INL/CON-21-61569-Revision-1

Design, Manufacturing and Performance Considerations in Reactor System, Components and Materials

March 2021

Changing the World's Energy Future

Isabella J Van Rooyen

Idaho National Laboratory

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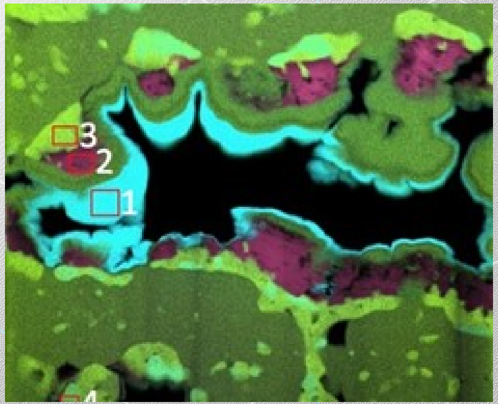
National Technical Director: DOE-NE Advanced Methods for Manufacturing



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Ohio State University Seminar; March 3, 2021

Idaho National Laboratory

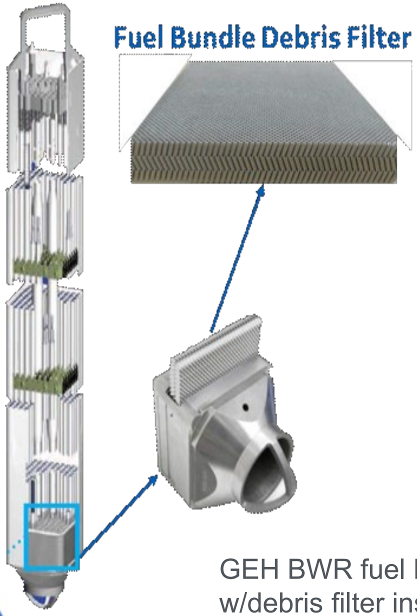
Advanced Methods for Manufacturing (AMM)

Vision

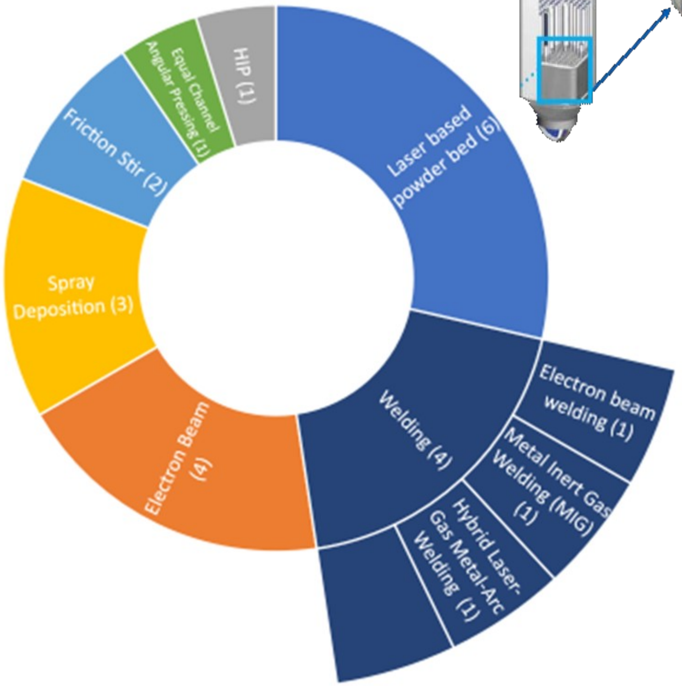
- To improve and demonstrate the methods by which nuclear equipment, components, and plants are manufactured, fabricated, and assembled by utilizing state-of-the-art methods

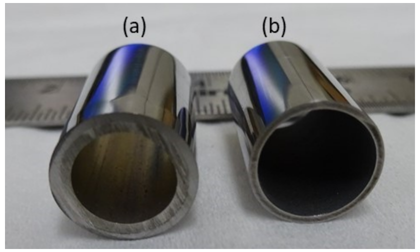
Goal

- To reduce cost and schedule for new nuclear plant construction
- To make fabrication of nuclear power plant (NPP) components faster, less expensive, and more reliable



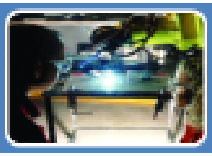
GEH BWR fuel bundle w/debris filter insert





Fuel tubes produced by cold spray

DOE-NE AMM Focus Areas: FY2021



Factory and Field Fabrication Techniques

- High Speed & High Productivity Welding
- Welding technologies for large weldments and fabrications
- Dissimilar Materials Joining
- Robotics and advanced automation

Modular Manufacturing

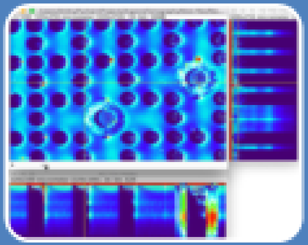
- Fabricated forgings
- Factory fabrication of piping systems
- PM-HIP

Advances in Manufacturing Processes

- Additive Manufacturing of metals
- Surface engineering
- Metamorphic Manufacturing
- Advanced sensors

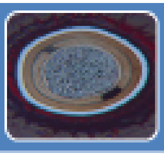
Improved Concrete Inspection, Acceptance, and Construction Methods

- Advances and innovation in high strength concrete and rebar
- NDE and field inspection for first time quality assurance and repair
- Improved methods to facilitate the curing of concrete



New Advanced Manufacturing Technologies for Qualification and Certification to Accelerate Licensing

- Advanced Manufacturing Methods Qualification approaches
- Verification and validation technologies
- Advanced Manufacturing Codes and Standards
- Big data
- Digital Thread and Digital Twin



Advanced Integrated Fuel System Concepts

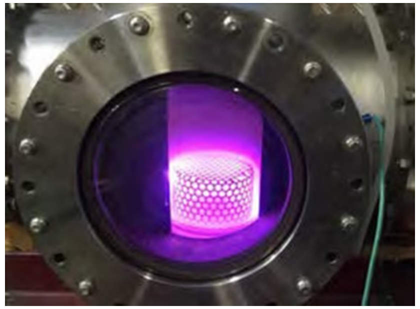
- Advanced thermal processing approaches
- Integrated manufacturing methods

Funding Vehicles – Competitive Solicitations

- Industry funding opportunities
  - Industry FOA (Advanced manufacturing, fabrication & construction techniques for nuclear parts, components, and full-scale plants, or integrated efforts that could positively impact the domestic nuclear manufacturing enterprise)
  - GAIN Vouchers
- Consolidated Innovative Nuclear Research (FOA)
  - Nuclear Energy University Program (NEUP)
  - NEET
  - NSUF
- Research Reactor Infrastructure (RRI)
- Integrated University Program (IUP)
- Small Business Innovation Research/Small Business Technology Transfer (SBIR/SBTR)
- Technology Commercialization Funds (TCF)
- Direct funded from DOE supported programs
- Direct funded by Industry

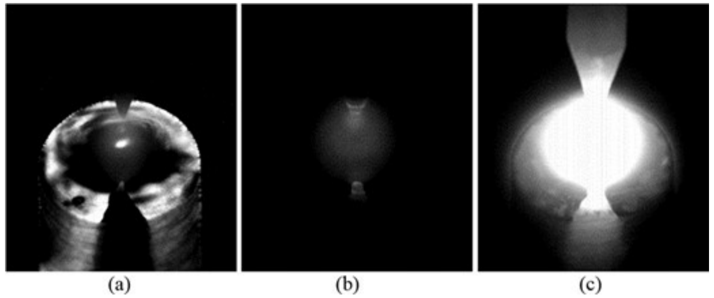
FY 2021 CINR FOA Focus Areas

- Factory and Field Fabrication Techniques
  - Surface Modifications and Cladding
  - **Modular fabrication** and installation



Advanced surface plasma nitriding for development of corrosion resistance and accident tolerant fuel cladding – Texas A&M University (10/1/2015 – 9/30/2018)

- Qualification Methodologies & Digital footprint

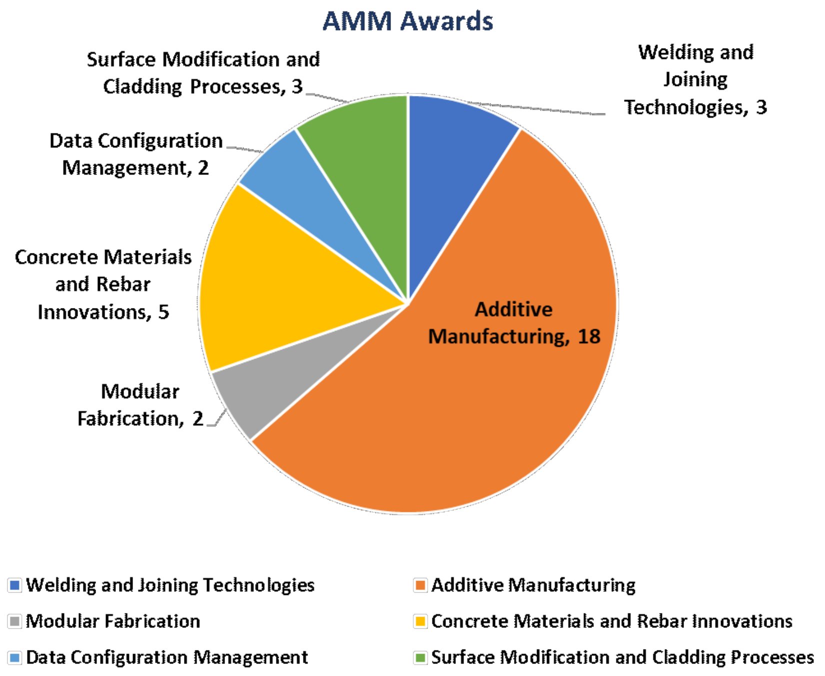


Improving Weld Productivity and Quality by means of Intelligent Real-Time Close-Looped Adaptive Welding Process Control through Integrated Optical Sensors – ORNL, University of Kentucky and EPRI (10/01/2014 – 6/30/2018)

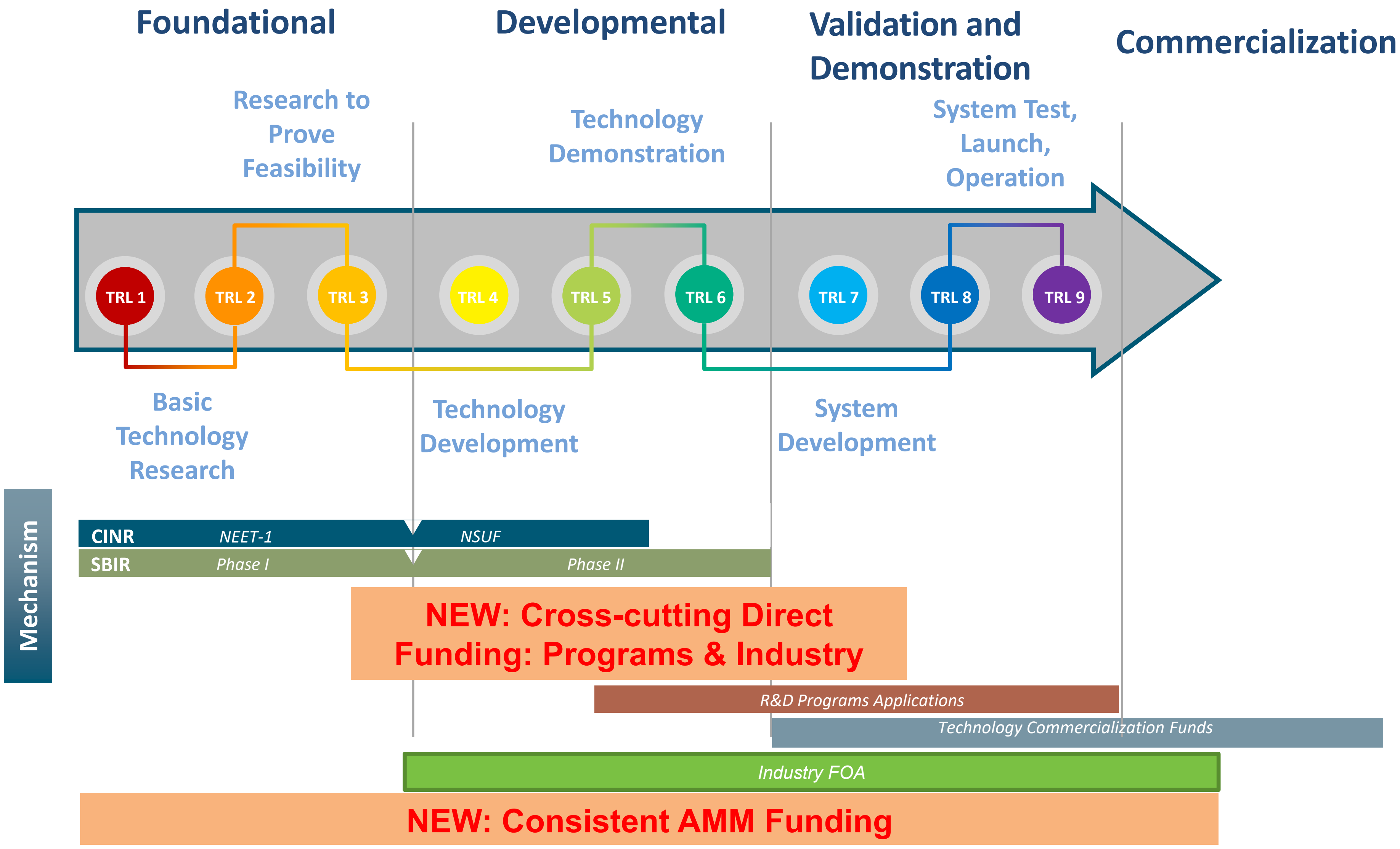
AMM Projects: Competitive Funds

Competitively selected projects via Consolidated Innovative Nuclear Research (CINR), Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR), and Industry FOA

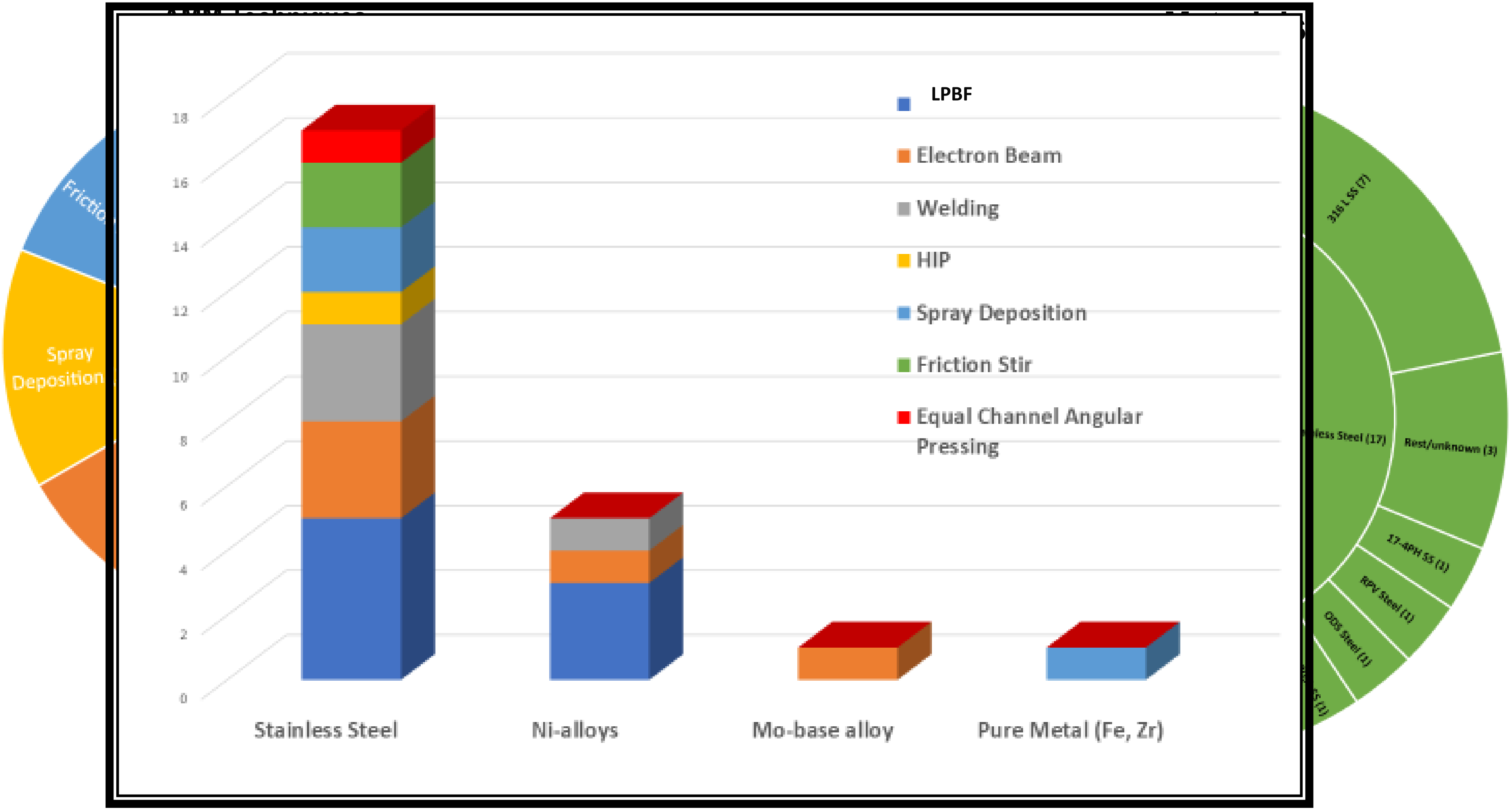
- Open to universities, national laboratories, and Industry
- R&D and irradiation/PIE projects funded
- FY2012 – FY 2019: ~$20M
  - In FY 2019 – 57 AMM CINR proposals received
    - 2 CINR projects – awarded - $1.5M
    - 3 Phase I SBIR projects – awarded $450K
    - 3 Phase II SBIR projects – awarded $3M
- Established separate Industry FOA in FY 2018
  - 3 projects – awarded ~$18.5M
- FY 2020: 10 AMM CINR full proposals (63 Pre-proposals)
  - 3 projects – awarded ~$3M
- FY 2021: 11 AMM CINR full proposals (55 Pre-proposals)



AMM Program Development FY21



Evaluate AMM Program Award Impact (NEET Awards 2011-2019)

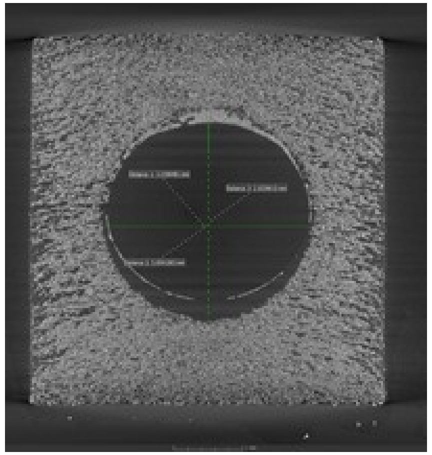


Courtesy Subhashish Meher

Gaps or Technology Challenges

Prioritizing Methods and Materials
Complex set of needs
Risk reduction methods
Speed to industry deployment
Qualification Processes
Maturity Level

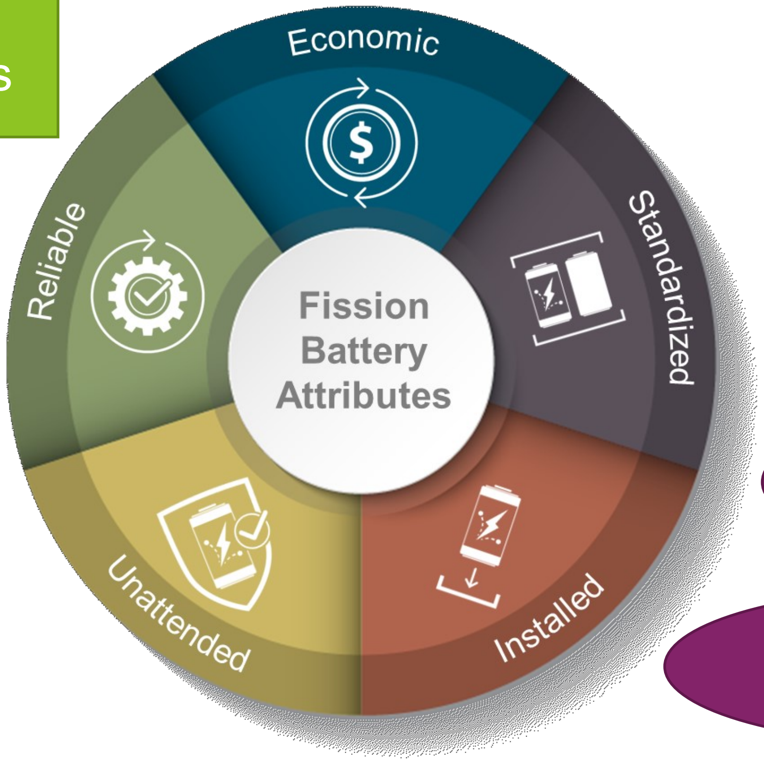
- Performance data in nuclear environments
- How do we measure or gauge applications of new AMM?
  - Technology readiness level
  - Qualification routes
  - Standards/codes
  - Risks
- Determining requirement and performance specifications for different manufacturing-process domains
- How do we measure and communicate the impact of our research (especially earlier TRLs)?
- Cybersecurity in:
  - Digital engineering
  - Machine-learning approaches
  - Big-data/artificial-intelligence applications
  - Automated manufacturing
  - *In situ* monitoring
  - Embedded sensor



Manufacturing and Fission Battery Needs

Repeatable
Decrease uncertainties
Predictable and measurable risks

Modular
Integrated manufacturing
Factory built?
On-site built?
On-site repair



- Digital Twins
- Embedded Sensors
- Containment Technologies
- Gradient Materials
- Coatings
- Topology Optimization
- Qualification Process Reimagined
- Supply Chain Sensitivities
- Design for AMM
- Industrialization /Upscale

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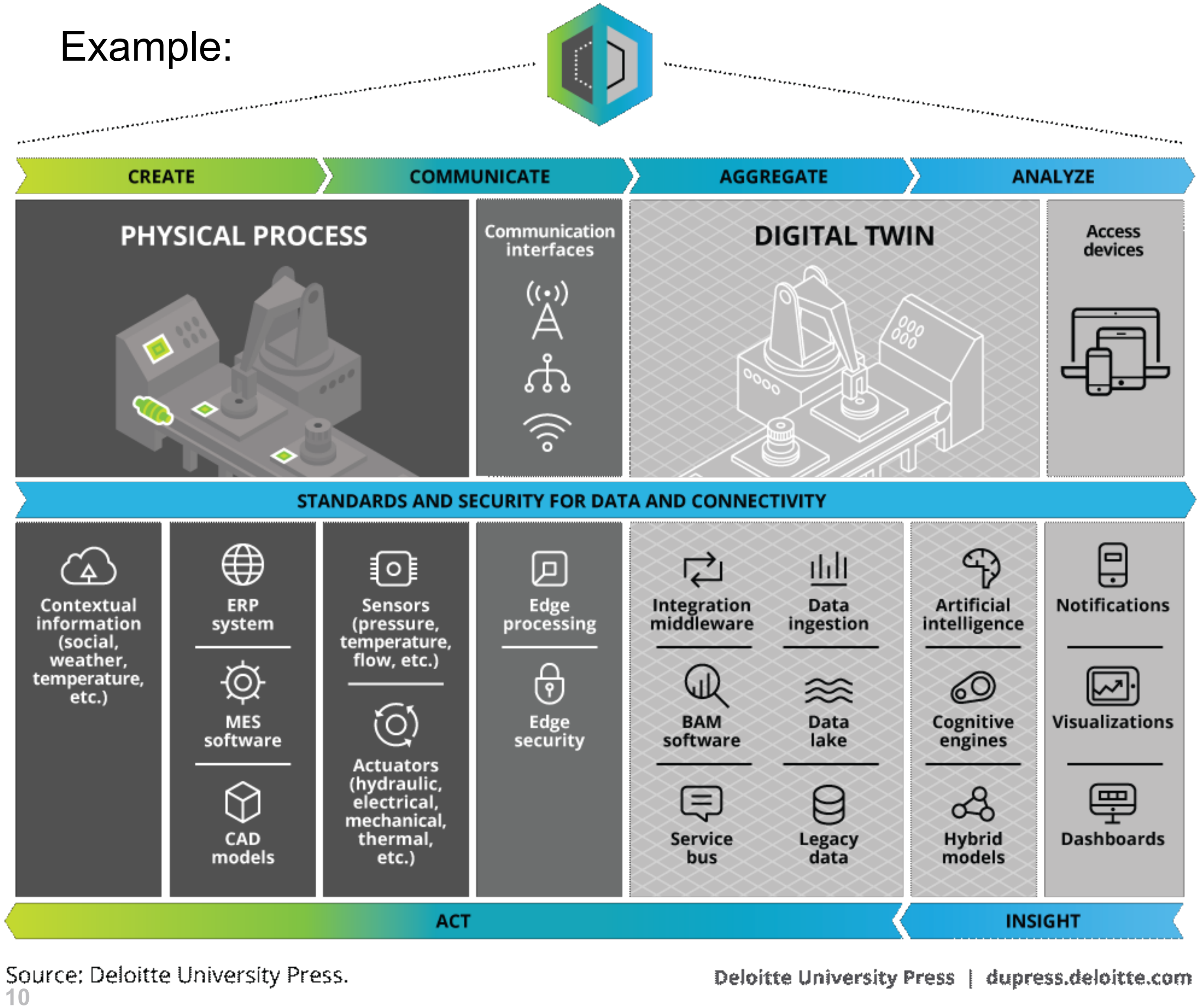
Manufacturing Process Digital-Twin Conceptual Architecture

Example:



Source: Deloitte University Press.

Major challenge in undertaking a digital twin process:

- Determining optimal level of detail in creating a digital twin model

Only a portion of the product life cycle:

- Manufacturing process
- Properties
- Performance

Product

Integrated system

Operation /use

Supply chain management /risk

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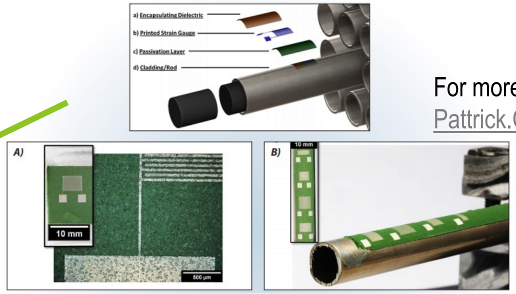
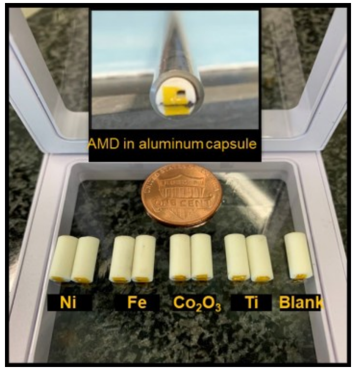
Embedded Sensors and Non-Contact Sensors

- Advanced Sensors and Instrumentation (ASI): https://www.energy.gov/ne/nuclear-energy-enabling-technologies/advanced-sensors-and-instrumentation
  - Sapphire single-mode fiber development towards high-temperature radiation resilient sensors
  - Acoustic sensors for in-core measurements
  - Aerosol AM strain gauge
  - Passive and active sensors capable of measuring temperature, thermal conductivity, strain, and neutron flux inside reactor core



For more information:
Pattrick.Calderoni@inl.gov

- Advanced manufactured dosimeters (AMDs): cost-effective, miniaturized, performance-enhanced alternative to standard dosimetry for characterization of neutron flux in irradiation experiments and demonstration facilities.
- NEEDS:
  - Wireless sensors
  - Embedded
  - Miniaturization
  - Multi-properties
  - Real time



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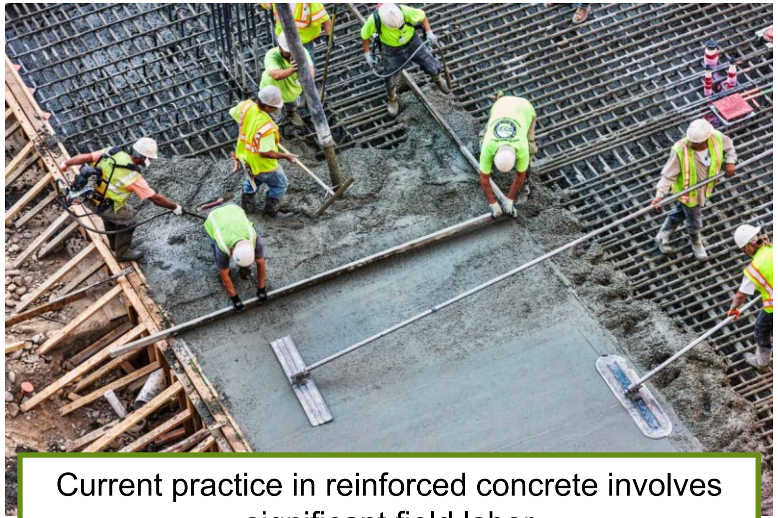
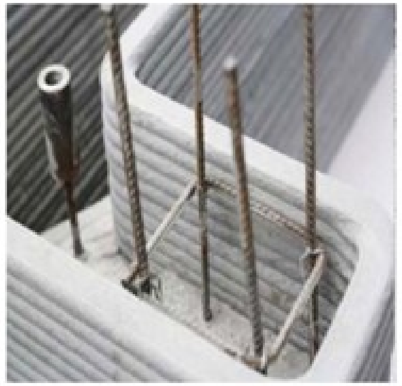
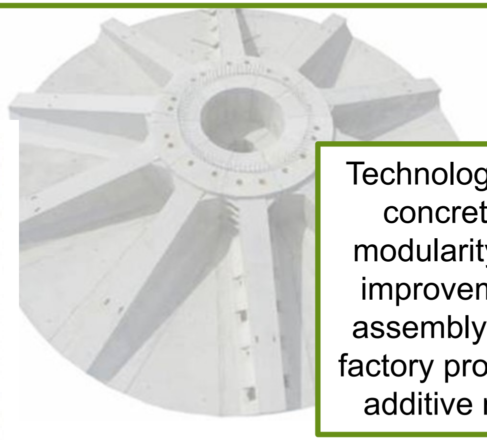
Technological Innovations in Reinforced Concrete

- Reinforced concrete structures may have to be used as secondary/tertiary containment for fission batteries
- Technologies that provide adequate structural performance, modularity, rapid assembly, and radiation shielding are needed
- Some innovations include:
  - Advanced manufacturing of reinforcement cages, including development of materials that can replace steel and can be additively manufactured
  - Manufacturing “foldable and transportable” reinforced concrete structures?
  - “Smart” concrete with embedded sensors
  - Concrete with superior radiation shielding properties to reduce (or eliminate) EPZs



Current practice in reinforced concrete involves significant field labor





Technologies like precast concrete offer some modularity, but still need improvements for rapid assembly and increased factory production through additive manufacturing

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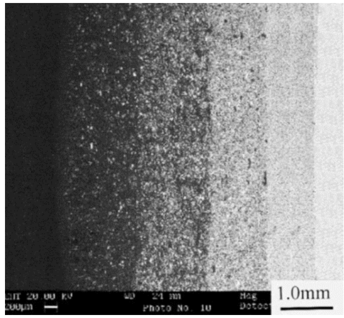
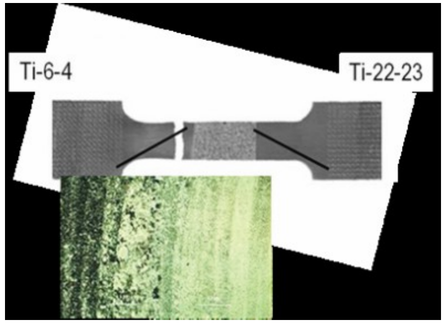
Efe Kurt: efe.kurt@inl.gov

Engineered Gradient Materials and Composition

- Multicomponent replacement with one integrated design (eliminates welding) and thin functional-gradient layer
  - Ni-Alloy N; Zr-Cr; Grade 91-316L
  - Interface behavior

SiC/Cu graded material





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

- Thermal barrier coatings
- Material composition for additive-manufacturing processes
  - Materials are designed, for example, to enable the fabrication processes, e.g., flowability for casting compositions
    - Is there a specific minor composition adjustment necessary for additive-manufactured materials?
- Surface behavior, corrosion properties, and irradiation behavior of additive-manufactured components
- AMM provides opportunities to discover and develop new materials

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High-Impact Manufacturing Technology Challenges

- Design approaches for manufacturing
  - More qualified materials are needed by reactor developers to allow for design flexibility and to meet performance targets.
  - Optimized process modeling and artificial intelligence
  - Interface design
  - Residual stresses relationships to design features
  - Topology optimization
- Develop and qualify high-strength, corrosion- and radiation-resistant materials for molten-salt reactors
- Accelerate qualification (new paradigm?)
  - Verification of quality and validation of modeling tools: specific manufacturing process modeling
  - New material discovery (or is it adoption of lessons learned from other disciplines?)
  - High-throughput testing and characterization
  - Verification of quality and validation of modeling tools: specific manufacturing process modeling
  - Acceptance protocols for high-temperature reactor components fabricated by advanced-manufacturing methods
  - Integrated shared databases
- Compact heat exchangers
  - Develop scientific understanding of processing-properties relation for enhanced diffusion-bond properties
- Large component fabrication and welding, size limitations (scalability—size, volume)
- Sensors
  - Radiation-tolerant sensors
  - Miniaturization of sensors
  - Integrated manufacturing processes
- Thermal barrier coatings: Interface designs to prevent scaling, functional materials, isolation

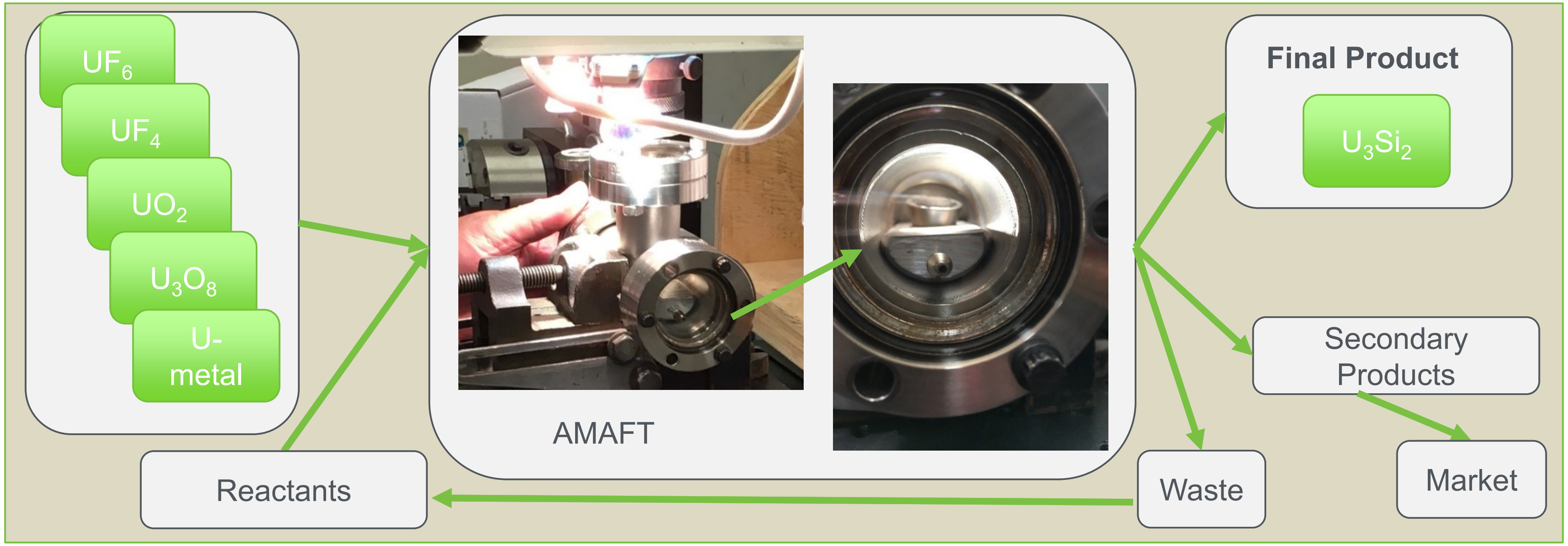
Fuel Technologies: What is the AMAFT Technology?

Case Study 1

Technology Commercialization Funding (TCF)

AMAFT process: Integrated Modular Additive Manufacturing

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



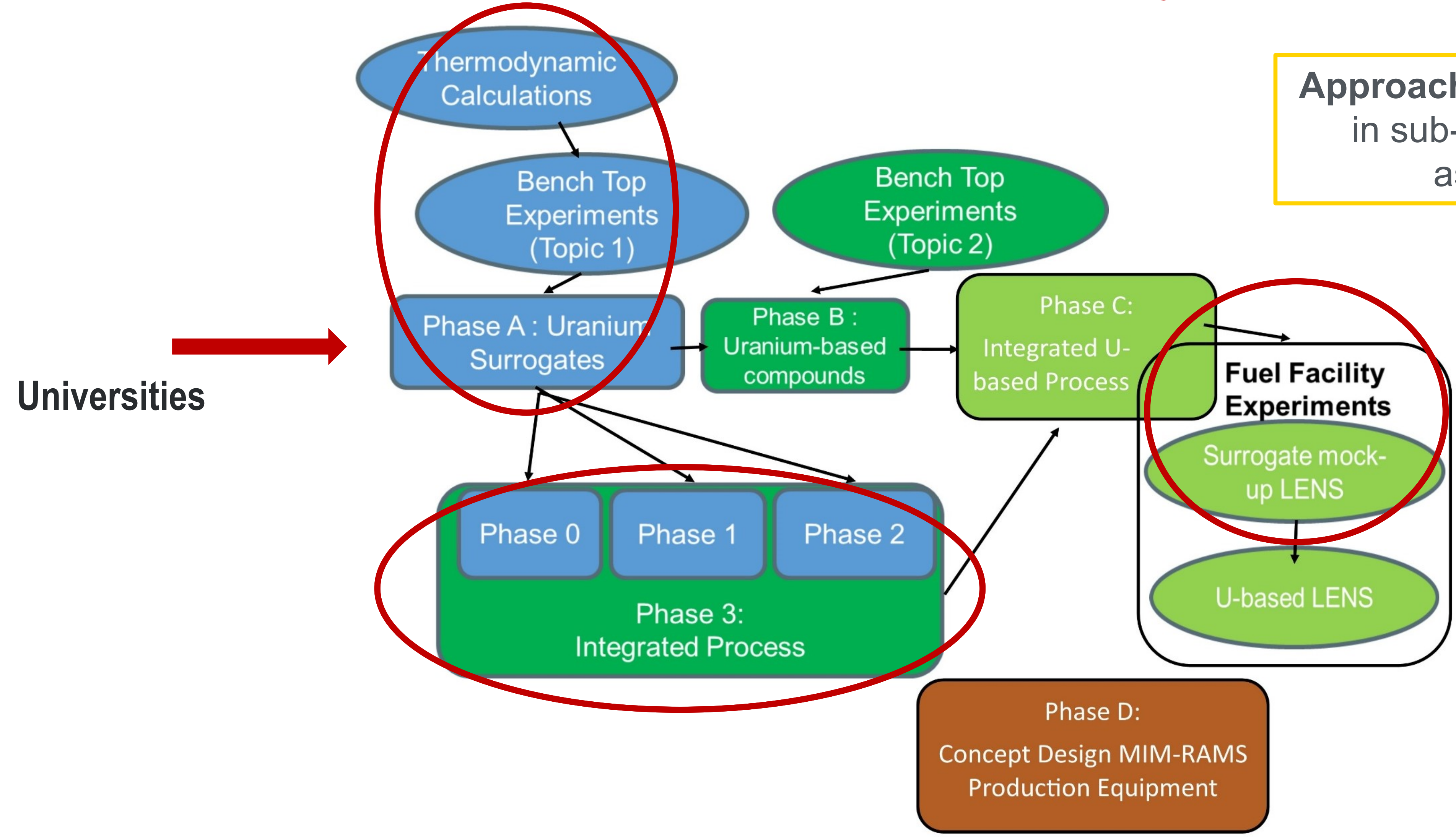
Benchtop Experimental Display

BA-894 March 2016,
Provisional Patent March 2017
Patent filed March 1, 2018

Experiments to Establish AMAFT Process

Example how universities can contribute towards research projects

Approach: Divide AMAFT process in sub-reactions to test each aspect's feasibility



INL/MIS-18-44587
INL/MIS-18-44584

Independent Qualification Review

Case Study 2

Strategic Partnership Project Funding (SPP)

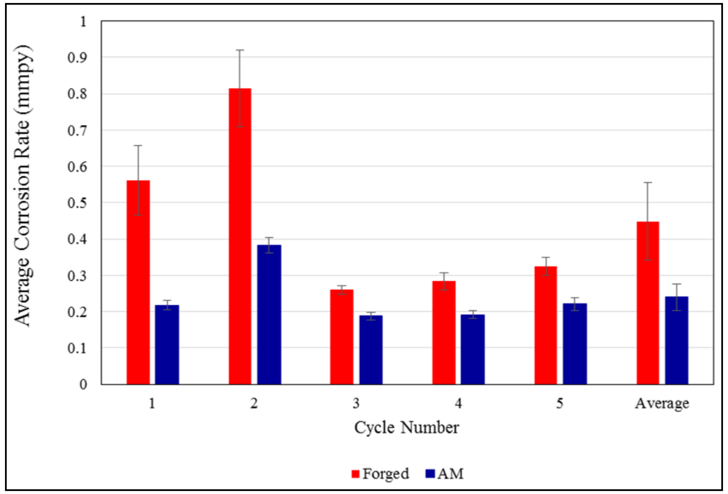
Advancement of state-of-the-art in additive manufacturing (AM) for naval applications

Objectives

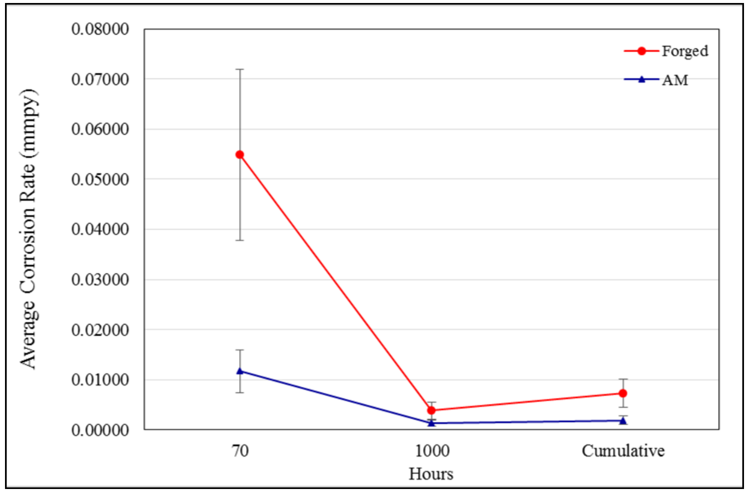
- **Independent evaluation on testing documentation supplied for an approach for product qualification.**
- **Comparative independent characterization and corrosion testing were performed on one AM and one forged 316SS valve.**

Forging

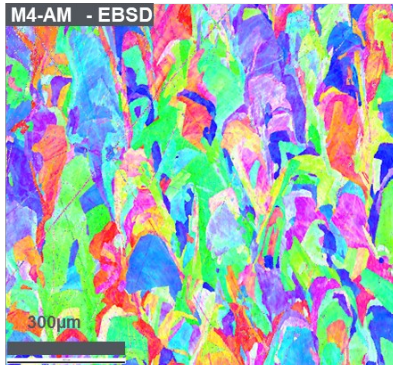
Laser powder bed fusion AM

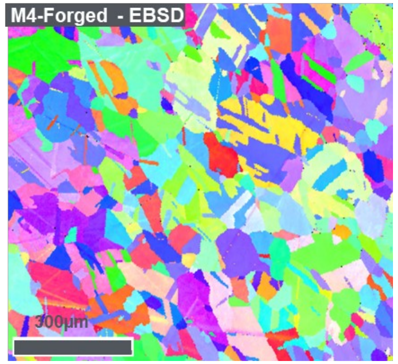


Nitric Acid Corrosion Tests (Practice C of ASTM A262-15)



Immersion Corrosion Test 5% NaCl, 50°C (ASTM G31-12a)





Newport News Shipbuilding
A Division of Huntington Ingalls Industries

Generally, the AM valve evaluation showed similar or better properties than the forged product (for parameters tested)

INL/CON-18-45816

A Metamodel for Predicting Effective Thermal Conductivity of Porous Materials

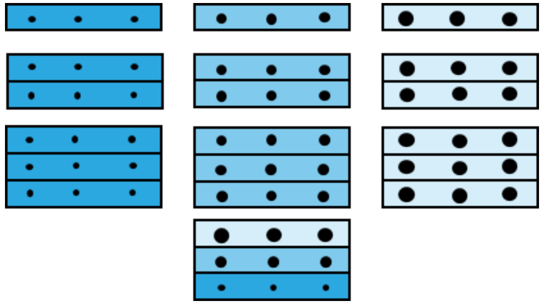
Functionally graded materials
Thermal barrier coating applications

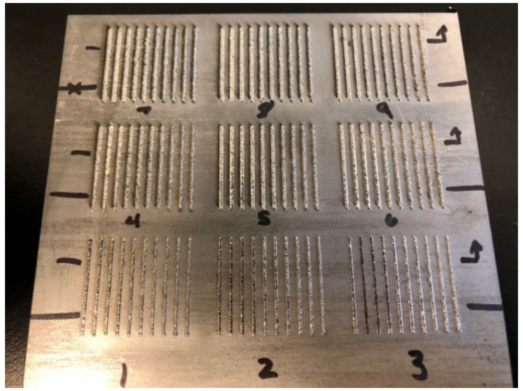
Case Study 3

Laboratory Directed Research and Development Funding (LDRD)

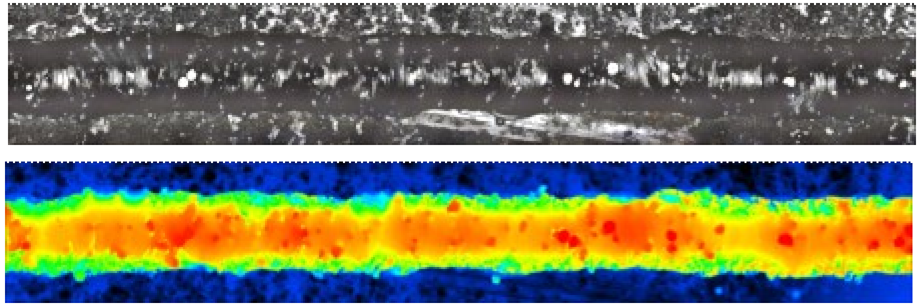
- Additively manufactured materials typically contain lack-of-fusion porosity, or technique is used to fabricate pre-designed porous or lattice structures.
- Effect of geometric configurations of porosity on overall **thermal conductivity** is important for energy applications, which calls for numerical modeling analyses.

- Sparse data from experiments can be used for validation and if the required accuracy is not met, a multi-fidelity Gaussian process can be used to incorporate the experimental data with the simulation data from the ROMs and hence build a more accurate. This mitigates the problem of sparsity of the experimental data while leverages insights from the finite element modeling and machine learning models.





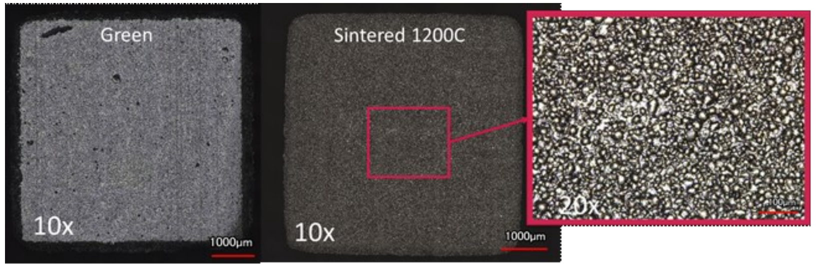
LENS Single-track beads



Laser-optical LENS clad Tracks. High powder feed rate, power, scan speed

WAAM deposition parameters

- Advanced microscopy with laser-optical imaging can give quick insight to topographical properties such as geometry and surface roughness and resulting microstructures

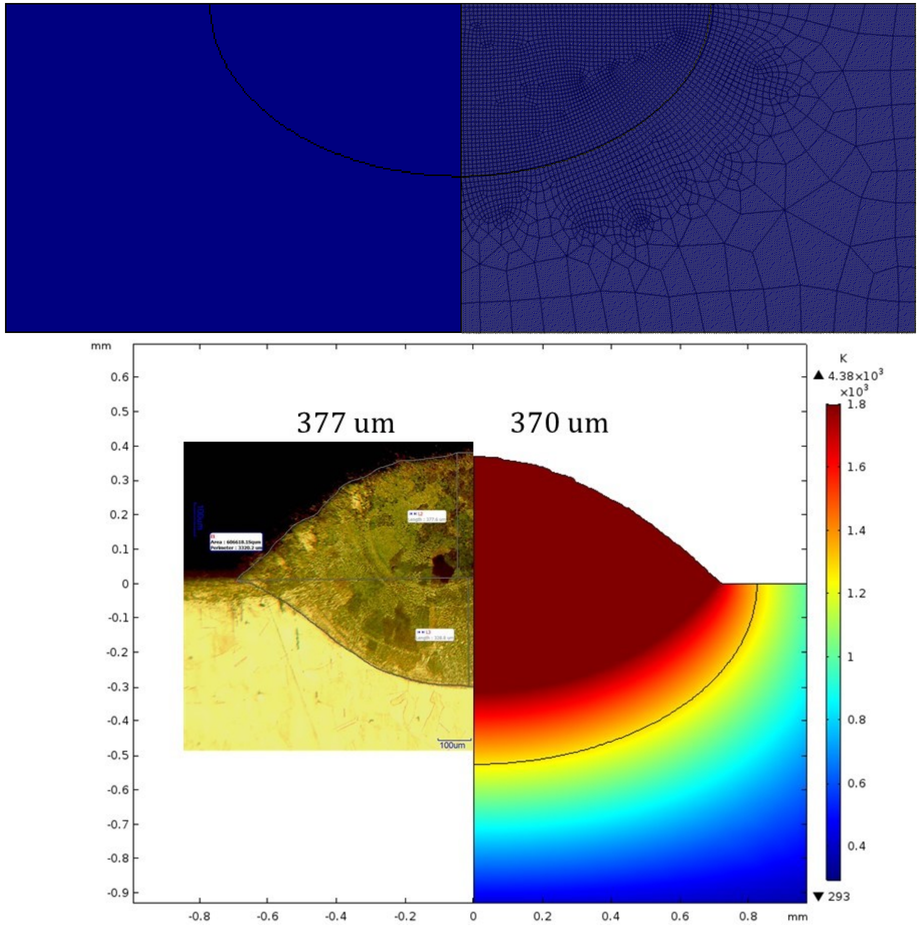


Digital light photoluminescence (DLP)
- Photo polymer-based additive that used UV light that cures resin with suspended particles

INL/CON-20-58911

AM Modeling

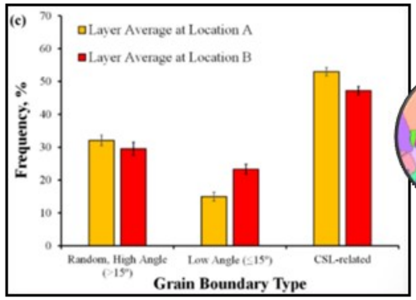
- Modeling is needed to better predict the effect of porosity and on processing and material properties
- Process Modeling
  - Determination of processing maps with physics based numerical modeling
    - Reduced iterative experimentation
- Property modeling
  - Predict microstructural growth, residual stresses, and mechanical strength based on coupled thermal-fluid process modeling
- Artificial Intelligence / Machine learning
  - Predicting porosity effects on bulk thermal properties with experimental and material modeling
  - Input from physics-based models as a better determination of final part properties

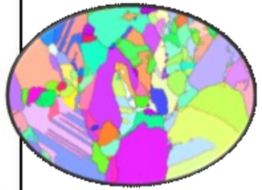


LENS process model developed by Luis Nunez

Nunez, Luis. Numerical and Experimental Validation for the Optimization of Directed Energy Deposition Processing Parameters, Northern Illinois University, Ann Arbor, 2019. ProQuest, https://search-proquest-com.auth.lib.niu.edu/disserations-theses/numerical-experimental-validation-optimization/docview/23827676473/se-2?accounted=12846.

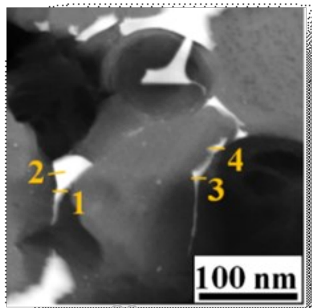
Current Focus of TRISO Advanced Microscopy and Micro-Analysis





AGR-2 Particle Examination
Predominantly SiC, IPyC

- Characterize Effects of Radiation upon:
  - Kernel porosity
  - Layer degradation or corrosion,
  - Layer debonding,
  - Fission product precipitation,
  - Microstructure; grain characteristics.
- Determine microstructural differences between particles exhibited high and low releases of Ag-110m



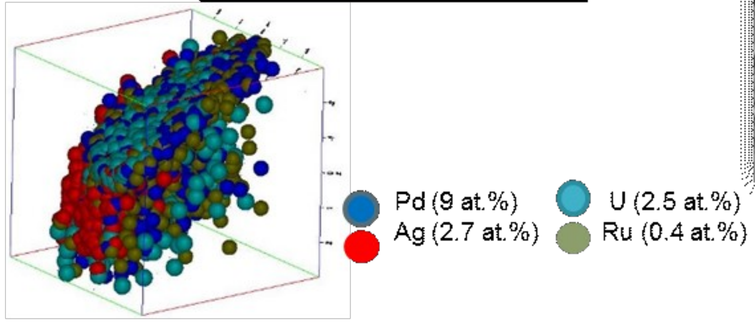
1

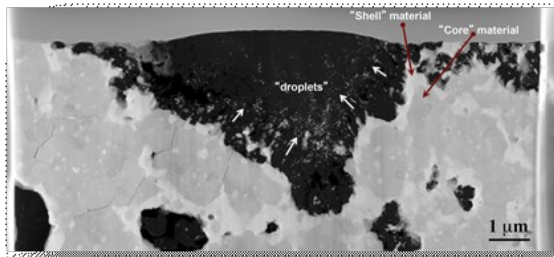
Kernel Examination

2

4

Fission Product Transport Mechanisms

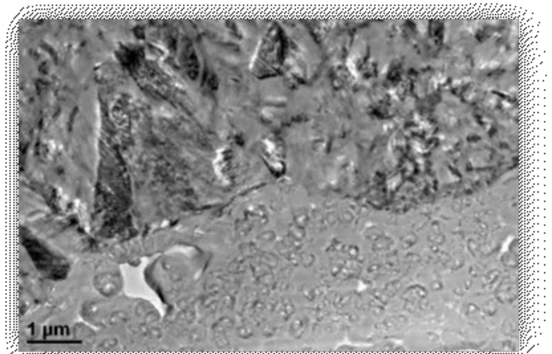




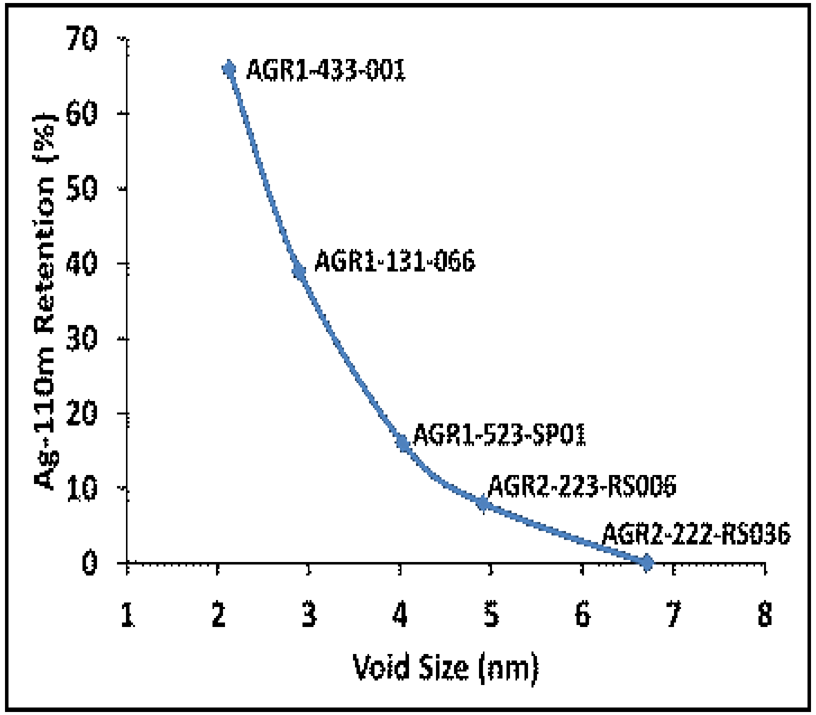
Characterize effects of Radiation upon:
- kernel porosity
- layer debonding,
- fission product precipitation,
- microstructure

3

Neutron Irradiation Damage

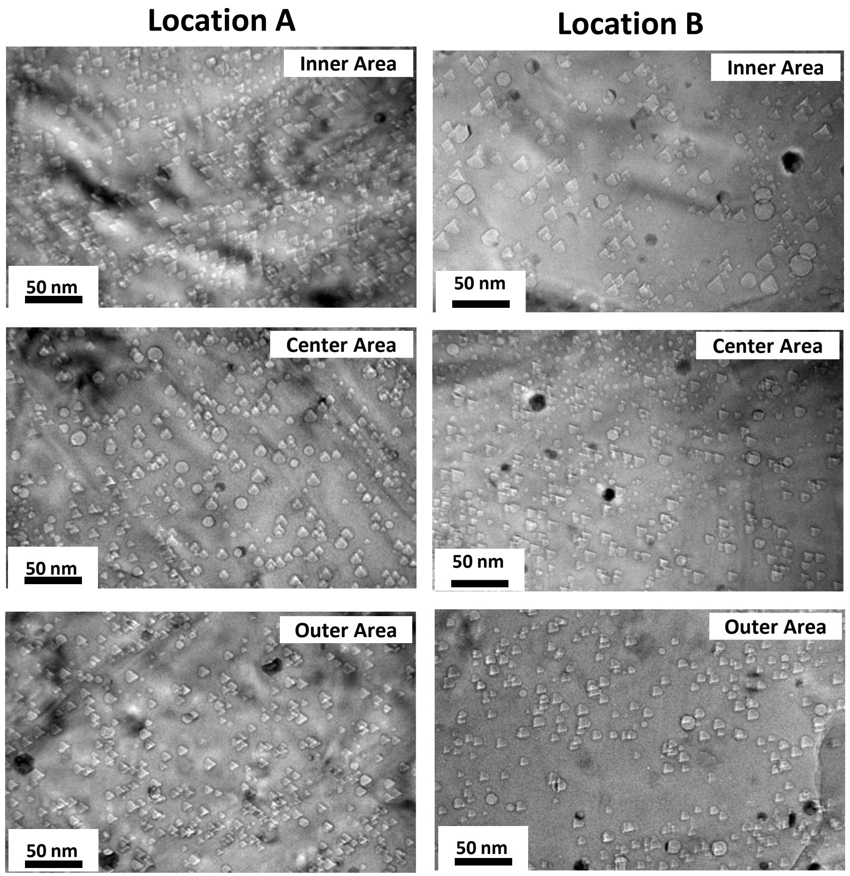


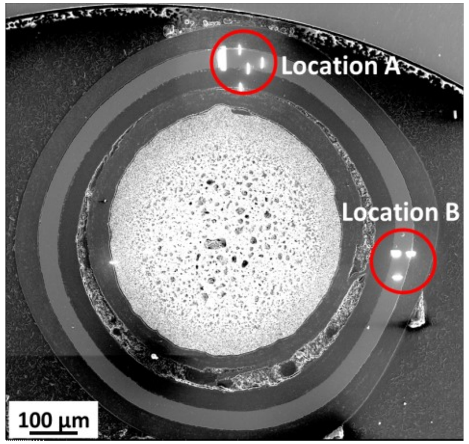
Effect of defect size on Ag retention

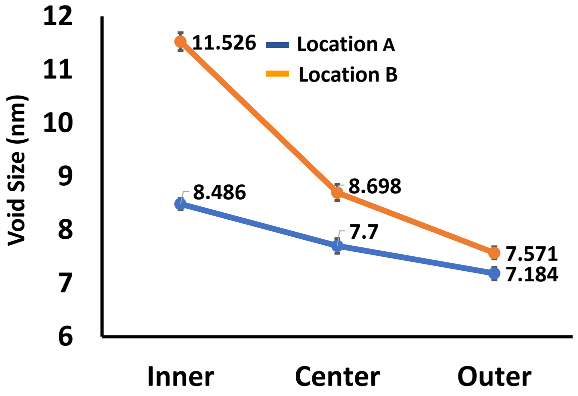


Ag-110m retention in the SiC layer appears to have an inverse relation with void sizes.

HTR-2018, 8-10 October, 2018, Warsaw, Poland

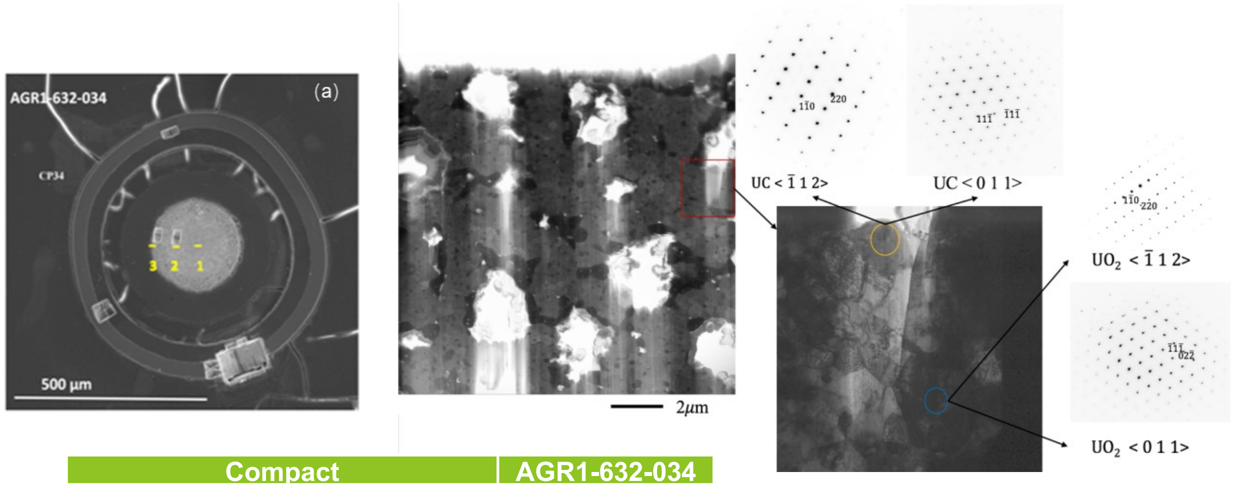


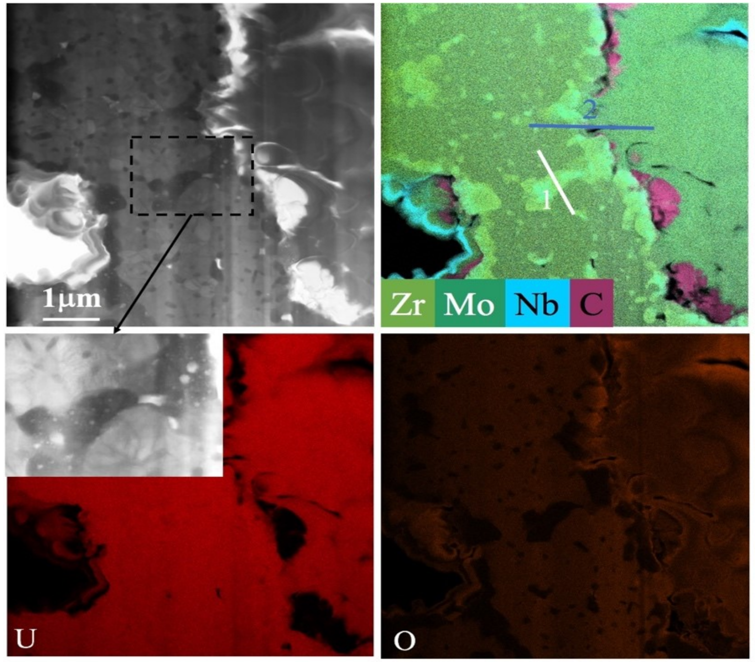


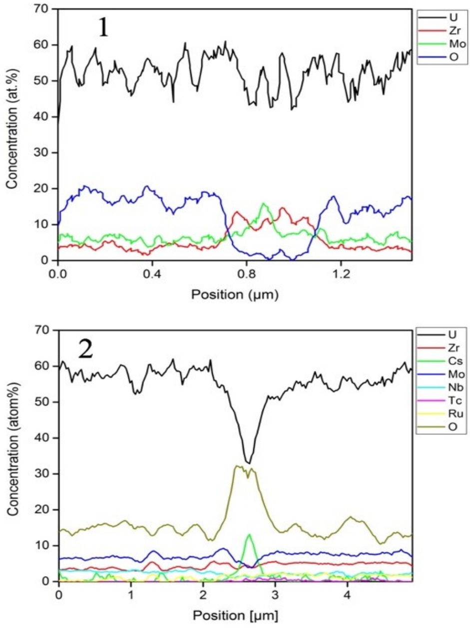


- The void sizes are larger in SiC layer adjacent to region where buffer layer is broken.
- The observed void size variation with integrity of buffer layer can potentially affect the fission product retention.

Irradiated Microstructure of AGR-1 Fuel Kernel







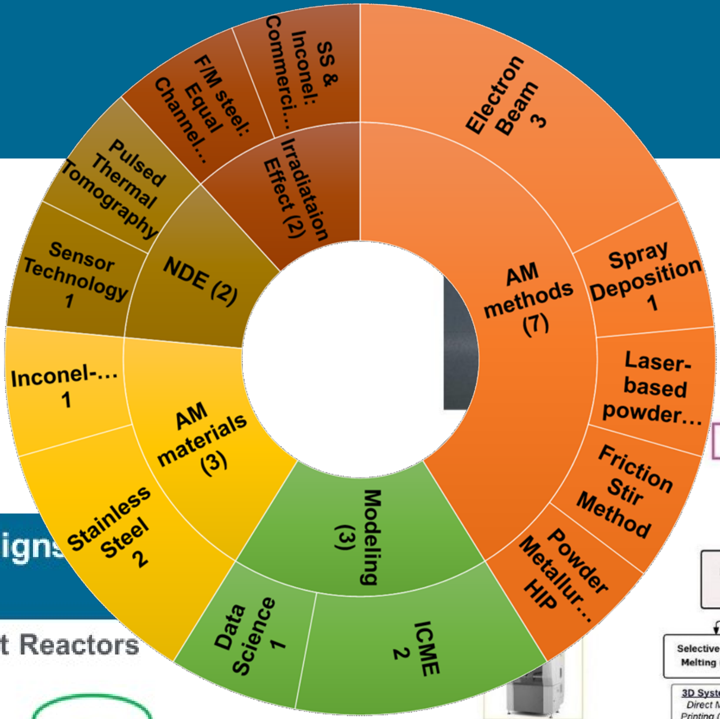
Compact	AGR1-632-034
Burnup (%FIMA)	11.4
Fast neutron fluence (x 10^{25} n/m^2), E>0.18 MeV	2.55
Time-average volume-average temperature (°C)	1070
Time-average peak temperature (°C)	1144

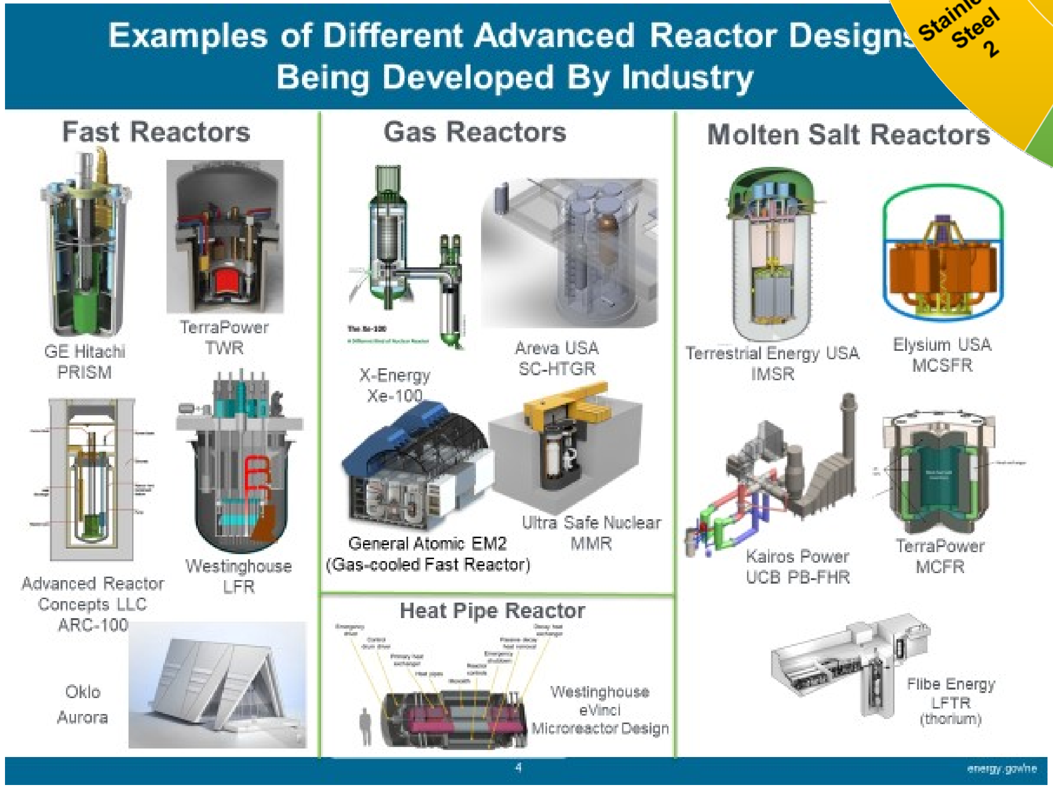
- Fuel matrix consists of UC and UO_2, and UO_2 presents as the dominating phase.
- Zr forms carbide in the solid solution of UC
- Mo, Ru and Tc also enrich in UC phase, and Nb tends to enrich at pore surface.
- Ultra-fine Fission gas bubbles located in UC phase, while UO_2 is free of fission gas bubbles.

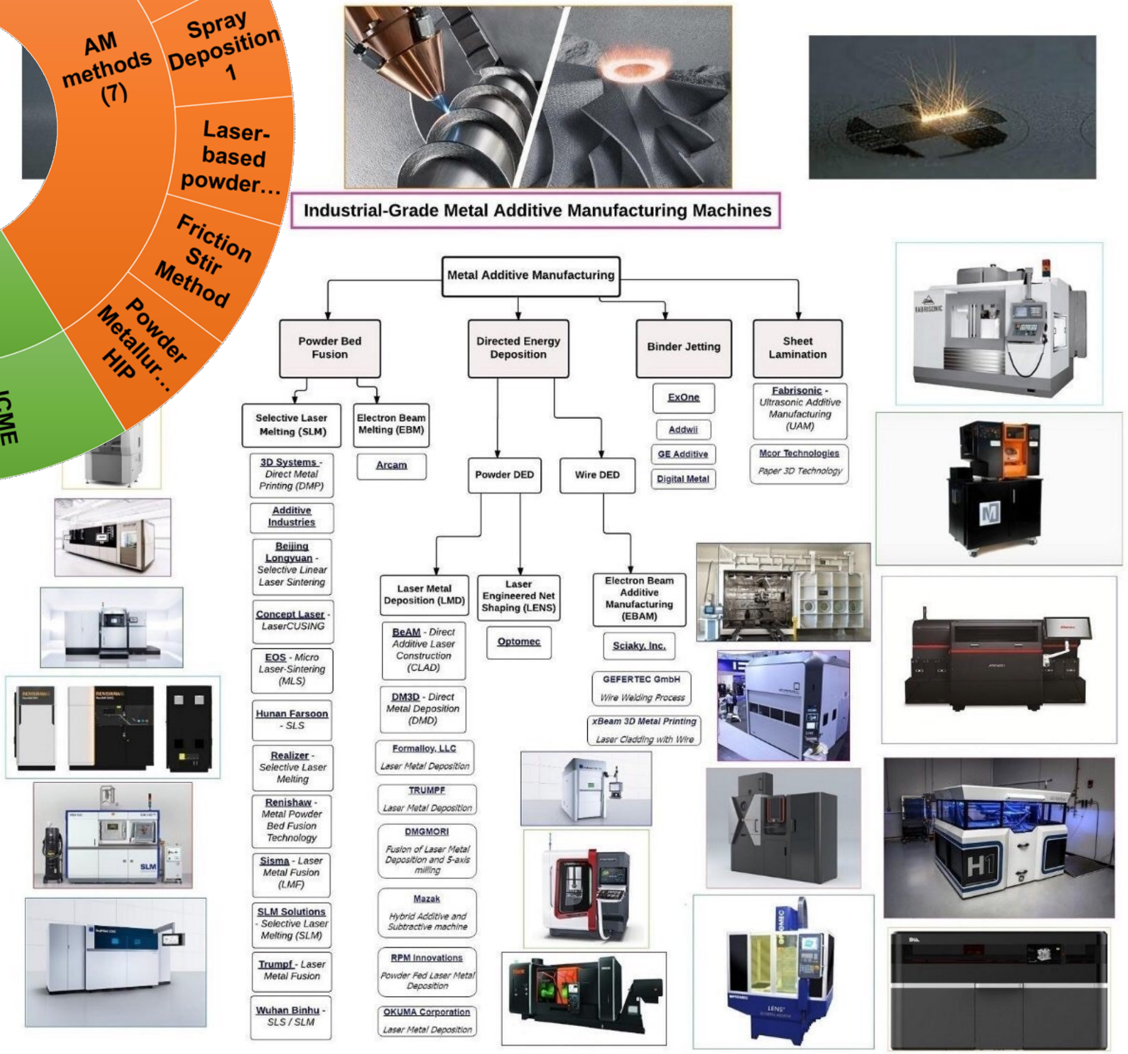
[Advanced Reactor Technologies Gas-Cooled Reactor Program Review, July 14-16, 2020, GoToWebinar]

What Next?

- Update Strategic Plan
- Mining previous awards
- Implement FY21 priorities







Advanced Manufacturing Methods Pertinent to Nuclear Power Plants

Most Interest for Near Term Deployment

- AMM ADDITIVE MANUFACTURING
  - Powder Bed
  - Directed Energy Deposition
  - Binder Jetting
- NEAR NET SHAPE MANUFACTURING
  - Powder Metallurgy - Hot Isostatic Pressing
  - Investment Casting
- JOINING/CLADDING
  - Adaptive Feedback Welding
  - Diode Laser Cladding
  - Electron Beam Welding with High PWHT
  - Friction Stir Welding (FSW)
  - Hybrid Laser Arc Welding
  - Hybrid Laser-GMAW
  - Laser Cladding Technology (LCT)
- SURFACE MODIFICATION/COATING
  - Chemical Vapor Deposition (CVD)
  - Cold Spray Additive Manufacturing
  - Physical Vapor Deposition (PVD)
  - Laser Peening

[NEI “Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry”, 2019]

Interest for Longer Term Deployment

[Notes from NuScale Power, 2017]

- ADDITIVE MANUFACTURING in NPM
  - Reactor Vessel Internals
    - HCSG Tube Supports
    - CRDS Supports
    - CRA Cards
    - Fuel Pins
  - Integral Safe Ends
  - Sub Supplier Components
    - Fuel Assembly
    - Valve Internals
    - Latch Mechanisms
- In 10 years
  - Traditional forgings
  - PM-HIP complex shapes
  - Additive Manufactured parts
  - Traditional welds
  - Advanced joining techniques
  - Laser clad components

Integration and keep abreast of current needs, while preparing for the new generation designs

Qualification Processes

Categorization of manufacturing processes?
Why is it advanced manufacturing?

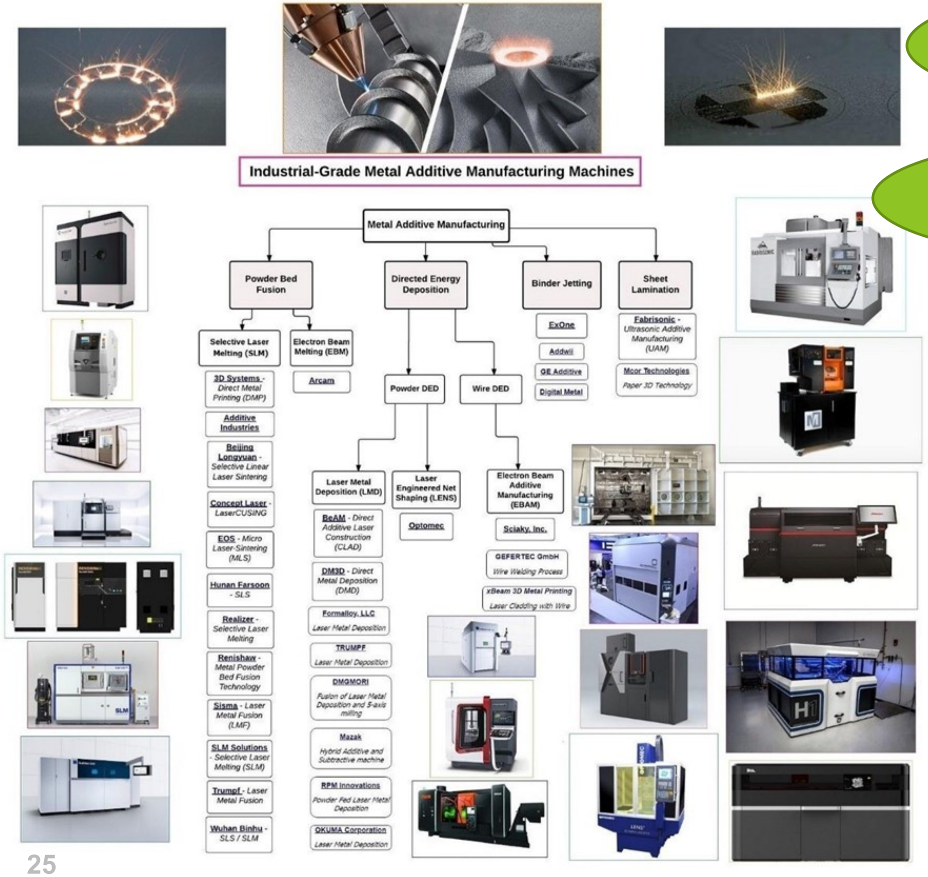
Additive Manufacturing

Coatings

Powder Metallurgy

Welding

Casting



Idaho National Laboratory

Current Research & Collaboration Opportunities

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