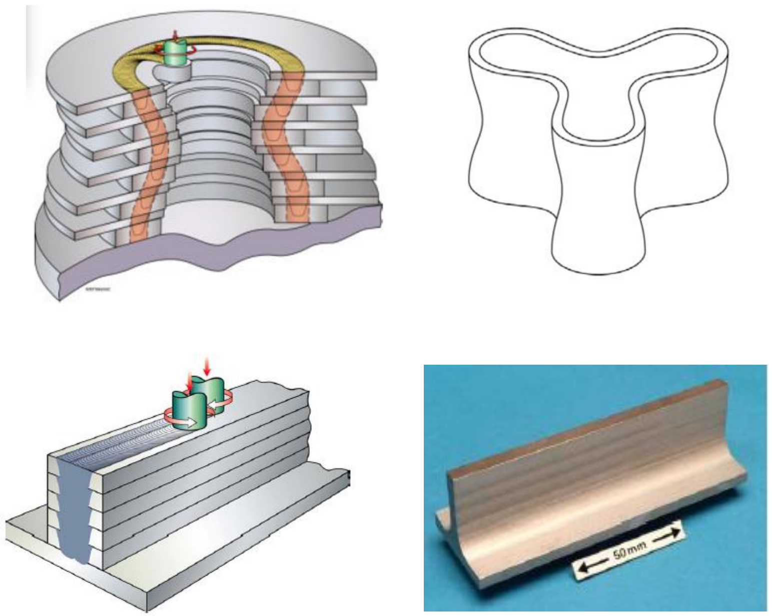


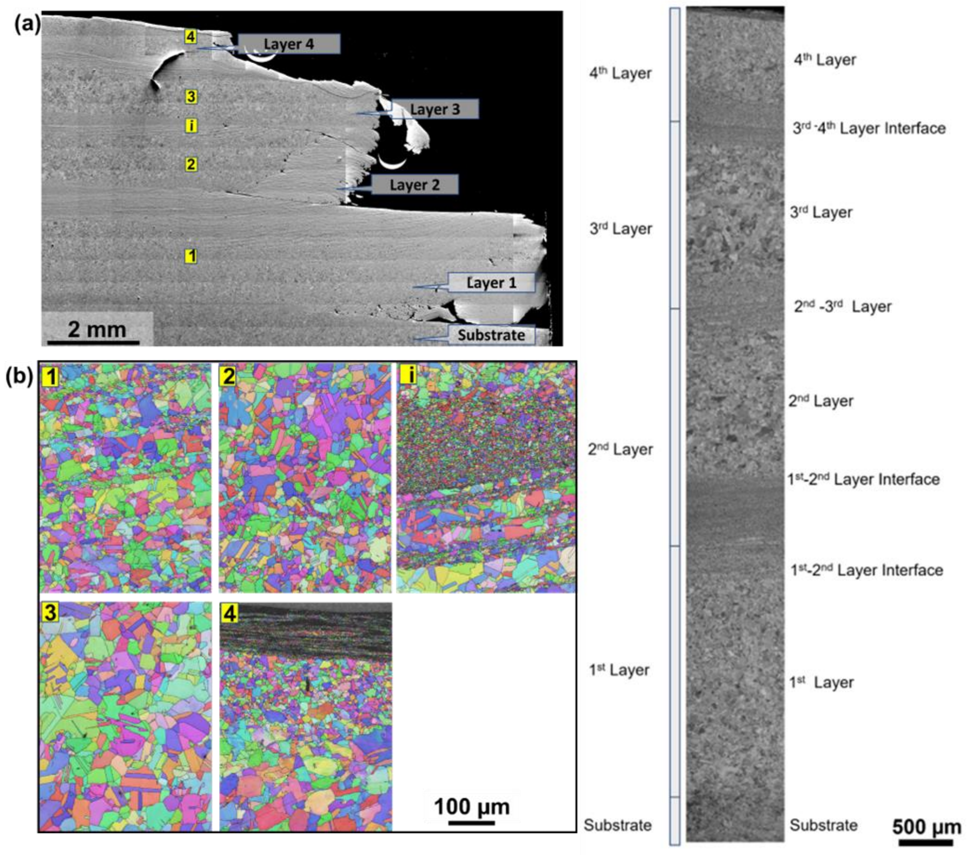
## MELD

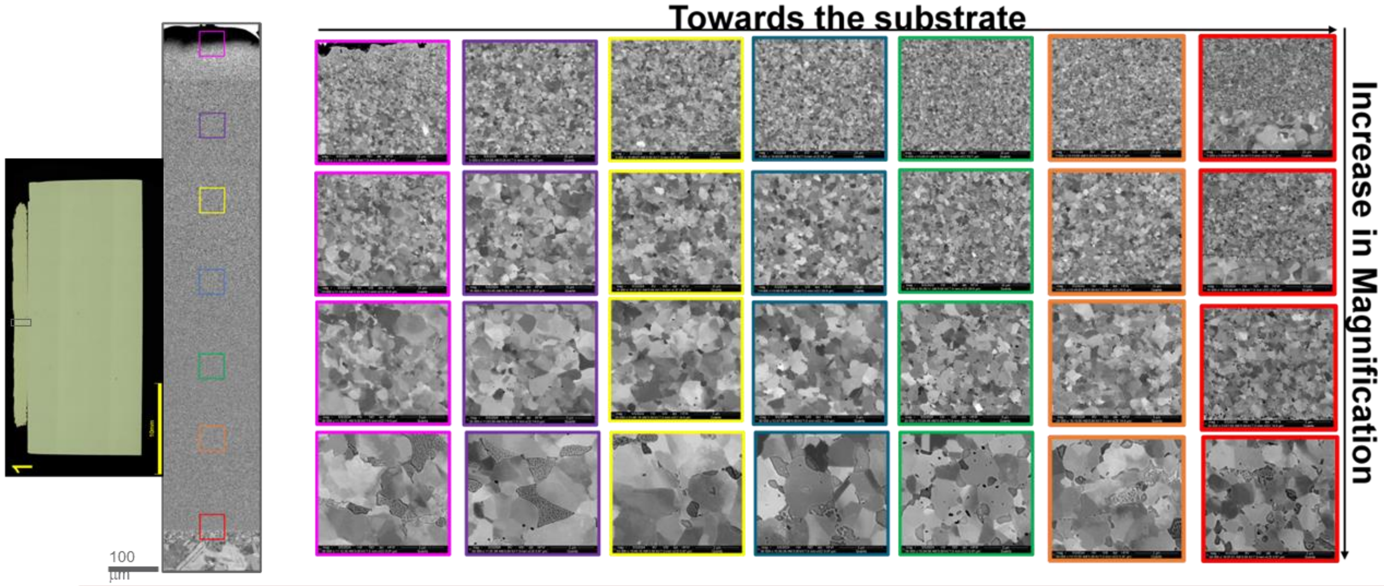



## Friction Stir Plate Stacking



# NiCoFeCr$Cu_{0.12}$ and Al10$Cr_{12}Fe_{35}Mn_{23}Ni_{20}$ High Entropy Alloys: FSLD Microstructure



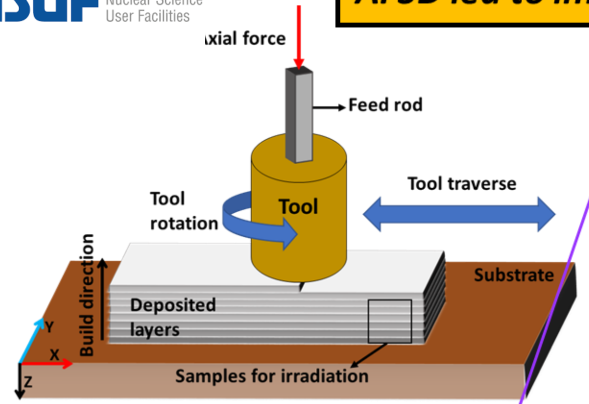



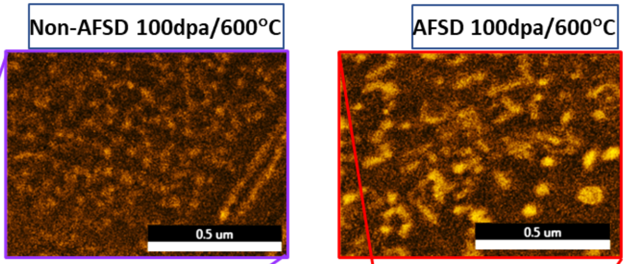

*Towards the bottom (near substrate): Grain refinement is observed possibly due to formation of oxides and presumably the higher cooling rate.*

- Offers a Bulk Manufacturing process for HEA
- Significant grain refinement in FSLD process compared to that in as-cast and solutionized sample.
- End Pieces needs optimization

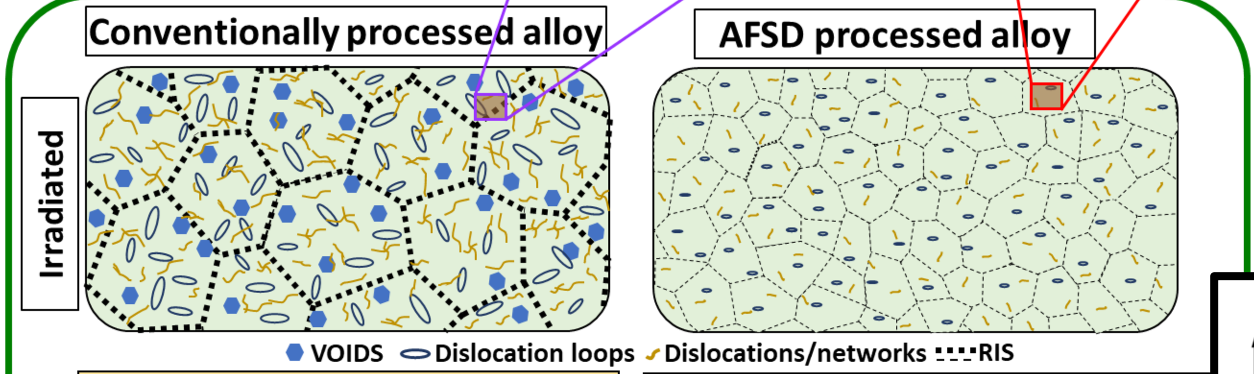
# Solid-stir Additive friction stir deposition of 316SS with improved radiation tolerance

**AFSD led to improved radiation tolerance**




**Coarser Ni-Si clusters → reduced radiation hardening**




**Voids and higher density of bigger dislocation loops and networks, RIS**

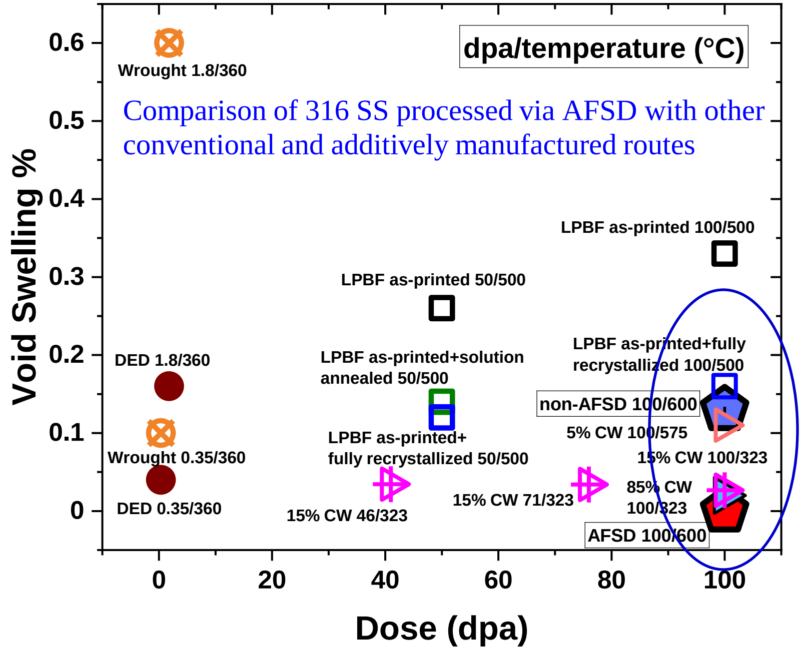
**Absence of voids, lower dislocation density and weaker RIS**

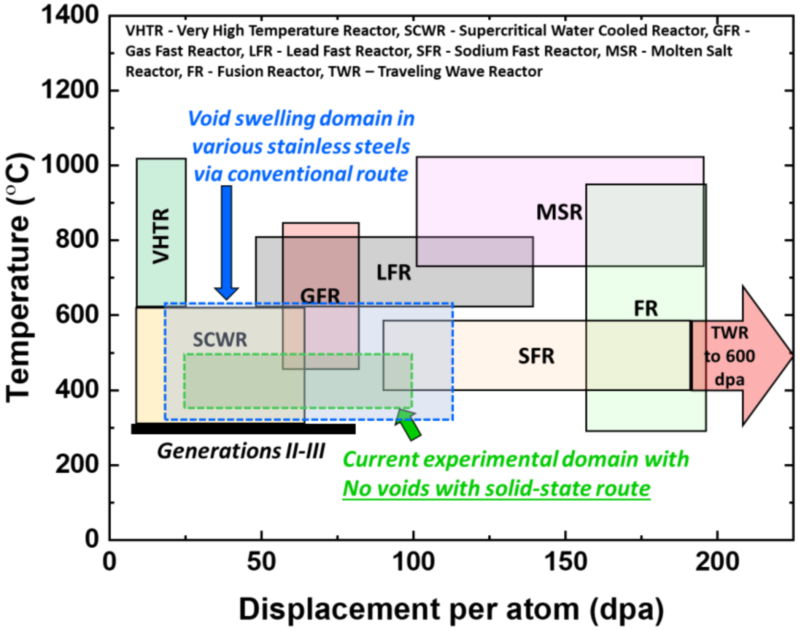

- AFSD leads to improved radiation tolerance
- Capable of building large 3D parts
- AFSD – push the dpa/°C to the right side

**RTE 21-4307 – awarded**
**RTE 20-4112 – awarded**

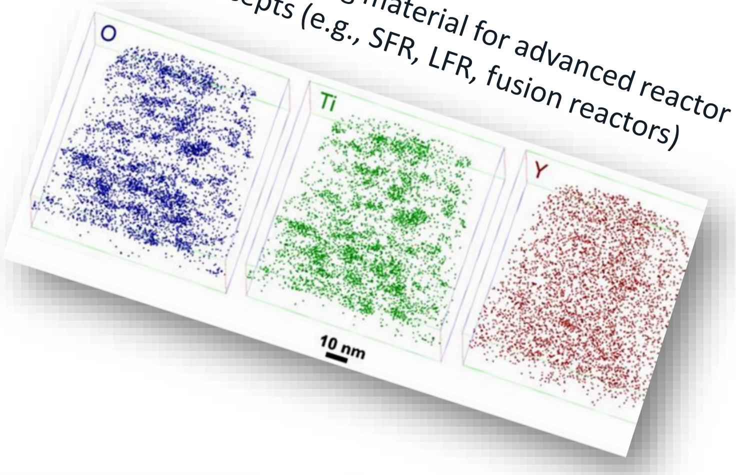
*P Agrawal et al., JMAD, 238, 2024, 112730*
*P Agrawal et al., JoNM, 574, 2023, 154217*
*P Agrawal et al., JoNM, 597, 2024, 155093*

316SS
HEA



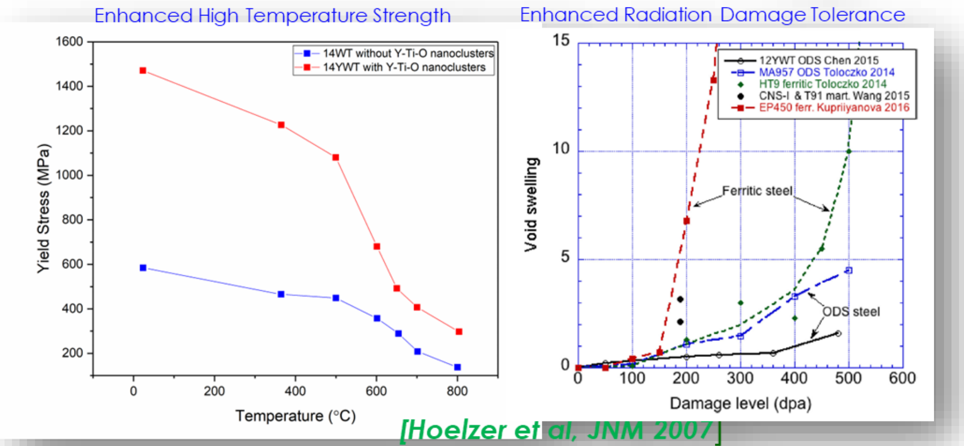



Cross-cutting material for advanced reactor concepts (e.g., SFR, LFR, fusion reactors)




# Profile Forming Processes

- ShAPE$^{TM}$ for nuclear energy applications (e.g., fuel cladding, heat exchanger tubing)
- ODS Cladding Tubes New Manufacturing Processes
  - Concept of Manufacturing ODS tube via Cold Spray Process
  - Direct Tube Manufacturing using ShAPE$^{TM}$
    - ✓ Produce bar then pilger process
    - ✓ Direct tube manufacturing from powder or solid
  - LPBF & DED with subsequent thermal mechanical processing (not discussed today)




[Hoelzer et al, JNM 2007]



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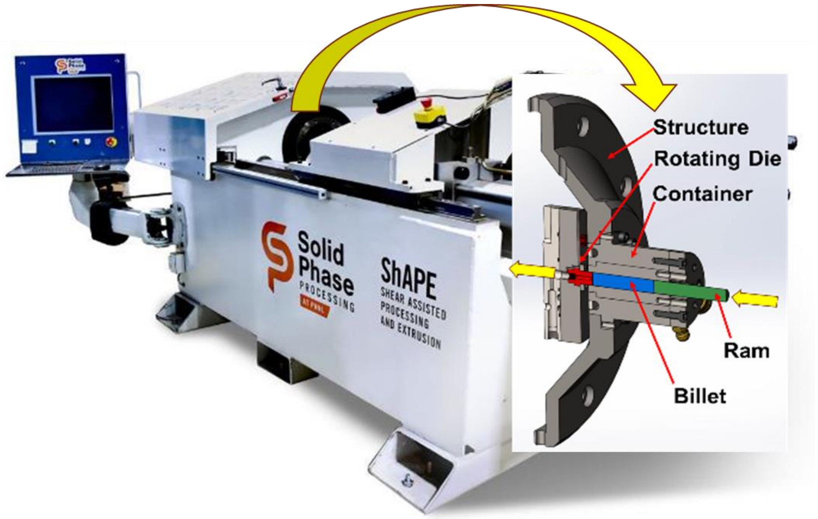
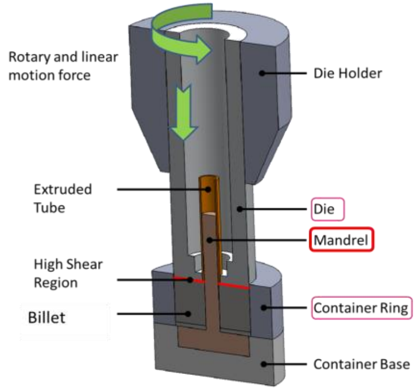
# Shear Assisted Processing and Extrusion (ShAPE™)

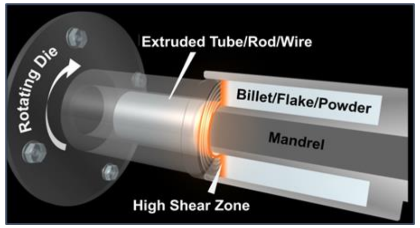



Developed at PNNL, ShAPE™ is a unique method for consolidating/extruding materials, in which linear and rotational shear are combined to plasticize.

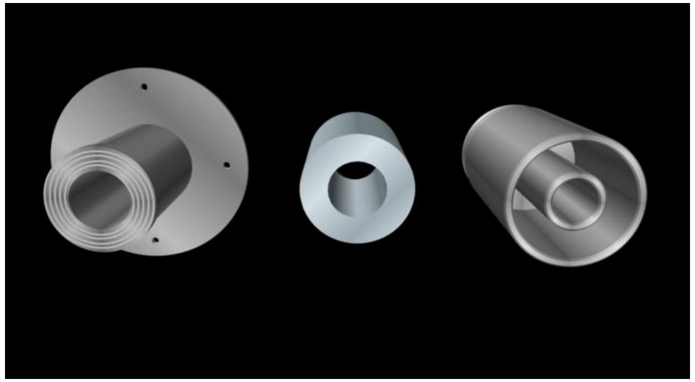
Benefits include:

- Grain refinement
- Texture alignment
- Breakdown of 2nd phases
- Mixing and homogenization
- Single step process
- Lower force and energy



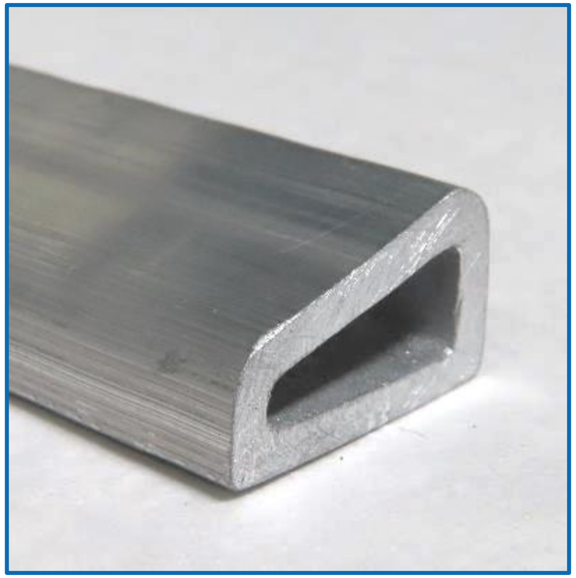




| Input: | Output: |
| --- | --- |
| Tool rotational speed | Temperature |
| Die advance rate | Torque/power |
| Extrusion ratio | Forces (X, Y, and Z) |



A rotating die is pushed into the billet material resulting in the fabrication of an extrudate between the mandrel and the die orifice or landing.

# ShAPE Profiles (Hollow Core)

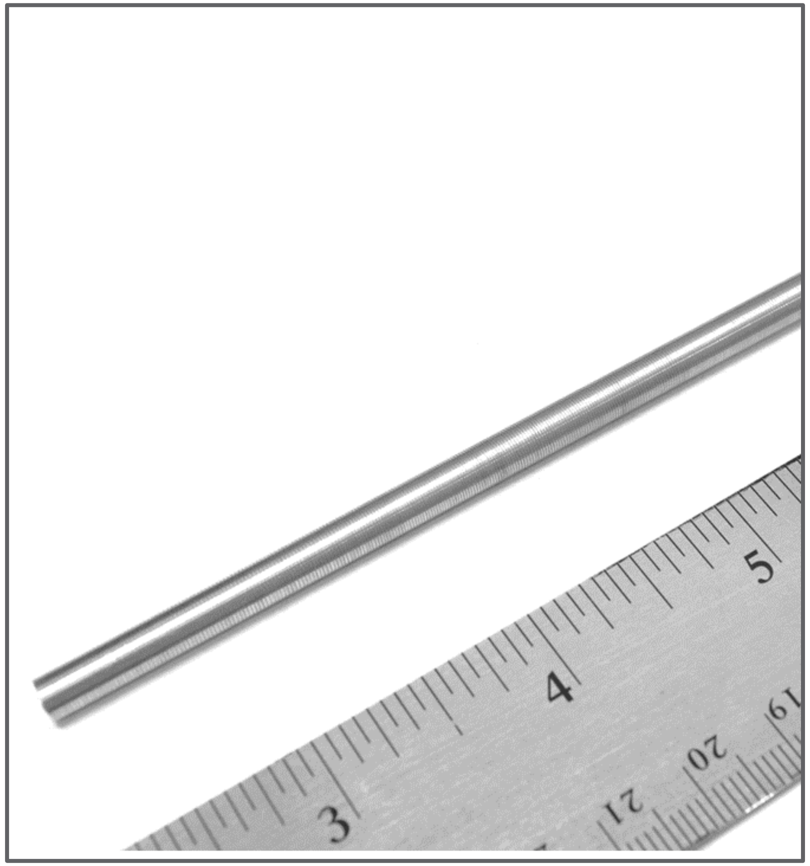
| Round | Square | Asymmetric | Multi-Cell |
|---|---|---|---|
|  |  |  |  |

S. Whalen, B.S. Taysom, N. Overman, Md. Reza-E-Rabby, Y. Qiao, T. Richter, T. Skszek, M. DiCiano, “Porthole Die Extrusion of Aluminum 6063 Industrial Scrap by Shear Assisted Processing and Extrusion,“ Manufacturing Letters, 36, pg. 52-56, 2023.

# ShAPE Profiles (Solid Core)

## Wire

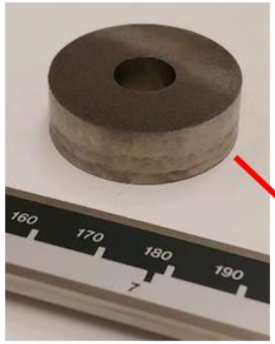
## Rod



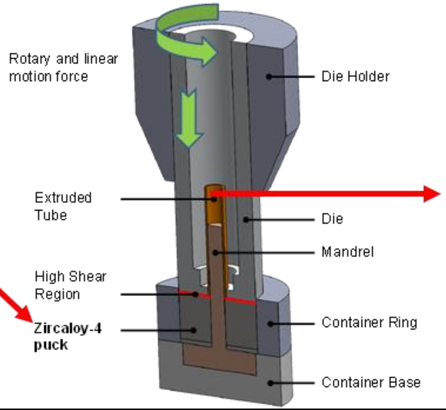

## Bar

# Zircaloy-4 tubing and Co-extrusion

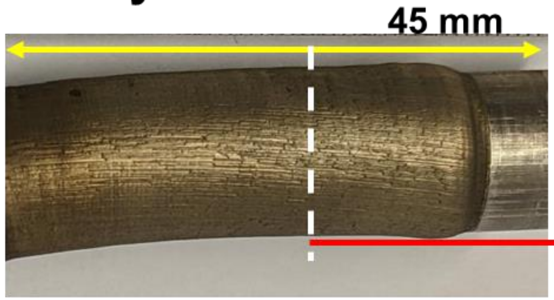
## Zircaloy-4 feedstock

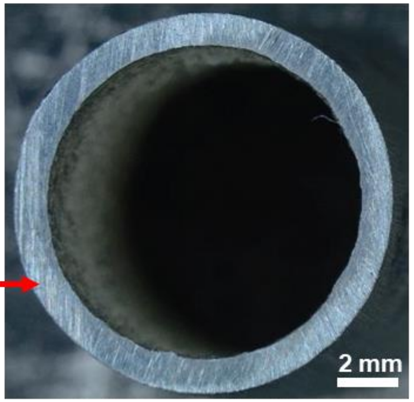


## ShAPE




## Zircaloy-4 tube



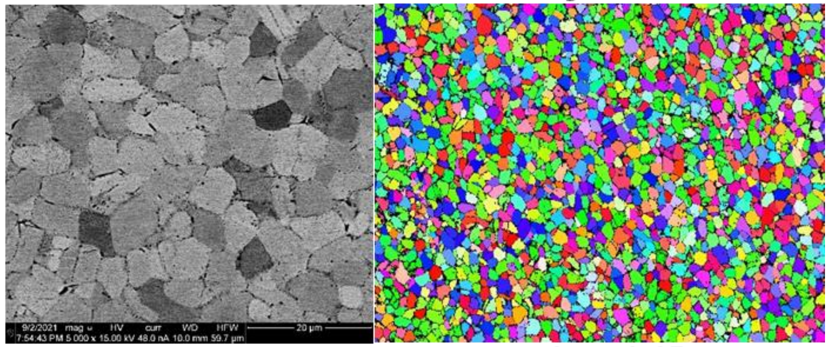




## Dimensions

**t**: 1.1±0.05
**ID:** 10.5±0.05
**OD**: 12.7±0.06
**Tolerance**: <10%

ID: Inner diameter and OD: outer diameter

## SEM and EBSD analysis



$d_{avg}$: 4.45 µm

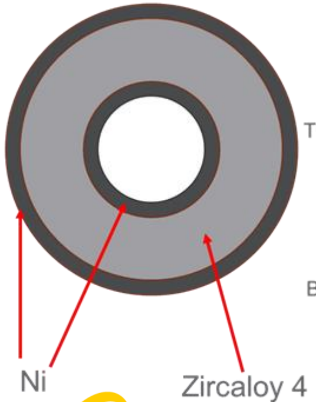
## Kearn's Values

$f_{ND} = 0.27$, $f_{Radial} = 0.44$, and $f_{Trans} = 0.29$

Fine equiaxed grain structure and random texture

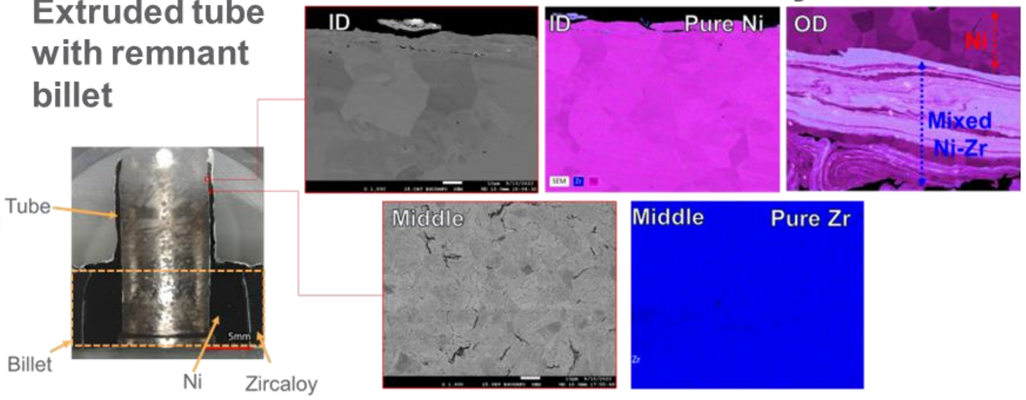
## Cladding

Billet Design




Extruded tube with remnant billet

## SEM and EDS analysis




Ni cladding is successfully produced on inner diameter and partially on outer diameter

2

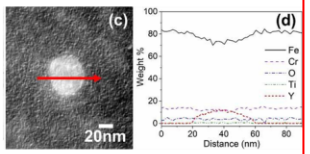
# Conventional Manufacturing of ODS Steel Tubes – Slow and Costly Process

Fe-14Cr-3W-0.4Ti-0.2Y (wt.%) (can introduce oxygen during atomization)

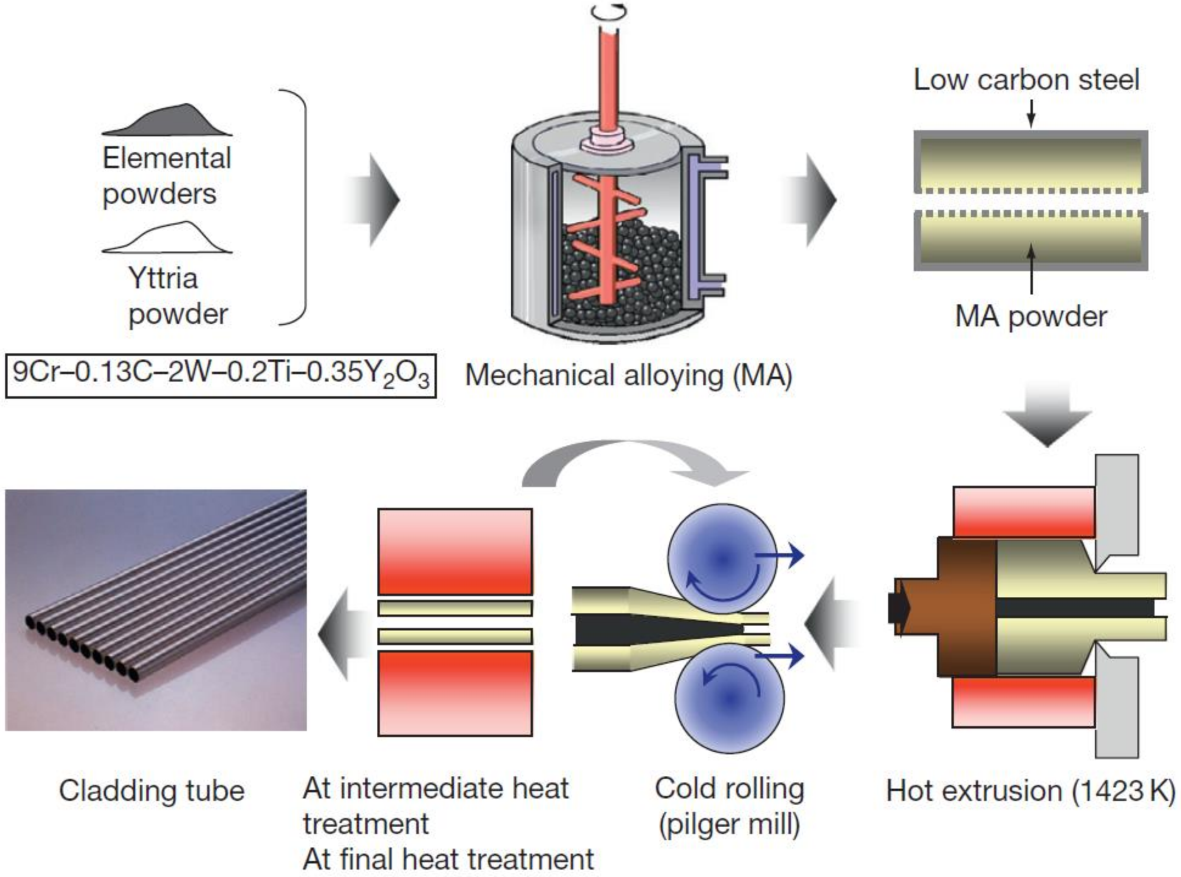
Atomized (Y and Ti not fully solutionized)

Ball milled with FeO powder (Complete solutionizing of

Annealing: Precipitation of Y-Ti-O nanoclusters

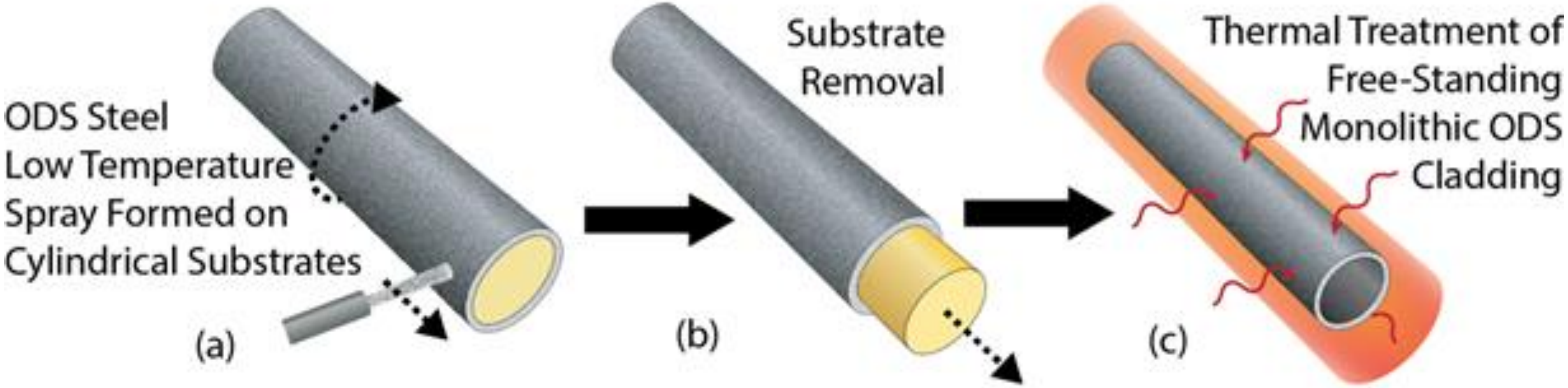



- Ball-milled powders canned and subjected to multiple hot extrusion and annealing steps (8 -10 steps).
- Not conducive to large-scale manufacturing




*G. Odette et al, Annu. Rev. Mater Res., 2008*]

# Concept of Manufacturing ODS tube via Cold Spray Process

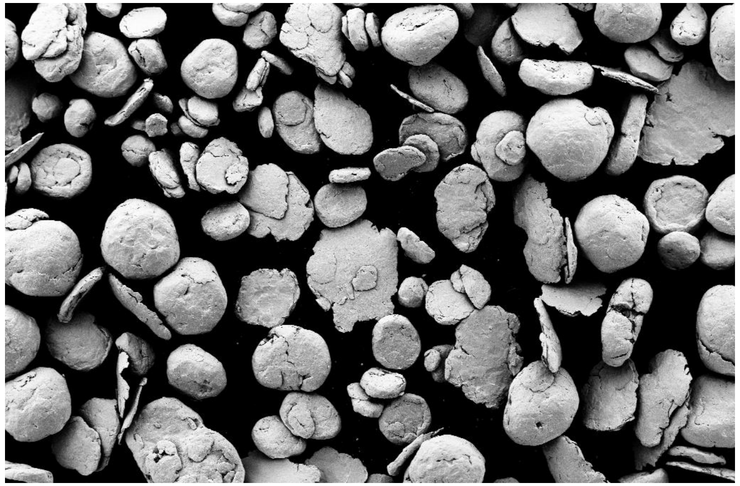



*Patent No. 1598008, 2023.*

Potential Benefits:

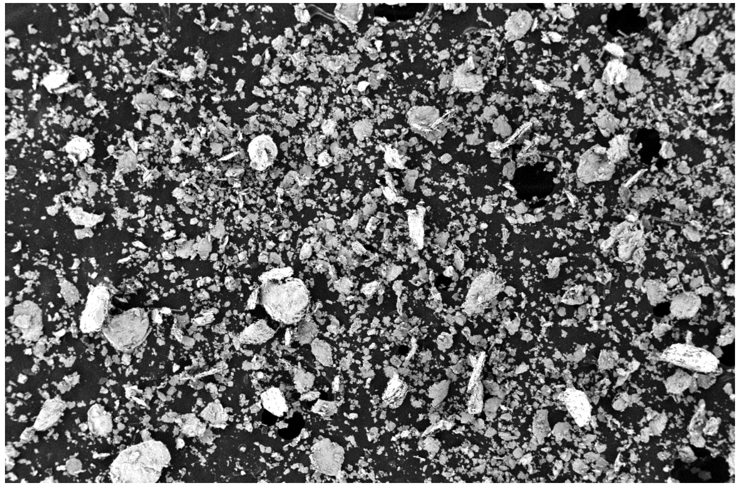
- Eliminates multiple extrusion steps
- Faster and cheaper manufacturing process

# Powder Engineering to Achieve Right Particle Microstructure and Size/Hardness for Cold Spray

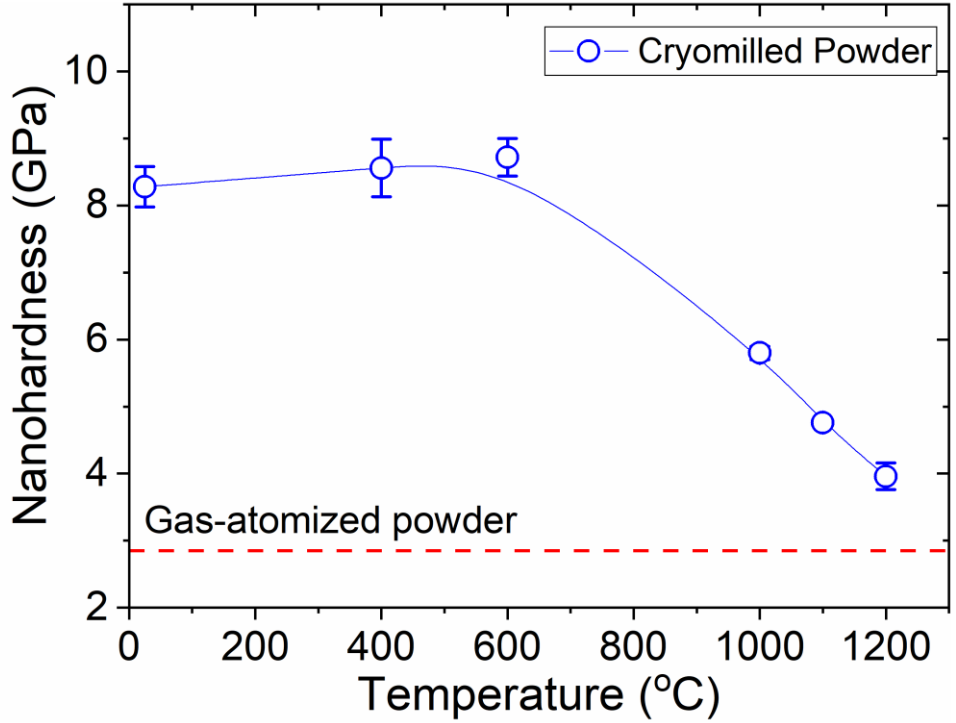


- Powder size reduction (Cryogenic milling)
- Hardness reduction (Heat treatment)

Cryo-milling in liquid $N_2$



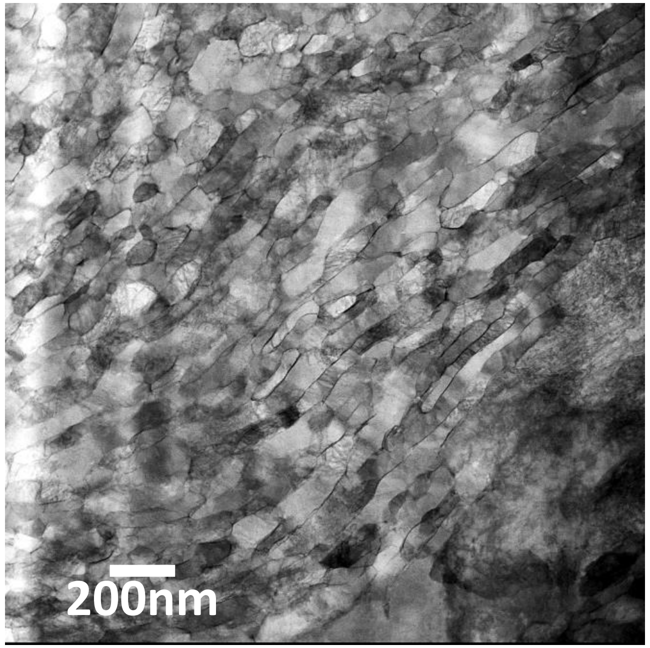
**Hardness reduction by heat treatment**




*"Cold Spray Manufacturing of Oxide-dispersion Strengthened (ODS) Steels using Gas-atomized and Ball-milled 14YWT Powders", H. Yeom, D. Hoelzer, S. Maloy, and K. Sridharan, Journal of Nuclear Materials, v. 174, 2023 154187*

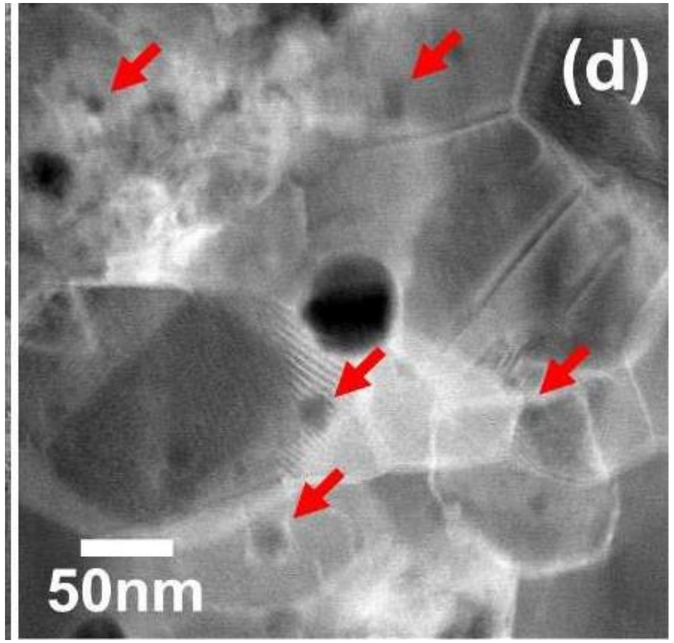
# TEM of Cold Spray Deposits using Engineered Powders

Low mag. BF



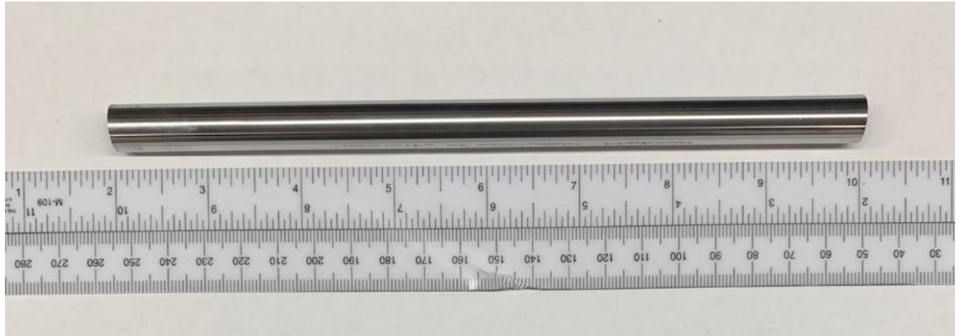

Fine grain structure (<500 nm)

High mag. BF



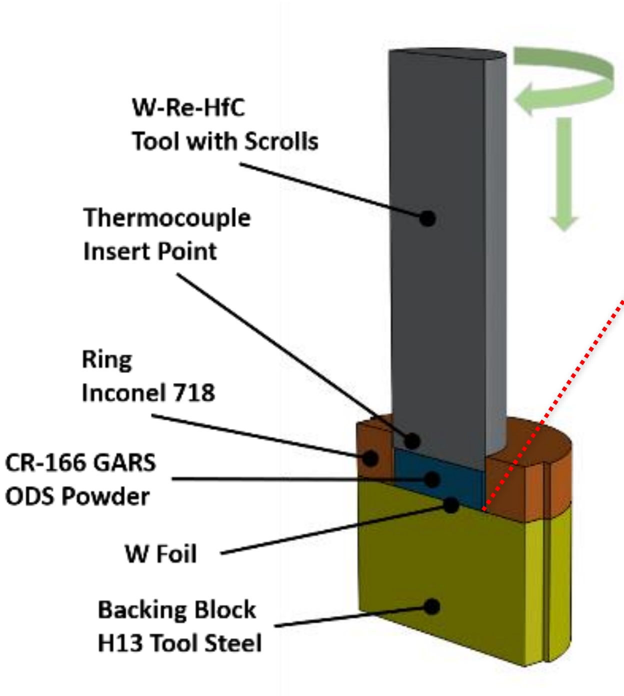

Fine nanoparticles(<20 nm)

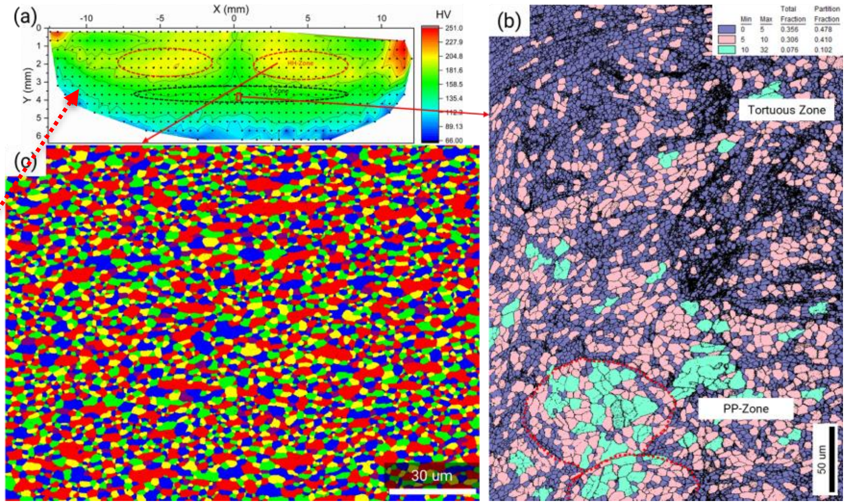
Near-net shape, free-standing ODS steel tube with right microstructure manufactured by cold spray



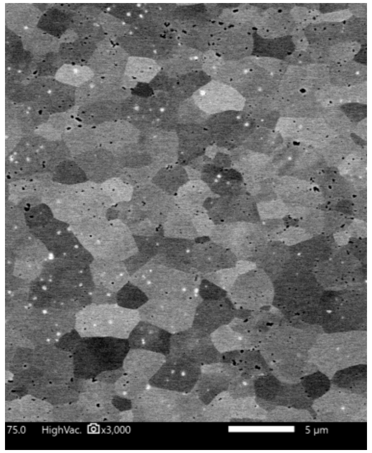
*"Cold Spray Manufacturing of Oxide-dispersion Strengthened (ODS) Steels using Gas-atomized and Ball-milled 14YWT Powders", H. Yeom, D. Hoelzer, S. Maloy, and K. Sridharan, Journal of Nuclear Materials, v. 174, 2023 154187*

# Consolidation and extrusion of GARS ODS powder with ShAPE platform



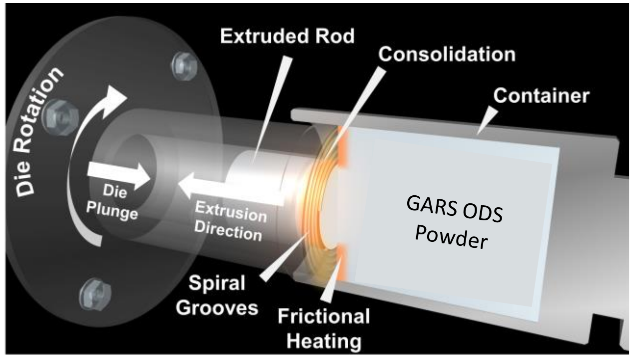


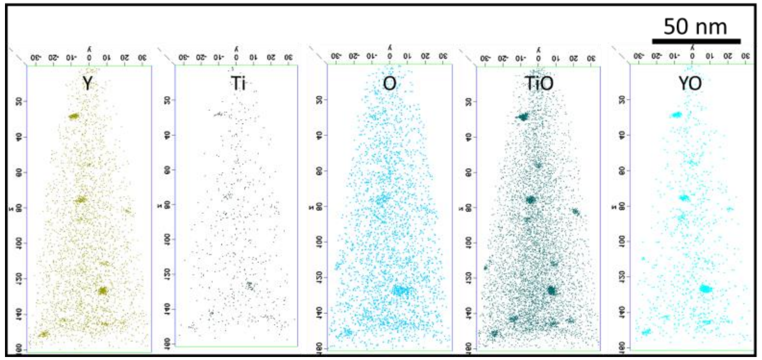



- Robust friction consolidation of GARS powder (< 1 min)
- In-situ formation of Y-Ti-O nano-oxide particles ($2.3\times10^{22}/m^3$)
- "Stratum" to study Y/Ti/O evolution with increasing deformation

Zhang et al., Journal of Nuclear Materials, 2022
https://www.sciencedirect.com/science/article/pii/S0022311522002550?via%3Dihub

- Friction extrusion following consolidation
- Crack-free, fully-dense ODS steel rod
- Preliminary results suggest presence of high-density, nano-sized particles

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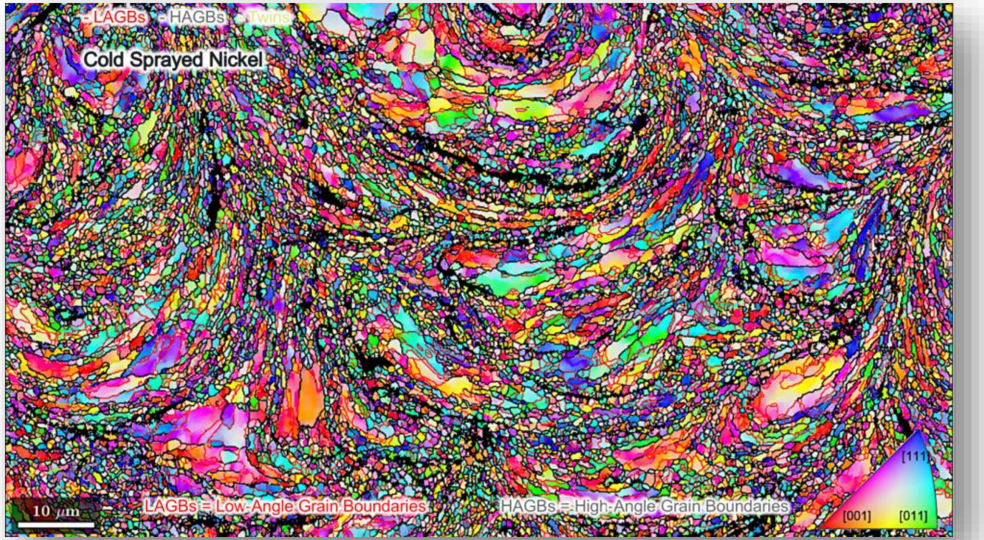
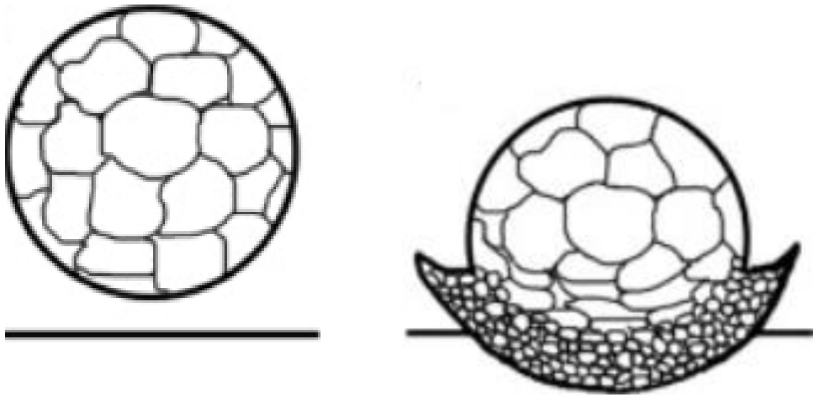
# Cold Spray Processing for Nuclear Energy Applications

- Full Lifecycle application for nuclear energy applications



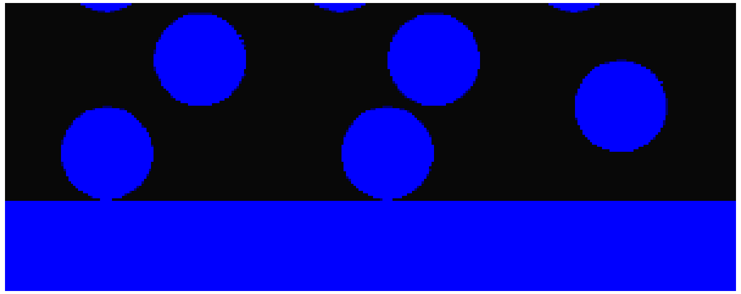
# Cold Spray: Process Details

- 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, mixtures of areas of extreme to low plastic deformation develop.
- Solid-phase process
  - No heat affected zone (HAZ)
  - No tensile residual stresses
- Does no harm to surrounding material



Grain structure of atomized particles prior to and immediately after impact
-courtesy of VRC Metal Systems

| | |
|---|---|
| Substrate: | Stainless steel |
| Powder: | Inconel 625 |
| Carrier Gas: Helium | |
| Deposition rate: | 350 g/min |
| Note: | |
| Arc welding is 0.25 lb/min =113.4 g/min | |
| Video courtesy of Plasma Giken | |

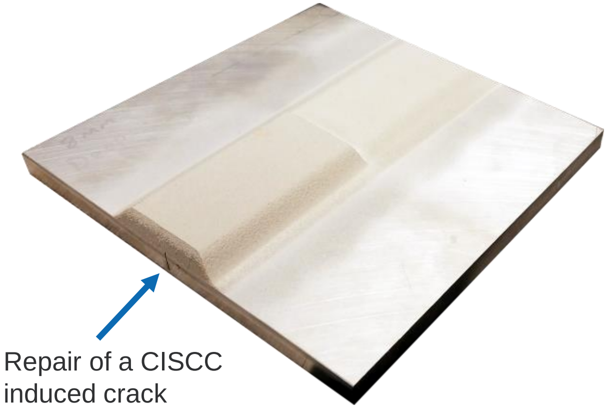


Video: Simulation of particle deformation during high-velocity cold spray
-courtesy of VRC Metal Systems

# Applications for Cold Spray

- Research & Development:
  - Rapid screening of new alloys
- New design
  - Induces compressive residual stresses: fatigue performance
  - Wear resistance
  - Corrosion barrier for MSR
  - Environmental barrier
  - **Cost competitiveness:** Improved economics
- Operations next generation reactors
  - Improved performance and economics
  - Life extension/Lifecycle
  - In-situ repair
  - Magnetostrictive condition monitoring at high temperatures
- Life extension of existing fleet

Ni Coating on SS



Repair of a CISCC induced crack

- 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)

# Fielded cold spray repair

Collaboration: Constellation, VRC and PNNL

- December 2020 Plant Authorized Cold Spray Mitigation of:
  - 1st 24” **Salt Water Check Valve Body** (AL6XN) Cold Sprayed (Spare, 1 of 7)
  - 1st 18” **Salt Water Flow Element Flanges** (316 SS) Cold Sprayed (Spare, 1 of 9)
- Check valve installed in 2021,
- Flow Element installed in 2022
- 2nd 24” Salt Water Check Valve Body (AL6XN) Cold Sprayed on 5/18/2022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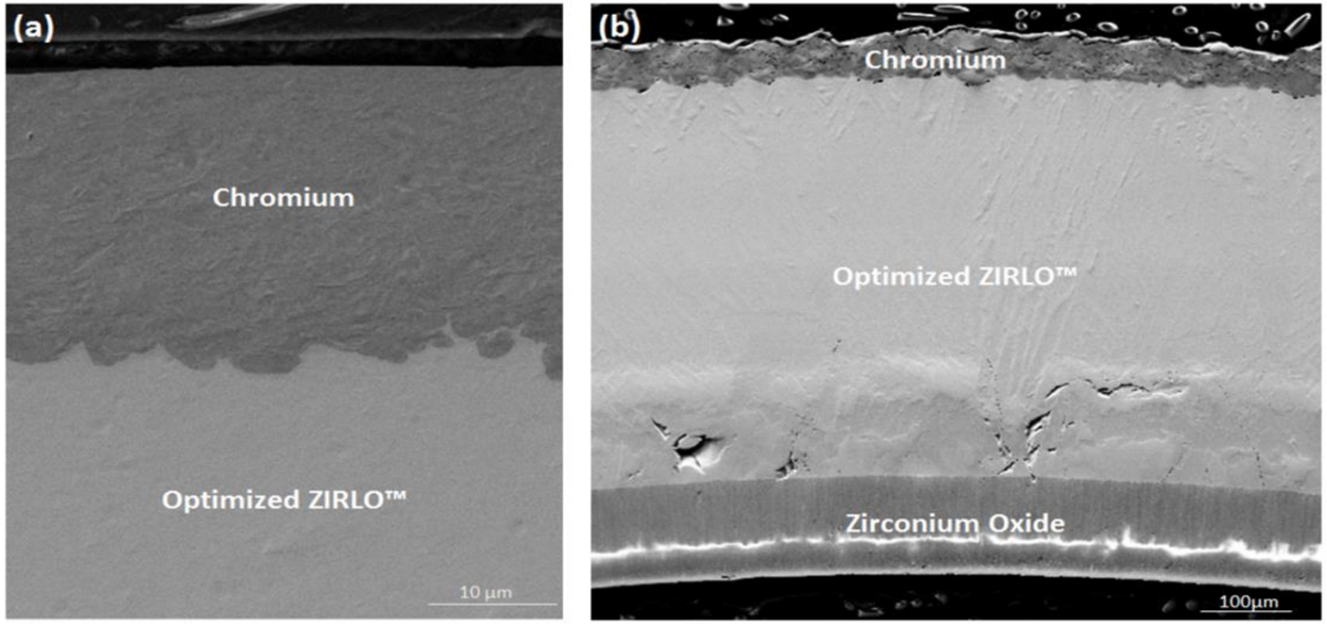
Pacific Northwest NATIONAL LABORATORY

# Westinghouse LWR fuel cladding

- Cold sprayed Chromium on Optimized ZIRLO
- Irradiation testing Byron Unit 2 Cycle 22
- Improved
  - Economics
  - Safety
  - Reliability




(a) As-fabricated microstructure of cold spray chromium coating on Optimized ZIRLO cladding, (b) 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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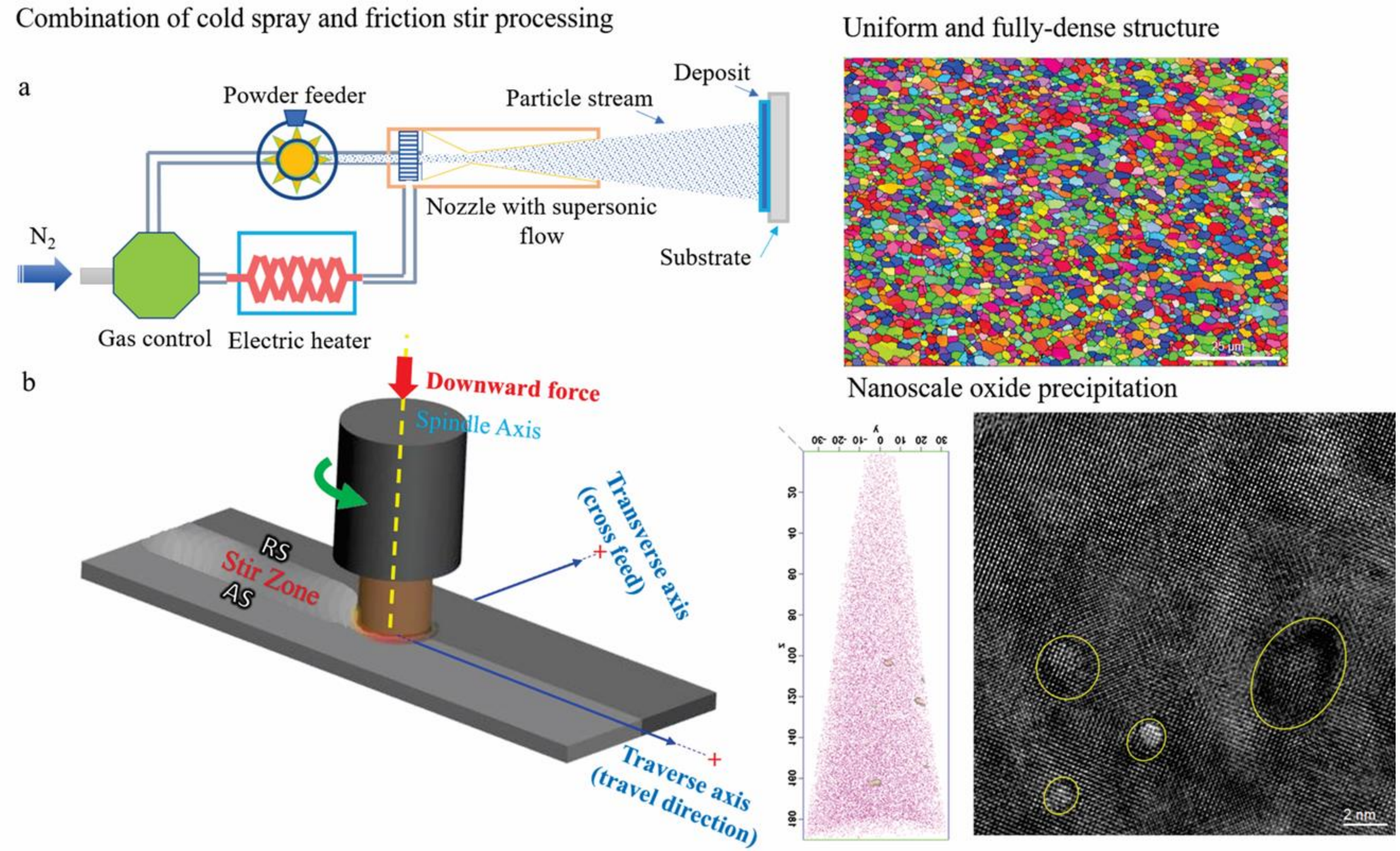
# New Techniques or Applications

- Iterative Cold Spray and Friction Stir Processing
- Advanced Fuels for GENIV systems
- Advanced Manufacturing Impact on Critical Minerals (CM) for Nuclear Materials
- Mining engineering
- Digital Casting Molds
- Printed Batteries and Energy Storage Applications

# Hybrid Processes: Iterative Cold Spray and Friction Stir Processing (FSP) for Fe-ODS plate

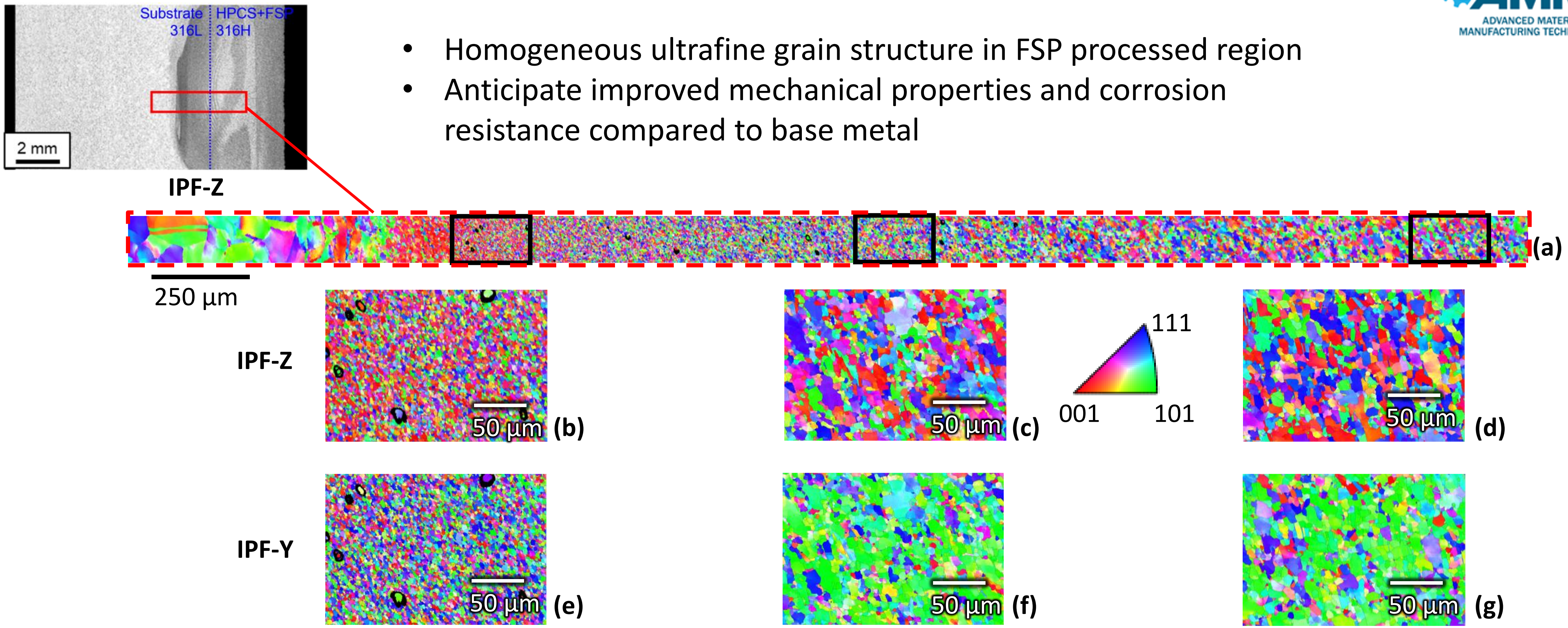
- Successful manufacturing of ODS plates without the need of ball milling feedstock powder and conventional hot rolling
- Generated ODS precursor via Gas Atomization Reaction Synthesis (GARS)
- Cost affective at scale
- Oxide particle density $2.8 \times 10^{22}/m^3$, with average size ~5 nm diameter
- 1.7µm average grain size



# Iterative Cold Spray and FSP of 316H Stainless Steel

Early research

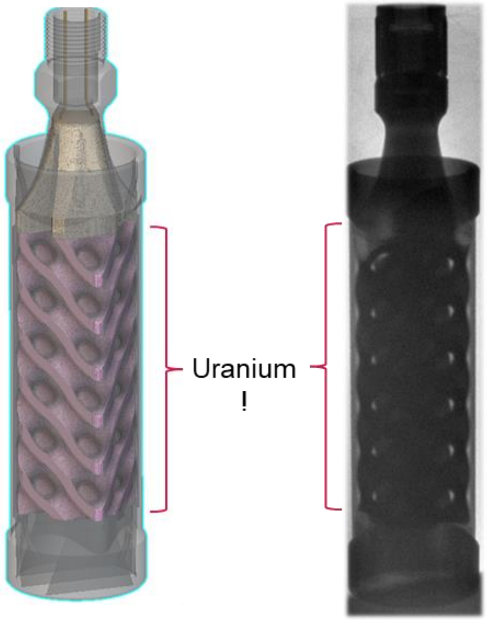
- Homogeneous ultrafine grain structure in FSP processed region
- Anticipate improved mechanical properties and corrosion resistance compared to base metal



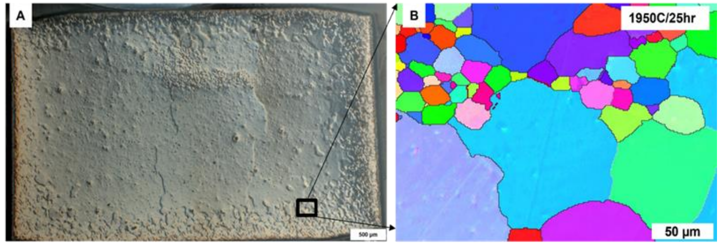

*2.09 µm average grain diameter* *3.97 µm average grain diameter* *3.97 µm average grain diameter*

# Advanced Fuels for Gen-IV

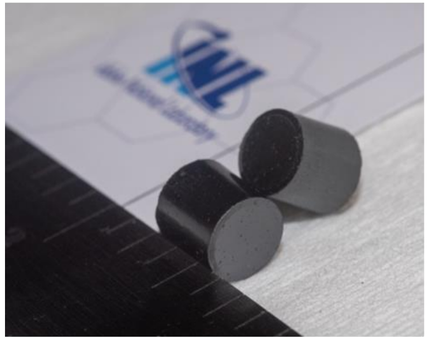
- Ceramic Fuels (pressureless sintering)
  - HALEU $UO_2$
  - HALEU UN and UC
    - Arc melting technique
    - Hydride/Dehydride/Nitride technique*
    - CTR technique
  - $U_3Si_2$, Westinghouse's Encore program
  - $UO_2$-$UB_2$ (90/10 wt%) composites**
- Metallic fuels
  - U-alloys
- Equipment
  - High temp furnace (2000C)
  - 25 ton EFAS
  - Casting
  - Extrusion and machining
- Researching the use of novel fuel and cladding forms




Novel fuel and cladding concept. Rendering and X-Radiograph of $UO_2$ Vibropac in Cladding Lattice, TREAT Test Specimen (Josh Zelina – MFC) {INL LDRD}




Sintered UN pellet. A) Optical image, B) EBSD inverse pole map

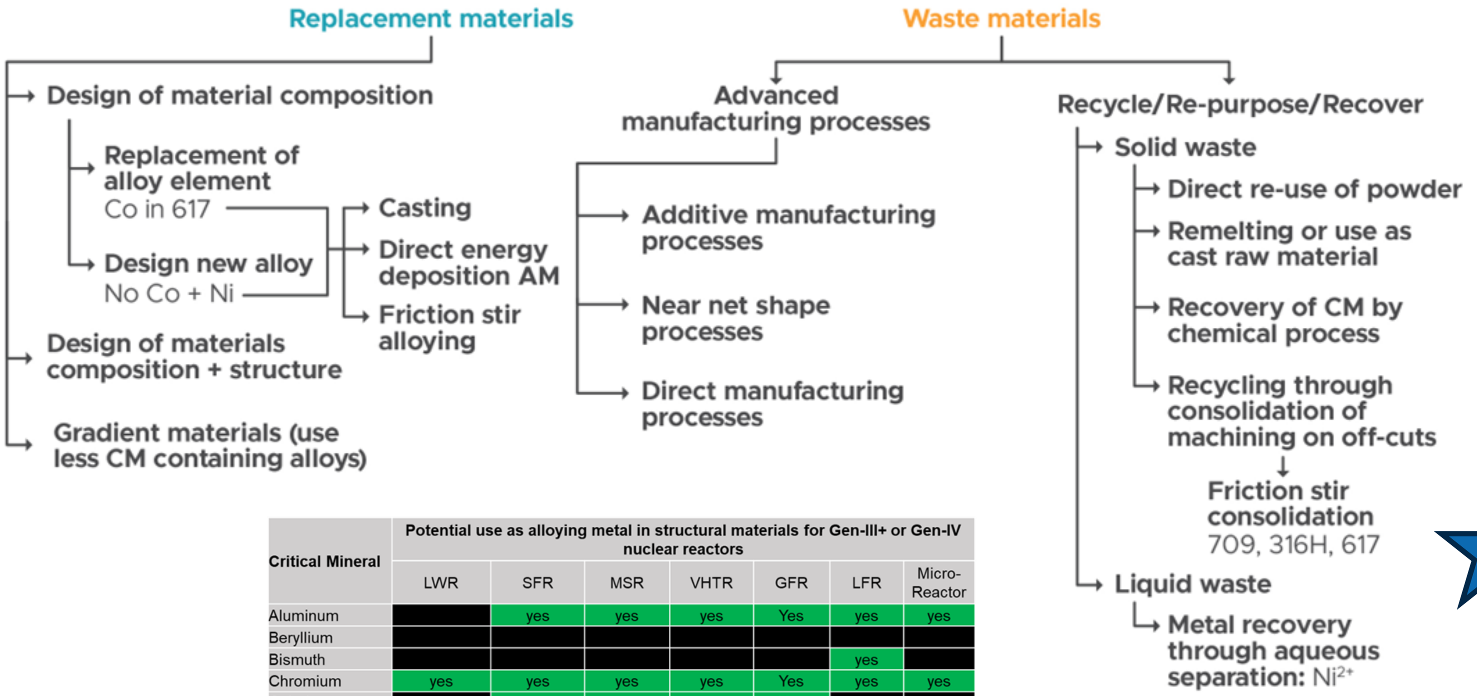



HALEU $UO_2$ (15% $^{235}U$) pellets fabricated to commercial standards

Sintered $U_3Si_2$ Pellets ~0.5 kg

* BJ Jaques *et al., Synthesis and Sintering of UN-$UO_2$ fuel Composites*, J. Nuc. Mater., **466**, 745-754, (2015)
**JK Watkins *et al., Enhancing Thermal Conductivity of $UO_2$ with the Addition of $UB_2$ via Conventional Sintering Techniques,* J. Nuc. Mater. **559**, 153421, (2022)

# Advanced Manufacturing Impact on Critical Minerals (CM) for Nuclear Materials




| Critical Mineral | Potential use as alloying metal in structural materials for Gen-III+ or Gen-IV nuclear reactors | | | | | | |
|---|---|---|---|---|---|---|---|
| | LWR | SFR | MSR | VHTR | GFR | LFR | Micro-Reactor |
| Aluminum | | yes | yes | yes | Yes | yes | yes |
| Beryllium | | | | | | | |
| Bismuth | | | | | | yes | |
| Chromium | yes | yes | yes | yes | Yes | yes | yes |
| Cobalt | | yes | yes | yes | Yes | | |
| Graphite | | | yes | yes | | | |
| Hafnium | yes | | | | | | |
| Manganese | yes | yes | yes | yes | Yes | yes | yes |
| Nickel | yes | yes | yes | yes | Yes | yes | yes |
| Niobium | | yes | yes | yes | Yes | yes | yes |
| Tin | yes | | | | | | |
| Titanium | | yes | yes | yes | Yes | yes | yes |
| Tungsten | | yes | yes | | | yes | yes |
| Vanadium | | yes | yes | | | yes | yes |
| Zirconium | yes | | | | | | |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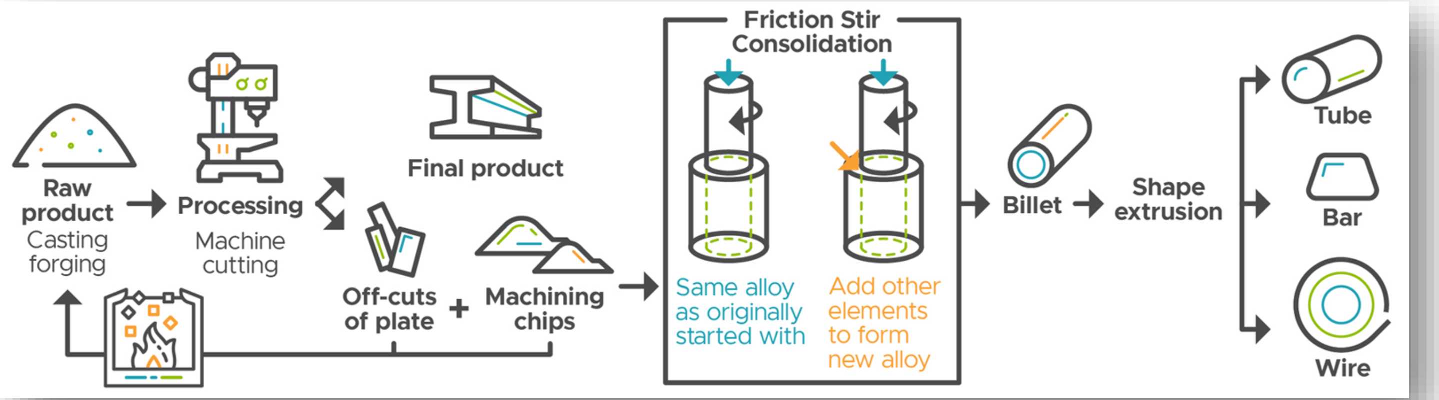
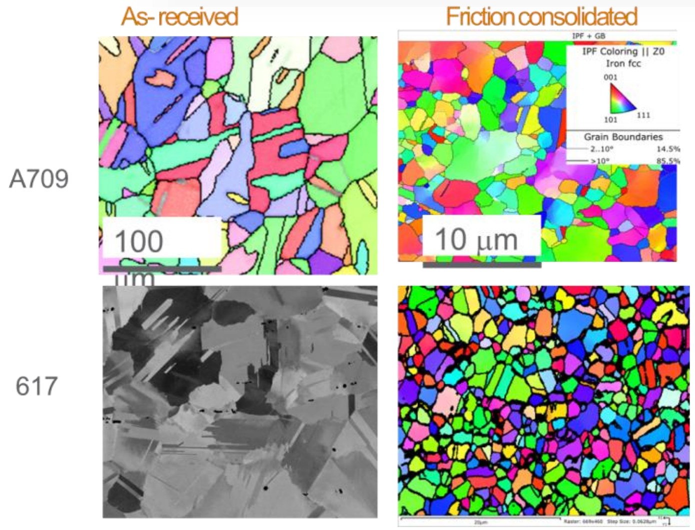
# Friction Stir Consolidation (FSC) a Means to Save Critical Minerals by Waste Minimization




- Grain refinement is observed during consolidation
- The average hardness of friction consolidated material is higher



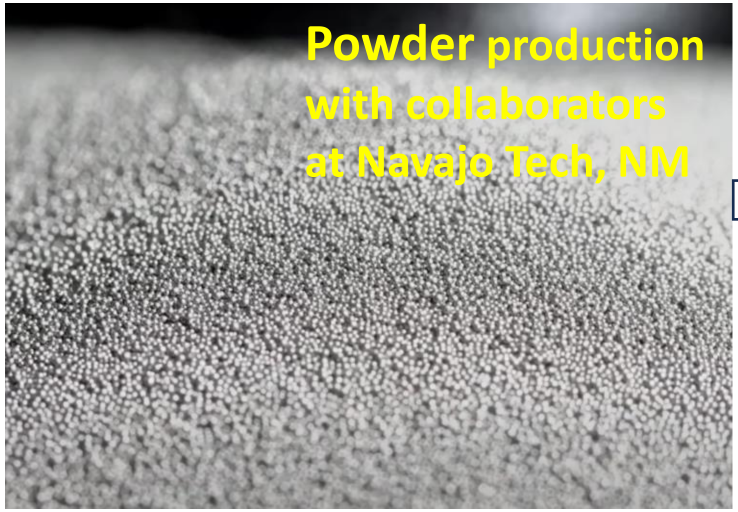

| Sample | Grain Size (µm) | Standard Deviation (µm) | Hardness (HV) | Standard Deviation (HV) |
|---|---|---|---|---|
| As-received | 10.2 | 6.8 | 194.3 | 3.3 |
| Run #1 | 3.6 | 0.9 | 287.3 | 12.9 |
| Run #2 | 1.58 | 1.1 | 246.6 | 28.2 |
| Run #3 | 1.95 | 1.0 | 260.2 | 16.2 |

| Sample | Grain Size (µm) | Standard Deviation (µm) | Hardness (HV) | Standard Deviation (HV) |
|---|---|---|---|---|
| As-received | 10.2 | 6.8 | 230.7 | 6.78 |
| Run #3 | 1.35 | 0.67 | 356.49 | 13.75 |
| Run #4 | 1.14 | 0.88 | 361.38 | 22.89 |

# Ore to More – Direct Digital Metal Fabrication

UTEP ENGINEERING

**Ore to More**
New undergraduate program in
**Mining Engineering**
Only Mining Program in the State of Texas






**Powder Metal 3D Printing**
Digital in situ alloying
Multi-material
Inconel, Copper, Steel
High resolution
**Only Blue Laser DMG in USA**

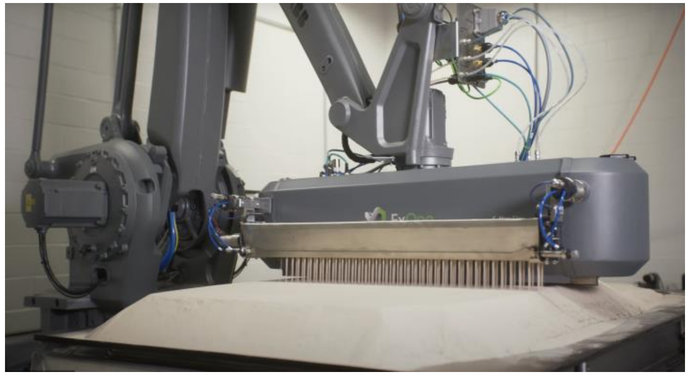
**Hybrid Directed Energy Deposition (DED)**

**Wire Metal 3D Printing**
Co-axial wire
Safety enhanced
Economical
High production rate

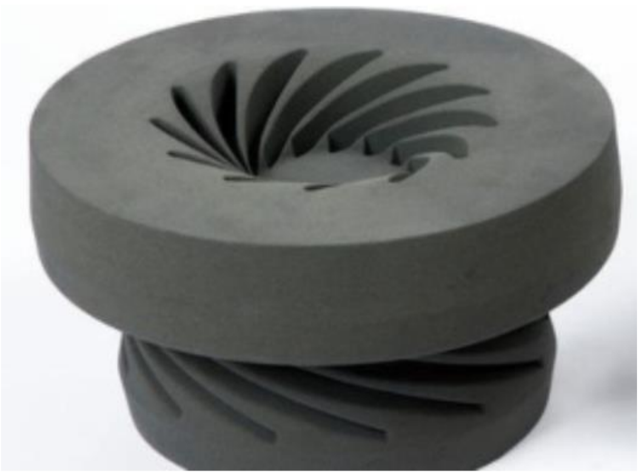
**Crucial national supply chain for rare Earth minerals**

# Digital Casting - 3D Printed Smart Sand Molds

UTEP ENGINEERING



3D Printed Sand



3D Printed Sand Mold

Traditional Casting with Automation
Youngstown State – Collaborator Brian Vuksanovich

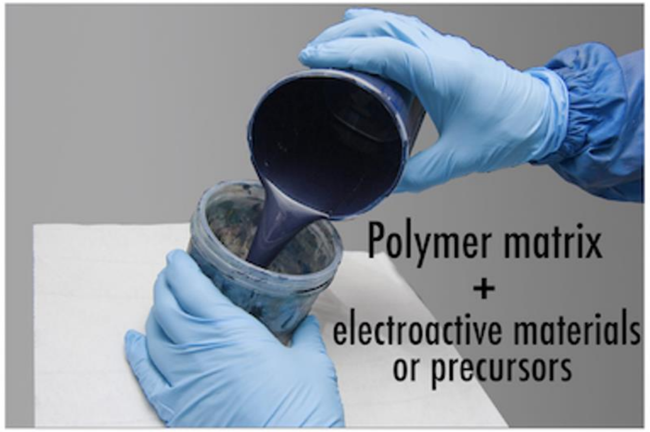
Complex Castings

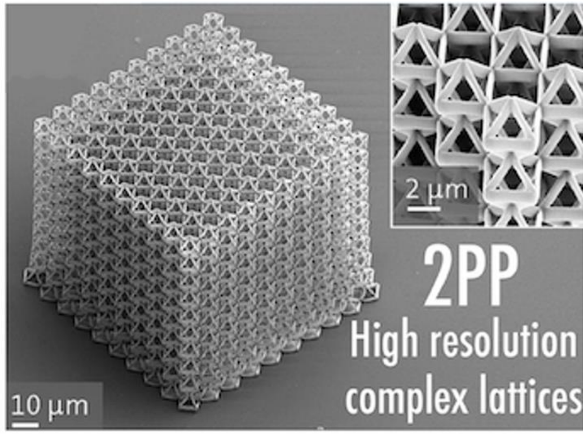
**UTEP is #1 in Publications Worldwide in Digital Casting with Sensing**

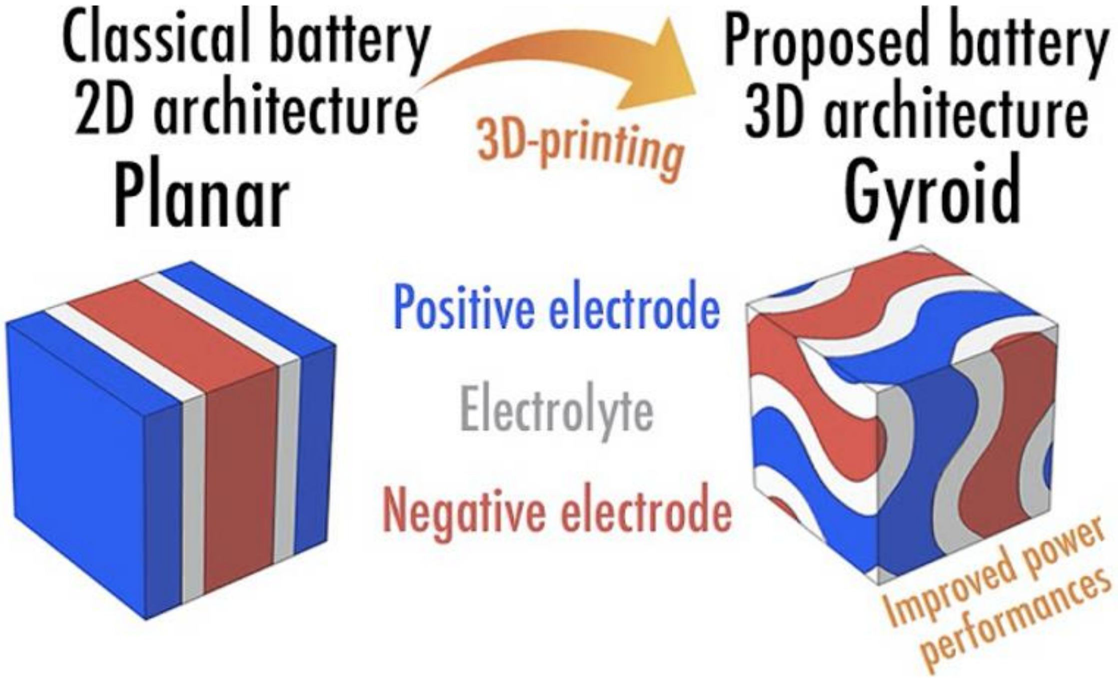
# 3D Printed Batteries and Energy Storage

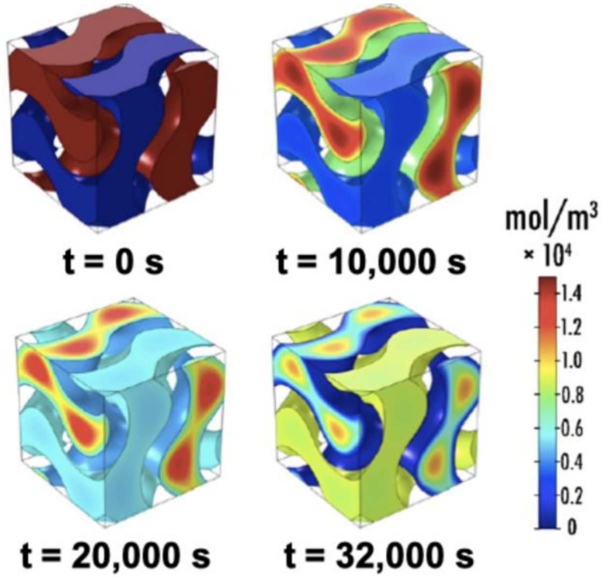
UTEP ENGINEERING

Sandia National Laboratories




NASA Marshall Space Flight Center

Two **Fulbrighters** from France/Mexico

Ana Martinez, PhD. Alexis Maurel, PhD

UNIVERSITÉ de Picardie Jules Verne

FULBRIGHT France COMMISSION FRANCO-AMERICAINE

**UTEP is #1 in Publications Worldwide in 3D Printed Batteries**

# IAEA ISOP award

## International Network on Innovation to Support Operating Nuclear Power Plants

## ISOP Award 2024 – Advanced Manufacturing


Figure 1. Transition of additive manufactured wireless valve position indication sensor system across the technology readiness level.

**Vivek Agarwal (Idaho National Laboratory - USA) received the award on behalf of INL Team**

Customized adjustable brackets (covered under the U.S. Patent # US 11,698,145 B2. July 11, 2023) were developed to support the Valve Position Indicator sensors. The brackets are printed using additive manufacturing techniques and can be either bolted to the valves themselves or to the valve-support structure without requiring any major change to the valve itself and without impacting valve integrity or qualification. The printed backets are lightweight and tested for seismic and other structural requirements.

[YouTube: Intelligent Plant Configuration Management using Wireless Sensors]

2

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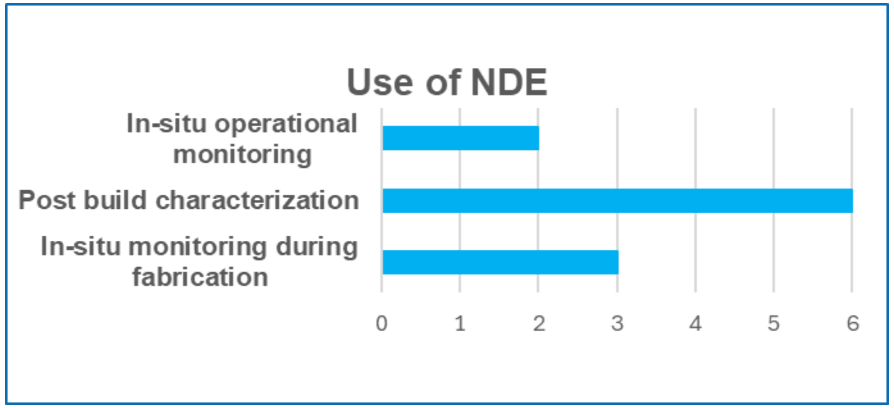
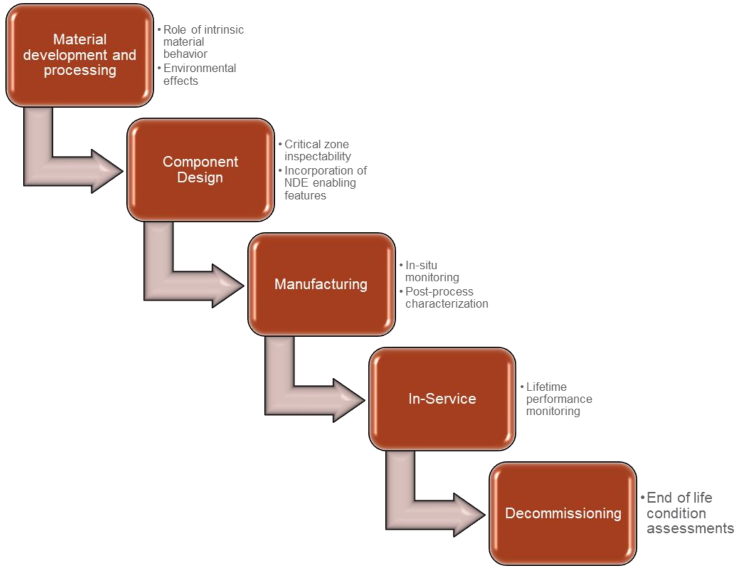
Preliminary, survey still open




# Non-Destructive Examination

**What is meant by Life Cycle NDE?**

- Incorporation of NDE principles throughout the life cycle of a component
- Confirmation that a component will meet performance requirements until EOL

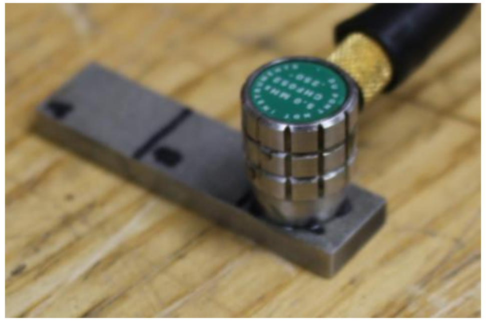


# NDE Gaps for Advanced Manufactured Components

## Challenges to NDE of AM Components

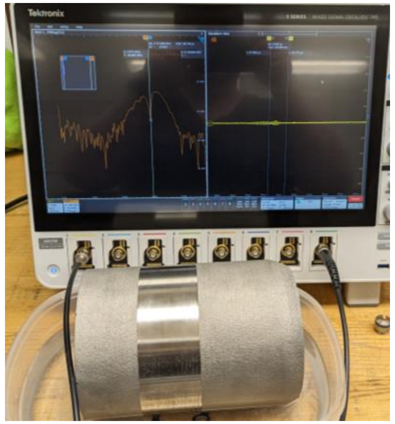
- Surface roughness
- Anisotropic microstructure and mechanical behavior
- Geometric complexities
- Inspection regions (weld vs. entire part, volumetric vs. surface, etc.)
- Unique imperfections/defect structures
- Critical flaw size
- Lack of experience with new in-service defect formation and degradation modes.

Ultrasonic Velocity Measurements

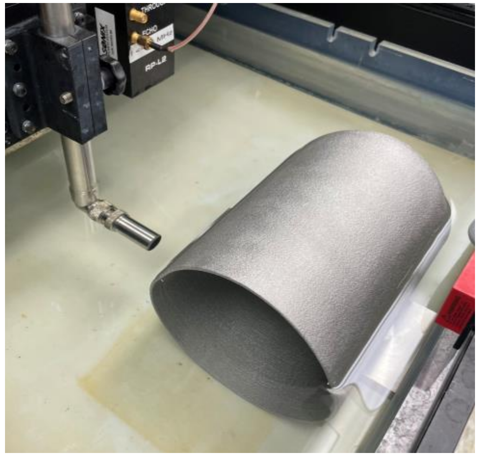


Resonance Ultrasound Spectroscopy (RUS) System

Reflected Ultrasonic Amplitude Spectrum Analysis (RUASA)




Scanning Acoustic Microscope Analysis



**Further reading/resources**

Jacob, R., et al. 2020, Survey of Pre-Service and In-Service Nondestructive Evaluation Techniques of AMT-Fabricated Components, PNNL-30759, United States Nuclear Regulatory Commission TLR-RES/DE/CIB-2020-12, ML20349A012.

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC), (2023) Standardization Roadmap for Additive Manufacturing, Version 3.0, July 2023.


Learn more and register at:
www.pnnl.gov/events

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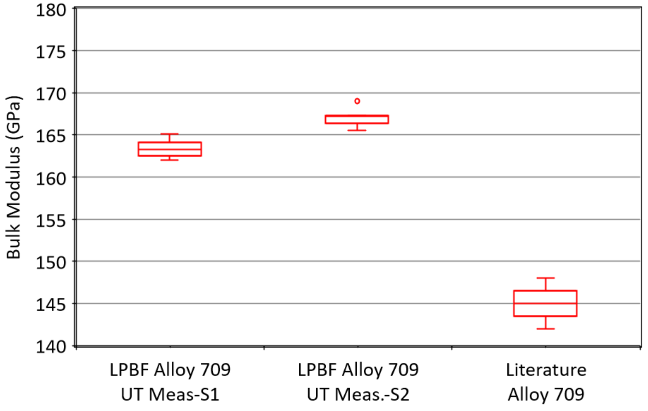
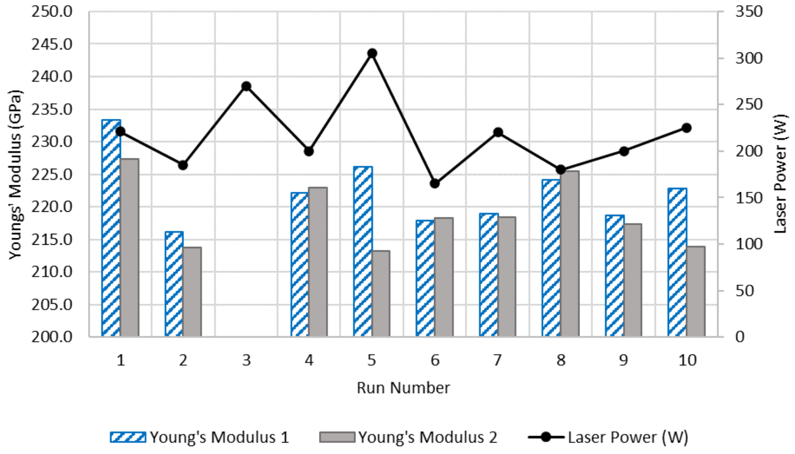
# Mechanical Properties of AM Materials by NDE Assessment

- Leverage relationship between unique ultrasonic properties of materials and physical characteristics to:
  - Verify materials properties (Bulk Modulus, Elastic modulus, Poisson's Ratio, Hardness…)
  - Microstructure analysis (grain size, porosity, etc..)
  - Detect material defects (lack of fusion/bonding, cracks, etc.)
  - Assess component features of interest (e.g. geometry)
- Elastic mechanical properties using
  - Ultrasonic velocity measurements
  - Resonant Ultrasound Spectroscopy (RUS)
- Observe influence of fabrication
  - Anisotropic behavior in shear velocities in LPBF coupons
  - Porosity in DED 316L influences mechanical properties

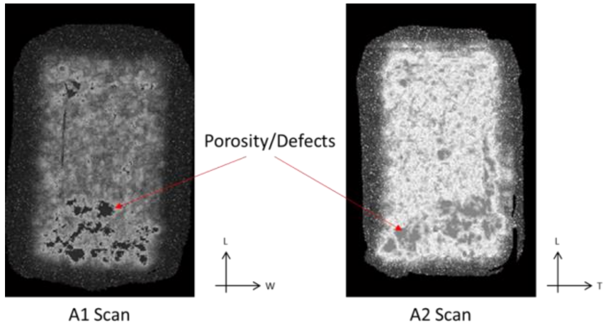
Bulk Modulus for LPBF Alloy 709 and wrought Alloy 709




Young's Modulus for Grade 92 LPBF Coupons




Acoustic Microscope Scan Images Showing the Porosity/Defects in the INL-DED-1 coupon




Elastic Mechanical Properties for INL-DED-1 Calculated from the Ultrasonic Velocity Measurements

| Sample | Young's Modulus (GPa) | Shear Modulus (GPa) | Bulk Modulus (GPa) | Poisson's Ratio (--) |
|---|---|---|---|---|
| INL-DED-1-T | 194.7 | 74.81 | 163.3 | 0.301 |
| INL-DED-1-W | 185.1 | 70.31 | 169.7 | 0.318 |
| INL-DED-1-L | 155.8 | 65.76 | 82.4 | 0.185 |

Elastic Constants from RUS Analysis and Mechanical Properties Computed Using Isotropic Material Relationship

| Parameter | INL-DED-1 | INL-DED-2 | Wrought 316L |
|---|---|---|---|
| **C11 (GPa)** | 242.3 | 203.7 | 247.8 |
| **C12 (GPa)** | 90.6 | 45.9 | 94.3 |
| **C44 (GPa)** | 74.1 | 73.2 | 76.7 |
| | | | |
| **Bulk M (K) (GPa)** | 141.2 | 98.5 | 145.5 |
| **Shear M (G) (GPa)** | 74.1 | 73.2 | 76.7 |
| **Youngs M (E) (GPa)** | 189.2 | 176.0 | 195.7 |
| **Poisson Ratio (--)** | 0.277 | 0.202 | 0.276 |
| **Density ($g/cm^3$)** | 7.886 | 7.653 | 8.0[1] |

[1] – Nominal material density for SS316L



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# Supply Chain Challenges and Opportunities

- Supply chain challenges present through the full life cycle products

# EPRI Advanced Energy Systems Supply Chain Workshops

- Inaugural Annual Workshop in Dallas, TX: June, 2022
  - 70 attendees from 48 organizations

First Workshop Summary Doc link: 3002025254

- 2nd Annual EPRI AES Supply Chain Workshop; April 12-13, 2023, in Dallas, TX
  - 97 Attendees: 66 Organizations, 45 speakers/panelists, 1.5 days

2nd Workshop Summary Doc: 3002027773

- 3rd Annual EPRI AES Supply Chain Workshop, April 10-11, 2024, in Dallas, TX

- 4th Annual EPRI Supply Chain Workshop for Structural Components in Advanced Energy Systems, September 23-25, 2025 in Pacific Northwest National Laboratory, Richland
  - Co-located with DOE-NE Advanced Materials & Manufacturing Technologies (AMMT) Program's:

# First Workshop – Key Takeaways
## Challenges and Opportunities Abound

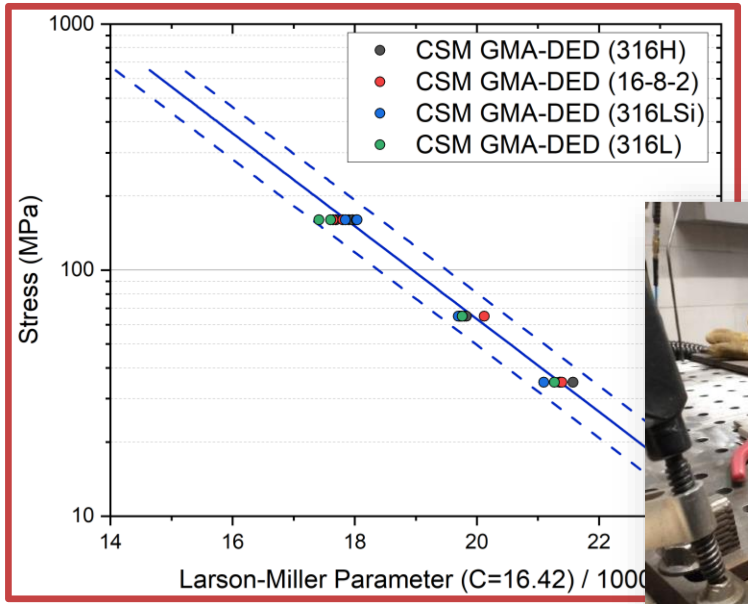
- High temperature material availability and new material qualification
- Forging size and throughput (& machining) inadequate to handle potential demand
- Supply Chain for nuclear components needs to be expanded
- Capital investments hindered without clear market
- Lack of skilled labor
- Test beds for demonstration and qualification

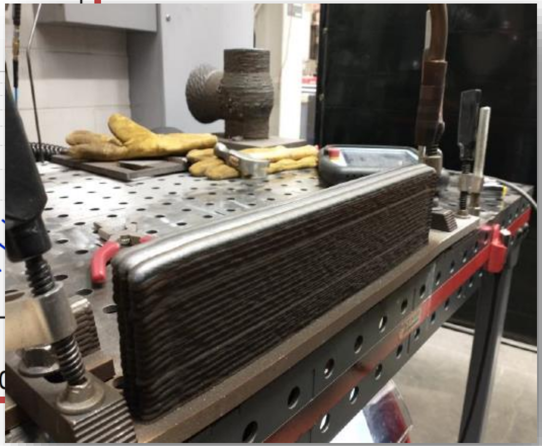
- De-risking FOAK components and projects
- Maximize factory fabrication and modularity
- Engagement of supplier early in design
- Design for manufacturability
- Commercialization of advanced manufacturing
- Collaboration & cooperation between competitors

# Section III TG on Advanced Manufacturing for Div.5

**No formal Record Numbers or ballots to date,**

however various efforts collecting technical data for ***elevated temperature service***



Section III Division 5 design parameters present unique challenges with respect to qualification

- **LPBF – 316H**
  - DOE AMMT Program executing test campaign to qualify 316H LPBF in Div. 5
  - https://publications.anl.gov/anlpubs/2023/08/184225.pdf
- **DED-AM (GMA-AM)**
  - EPRI presented AM-SRF (Additive Manufacturing Strength Reduction Factor) Approach
  - EPRI collecting technical data and executing test programs on 316H and Gr91 (also in support of EPRI led Section I code case)
- **Powder Metallurgy HIP**
  - Ongoing research focused on time-dependent properties of 316, 709, 625, and others.
  - Note Grade 91 is approved in ***Section I Only*** via Code Case 2770)

# ASME B&PV Progress* on Advanced Manufacturing

| | Powder Metallurgy Hot Isostatic Pressing (PM-HIP) | Wire-Based Directed Energy Deposition (DED) | LB/EB-PBF |
|---|---|---|---|
| Governing Specs / Standards | ASTM defines mat. specs | Section IX QW-600 | Guideline: ASME PTB-13-2021 |
| Approval Time-Independent Regime | SA988/988M – Stainless Steel,<br>SA989/989M – Ferritics,<br>SB834/834M – Nickel-based alloys<br>**316L: CC N-834 for Section III and 2023 Edition of ASME Section III** | **ASME proposed code case for Section I, III, VIII, B31. Record No. 22-1598:** material equivalences | **ASME proposed code case for Section III (316L Database) Record No. 23-1593** |
| Approval Time-Dependent Regime | Code Case: Material by material approval based on Appendix 5: **Grade 91 (CC-2770)** | Technical approaches being considered, **EPRI proposal for AM-SRF**** | US DOE National Labs led Section III project on time-dependent 316 |
| Other notes | **SA508 development part of SMR Adv. Manuf. DOE project**<br>KIWG focused on XM-19 and 6NM | **EPRI projects on Gr. 91 and 316/316H/316L creep behavior** | |


**EPRI-led activities highlighted**

**Based on general status for Sections I, III, VIII, and B31.1*
***SRF=Strength Reduction Factor*

# Advanced Materials and Manufacturing Technologies (AMMT) Program

**AMMT website**
**https://ammt.anl.gov**


**Meimei Li, National Technical Director**,
Argonne National Laboratory

**Isabella van Rooyen, Technical Area Lead for Advanced Materials & Manufacturing,** Pacific Northwest National Laboratory

**Ryan Dehoff, Technical Area Lead for Rapid Qualification**,
Oak Ridge National Laboratory

**Andrea Jokisaari, Technical Area Lead for Environmental Effects**, Idaho National Laboratory

**Mike McMurtrey, Technical Area Lead for Technology Maturation**, Idaho National Laboratory

**Dirk Cairns-Gallimore, Federal Program Manager,**
Department of Energy, Office of Nuclear Energy


## Mission, Vision and Goals

### Mission

Accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies in support of U.S. leadership in a broad range of nuclear energy applications.

### Vision

Expansion of reliable and economical nuclear energy enabled by advanced materials and manufacturing technologies.

### Goals

- Develop advanced materials & manufacturing technologies.
- Establish and demonstrate a rapid qualification framework.
- Evaluate materials performance in nuclear environments.
- Accelerate commercialization through technology maturation.

Argonne NATIONAL LABORATORY | INL Idaho National Laboratory | Los Alamos NATIONAL LABORATORY | OAK RIDGE National Laboratory | Pacific Northwest NATIONAL LABORATORY

AMMT

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

# Technical Areas

## Advanced Materials & Manufacturing

- Advanced Metallic Materials
- Advanced Manufacturing Technologies
- Traditional Manufacturing & System Integration

## Rapid Qualification

- Rapid Qualification Framework
- High-temperature Materials Qualification
- Advanced Manufacturing Qualification

## Environmental Effects

- Neutron Irradiation & Post-irradiation Examination
- Accelerated Qualification for Radiation Effects
- Corrosion Effects in Nuclear Environments

## Technology Maturation

- Component Fabrication & Evaluation
- Codes and Standards
- Regulatory Acceptance & Licensing

**Impact**: The AMMT program will provide the nuclear industry with next-generation high-performance materials and advanced fabrication methods for expanded supply chains and demonstrate new technologies within the next decade.

# Advanced Materials & Manufacturing

Integrated Materials and Manufacturing Development

**Develop and optimize materials through composition and processing to achieve high performance.**

- **Apply advanced manufacturing to existing reactor materials**
  - Optimize advanced manufacturing processes to expand the applications of current reactor materials.
- **Optimize non-nuclear commercial materials for nuclear applications**
  - Optimize materials/processes for enhanced resistance to nuclear environments to enable their nuclear applications.
- **Develop innovative new materials**
  - Develop new materials enabled by advanced manufacturing (e.g., multi-material, multi-functional designs) or new material design concepts.

**Materials of Interest**

- Fe-based alloys
- Ni-based alloys
- Refractory alloys
- ODS alloys
- High entropy alloys
- Functionally graded materials
- Cladding/coating materials

ADVANCED MATERIALS AND MANUFACTURING TECHNOLOGIES

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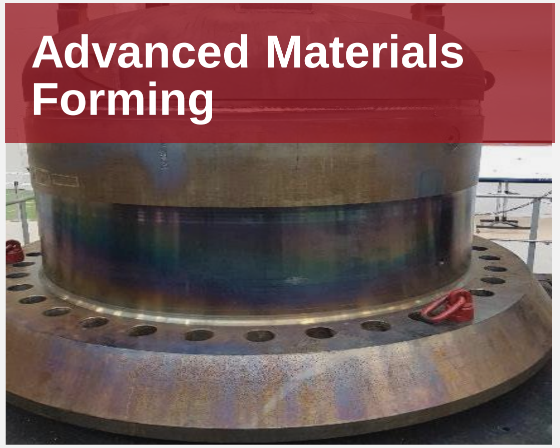
# Materials Processing for Nuclear Components










**Integrated materials & manufacturing development**

# Focus on Qualification:

Qualification of High Temperature Materials for Nuclear Construction

## Code qualifying a new material for high temperature nuclear structural design is a lengthy process.

- ASME Section III, Rules for Construction of Nuclear Facility Components - Division 5, High Temperature Reactors.
  - Governs the construction of structural components for use in high temperature reactors including GCR, SFR, LFR, MSR.
  - Specifies the mechanical properties and allowable stresses to be used for design of components in high temperature reactors.
- Only **six materials** have been approved for elevated-temperature nuclear construction in Section III Division 5.
- Approval of a new material under the Code involves rigorous testing, documentation, and approval processes.
  - Specification, product form, size/thickness, hear treatment, metallurgical structure.
  - Data are generated from at least 3 different “heats” of the material.
  - Exhaustive mechanical property tests (tension, creep, fatigue, creep-fatigue, etc.).
  - For time-dependent properties (e.g. creep), allowed time extrapolation factor, 3-5.
  - Consider long-term properties stability, e.g. structural stability due to thermal aging.


- 304 SS
- 316 SS
- 2.25Cr-1Mo
- 9Cr-1Mo
- Alloy 800H
- Alloy 617

ADVANCED MATERIALS AND MANUFACTURING TECHNOLOGIES

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# Focus on Qualification:

## Qualification for Nuclear Environmental Effects

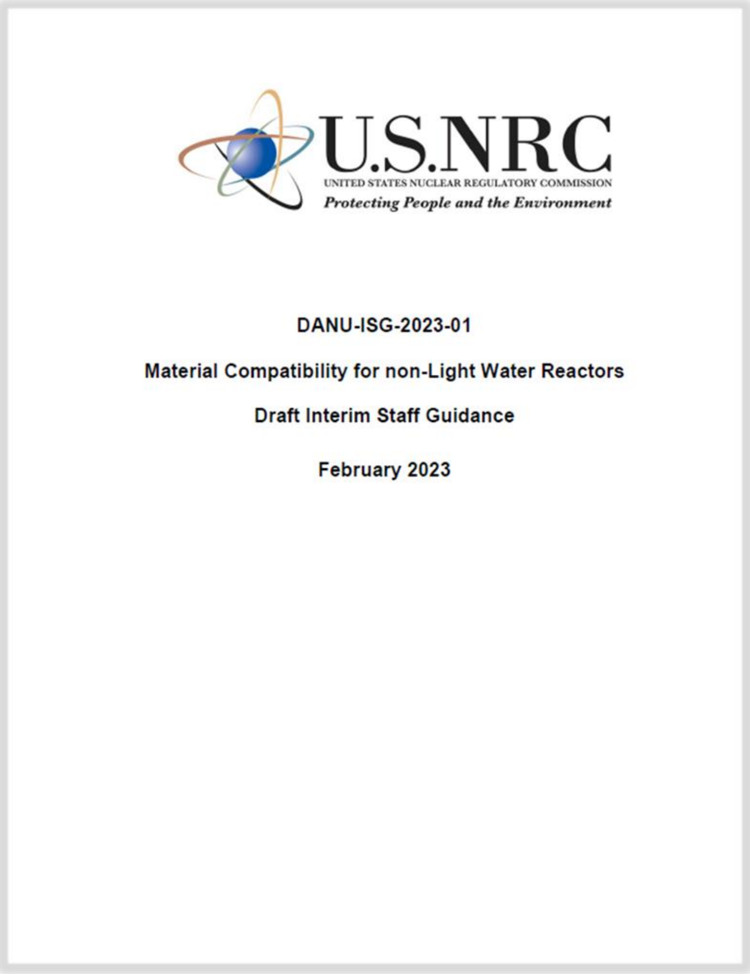
- ASME Code rules do not provide methods to evaluate deterioration from corrosion, mass transfer phenomena, or radiation effects.
- NRC has issued “***Material Compatibility for non-Light Water Reactor Draft Interim Staff Guidance***” as part of its evaluation of a non-LWR application to review applicable design requirements including environmental compatibility, qualification and monitoring programs for safety-significant structures, systems, and components (SSCs).
- Demonstrates material performance to satisfy regulatory requirements.

### Irradiation Effects

- The cost and time required for neutron irradiation and post-irradiation examinations only allow for exploration of a limited set of metallurgical and irradiation conditions. Extrapolation of data beyond testing conditions and prediction of long-term performance is a challenge.

### Corrosion Effects

- Comprehensively evaluate the corrosion performance of materials in various reactor coolant environments (e.g. molten salt, sodium, lead, helium) is a challenge.


U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
*Protecting People and the Environment*

DANU-ISG-2023-01

Material Compatibility for non-Light Water Reactors

Draft Interim Staff Guidance

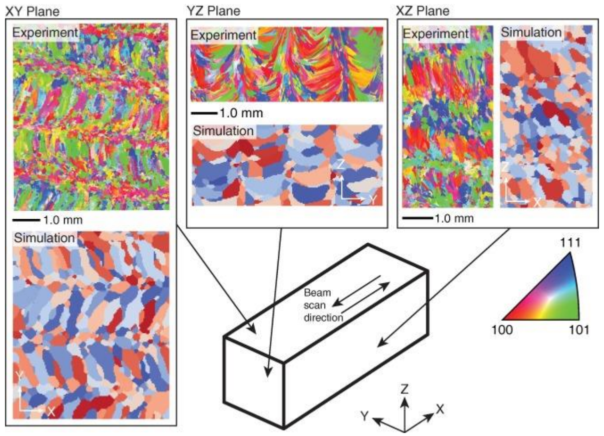
February 2023

# Focus on Qualification:

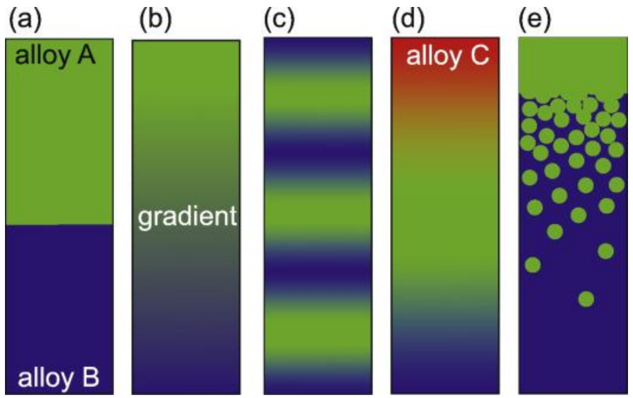
Qualification of AM Materials for Nuclear Applications

**Qualification of AM materials/components for nuclear applications needs a paradigm shift.**

- Adding AM materials into ASME Division 5 is critical to the wide adoption of AM technologies in advanced reactors.
- Qualification of materials made by advanced manufacturing (AM) processes (e.g. laser powder bed fusion, directed energy deposition) for nuclear applications presents a new challenge.
- Unlike traditional manufacturing, additive manufacturing creates geometric forms simultaneously with the material.
- Additive manufacturing is a highly-localized process, creating spatial variations in response to differences in geometry and processing conditions.
- Materials properties are related to the component geometries and may vary throughout the component.
- AM plays a crucial role in accelerating material qualification by introducing new challenges that necessitate innovative approaches.




Spatially heterogenous microstructures of an additively manufactured alloy revealed by experiments and modeling (T. M. Rodgers, et al, Comput. Mater. Sci. 135 (2017) 78).




Composition of different alloys to form functionally graded parts (N. G. March, et al, Add. Manu. 64 (2023) 103415).

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# Rapid Qualification Framework

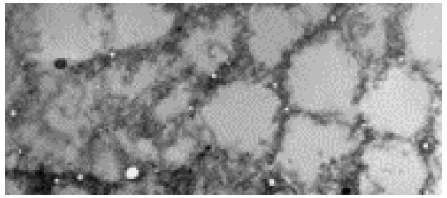
**A science-based engineering approach: combining scientific understanding with engineering data.**

## Develop Processing-Structure-Property-Performance based qualification framework

A P-S-P-P based qualification framework requires a fundamental understanding of processing-structure-property-performance relationship through experimental and computational approaches.

## Use integrated experimental, modeling and data-driven tools

Capitalize on the wealth of digital manufacturing data, integrated computational materials engineering (ICME) and machine learning/artificial intelligence (ML/AI) tools, and accelerated, high-throughput testing and characterization techniques.



## Integrate *in situ* process monitoring and digital data into the qualification process

Monitor and analyze the printing process in real-time to ensure the quality and integrity of the fabricated part. Use *in situ* process monitoring data to detect defects and as a QA tool to assess part quality.

## Demonstrate accelerated qualification methods through qualifying LPBF 316H SS

Laser powder bed fusion 316H stainless steel (LPBF 316H SS) serves as a test case for demonstration of a new qualification framework.

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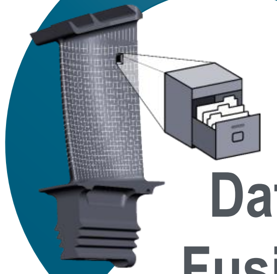
# Multi-Dimensional Data Correlation (MDDC) Platform

## Digital Twin

### Spatially Tracked Data

4 5 1 8
9 6 3 2



Data Fusion

### Manufacturing

- Process Parameters
- Feedstock Information
- In-Situ Data
- Post Processing

### Characterization

- Material Characterization
- Non-Destructive Testing
- Destructive Testing
- Lifetime & Performance

## MDDC

Twin 1

Twin 2

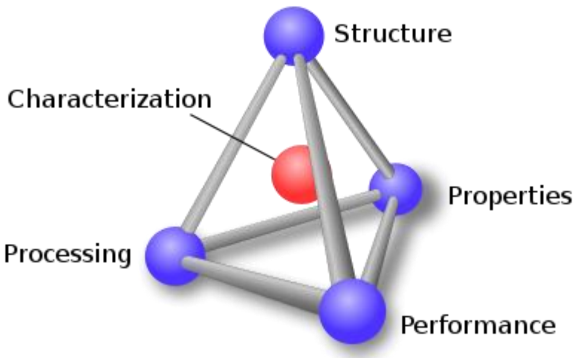
Twin 3

…

Twin n

### Toolkit

- Artificial Intelligence
- Machine Learning
- Data Analytics
- Process Models
- Materials Models
- Performance Models




**Digital Twins and MDDC Toolkit Accelerates Development**

Demonstrations — 3 years

Digitally Aided Qualification — 5 years

AI Based Design — 10 years

**Improve Performance, Reliability and Lifetime of Nuclear Components**

*"Advanced Materials and Manufacturing Technologies (AMMT) 2022 Roadmap" (https://www.energy.gov/sites/default/files/2023-03/ne-ammt-roadmap-030823.pdf)*

# Performance Evaluation under Neutron Irradiation

## Ongoing HIFR Irradiation

- 8 capsules were inserted in Cycle 506 (April 2024)
  - Irr. temp.: 400, 600°C
  - Doses: 2, 10 dpa
  - Materials: AM 316H, wrought 316H, wrought 709, AM 316L
  - Specimens: tensile, bend bars
- 12 capsules to be inserted in cycle 507 (June 2024)
- PIE of the 2 dpa capsules will start in July 2024.

## ATR Irradiation Planning

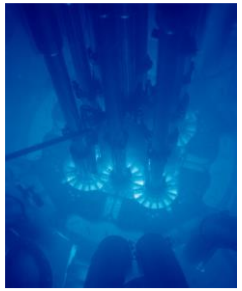
- Neutron irradiation experiments at the ATR are being planned (targeting Cycle 175-C, 06/2025).

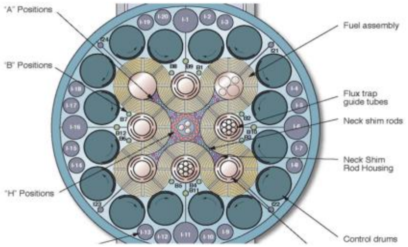
**Irradiation Experiments**

- Primarily thermal spectrum
- Pressurized water at ~50°C
- Experiment positions vary between 5/8” to 3” diameter
- Fast flux: $8.1x10^{13}$ n/cm$^2$/s
- Thermal flux: $2.5x10^{14}$ n/cm$^2$/s

**Specimens**

- SS-J tensiles, bend bars. round compact tension






## A709 Irradiation Planning

- Two work packages have been created to develop a neutron irradiation and PIE plan for A709.
- Funding was provided by the ART Fast Reactor Program.
- INL and ORNL will jointly develop a detailed plan for generating A709 irradiation data in support of advanced reactor license application and its integration with the AMMT current neutron irradiation campaign plan.

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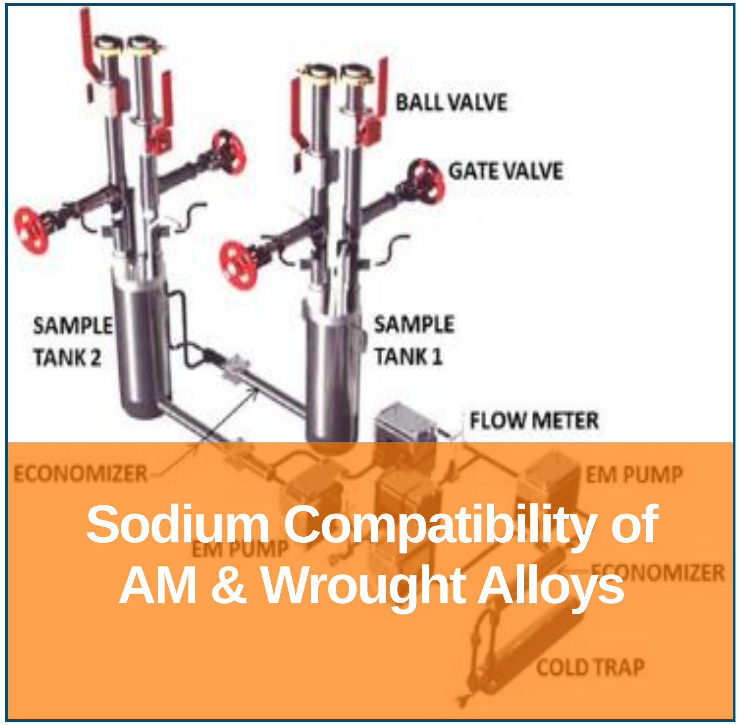
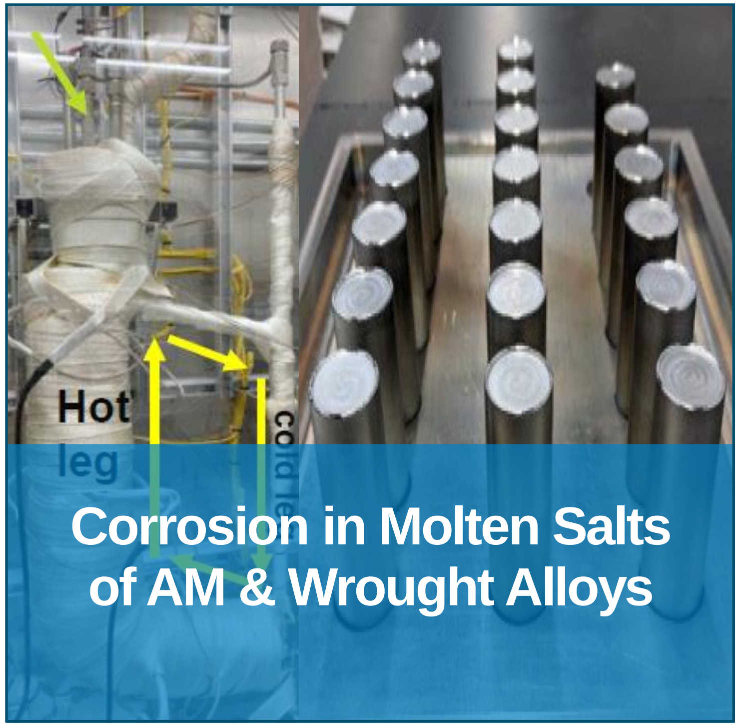
# Corrosion Effects in Nuclear Environments




**Sodium Compatibility of AM & Wrought Alloys**




**Corrosion in Molten Salts of AM & Wrought Alloys**


**AM Materials in LWR Environment**
(under LWRS)

# Technology Maturation

**Goal is to advance a technology by increasing its TRL to accelerate the adoption of advanced materials and manufacturing processes in nuclear applications.**

## Component Fabrication and Evaluation for Technology Demonstration

- Demonstrate the fabrication feasibility of reactor components using new materials or AM technologies.
- Evaluate the component performance in relevant reactor environments.

## Codes and Standards

- Introduce new materials and manufacturing methods into ASME Code.
- Incorporate the rapid qualification framework and methods into Codes and Standards development.

## Regulatory Acceptance and Licensing

- Establish design and operational limits and guidelines to support advanced reactor licensing applications.
- Develop material surveillance programs to monitor material degradation during service.

# Final Remarks

Providing Industry Solutions

No one Recipe for all

- **Collaboration and Sharing of Data**
- **Accelerated Qualification & Qualification Technologies**
- **Technologies:**
  - Dissimilar material joining
    - ✓ low melting temp metals joined to high melt, steel to ceramics or refractories
    - ✓ Cladding/Coating
  - Alloys for extreme environments
    - ✓ made from elements that could not have been alloyed previously due to constraints imposed by melting

Each contribute to a puzzle piece, lets work together for full integration and momentum for acceleration of deployment

# Upcoming Webinars

| Date | Title | Presenter |
|---|---|---|
| 14 May 2025 | Advanced Nuclear Technologies for Maritime Application | Hussam Khartabil, IAEA<br>Nadezhda Salnikova, OKBM, Russia<br>Kirk Sorensen, Flibe Energy, USA<br>Andreas Vigand Schofield, Seaborg Technologies, Denmark |
| 12 June 2025 | Modeling $UO_2$ Fission Gas Release (FGR) Thresholds in BISON | Kelly Cunningham, UFL, USA – winner of the ANS 2024 PhD Competition |
| 30 July 2025 | Thermal Hydraulics of Supercritical Water Reactor (SCWR) | Prof. Liu Xiaojing, from Shanghai Jiao Tong University of China |