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

Clean. Reliable. Nuclear.

Advanced Methods for Manufacturing Program Overview

NRC Public Workshop on Advanced Manufacturing

December 7-10, 2020

Isabella J. van Rooyen

National Technical Director: Advanced Methods for Manufacturing (AMM)

Dirk Cairns-Gallimore

DOE-NEET-AMM Federal Program Manager

Office of Nuclear Energy: Mission Pillars

- Advance nuclear power to meet the nation's energy, environmental, and national security needs.
- Resolve technical, cost, safety, security and regulatory issues through research, development and demonstration.

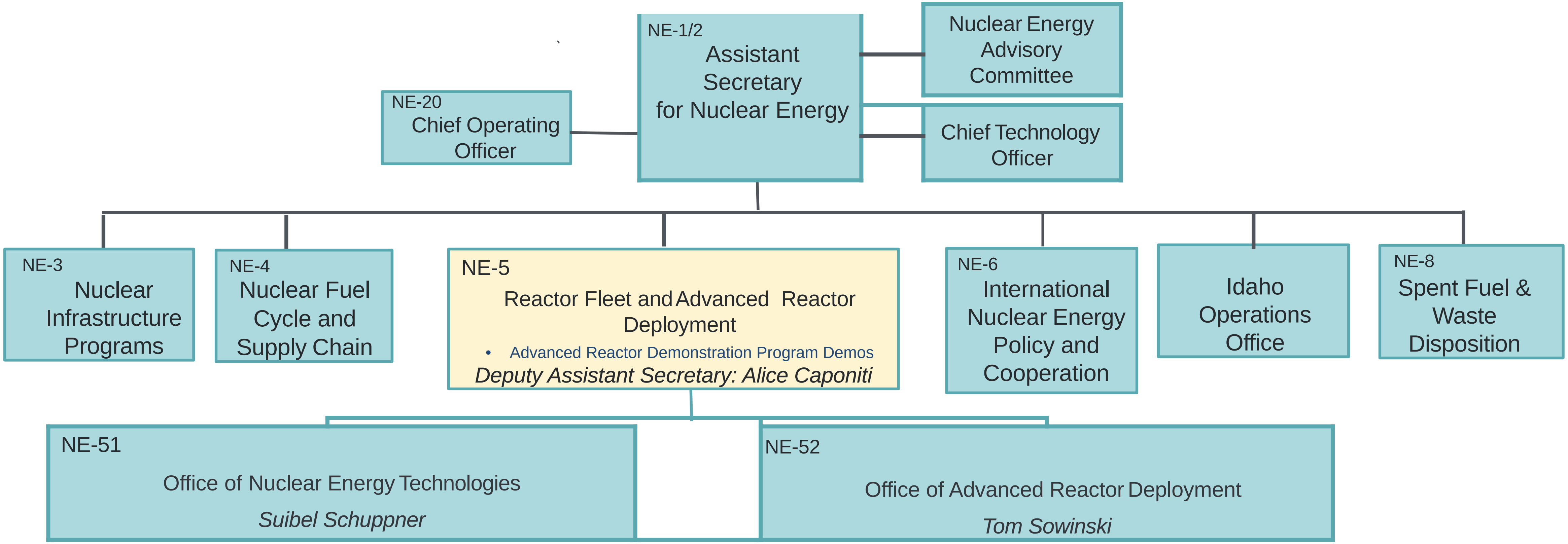
Existing Fleet

Advanced Reactor Pipeline

Fuel Cycle Infrastructure

Global Competitiveness

Office of Nuclear Energy



Enabling Technologies Team
- Advanced Sensors and Instrumentation (ASI)
- **Advanced Methods for Manufacturing (AMM)**
- Nuclear Energy Advanced Modeling and Simulation (NEAMS)
- Nuclear Science User Facilities (NSUF)
- Transformational Challenge Reactor (TCR)

University and Competitive Research Team
- Nuclear Energy University Program (NEUP)
- Integrated University Program (IUP)
- Research Reactor Infrastructure (RRI)
- Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR)
- Gateway for Accelerated Innovation in Nuclear (GAIN) Advanced Nuclear Industry Funding Opportunity (Industry FOA)
- Technology Commercialization Fund (TCF)

Reactor Optimization and Modernization Team
- Light Water Reactor Sustainability
- Advanced Small Modular Reactor R&D
- Integrated Energy Systems (IES)
- Nuclear Cyber Security (NCS)
- Advanced Reactors Safeguards (ARS)

Advanced Reactor Development Team
- Sodium-Cooled Fast Reactor
- Gas-Cooled High-Temperature Reactors
- Molten Salt Reactors
- Microreactors
- National Reactor Innovation Center (NRIC)
- Risk Reduction
- Advanced Reactor Regulatory Development

Office of Reactor Fleet and Advanced Reactor Deployment Mission (NE-5)

- **Vision –** Be a catalyst for the commercialization of NE-sponsored research, development and demonstration products
- **Mission –** Integrate NE's research investments to achieve a productive and balanced portfolio of competitive and crosscutting research, development, and demonstration (RD&D) and research infrastructure to enable expansion of the U.S. commercial nuclear industry
- **Objectives**
  - Full and effective integration of NE RD&D planning, execution and oversight
  - Systematic management of NE investments in research capabilities
  - Alignment of NE's RD&D programs with industry-identified technical and regulatory needs
  - Accelerate the introduction of innovative technologies into the marketplace through multiple mechanisms

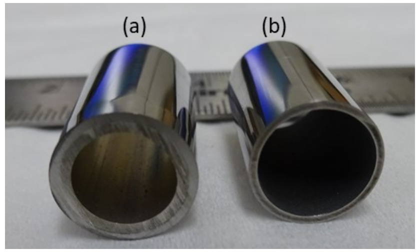
Advanced Methods for Manufacturing (AMM)

Vision

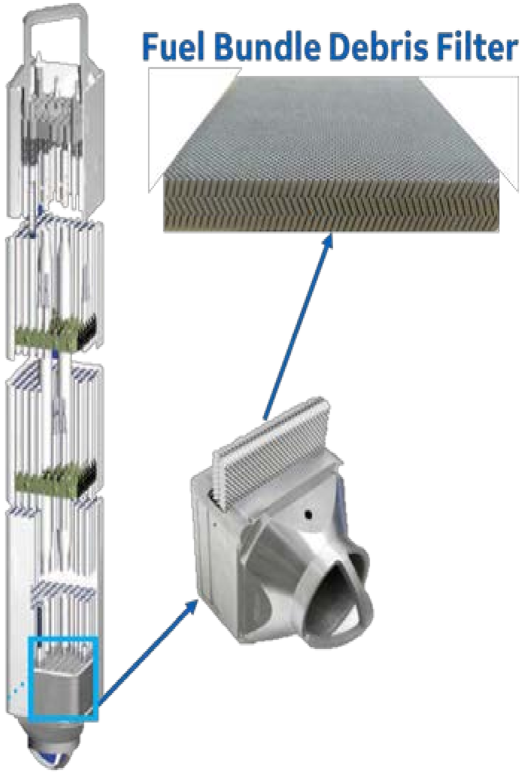
- To improve and demonstrate the methods by which nuclear equipment, components, and plants are manufactured, fabricated, and assembled by utilizing 'state of the art' methods

Goal

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



Fuel tubes produced by cold spray



GEH BWR fuel bundle w/debris filter insert

5

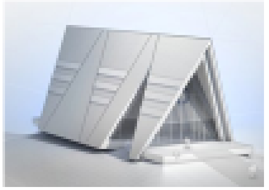
Connections of AMM program to other R&D programs, NRC, Industry

- NEAMS
- ART
- ASI
- GAIN
- NSUF & NMDQi
- TCR
- IES
- NE-4 - VTR -TREAT

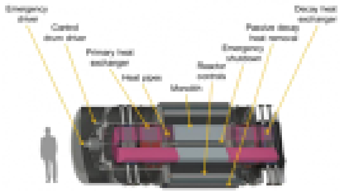
NE – 5 & Other DOE NE Programs | NNSA & NASA | DoD Programs

Existing Fleet

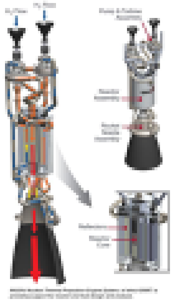
Advanced Reactors, SMRs, & ARPs



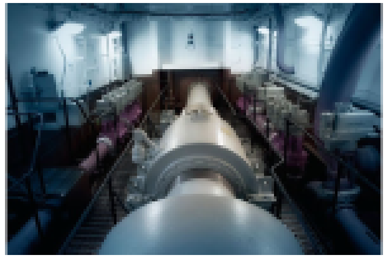
Nuclear Battery & Micro Reactors



Space Reactors



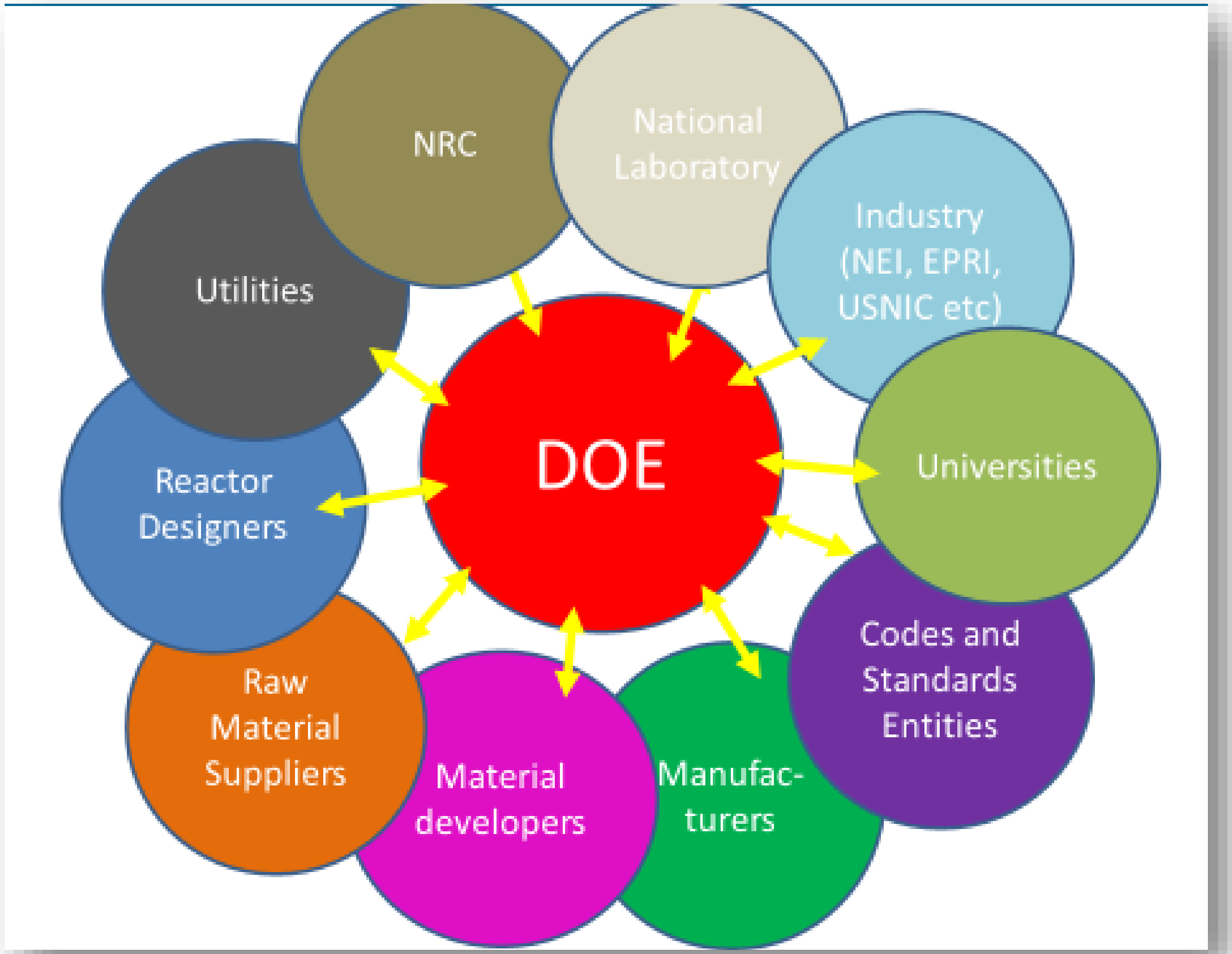
Defense



Cross-cutting AMM research focus areas support all major Nuclear programs across DOE, DoD, NASA, and Industry Stakeholders

- Factory and Field Fabrication Techniques
- Modular Manufacturing
- Advances in Manufacturing Processes
- Advances in Concrete
- New Adv. Man. Tech. for Qualification and Certification to Accelerate Licensing
- Advanced Integrated Fuel System Concepts

Stakeholder Engagement ("Customers")



Internal DOE Supported Programs

- Advanced Reactors
- LWRS
- Other elements of NEET

Industry Connections

- NEI
- USNIC
- EPRI
- IFOA
- Fuel Vendors

External Governmental Programmatic Synergies/Overlaps

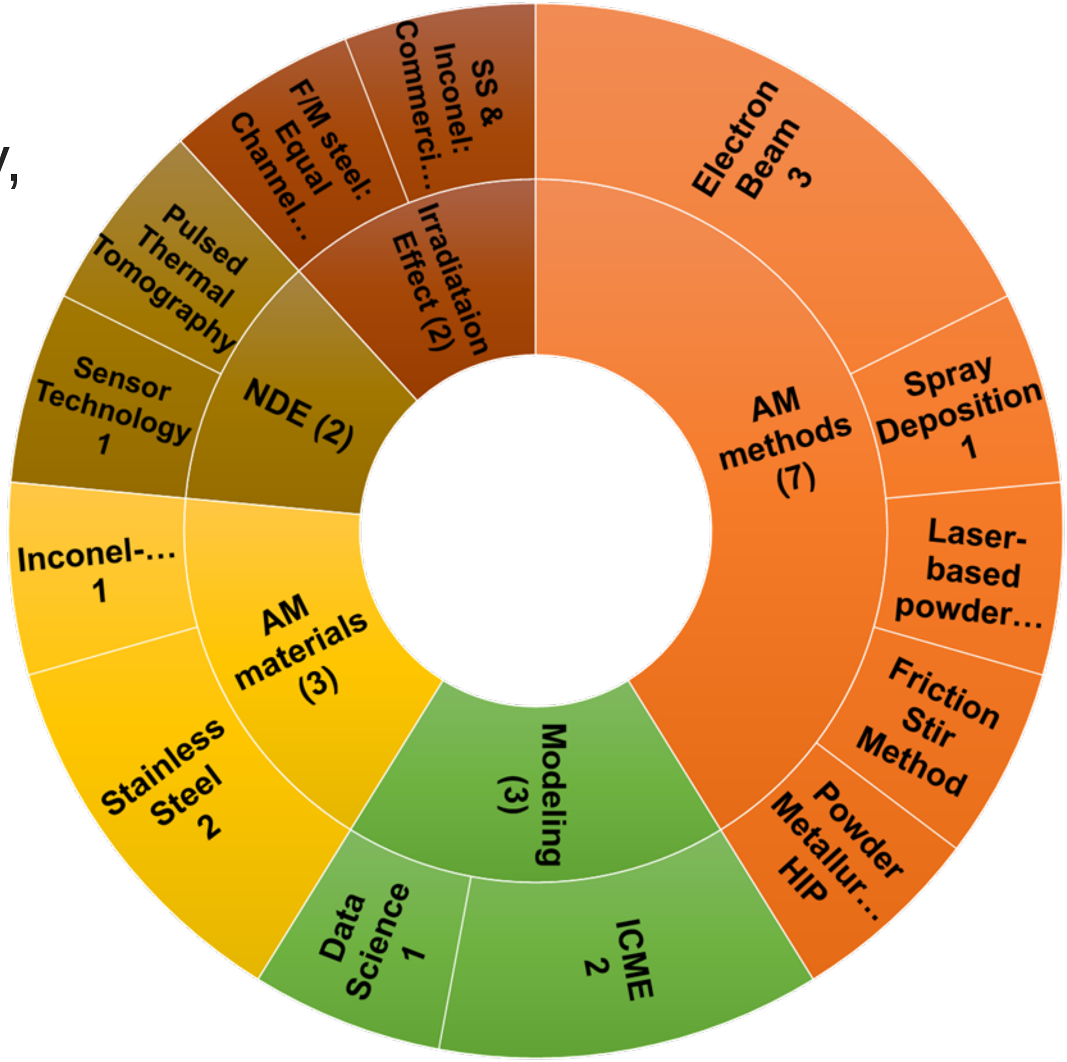
- **NRC**
- EERE
- NIST
- DoD

The Goal is for DOE-NE to be the nexus for AMM development and leadership

FY21 Objectives and Priorities

The Goal is for DOE-NE to be the nexus for AMM development and leadership

- Increase **stakeholder participation** (Industry, DOE offices, Standards, NRC, National laboratories etc.)
- Leverage the **impact of research work** and understand how the technology can potentially be adopted & commercialized
- Continue to reevaluate strategic intent and **identify gaps, needs**
- Increase **collaboration** with DOE programs (identify cross cutting similar needs)
- Establish **direct funded** project(s)
- Re-evaluate Strategy



Communication

AMM Newsletter

Advanced Methods for Manufacturing

Issue 11 • April 2020

Dirk Cairns–Gillamore Joins AMM Program

Dirk Cairns-Gallimore has joined the Advanced Methods for Manufacturing team as the DOE-NE headquarters program manager. Cairns-Gallimore is a native of the Pacific Northwest. He graduated in 2001 from Oregon State University with a degree in nuclear engineering and started his career in 2002 in the Department of Energy's Office of Nuclear Energy, working in the Office of Space and Defense Power Systems. Over the course of 18 years, he was program manager for the multi-mission thermoelectric generator (MMRTG) that was used on Curiosity Rover and will power the upcoming Mars 2020 mission of the Perseverance Rover. He was also the NE-headquarters manager for the activities at the Space and Security Power Systems Facility at INL during the fueling of the General Purpose Heat Source—Radioisotope Thermoelectric Generator (GPHS RTG) for the New Horizons mission to Pluto. Prior to joining the AMM program, he spent a year on detail with the U.S. Coast Guard at their headquarters in Anacostia, Virginia. There he helped further enhance and integrate the Coast Guard's enterprise risk-management system across 23 organizations.

Dirk Cairns-Gillamore
DOE-NE program manager

Mr. Cairns-Gallimore brings an interesting perspective to the program. Through his work with space and defense, he was able to be part of a program that integrated expertise from private industry, academia, the national labs, and multiple agencies into mission-critical, time-sensitive product delivery. The production of an RTG is complex, an interdisciplinary engineering process that requires knowledge of manufacturing and fabrication processes, including welding, chemistry, and materials science (including, e.g., carbon-carbon composites, aluminum, and iridium). Cairns-Gallimore's experience gained during the production of MMRTGs is germane to many of the processes involved in the AMM program: ball milling, powder metallurgy, hot isostatic pressing, and welding processes, including thermogravimetric analysis , laser and e-beam welding, and others. This background is crucial to the expansion of research and development towards commercial deployment of advanced manufacturing, in accordance with ASME NQA-1 standards.

Mr. Cairns-Gallimore is an ardent supporter of deploying AMM processes for use by the nuclear industry. He believes that it will be critical for the continued success of both the current reactor fleet and future investment in advance reactors. His time at the Coast Guard reemphasized the power of teamwork and showed that the focus of a determined group of people can create success despite a challenging environment. One of his main goals for the program is to establish priorities for materials and processes so that AMM can be deployed for first-of-a-kind uses. The ability of the AMM community to come together and push toward this goal will determine its success.

In This Issue

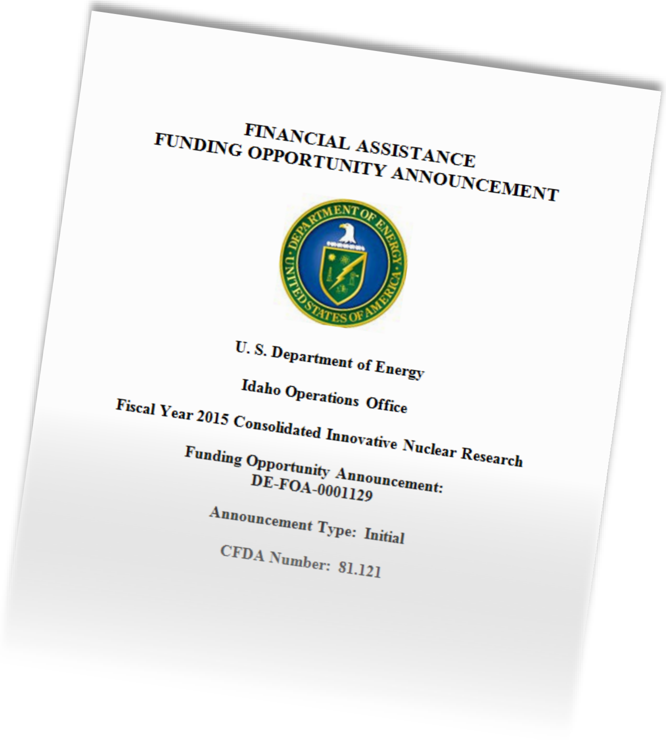
For more program information, including recent publications, please visit www.energy.gov/ne

U.S. DEPARTMENT OF ENERGY

- Surveys
- Conferences
- E-mail contact list
- Outreach presentations
- NEI workgroups
- Publications

Addressing Challenges

- **Competitively selected projects via Consolidated Innovative Nuclear Research (CINR) & Industry FOA**
  - Open to universities, national laboratories and Industry
  - R&D and irradiation/PIE projects funded
  - FY 21 work scopes
    - MODULAR ADVANCED MANUFACTURING APPROACHES
    - NEW ADVANCED MANUFACTURING TECHNOLOGIES FOR QUALIFICATION AND CERTIFICATION TO ACCELERATE LICENSING
    - IRRADIATION TESTING OF MATERIALS PRODUCED BY INNOVATIVE MANUFACTURING TECHNIQUES
  - AMM Qualification Workshop
    - GAIN-EPRI-NEI
    - Develop an integrated approach to the AMM qualification process for materials and components


FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Idaho Operations Office
Fiscal Year 2015 Consolidated Innovative Nuclear Research
Funding Opportunity Announcement:
DE-FOA-0001129
Announcement Type: Initial
CFDA Number: 81.121

AMM Focus Areas: FY2021

Factory and Field Fabrication Techniques

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

Modular Manufacturing

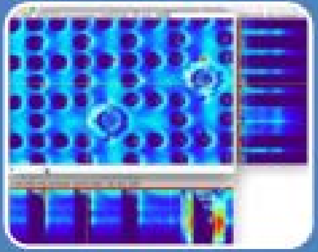
Fabricated forgings
Factory fabrication of piping systems
PM-HIP

Advances in Manufacturing Processes

Additive Manufacturing of metals
Surface engineering
Metamorphic Manufacturing
Advanced sensors

Improved Concrete Inspection, Acceptance, and Construction Methods

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



New Advanced Manufacturing Technologies for Qualification and Certification to Accelerate Licensing

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

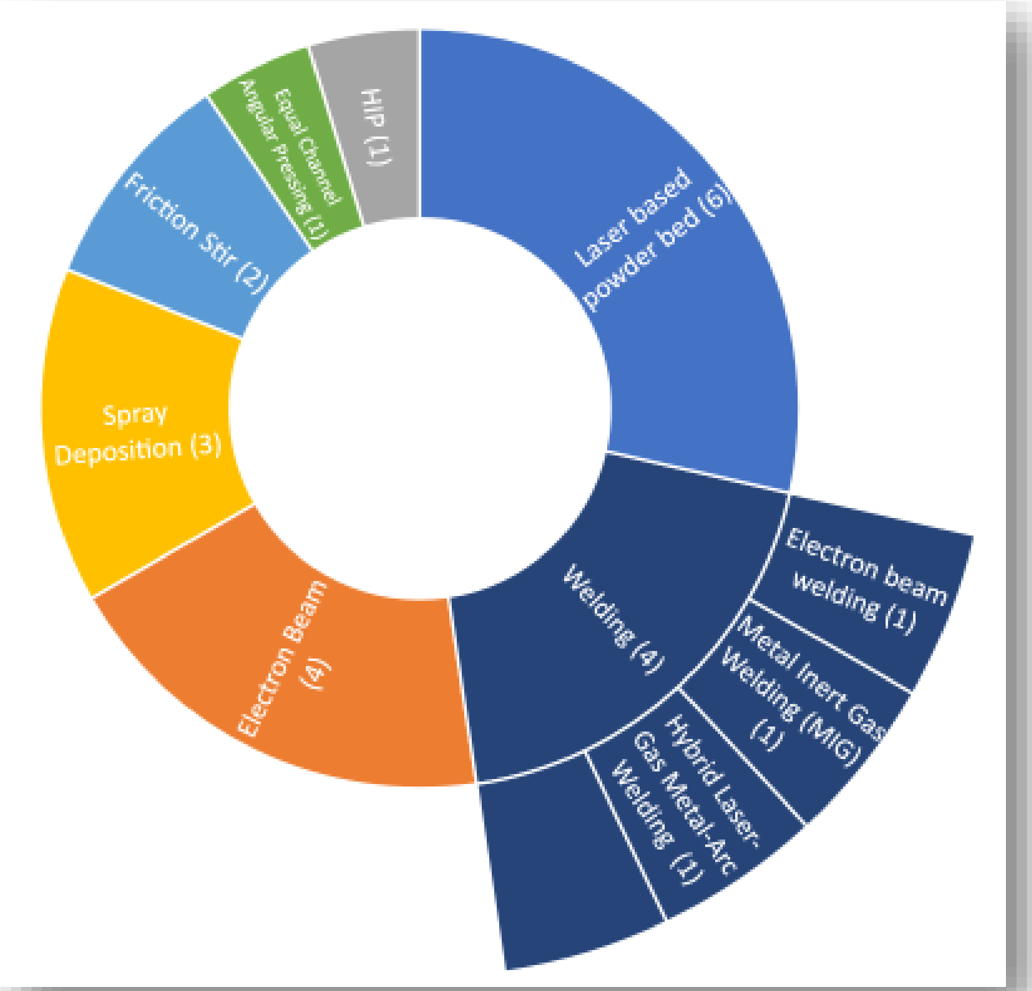
Advanced Integrated Fuel System Concepts

Advanced thermal processing approaches
Integrated manufacturing methods

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

DRAFT

AMM Techniques



Materials

Courtesy Subhashish Meher

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

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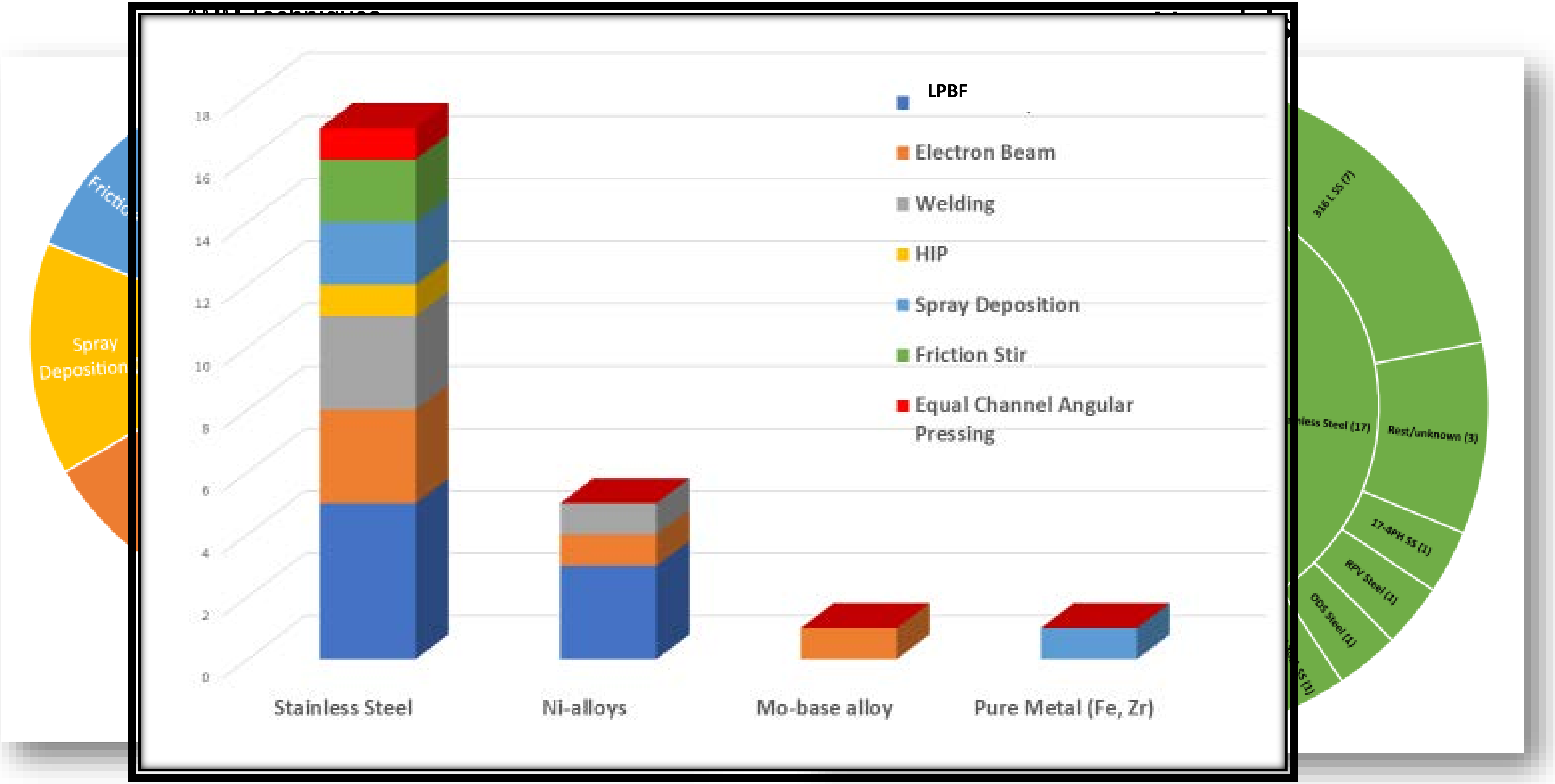
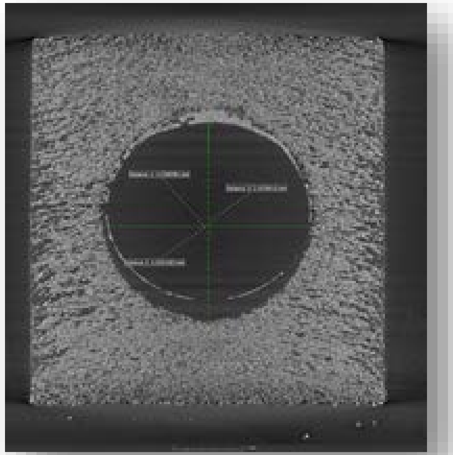


Courtesy Subhashish Meher

Gaps or Technology Challenges

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

- Performance data in “nuclear” environments
- How do we measure or gauge applications of new advanced manufacturing methods?
  - Technology readiness level
  - Qualification routes
  - Standards/Codes
  - Risks
- Determining requirement & performance specifications for different manufacturing process domains
- How do we measure & communicate the impact of our research (especially earlier TRL)?
- Cybersecurity in:
  - Digital Engineering
  - Machine Learning approaches
  - Big Data/Artificial Intelligence Applications
  - Automated Manufacturing
  - In-situ monitoring
  - Embedded sensor



High Impact Materials & Manufacturing Technology Challenges

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

CURRENT AMM NEET PROJECTS

HIP Cladding and Joining to Manufacture Large Dissimilar Metal Structures for Modular and GEN IV Reactors *(Project awarded FY 21)*	Xiaoyuan Lou *Auburn University*
Fiber Sensor Fused Additive Manufacturing for Smart Component Fabrication for Nuclear Energy *(Project awarded FY 21)*	Kevin Chen *University of Pittsburgh*
Diffuse Field Ultrasonics for In Situ Material Property Monitoring During Additive Manufacturing Using the SMART Platform *(Project awarded FY 21)*	Christopher M. Kube *Pennsylvania State University*
Machine Learning-based Processing of Thermal Tomography Images for Automated Quality Control of Additively Manufactured Stainless Steel and Inconel Structures	Alexander Heifetz *Argonne National Laboratory*
Development of Innovative Manufacturing Approach for Oxide-Dispersion Strengthened (ODS) Steel Cladding Tubes using a Low Temperature Spray Process	Kumar Sridharan *University of Wisconsin*
Integrated Computational Materials Engineering (ICME) and In-situ Process Monitoring for Rapid Qualification of Components Made by Laser-Based Powder Bed AM Processes for Nuclear Structural and Pressure Boundary Applications	David Gandy & Marc Albert *Electric Power Research Institute*
Integrating Dissolvable Supports, Topology Optimization, and Microstructure Design to Drastically Reduce Costs in Developing and Post-Processing Nuclear Plant Components Produced by Laser-based Powder Bed Additive Manufacturing	Albert To *University of Pittsburgh*
All-position Cladding by Friction Stir Additive Manufacturing	Zhili Feng *Oak Ridge National Lab*
Laser Additive Manufacturing of Grade 91 Steel for Affordable Nuclear Reactor Components	Stuart Maloy *Los Alamos National Lab*

Additive Manufacturing Projects – Code Case

Integrated Computational Materials Engineering & In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder bed Additive Manufacturing Processes for Nuclear Structural

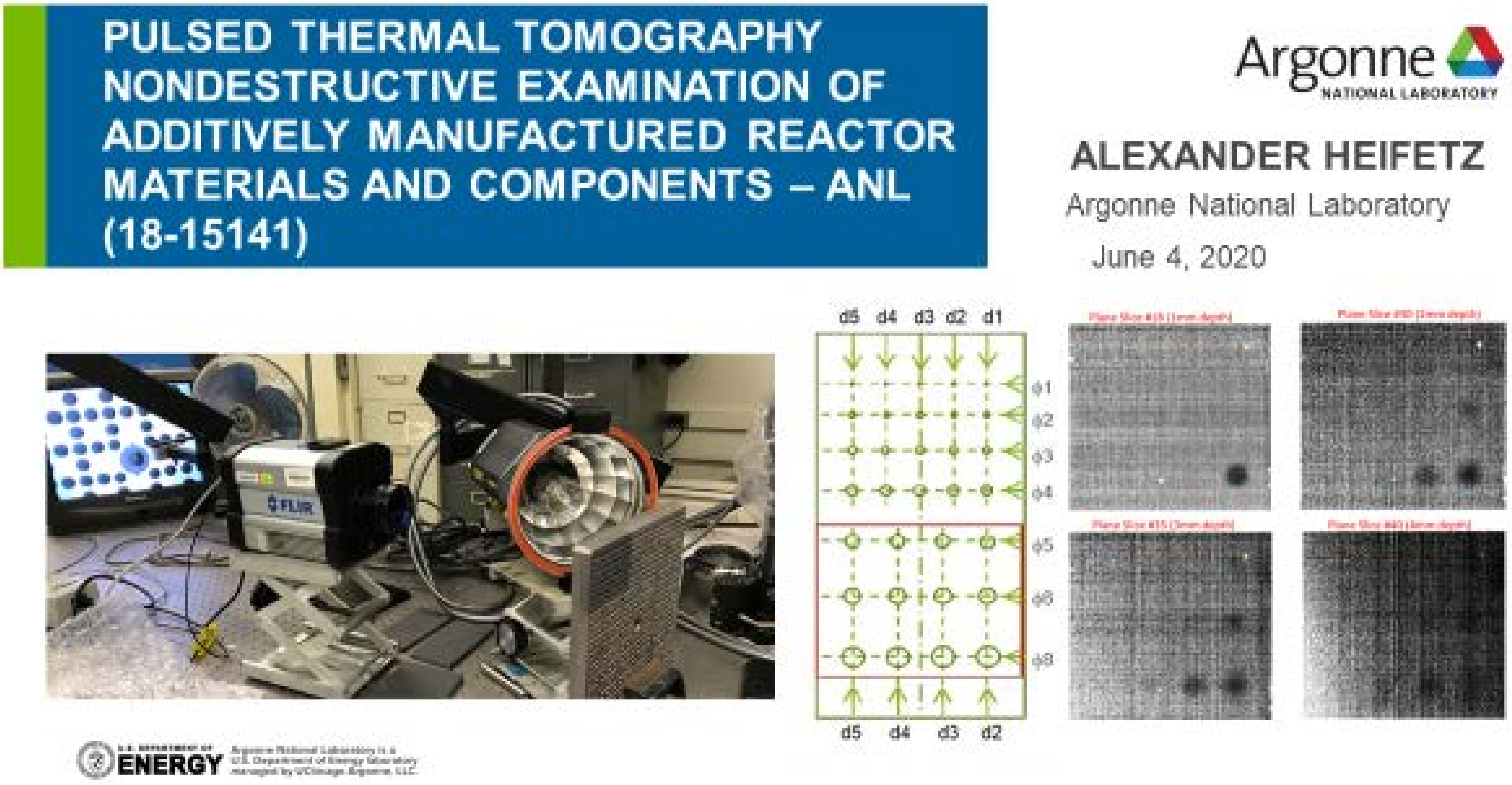
Award Number: DE-NE0008521
Award Dates : 10/2016 to 06/2020
PI: David Gandy
Team Members: ORNL, Westinghouse, Rolls-Royce

Figure 1a. A 316L SS Pipe Tee fitting is being produced via LPB-AM.

Figure 1b. A 316L SS section of a valve body was produced via LPB-AM.

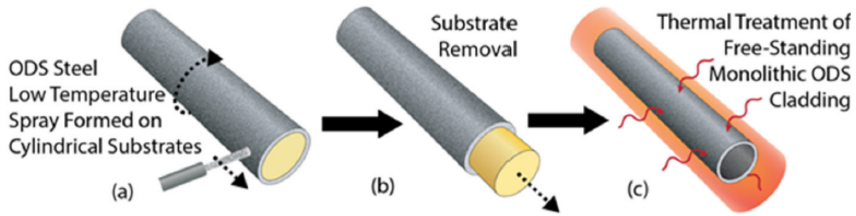
- Working with ASME Special Committee on Additive Manufacturing and BPV-III to develop and submit Data Package and Code Case (with Westinghouse)
  - ASME Special Committee has drafted Guideline document for AM welding of 316L SS.
- Data Package finalized
- **Code Case submitted August 2020**

Non-Destructive Testing



Development of Innovative Manufacturing Approach for ODS Steel Cladding Tubes using a Low Temperature Spray Process

Concept of Manufacturing ODS tube via Cold Spray Process – Three Major Steps



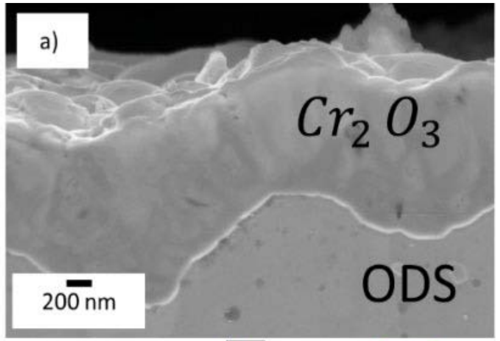
Potential Benefits:

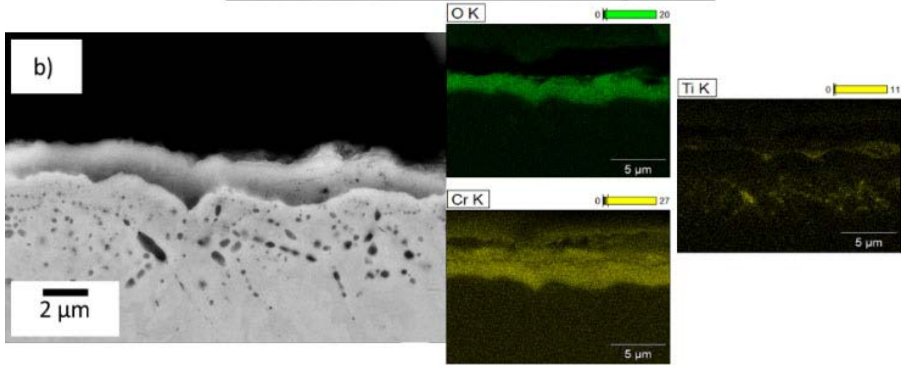
- **Eliminates multiple extrusion steps**
- **Eliminate ball milling step**
- **Faster and cheaper manufacturing process**

AMM TECHNICAL REVIEW MEETING (FY-20) DEC 2 – 3, 2020

ODS coated Al-alloy mandrel

Removal of Al-alloy mandrel





Kumar Sridharan
University of Wisconsin

CURRENT AMM INDUSTRY PROJECTS

IFOA Scope: Advanced manufacturing, fabrication and construction techniques for nuclear parts, components, and full-scale plants, or integrated efforts that could positively impact the domestic nuclear manufacturing enterprise

Representative Model of NuScale Power Reactor Vessel

Establishment of an Integrated Advanced Manufacturing and Data Science Driven Paradigm for Advanced Reactor Systems	Scott Shargots *BWXT*
Small Modular Reactor Pressure-vessel Manufacturing & Fabrication-technology Development (sole sourced)	David Gandy *Electric Power Research Institute*
EPRI: Modular In-Chamber Electron Beam Welding Capability (Large Thick Section Components)	David Gandy *Electric Power Research Institute*
Advancing and Commercializing Hybrid laser Arc Welding (HLAW) for Nuclear Vessel Fabrication, Including Small Modular Reactors (SMR)	Brian Farnsworth *Holtec Manufacturing*

SMR RPV Manufacturing & Fabrication Technology Development

SMR Reactor Pressure Vessel Manufacturing & Fabrication Technology Development – EPRI (10/01/2017 – 09/30/2021)

Overall industry goal is to produce a code-acceptable SMR Reactor Pressure Vessel (RPV) within 12 months

- 18-month schedule reduction
- 40% cost reduction

R&D project objective is to manufacture the major components for a 2/3 scale (44' long x 6' in diameter) NuScale RPV utilizing:

- Powder Metallurgy/ Hot Isostatic Processing (PM/HIP)
- Electron Beam Welding
- Diode Laser Cladding
- Cryogenic Machining

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

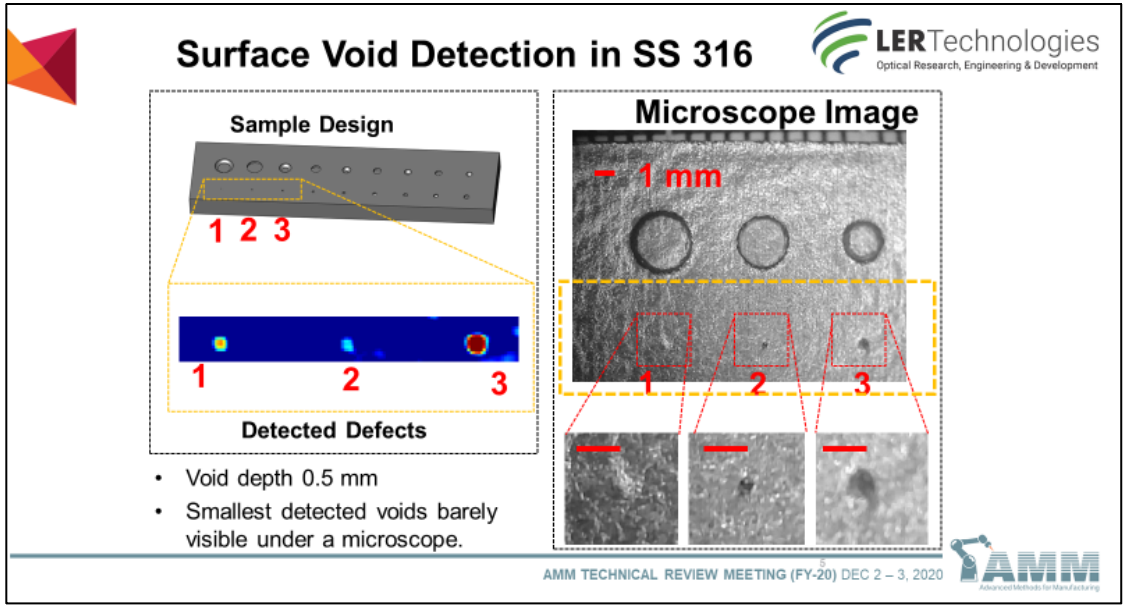
Representative Model of NuScale Power Reactor Vessel

Mockup EB weld of lower head

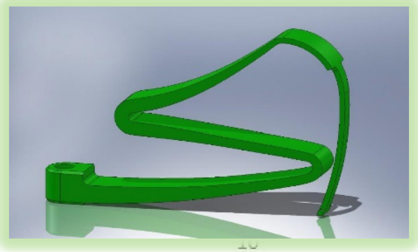
CURRENT AMM SBIR PROJECTS

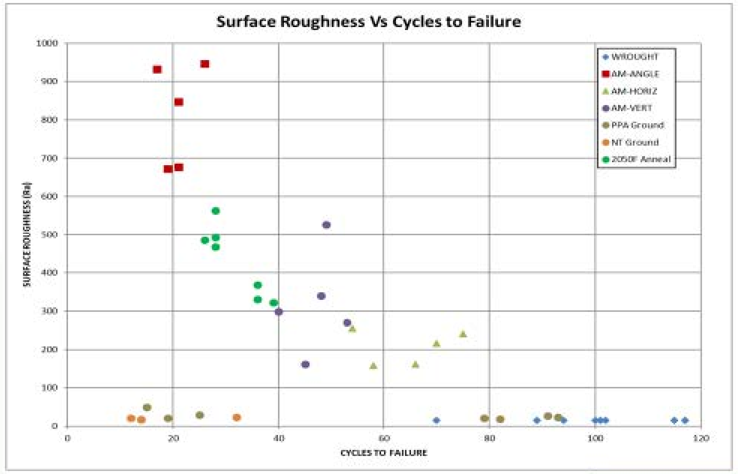
Real Time NDE During 3D Manufacturing	Araz Yacoubian *LER Technologies*
Additive Manufacturing of BWR Lower Tie Plates and other Fuel Assembly Components	Lauren Gramlich *Novatech*
Additive Manufacturing of SMR Holddown Springs and Upper Nozzle Interfaces	George Pabis *Novatech*

NovaTech printed Lower Tie plate concept E, Inconel & SS



NovaTech design for a hold down spring that takes advantage of the capability of AM to produce complex geometries





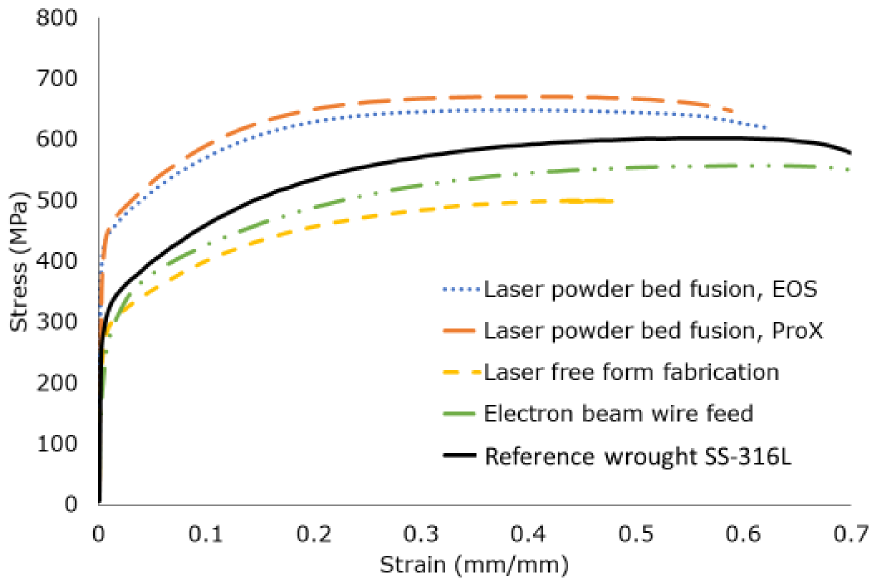
NOVATECH

CURRENT AMM NEET NSUF PROJECTS

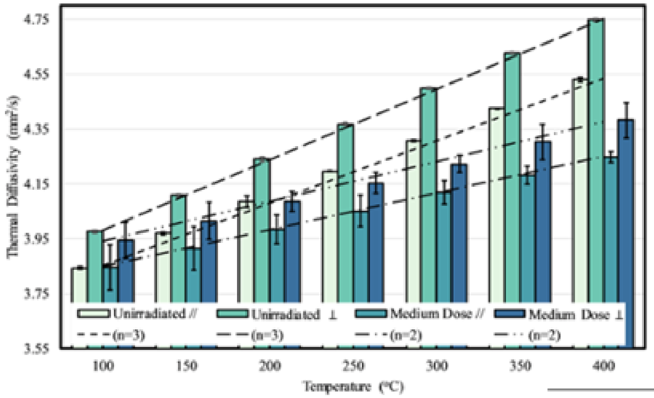
Project	PI
Irradiation Studies on Electron Beam Welded PM-HIP Pressure Vessel	Janelle Wharry *Purdue University*
Irradiation-Performance Testing of Specimens Produced by Commercially Available AM	Jeffrey King *Colorado School of Mines*
Nanodispersion Strengthened Metallic Composites with Enhanced Neutron Irradiation Tolerance	Ju Li *Massachusetts Institute of Technology*
Enhancing Irradiation Tolerance of Steels via Nanostructuring by Innovative Manufacturing Techniques	Mary Lou Dunzik-Gougar *Idaho State University* Haiming Wen *Missouri University of Science and Technology*
Performance of SiC-SiC Cladding and Endplug Joints under Neutron Irradiation with a Thermal Gradient (Recap of Project)	Christian Deck *General Atomics*
Irradiation Testing of Materials Produced by Additive Friction Stir Manufacturing (Recap of Project)	Chase Cox *Aeroprobe Corporation*

Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

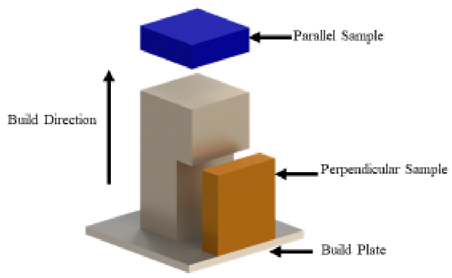
Mechanical Test Results (SS-316L)



Anisotropic Thermal Diffusivity?



SS-P2 (LPBF-vacuum)



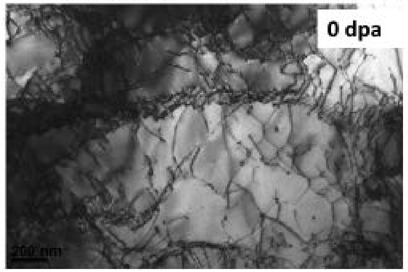
Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

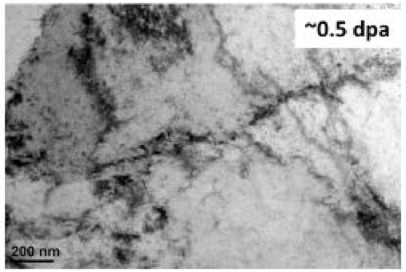
Temperature	Unirradiated SS-P1 (n=6) p-value	Unirradiated SS-P1 (n=6) t-value*	Unirradiated SS-P2 (n=6) p-value	Unirradiated SS-P2 (n=6) t-value*	Medium Dose SS-P2 (n=4) p-value	Medium Dose SS-P2 (n=4) t-value+	Unirradiated SS-P3 (n=6) p-value	Unirradiated SS-P3 (n=6) t-value*
100 °C	0.450	1.169	0.115	2.007	0.134	4.683	0.857	0.197
150 °C	0.453	1.161	0.115	2.009	0.029	5.754	0.323	1.126
200 °C	0.459	1.137	0.115	2.005	0.136	4.617	0.288	1.223
250 °C	0.455	1.152	0.078	2.359	0.042	4.733	0.108	2.065
300 °C	0.451	1.167	0.062	2.568	0.152	4.108	0.106	2.289
350 °C	0.453	1.162	0.061	2.581	0.016	7.776	0.087	2.508
400 °C	0.454	1.155	0.070	2.458	0.038	16.574	0.090	2.469

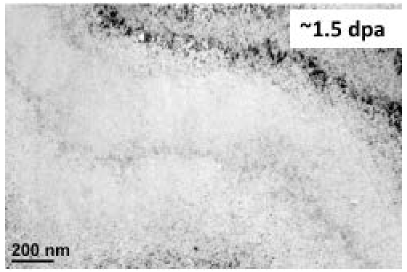
*T-critical=1.728 (DOF=2, α=0.159)
+T-critical=1.833 (DOF=1, α=0.159)

Initial Post-Irradiation TEM Results

SS-P2 (Laser Powder Bed Fusion SS-316L)

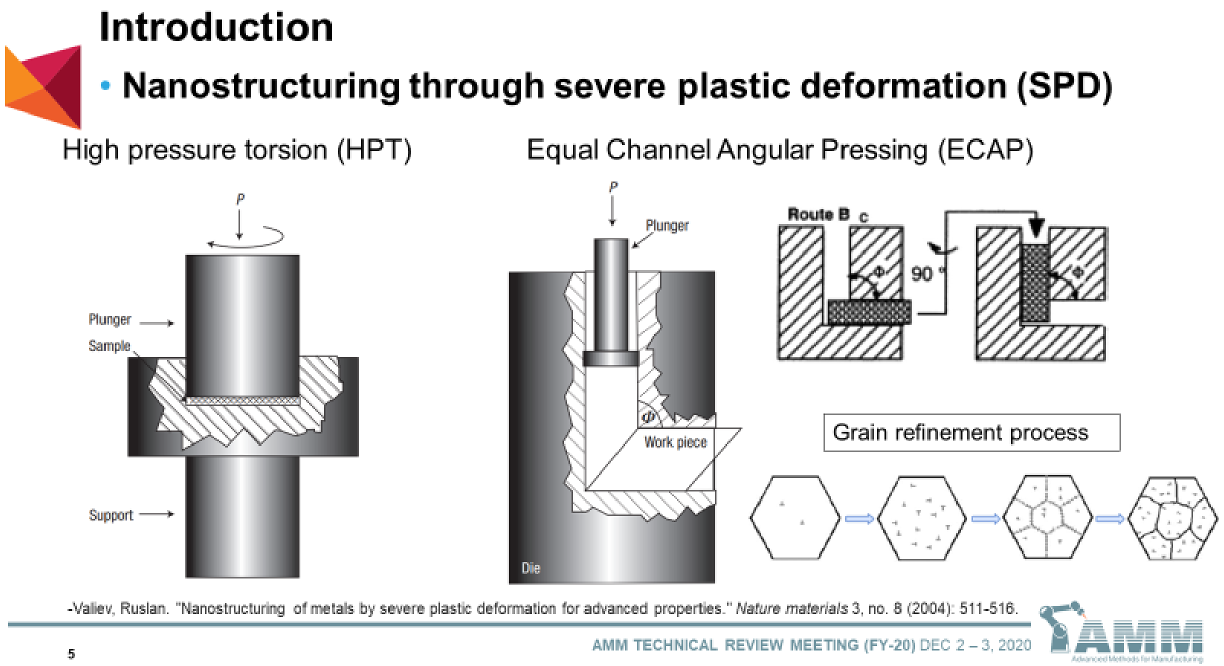


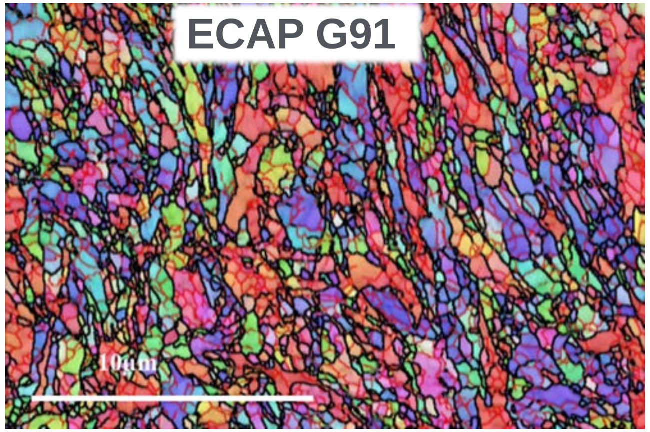


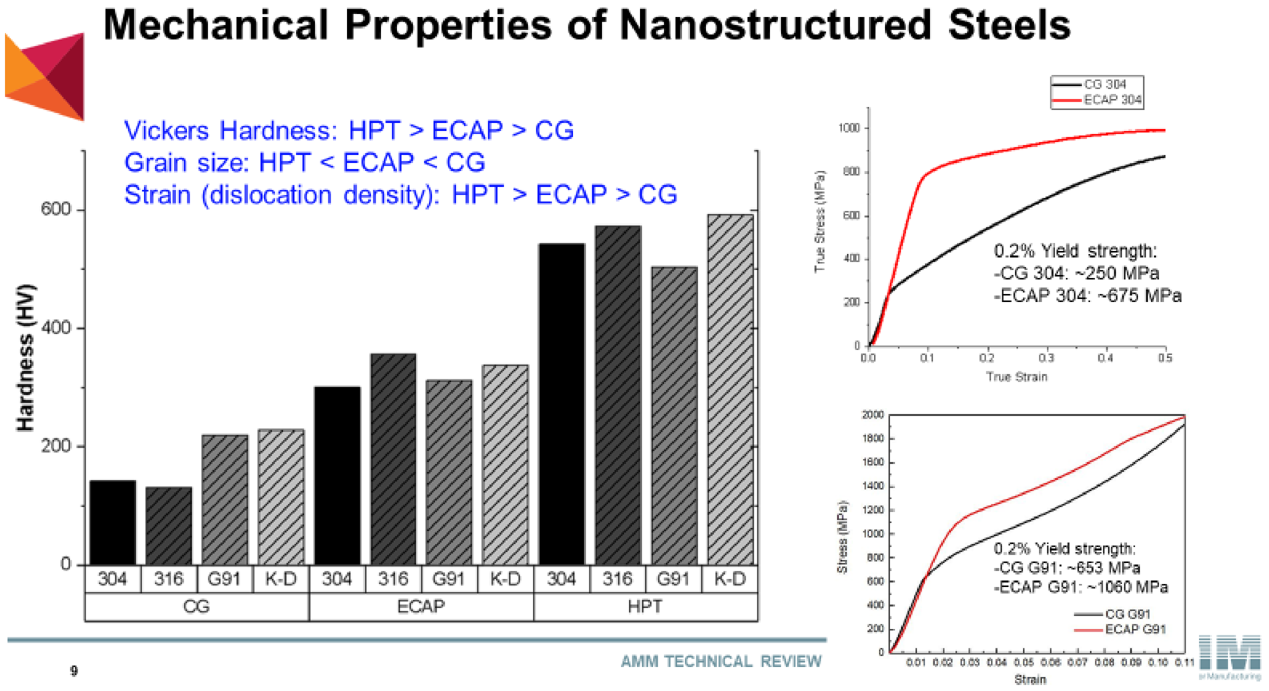


Jeffrey King
Colorado School of Mines

Enhancing irradiation tolerance of steels via nanostructuring by innovative manufacturing techniques



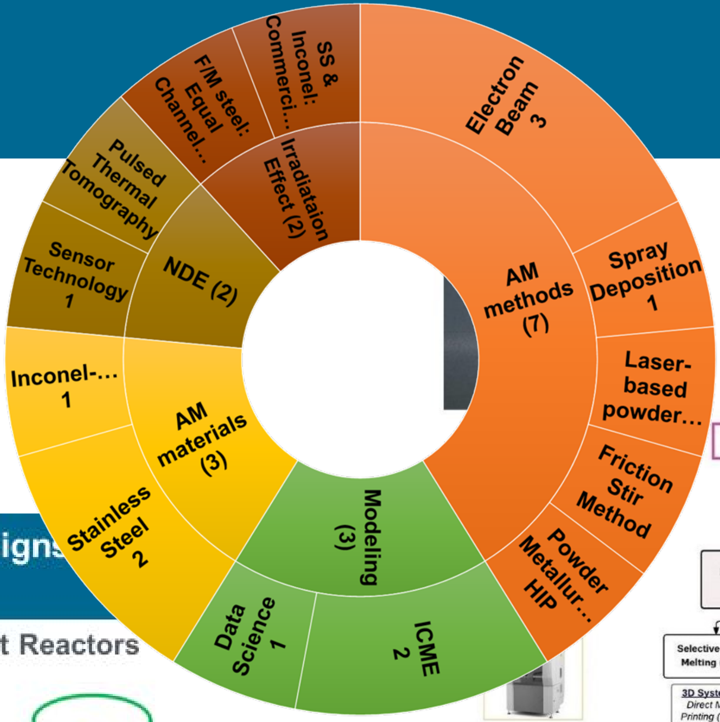


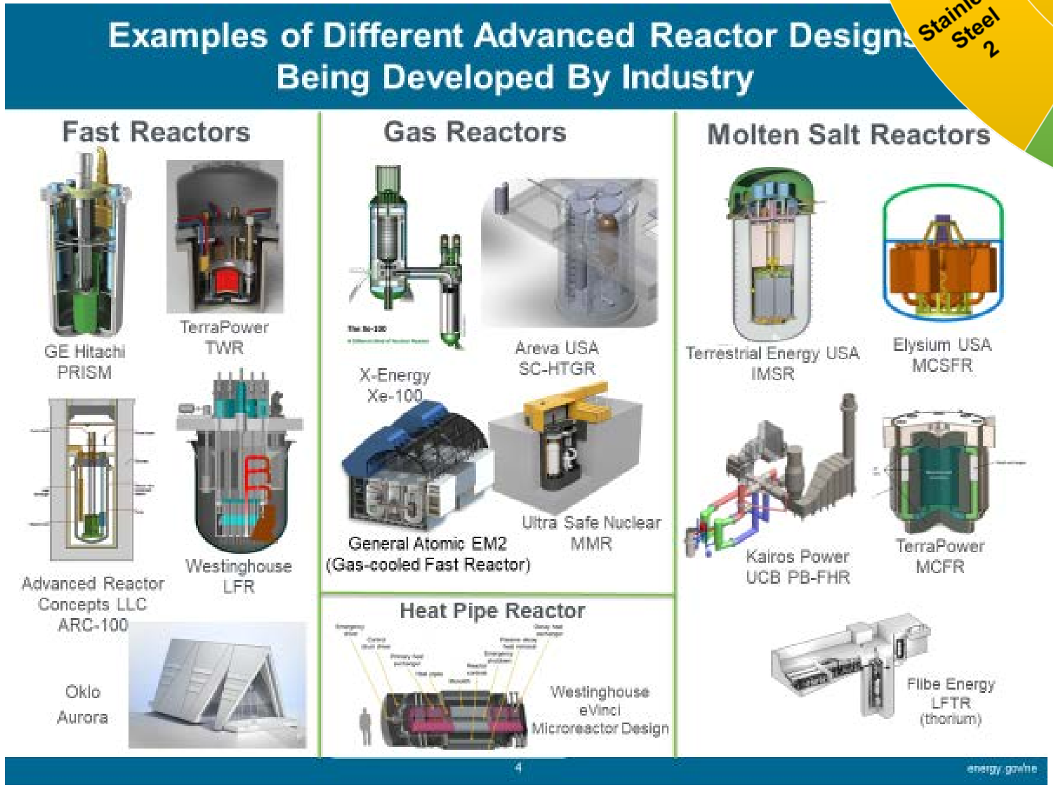


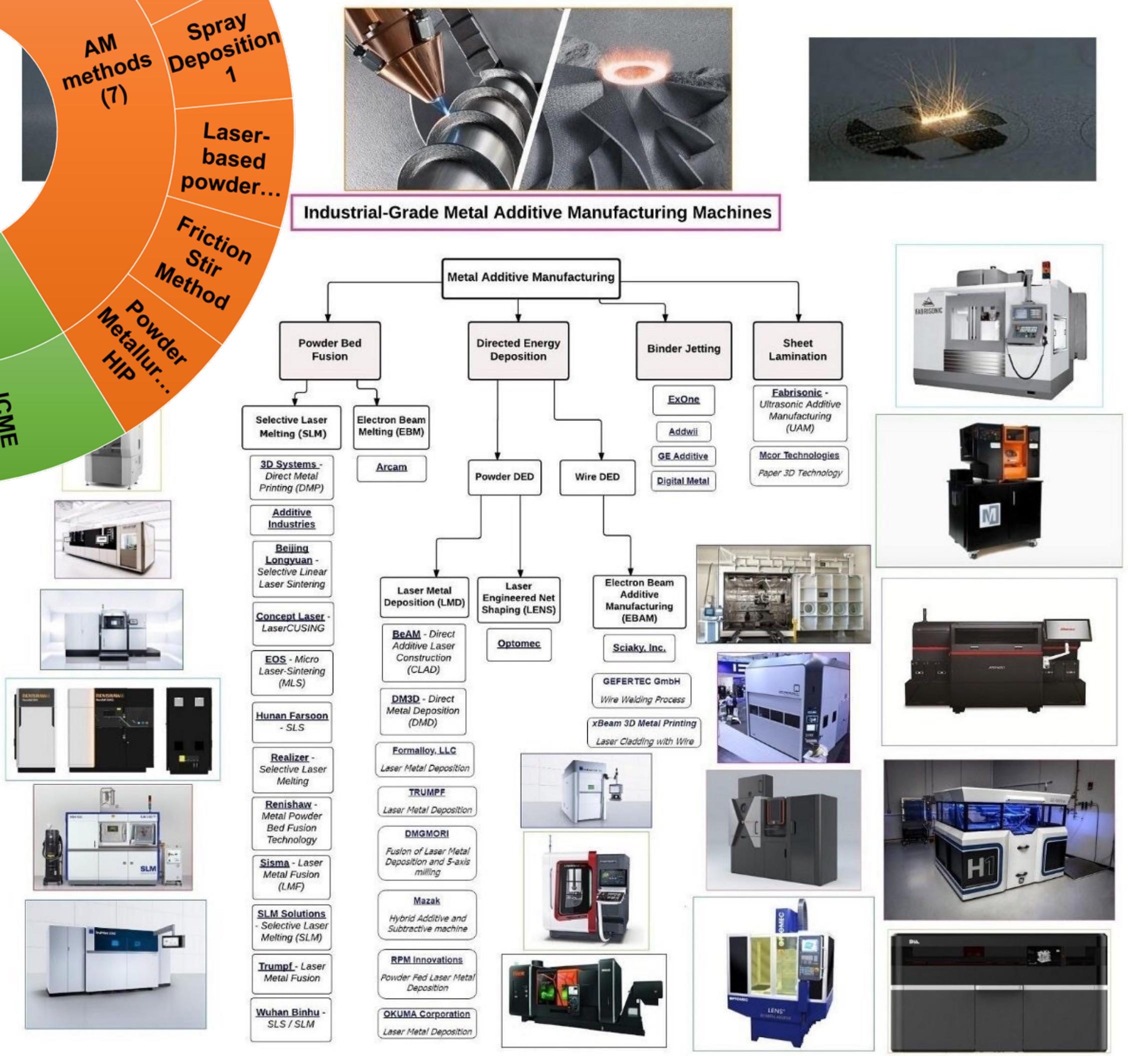
Haiming Wen (Missouri S&T)

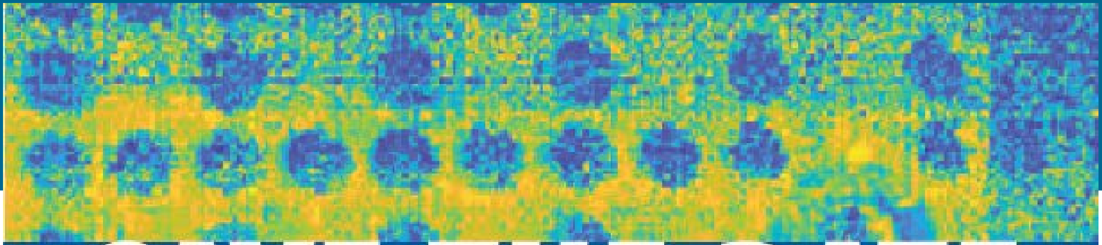
What Next?

Update Strategic Plan
Mining previous awards
Implement FY21 priorities









SAVE THE DATE

GAIN-EPRI-NEI Advanced Methods for Manufacturing QUALIFICATION WORKSHOP

AMM Advanced Methods for Manufacturing

AUGUST 24-26, 2021

INL Meeting Center, 775 MK Simpson Blvd, Idaho Falls, ID 83401

PURPOSE:

Develop an integrated approach to the AMM qualification process for materials and components and identify current blind spots.

OBJECTIVES:

- Understand current qualification processes
- Create novel approaches to process qualification
- Identify "what" industry needs in product, properties, and performance
- Identify areas in the AMM Supply Chain qualification that are lacking
- Identify possible synergistic qualification needs from industry through performance requirements
- Identify opportunities to shorten qualification by using AMM techniques
- Identify opportunities to reduce project cost by using AMM techniques

Check out the workshops tab at https://gain.inl.gov

GAIN Gateway for Accelerated Innovation in Nuclear | EPRI ELECTRIC POWER RESEARCH INSTITUTE | NEI NUCLEAR ENERGY INSTITUTE

FIRST NAME	LAST NAME	ORGANIZATION
Marc	Albert	EPRI/AMM
Marsha	Bala	INL/AMM Program
Lori	Braase	GAIN
Dirk	Cairns-Gallimore	DOE-NE
John	Carpenter	LANL/AMM Technical Team
Jason	Christensen	INL/AMM Regulatory
David	Gandy	EPRI/AMM
Ed	Herderick	OSU/AMM Technical Team
Ryan	deHoff	ORNL/Secure & Digital Manuf
Teresa	Krynicki	GAIN
Hillary	Lane	NEI/AMM
Kun	Mo	ANL/Adv Manuf
Everett	Redmond	NEI/GAIN
Sarah	Roberts	INL/AMM Support
Andrew	Sowder	EPRI/GAIN
Isabella	Van Rooyen	INL/AMM NTD
Ali	Zbib	PNNL/AMM Technical Team

Industry input on needs and qualification approaches will form the basis for the AMM Roadmap in 2021 and Implementation Plan.

Lori.braase@inl.gov Program Manager GAIN

Contact Information

Dirk Cairns-Gallimore: AMM DOE federal program manager
dirk.cairns-gallimore@nuclear.energy.gov

Dr. Isabella van Rooyen: AMM program National Technical Director
Isabella.vanrooyen@inl.gov

For more program information, including recent publications:
www.energy.gov/ne

SMR Reactor Pressure Vessel (EPRI)
One-half lower head: Forge and electron bean weld

Questions?

Clean. Reliable. **Nuclear.**