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Opportunities for Generation-IV Reactor Designers through Advanced Manufacturing Techniques

Dr. Isabella J. van Rooyen, INL, USA

25 May 2021

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

NEA Nuclear Energy Agency

cea

Argonne NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

NATIONAL NUCLEAR LABORATORY

INL Idaho National Laboratory

NPS

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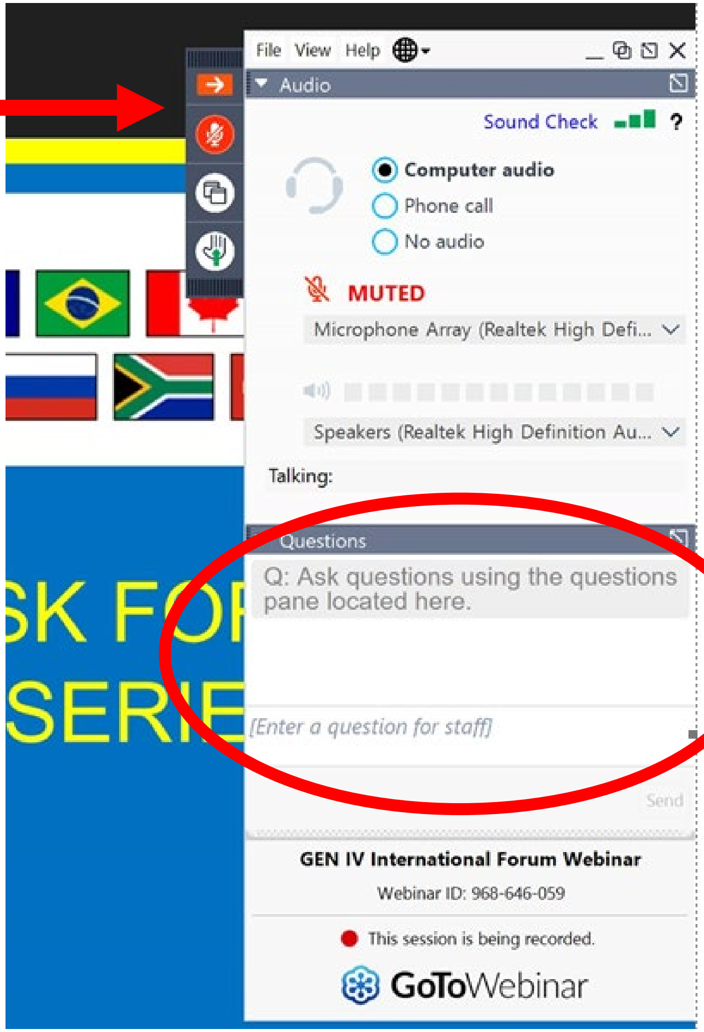

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INL/MIS-21-62874

Idaho National Laboratory

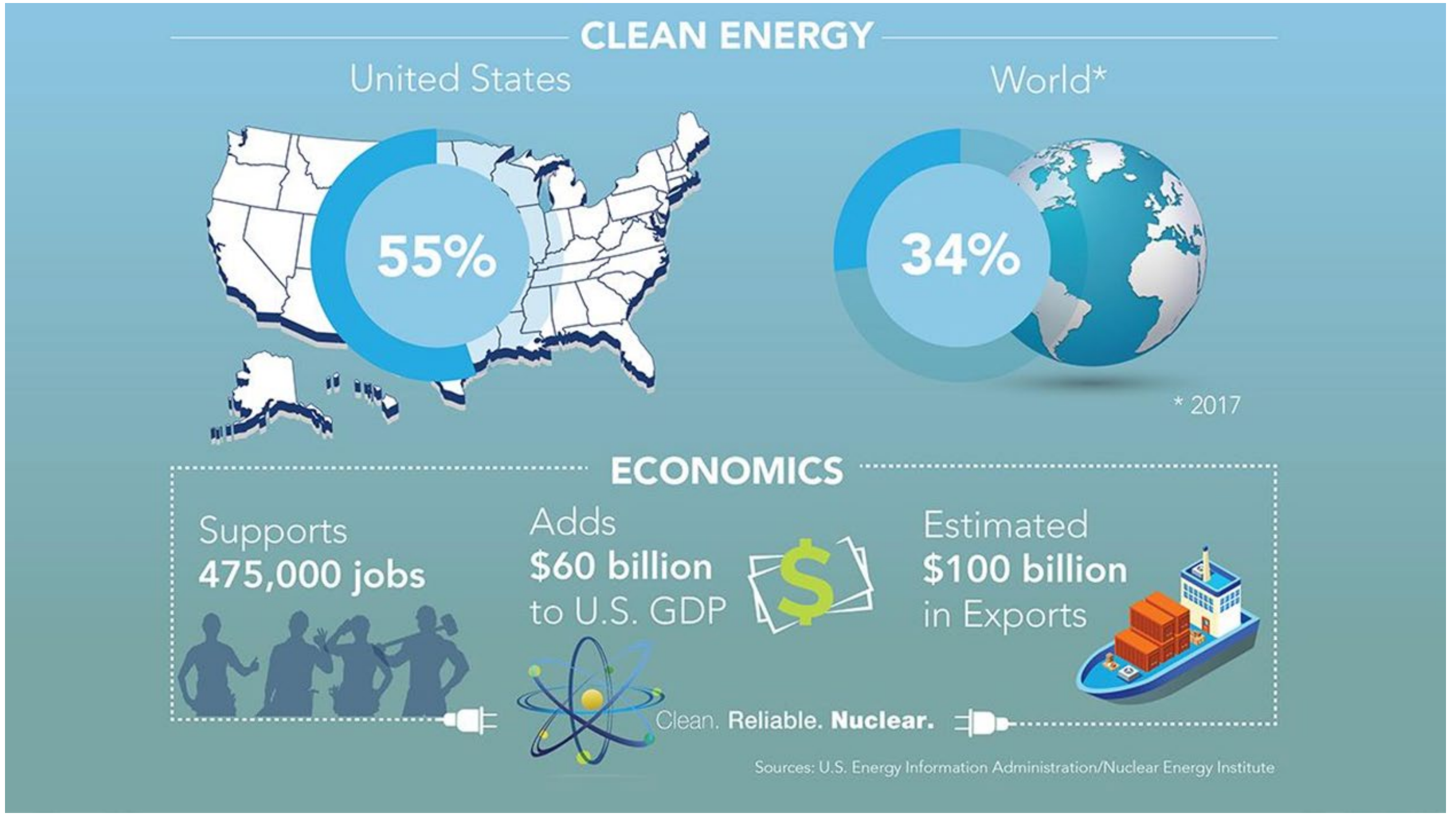
Meet the Presenter

Dr. Isabella J. van Rooyen holds a PhD in physics, an MSc in metallurgy, and an MBA. She is the National Technical Director for Advanced Methods for Manufacturing Programs for the Department of Energy-Nuclear Energy Enabling Technologies. She is also a distinguished staff scientist at the Idaho National Laboratory (INL) where she has led as principal investigator (PI) a variety of research projects for nuclear applications through competitive awards by industry strategic partners, lab-directed research funds, National Scientific User Facility (NSUF), and the Nuclear Engineering University Program (NEUP). These research projects focus on tristructural isotropic (TRISO)-coated particles, U3Si2, integrated fuel fabrication processes, high-temperature compact heat exchangers, SiC-ODS alloy gradient nano-composite cladding, fission product transport mechanisms, additive manufacturing qualification reviews, and advanced manufacturing methods. Dr. van Rooyen also led the advanced electron microscopy and micro-analysis examinations for the Advanced Gas Reactor TRISO fuel development program from May 2011–January 2021.

Dr. van Rooyen's engineering and scientific exposure includes hands-on experience in a wide variety of pursuits; examples include heat treatment, surface treatments and coatings, welding procedures, casting processes, powder fabrication, and consolidation processes. Prior to joining INL in 2011, Dr. van Rooyen held various technical leadership roles in the nuclear, aerospace, and automotive industries in South Africa, most notably the research at Pebble Bed Modular Reactor (PBMR) Company and NECSA and DENEL Aviation. Dr. van Rooyen has more than 50 peer-reviewed journal publications, more than 40 conference papers and presentations, over 100 company-specific technical and scientific reports, seven invention disclosures, one additive manufacturing patent awarded in 2020, one patent in process of issuing, and five patents filed on additive manufacturing in 2018–2020.

Email: isabella.vanrooyen@inl.gov

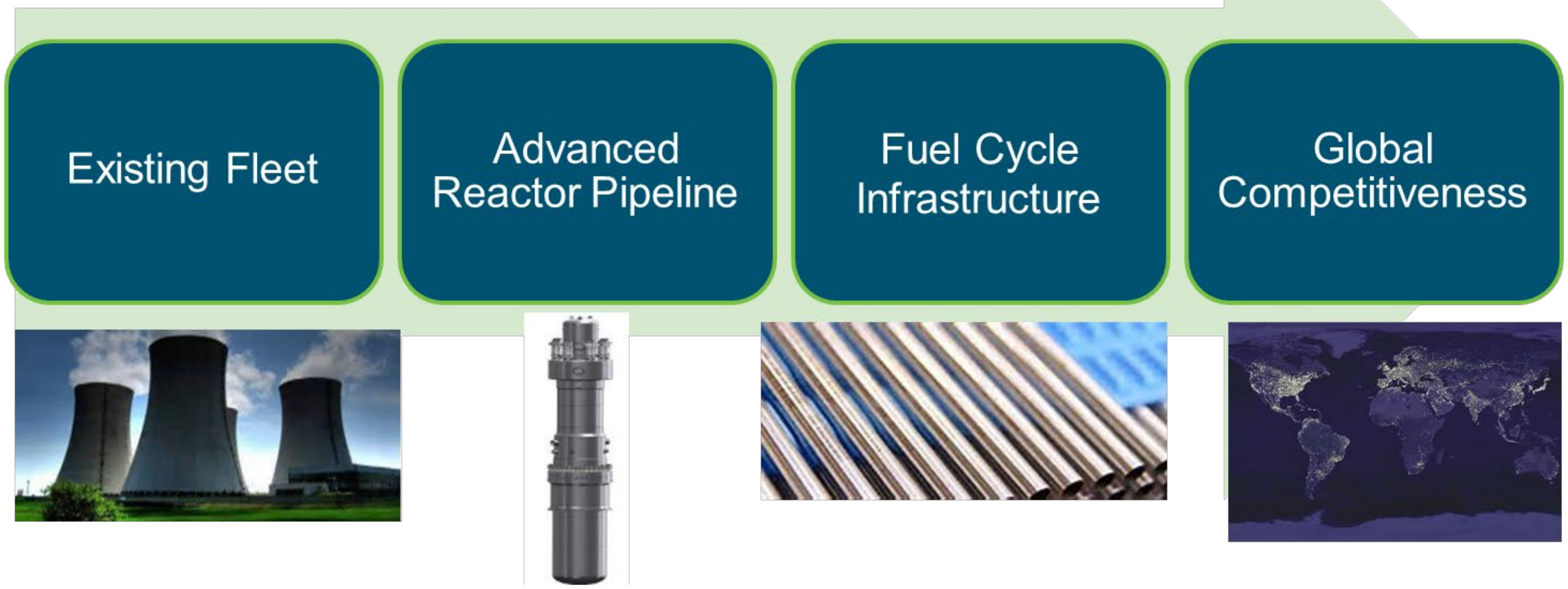
Nuclear at a Glance



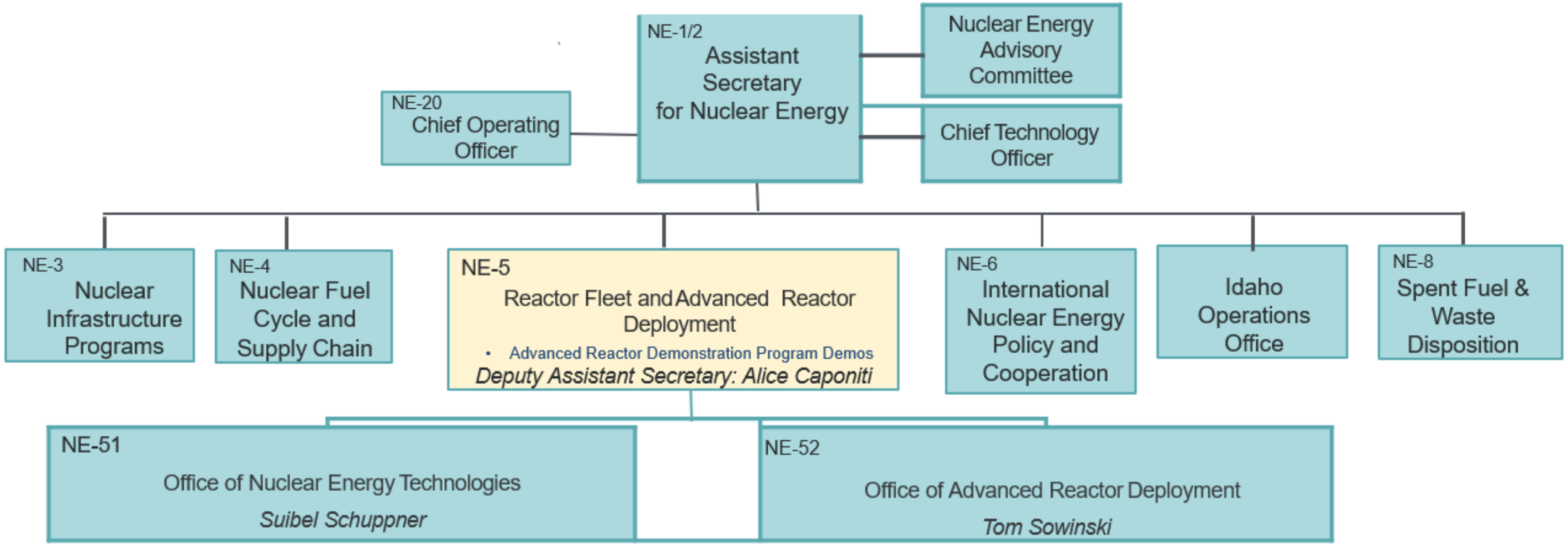
- From clean energy generation to economics, U.S. nuclear is definitely contributing to America’s energy mix and our GDP
- In this pandemic environment, nuclear reactors keep air clean; removing thousands of tons of harmful air pollutants that contribute to acid rain, smog, lung cancer and cardiovascular disease.

Office of Nuclear Energy: Mission Pillars

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



Office of Nuclear Energy



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

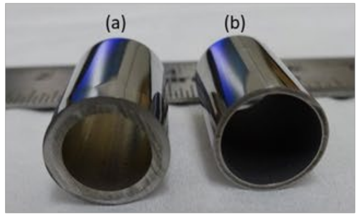
Advanced Methods for Manufacturing (AMM)

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

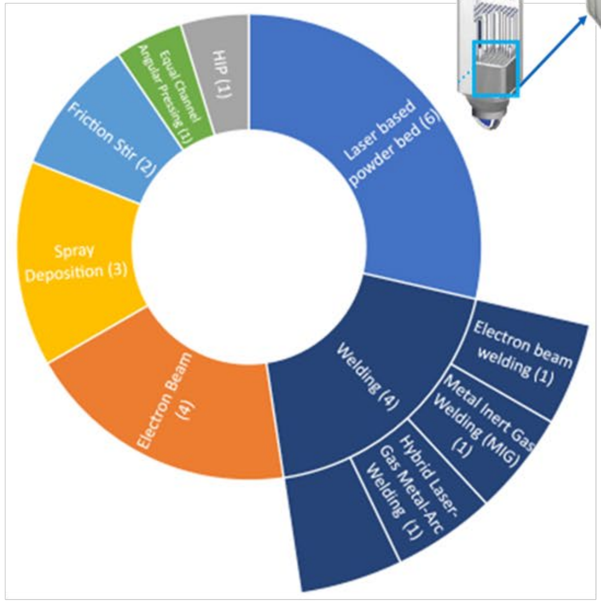
Goal

- 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

Technology Innovations for Fission Batteries: Fission Battery Webinar Series; February 24, 2021



GEH BWR fuel bundle w/debris filter insert

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

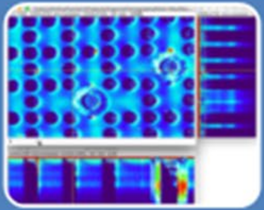
- Fabricated forgings
- Factory fabrication of piping systems
- PM-HIP

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



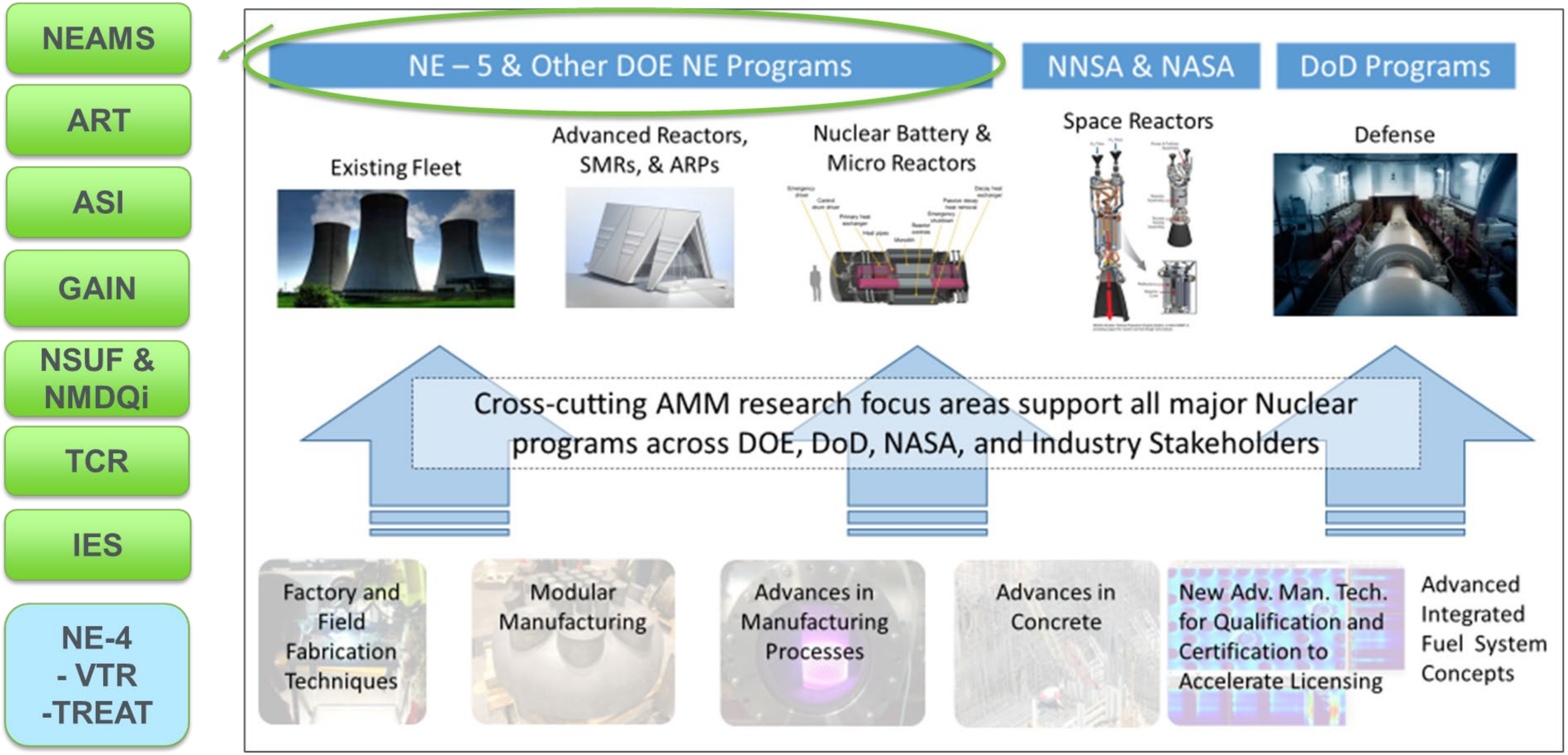
New Advanced Manufacturing Technologies for Qualification and Certification to Accelerate Licensing

- 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

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



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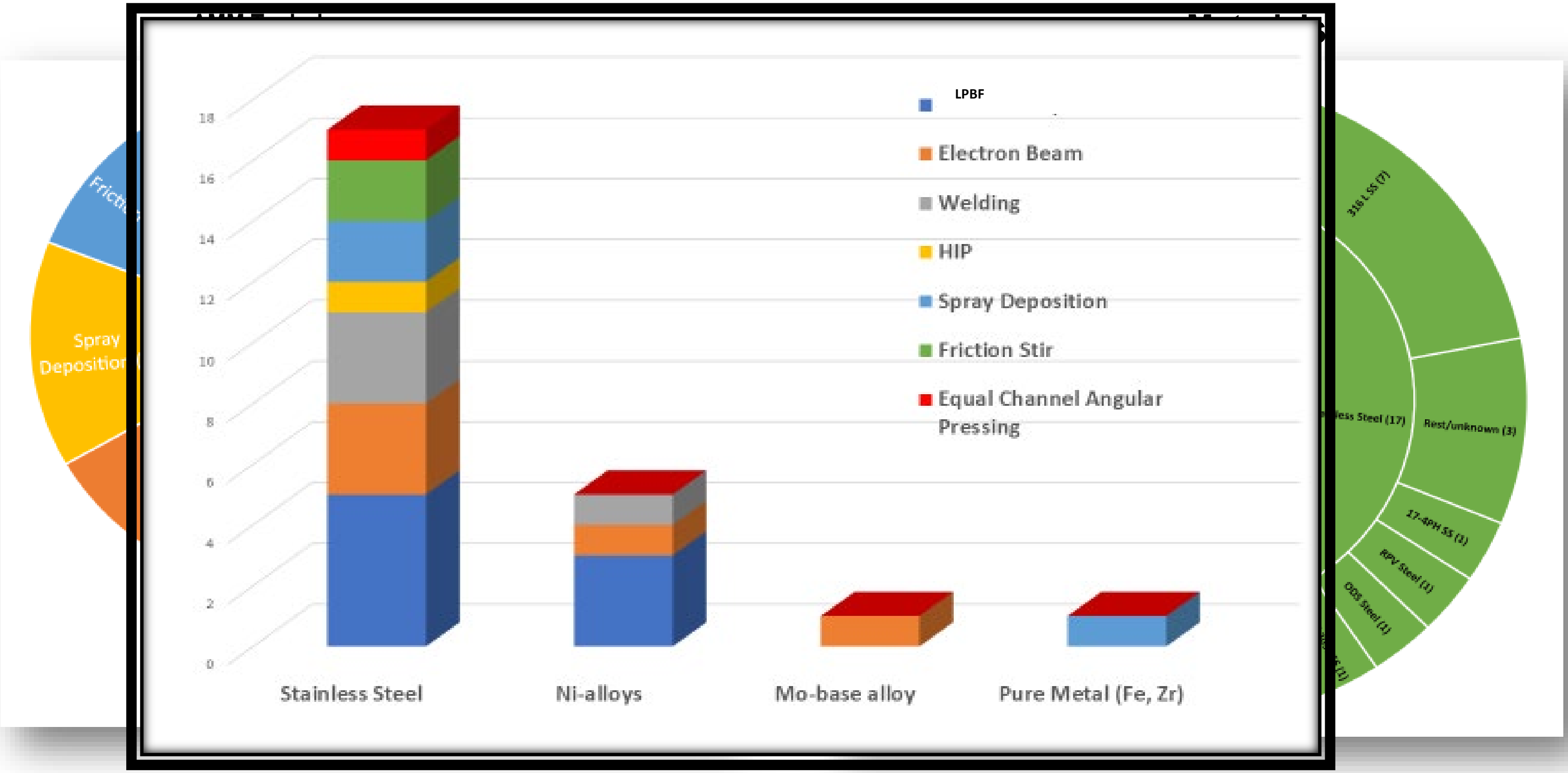
Evaluate AMM Program Award Impact
(NEET Awards 2011-2019)

DRAFT



Technology Innovations for Fission Batteries: Fission Battery Webinar Series; February 24, 2021

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-Gallimore
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

Publications

Conferences

E-mail contact list

Outreach Presentations

NEI Workgroups

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

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Additive Manufacturing Projects – Code Case

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

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

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

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

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

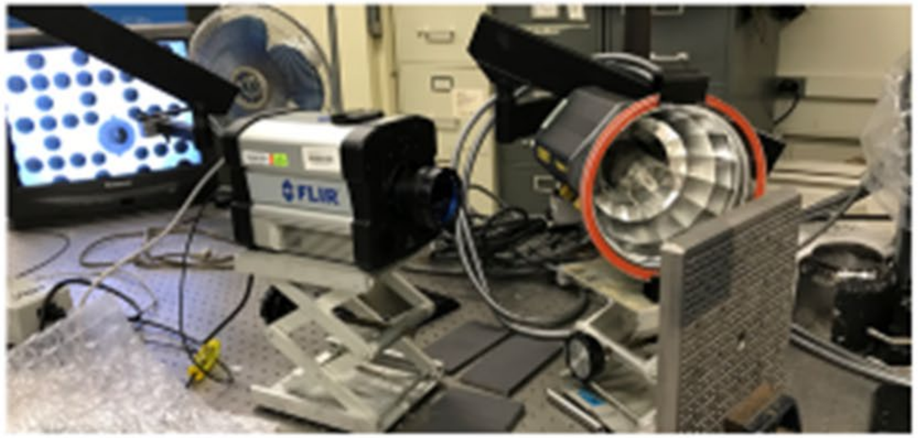
Non-Destructive Testing

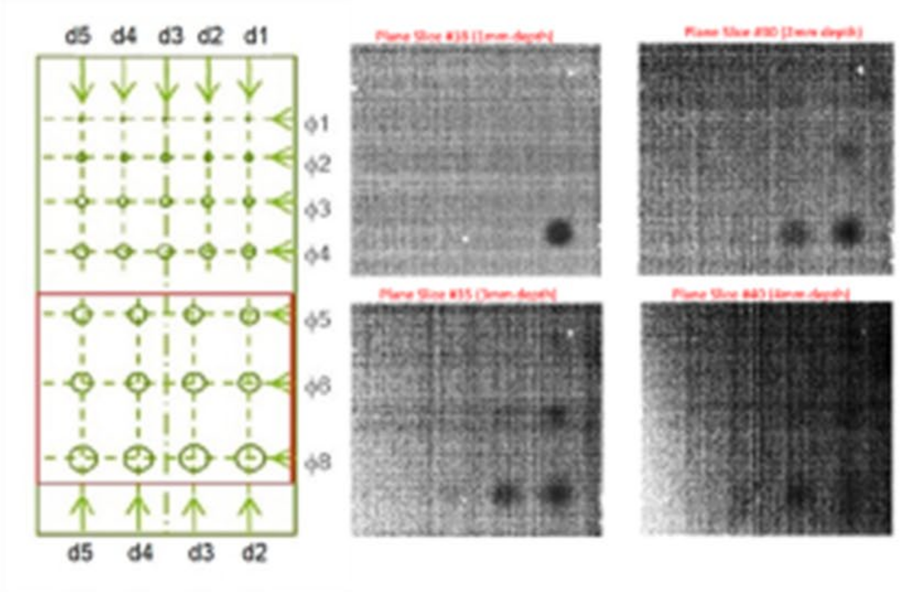
PULSED THERMAL TOMOGRAPHY NONDESTRUCTIVE EXAMINATION OF ADDITIVELY MANUFACTURED REACTOR MATERIALS AND COMPONENTS – ANL (18-15141)

Argonne NATIONAL LABORATORY

ALEXANDER HEIFETZ
Argonne National Laboratory

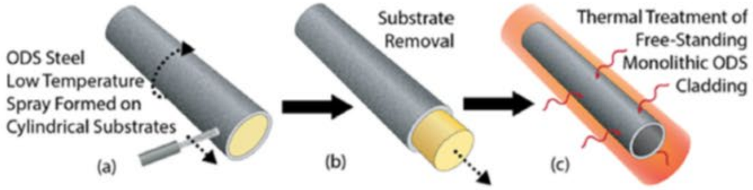
June 4, 2020





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

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

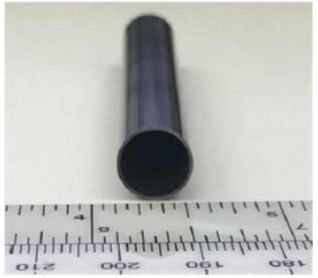


Potential Benefits:

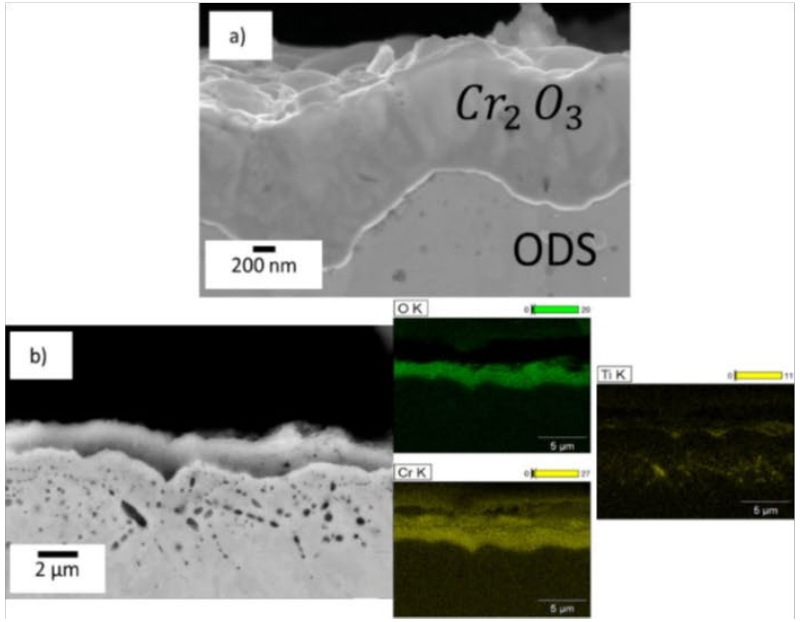
- Eliminates multiple extrusion steps
- Eliminate ball milling step
- Faster and cheaper manufacturing process

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

SMR RPV Manufacturing & Fabrication Technology Development

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

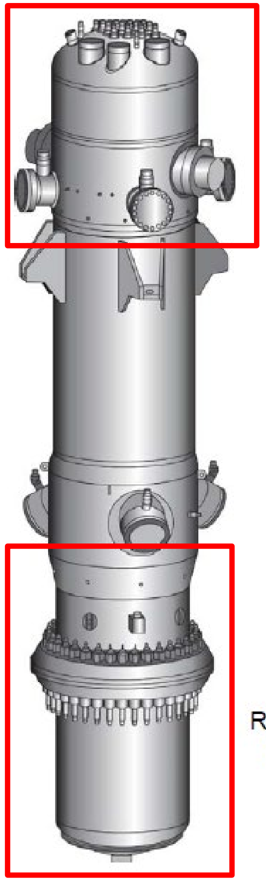
Overall industry goal is to produce a code-acceptable SMR Reactor Pressure Vessel (RPV) within 12 months

- 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

Examples: AMM SBIR PROJECTS

Real Time NDE During 3D Manufacturing

Araz Yacoubian
LER Technologies

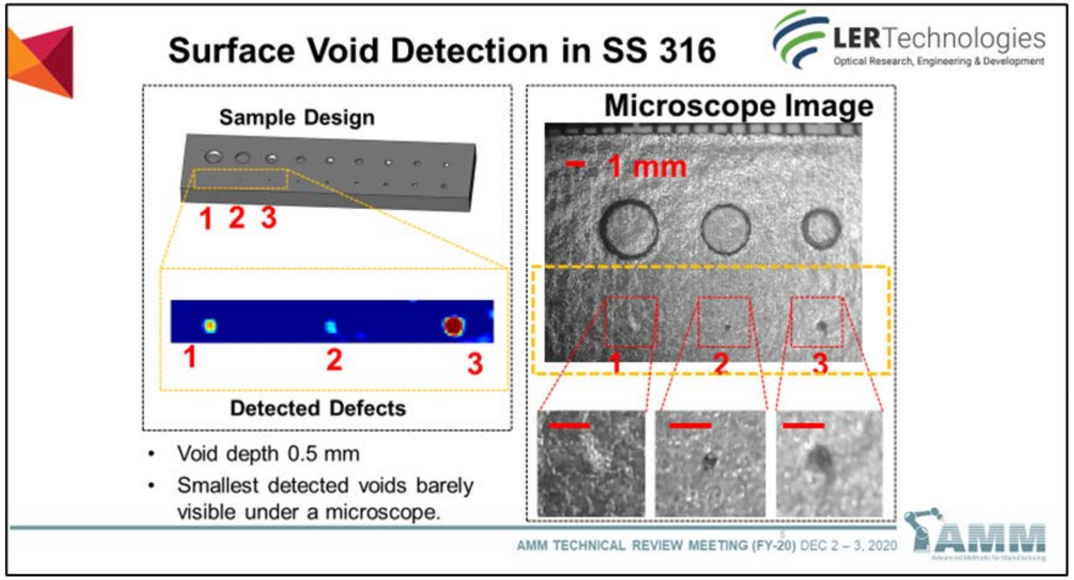
Additive Manufacturing of BWR Lower Tie Plates and other Fuel Assembly Components

Lauren Gramlich
Novatech

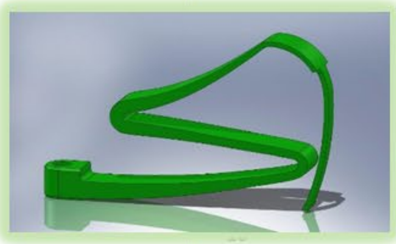
Additive Manufacturing of SMR Holddown Springs and Upper Nozzle Interfaces

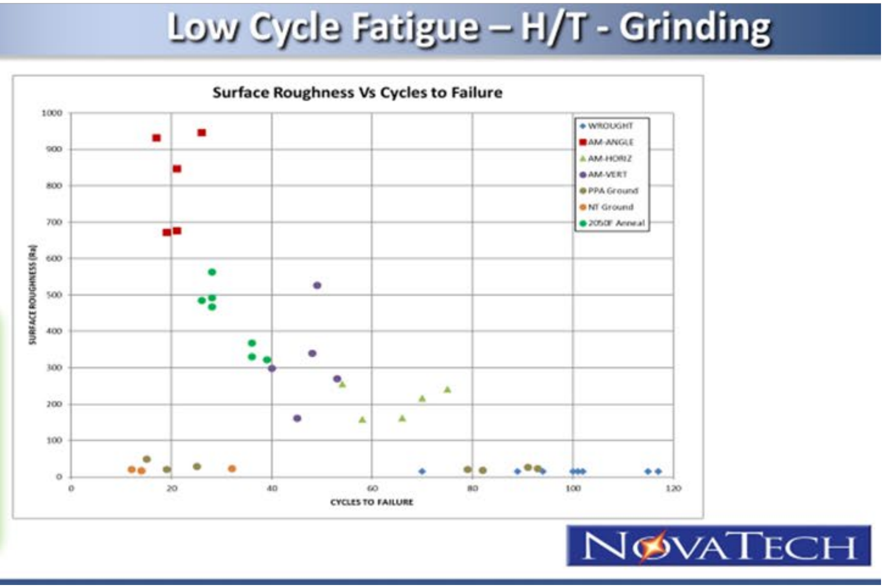
George Pabis
Novatech

NovaTech printed Lower Tie plate concept E, Inconel & SS



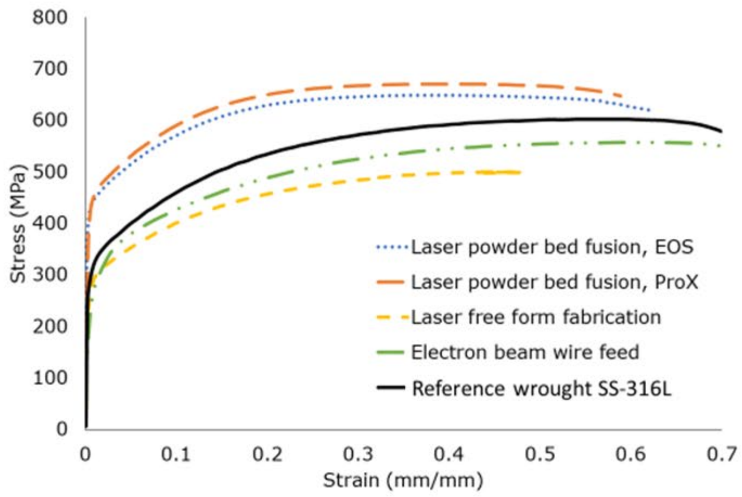
NovaTech design for a hold down spring that takes advantage of the capability of AM to produce complex geometries



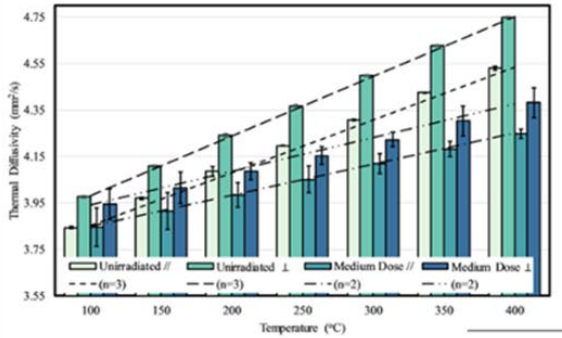


Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

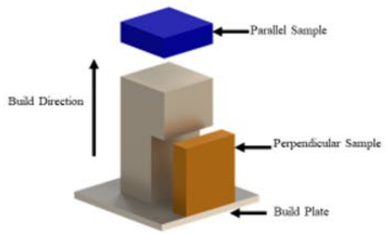
Mechanical Test Results (SS-316L)



Anisotropic Thermal Diffusivity?



SS-P2 (LPBF-vacuum)



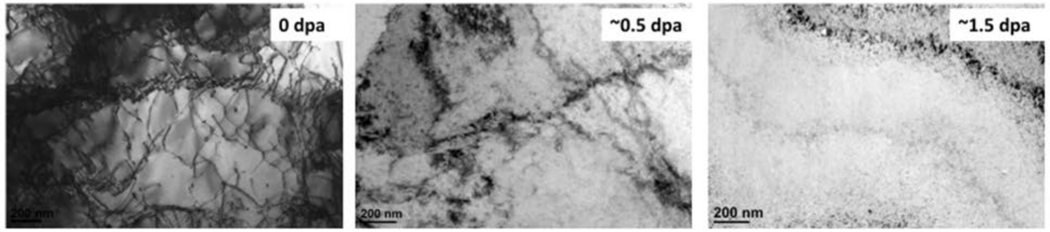
Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

	Unirradiated SS-P1 (n=6)		Unirradiated SS-P2 (n=6)		Medium Dose SS-P2 (n=4)		Unirradiated SS-P3 (n=6)	
Temperature	p-value	t-value*	p-value	t-value*	p-value	t-value*	p-value	t-value*
100 °C	0.450	1.169	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)



AMM NEET NSUF PROJECTS

Jeffrey King
Colorado School of Mines

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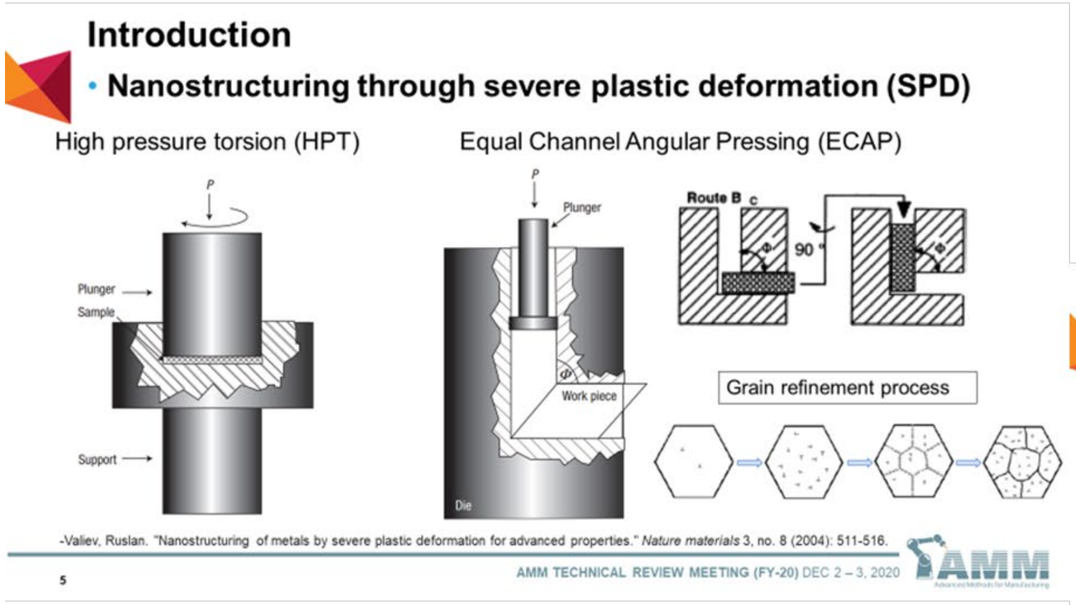
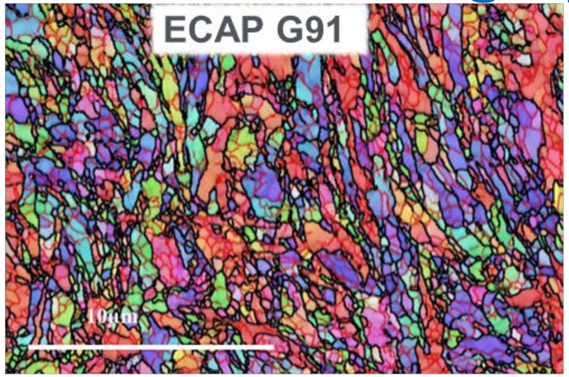
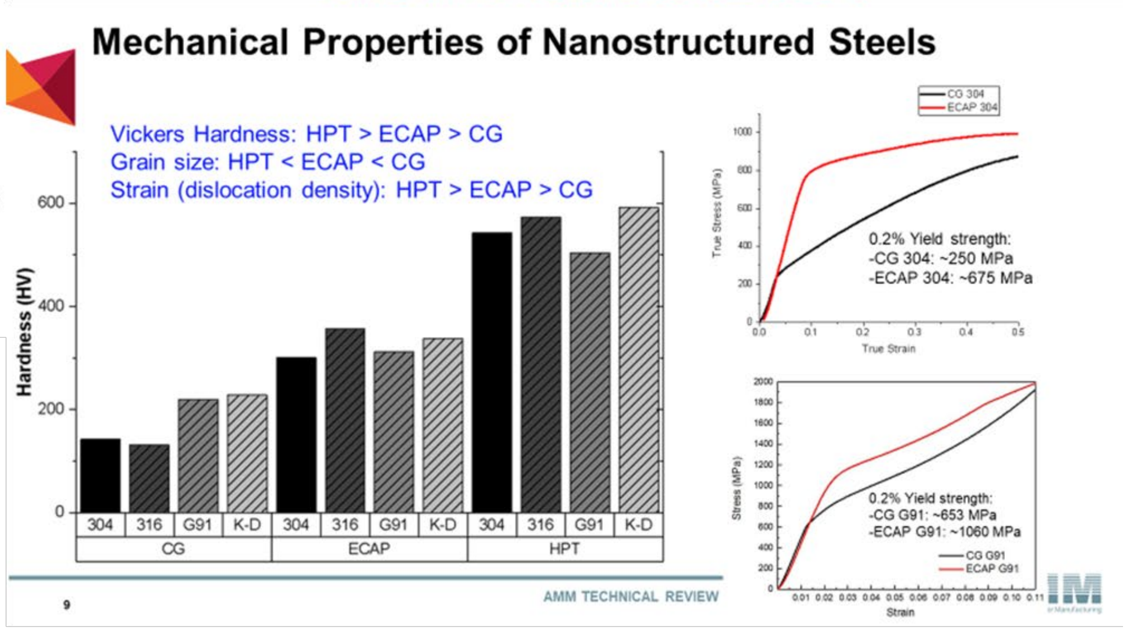
Enhancing irradiation tolerance of steels via nanostructuring by innovative manufacturing techniques





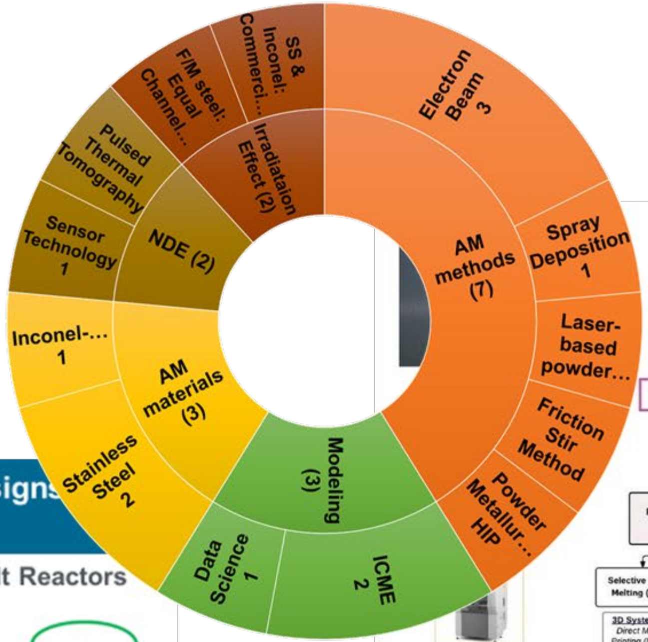


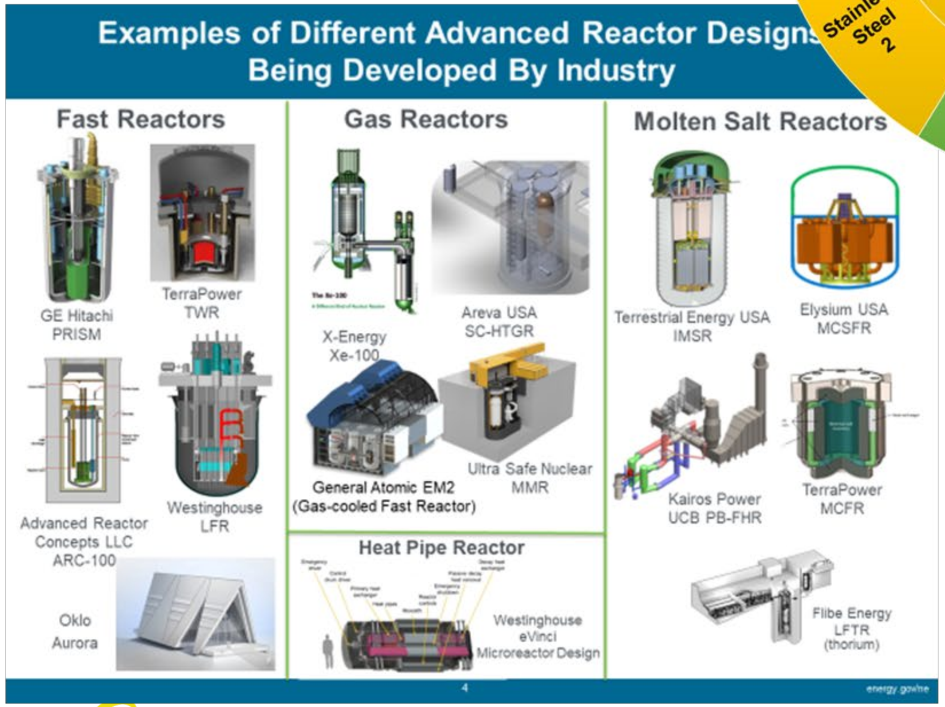
AMM NEET NSUF PROJECTS

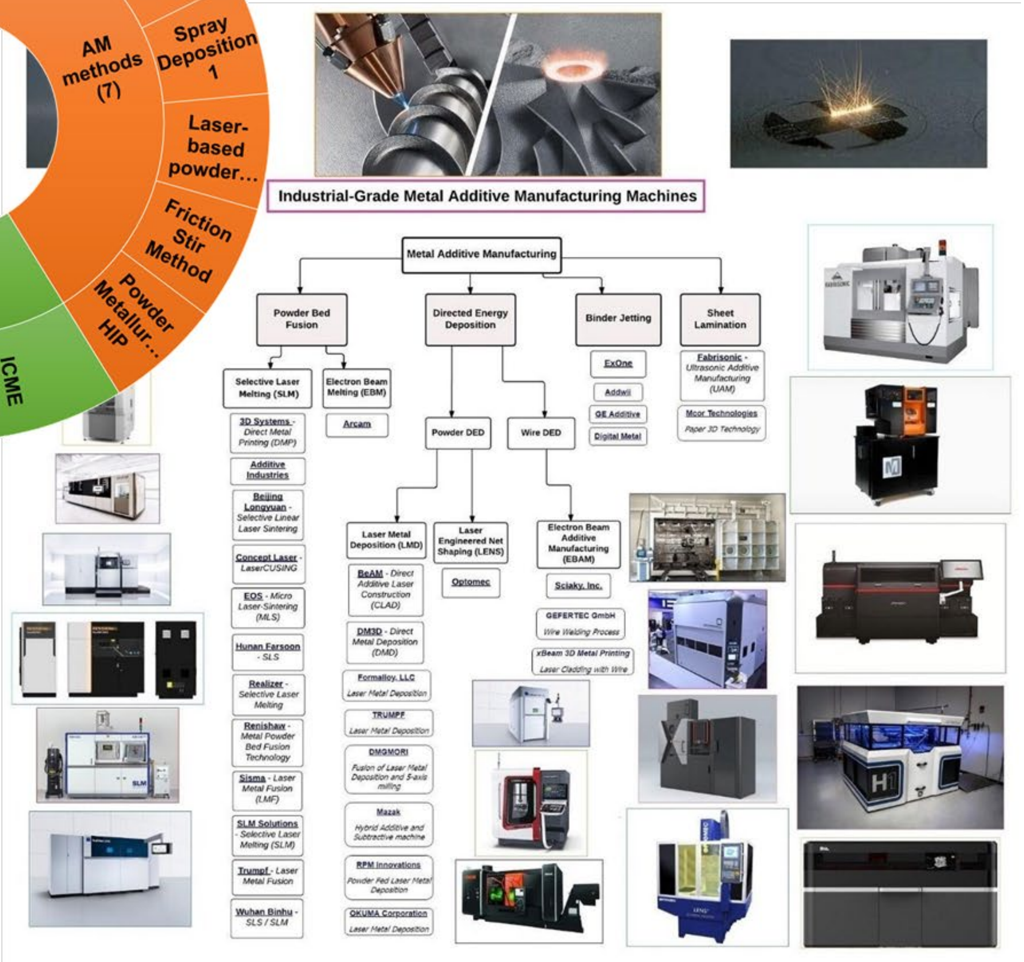
Haiming Wen (Missouri S&T)

What Next?

Update Strategic Plan
Mining previous awards
Implement FY21 priorities







Translate Challenges into Opportunities

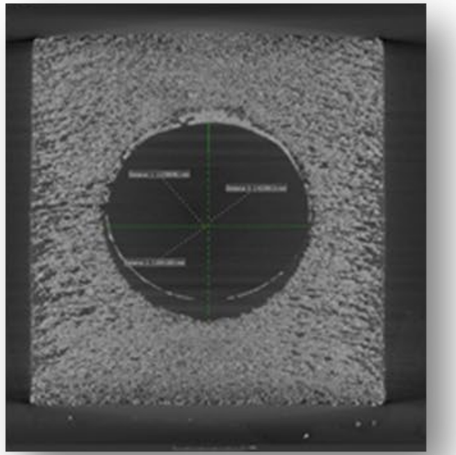
Strong research focus needed

- not only just solving individual / specific manufacturing technique and materials problems,
- identifying **strategic path forward in technologies**, capabilities or other resources that will broadly benefit application operating in harsh service conditions.

Gaps or Technology Challenges

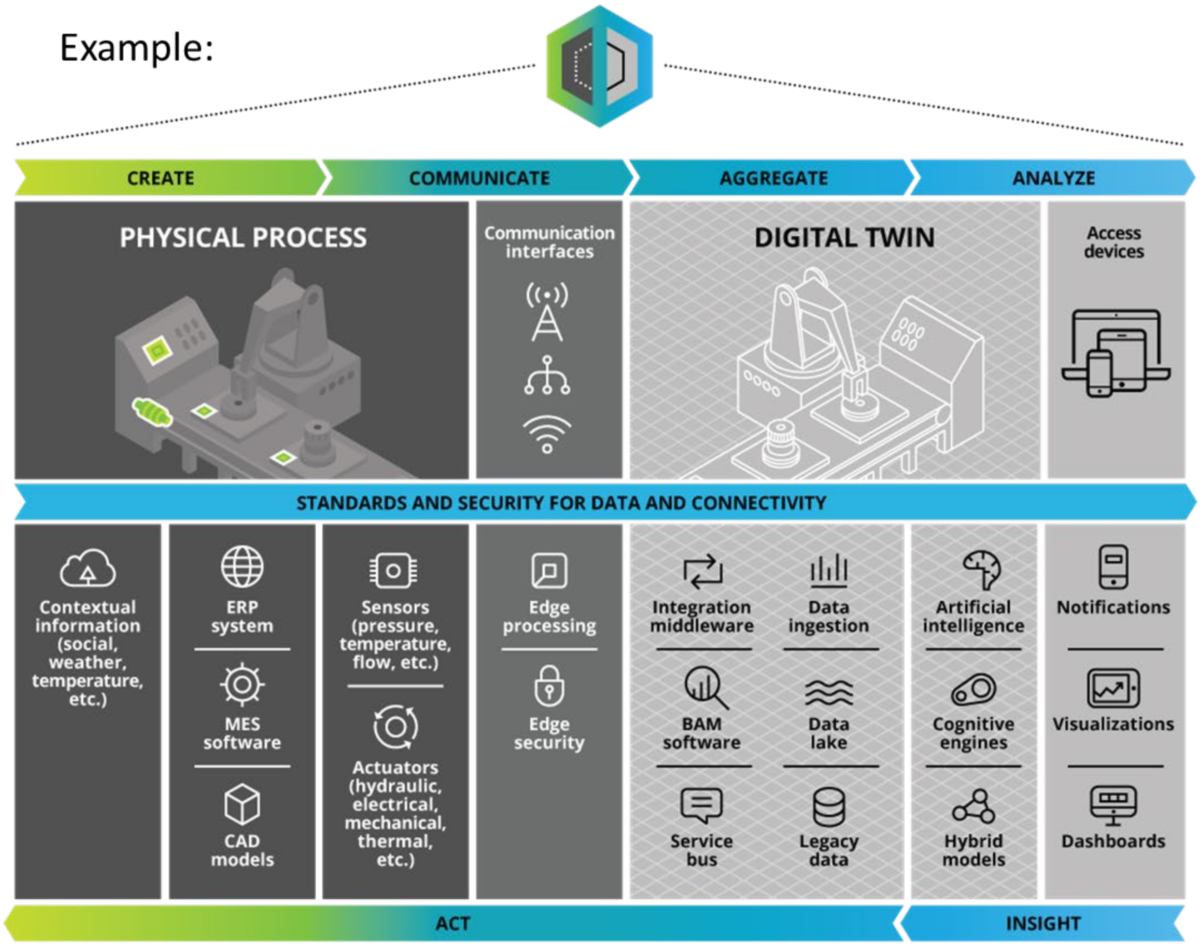
Prioritizing Methods and Materials
Complex set of needs
Risk reduction methods
Speed to industry deployment
Qualification Processes
Maturity Level

- 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



Manufacturing Process Digital-Twin Conceptual Architecture

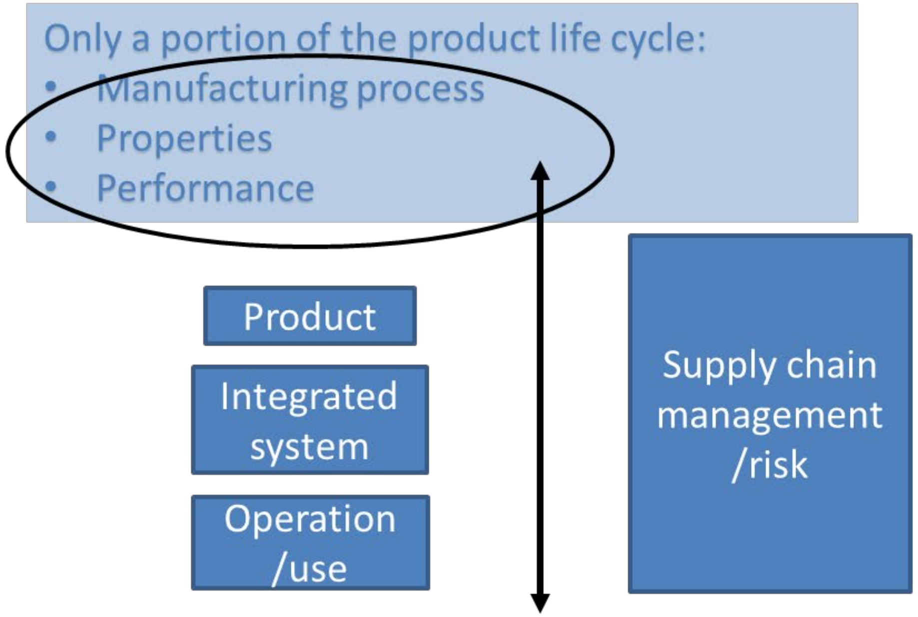
Example:



Source: Deloitte University Press.

Major challenge in undertaking a digital twin process:

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



Digital Twin Business Values

Category of business value	Potential specific business values
Quality	• Improve overall quality • Predict and detect quality trend defects sooner • Control quality escapes and be able to determine when quality issue started
Warranty cost and services	• Understand current configuration of equipment in the field to be able to service more efficiently • Proactively and more accurately determine warranty and claims issues to reduce overall warranty cost and improve customer experiences
Operations cost	• Improve product design and engineering change execution • Improve performance of manufacturing equipment • Reduce operations and process variability
Record retention and serialization	• Create a digital record of serialized parts and raw materials to better manage recalls and warranty claims and meet mandated tracking requirements
New product introduction cost and lead time	• Reduce the time to market for a new product • Reduce overall cost to produce new product • Better recognize long-lead-time components and impact to supply chain
Revenue growth opportunities	• Identify products in the field that are ready for upgrade • Improve efficiency and cost to service product

Source: Deloitte analysis

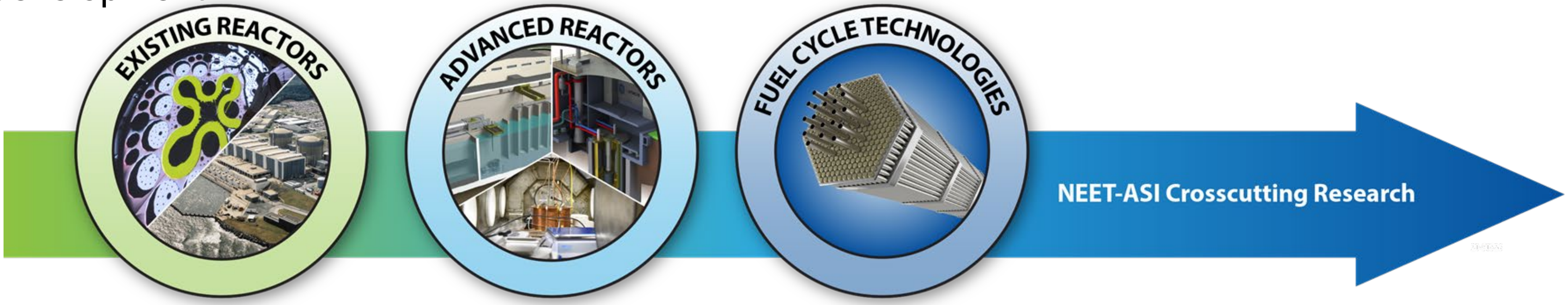
The Advanced Sensors and Instrumentation (ASI) program DOE NEET Crosscutting Technology Development

Mission

Develop **advanced sensors and I&C** that address **critical technology gaps** for monitoring and controlling existing and advanced **reactors** and supporting **fuel cycle** development

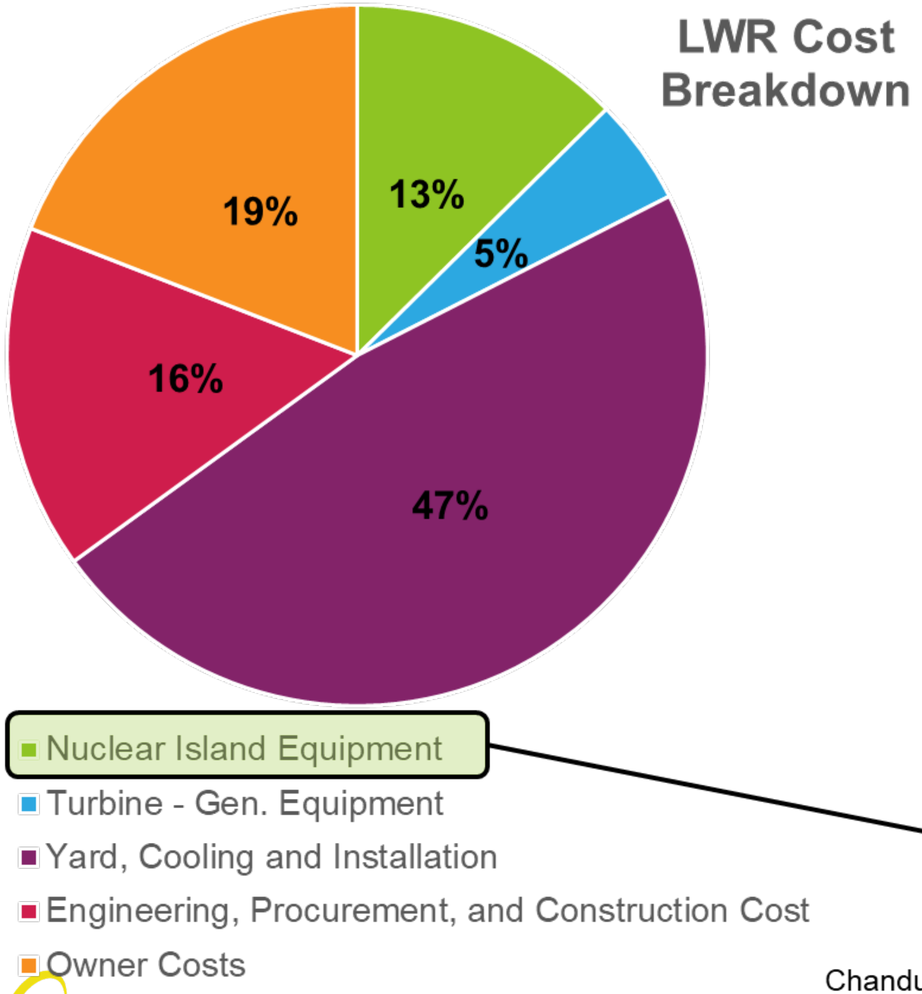
Vision

NEET ASI Research results in advanced sensors and I&C technologies that are **qualified**, **validated**, **and ready to be adopted by the nuclear industry**



Pattrick Calderoni
National Technical Director, Advanced Sensors and Instrumentation

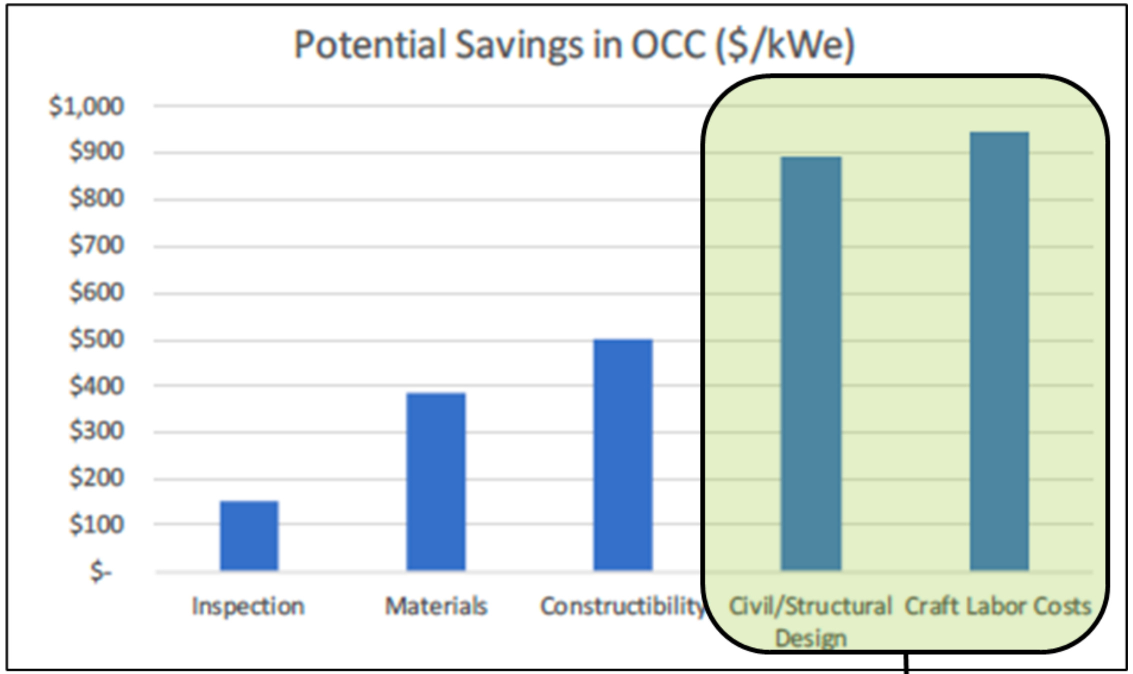
Capital costs of nuclear and the opportunity for AMM



Source: MIT-EI (2018)

Solutions

Source: EPRI, 2019



Current AMM primary focus

AMM opportunity

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Advanced Methods for Manufacturing

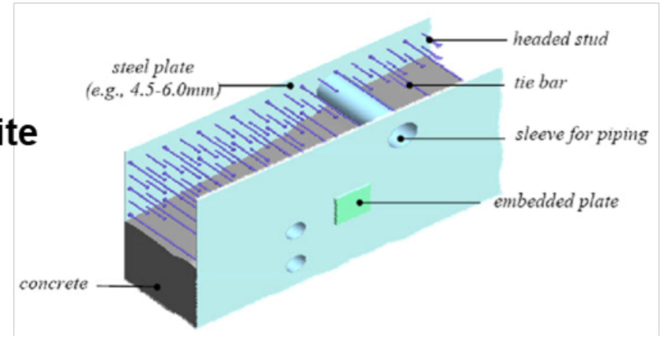
- About 50% of the cost of existing NPPs is from civil works - buildings, foundation, etc., which are mainly made of concrete
- Plenty of R&D is needed in concrete construction, that is, efficient ways for modular construction that ensures safety, economy, and quality assurance
  - Maximize off-site construction
  - Use existing supply chains as much as possible
  - Avoid the need for specialized technicians such as nuclear-quality welders
  - Not much need for new types of concrete, per se
- These problems have long been solved in the non-nuclear industry (e.g., high-rise buildings)

"The overall purpose of the Advanced Methods for Manufacturing (AMM) Crosscut program is to accelerate innovations that reduce the cost and schedule of constructing new nuclear plants and make fabrication of nuclear power plant components faster, cheaper, and more reliable."

https://www.energy.gov/ne/nuclear-energy-enabling-technologies/advanced-methods-manufacturing

Precast concrete wind turbine foundation
(Sargent & Lundy)

Steel-composite (SC) walls
Bruhl (2015)



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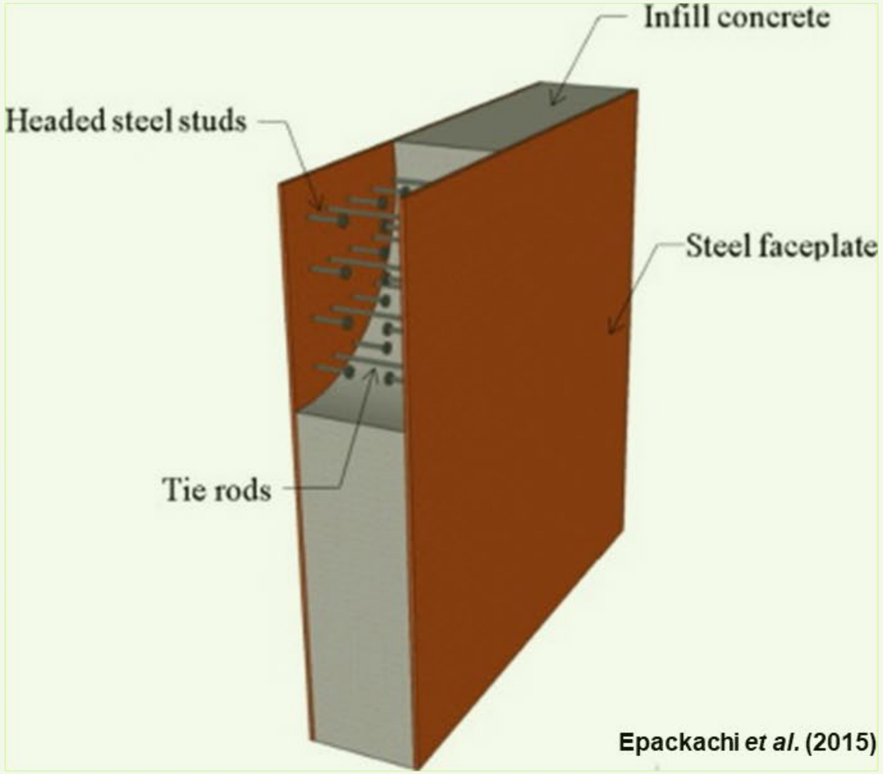
State of practice

Wikipedia

Reinforced Concrete (RC)



Steel-plate Composite (SC)

Nuclear construction

http://www.windfarmbop.com

Precast Concrete

Not nuclear construction (yet)

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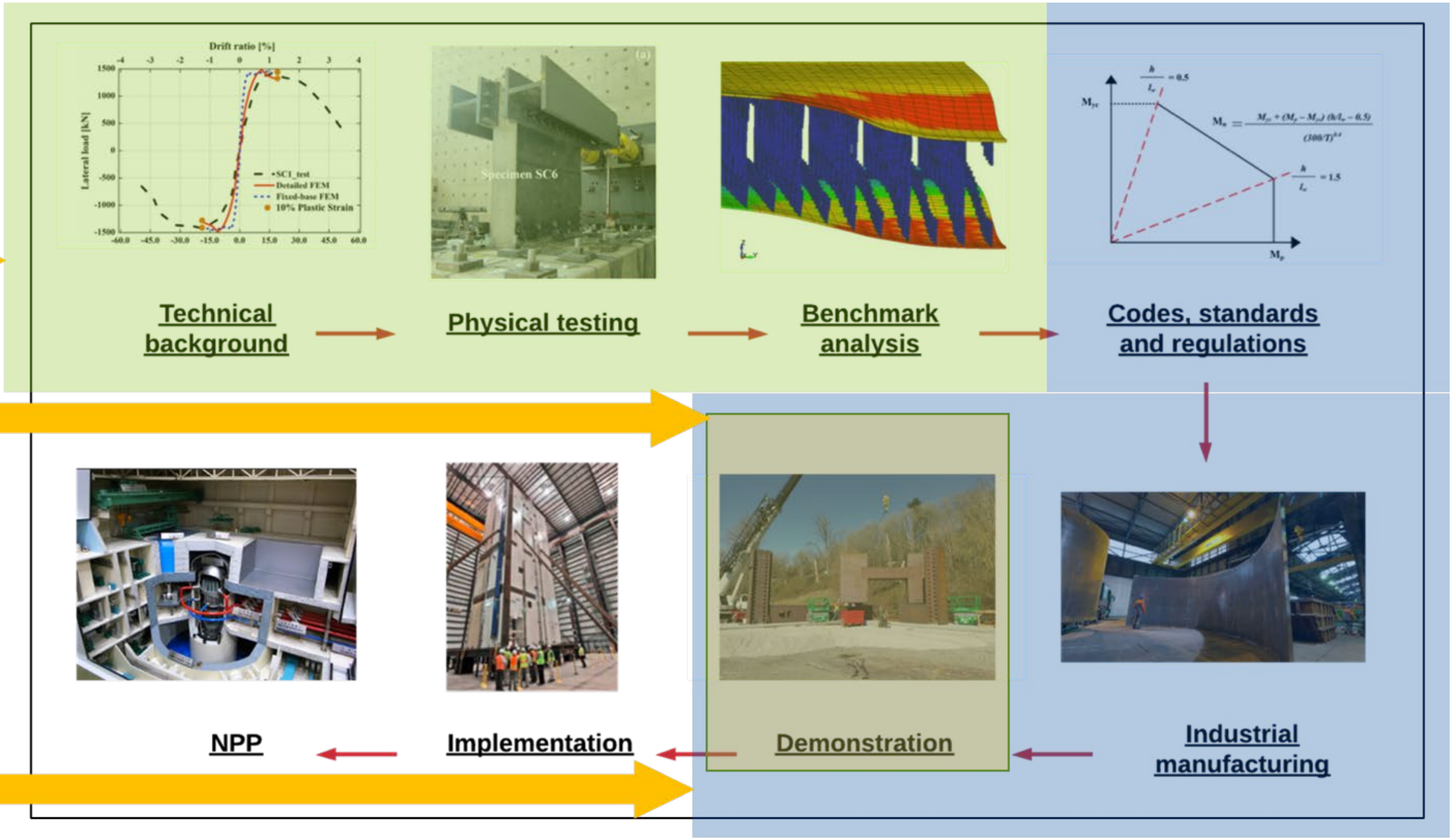
Deployment of new construction technologies in nuclear

Scope of a typical research project

Current NRIC focus

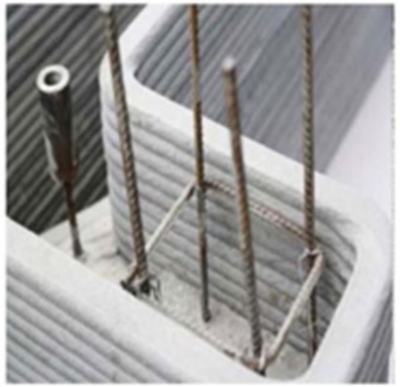
Need all of this for regulatory acceptance and industry adoption



No DOE program is focusing on improving TRL/RRL in construction technologies

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



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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LWRs vs. Advanced Reactors

- Current LWR containments are designed for high pressures
- They need an air-tight containment that can withstand high pressures and temperatures. Modular construction of these containments is therefore challenging and is one of the reasons why non-nuclear concrete technologies are not used.
- Many advanced reactors involve passive safety systems and are operated at (or near) atmospheric pressures
- There are upcoming regulatory changes that are more risk-informed and performance-based and can leverage ‘functional containment’ provided by the fuel itself (e.g., TRISO fuel)
- Given these developments it might be possible to adopt non-nuclear concrete technologies (e.g., precast concrete) that have existing supply chains and decades of experience
  - However, they still need to be adopted to the nuclear domain and demonstrated adequately

Containment dome at plant Vogtle under construction. Vogtle is an LWR type plant.

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Advanced Methods for Manufacturing

New materials can take decades before being adopted into the nuclear industry

- Therefore, we need to adopt technologies that already have a head start
- Non-nuclear industry is an obvious place to look (existing experience and supply chain)
- Advanced reactors will have structure with lower safety requirements (with LMP-based recommendations like functional containment): these structures are good candidates for technologies from non-nuclear construction

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Advanced Manufacturing use in Commercial Nuclear Power Plants

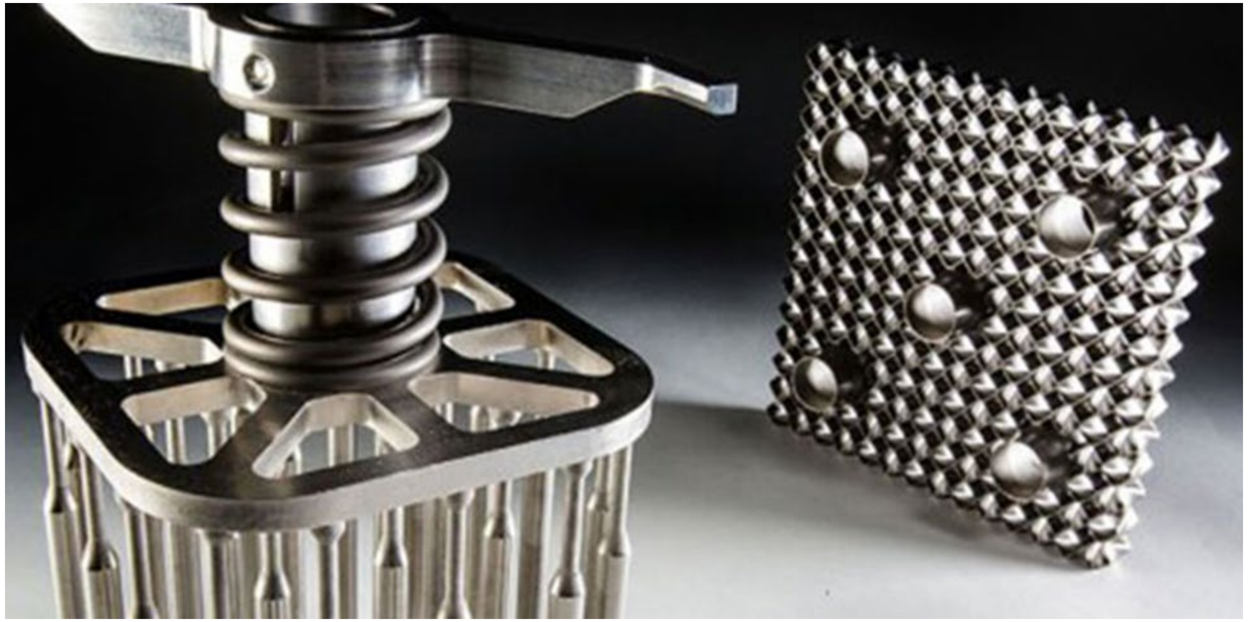
Fuel Assembly Channel Fasteners

Brown's Ferry in Alabama, (Oak Ridge National Laboratory in partnership with Framatome and Tennessee Valley Authority).

https://www.ornl.gov/news/additively-manufactured-components-ornl-headed-tva-nuclear-reactor

Thimble Plugging Device

Exelon's Byron unit 1 in 2020.(Westinghouse and ORNL



https://world-nuclear-news.org/Articles/Westinghouse-3D-printed-component-installed-in-ind

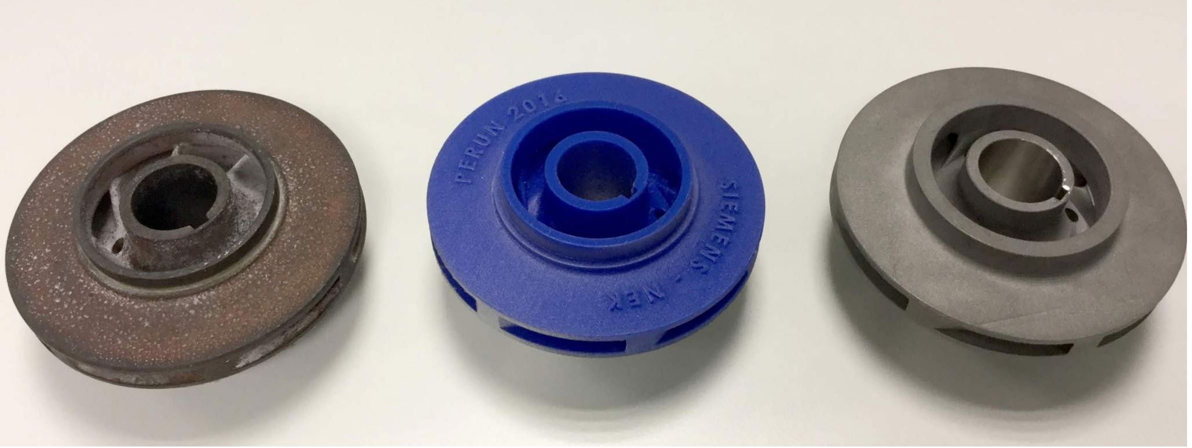
Advanced Manufacturing use in Commercial Nuclear Power Plants

Chemical and Volume Control System (CVCS) safety valve

Korean Atomic Energy Research Institute (KAERI)
Match Class 1 safety
20MPa in a 3" diamter volume at 650C.
The chromium and nickel component fabricated by using Direct Energy Deposition with a 5-axis CNC machine.

Impeller

Siemens, Krško nuclear power plant in Vrbina, Slovenia.



Original, obsolete water impeller, Siemens' 3D printed prototype and the resulting 3D-printed replacement

https://3dprintingindustry.com/news/siemens-3d-prints-part-nuclear-power-plant-107666/

https://3dprintingindustry.com/news/korean-researchers-3d-print-highly-resistant-large-format-nuclear-safety-valve-183362/

Surface Technologies: Large Potential

- Spray coatings (e.g., plasma spray techniques), vapor deposition (e.g., CVD, PECVD, Laser CVD etc.), and sputter coating deposition processes are major techniques.
- Diffusion coating, Ni-dispersion coating, electric arc wire spray coating, electroplating, electroless plating, electrospinning, hot dipping, powder coating, ion implantation, anodizing, galvanizing, thin film vacuum coating, laser Cladding, friction surfacing, and resistance seam welding coatings are also notable.

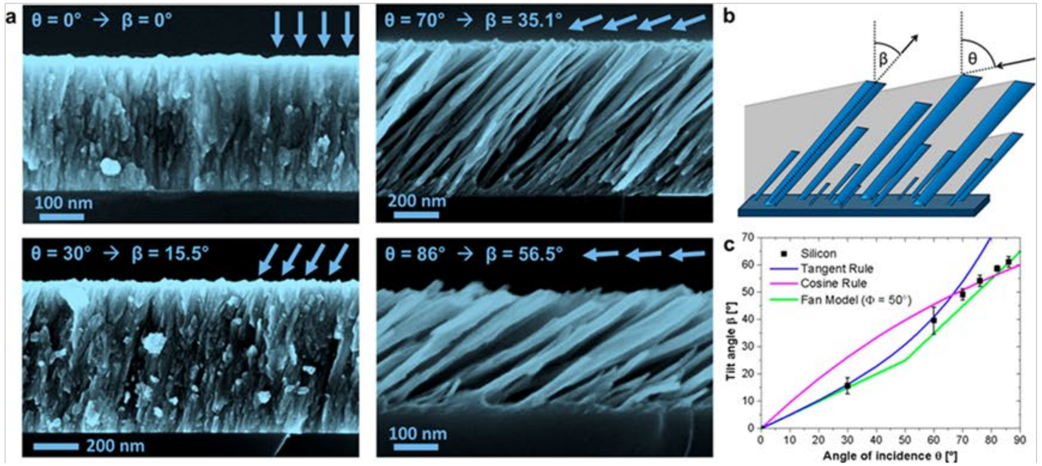
Thermal Barrier Coatings

Corrosion Protective Coatings

Waste packaging

Rare earth metals additions (Neutron absorbers)

High-velocity oxy-fuel process at Caterpillar expended to spray coat half-scale waste packages with SAM1651 amorphous metal.. https://doi.org/10.1007/s11661-009-9830-4



Physical Vapor Deposition (PVD) obliquely deposited molybdenum thin films

Grüner et al., 2018

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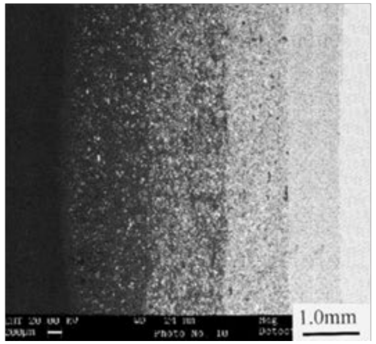
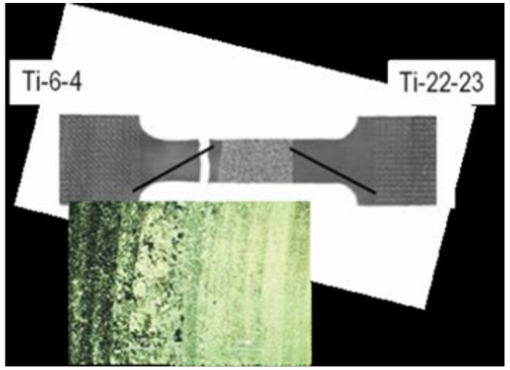
Engineered Gradient Materials and Composition

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

SiC/Cu graded material





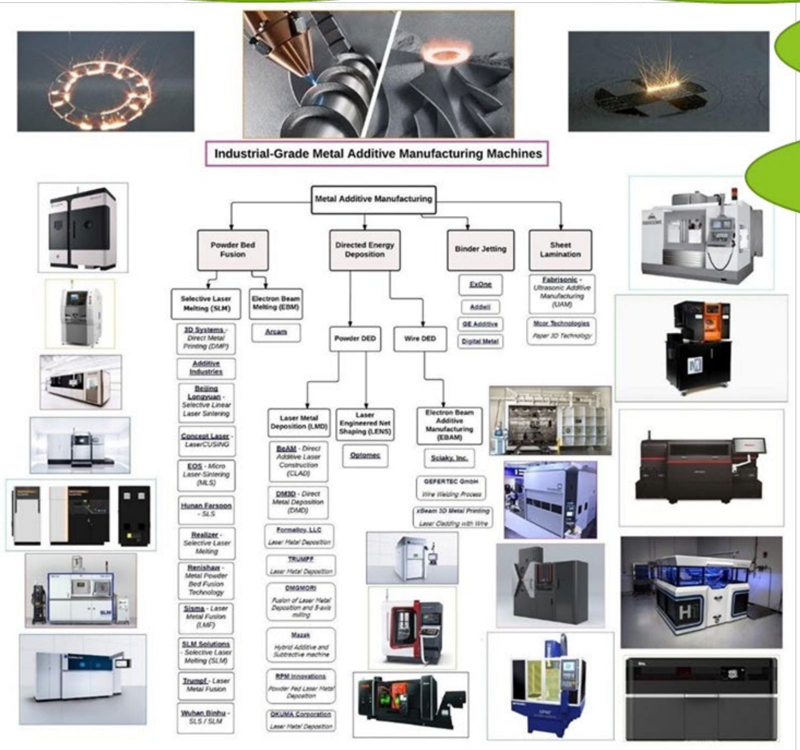
[Y. –H. Ling, Journal of Nuclear materials, 303 (2002) 188-195]
[Advances in Laser Deposition Technology and Applications R. Grylls, T. Marchione, D. Keicher; ALAC Conference Proceedings, 2006.]

- 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

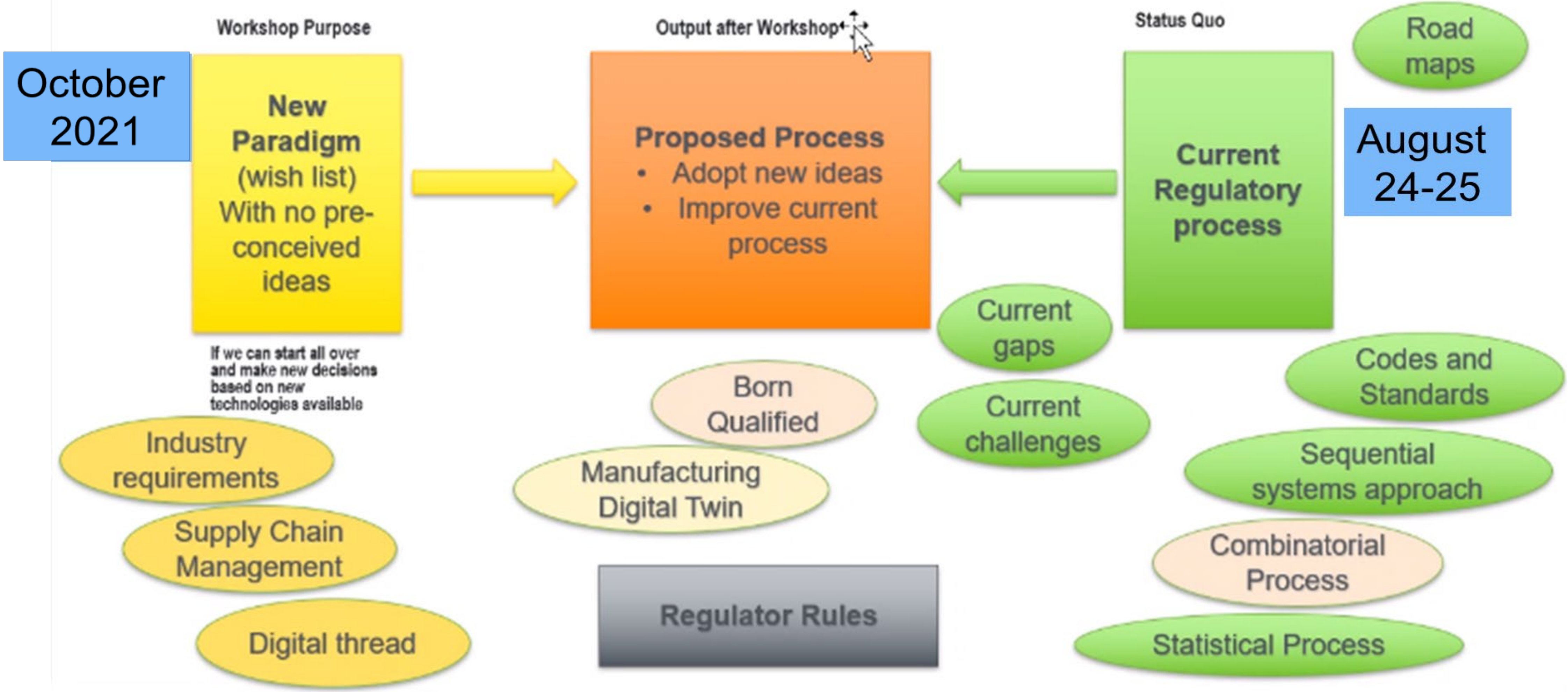
Qualification Processes

Categorization of manufacturing processes?
Why is it advanced manufacturing?

- Additive Manufacturing
- Coatings
- Powder Metallurgy
- Welding
- Casting



Workshop



October 2021
Workshop Purpose
New Paradigm (wish list) With no pre-conceived ideas
If we can start all over and make new decisions based on new technologies available
Industry requirements
Supply Chain Management
Digital thread
Output after Workshop
Proposed Process
• Adopt new ideas
• Improve current process
Born Qualified
Manufacturing Digital Twin
Regulator Rules
Status Quo
Current Regulatory process
Road maps
August 24-25
Current gaps
Current challenges
Codes and Standards
Sequential systems approach
Combinatorial Process
Statistical Process

Modeling Framework

Driving Factors and Inputs
Product System Requirements per Reactor type

Modeling for Advanced Manufacturing Design

Advanced Manufacturing Process Modeling

Advanced Manufacturing Performance Modeling

Multi-Scale & Multi-Physics Coupling Modeling

Benefits

- Modelling gap-analysis
- Acceleration of qualification and licensing processes
- Accelerated product development, therefore the application and adoption of AMM processes
- Identification of possible collaborative cross-country research agreements
- Decrease product uncertainties and to increase multiscale and Physics based processes

ART Advanced Materials – Providing Materials Solutions to Enable Design, Construction, and Operation of Licensable Advanced Reactor Systems

Reduce Risk in Licensing

Codes & Standards
ASME Sec III, Div 5

- Material, design, fabrication, installation, examination, testing, overpressure protection, inspection, stamping, and certification

Regulatory Space
Materials Degradation

- Coolant compatibility
- Radiation
- Mass transfer
- Materials surveillance
- Etc.

Codes and Standards
ASME Sec XI, Div 2, 3

- In-service inspection
- Etc.

Dr Sam Sham

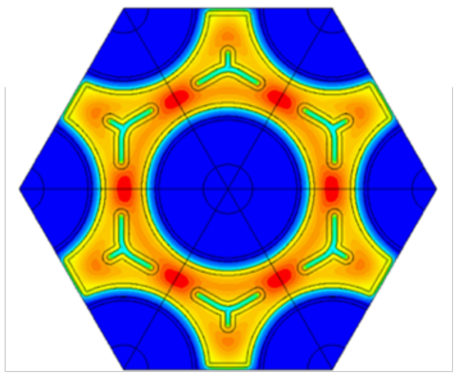
The Transformational Challenge Reactor Program is applying additive manufacturing (AM) and artificial intelligence (AI) to deliver a new approach

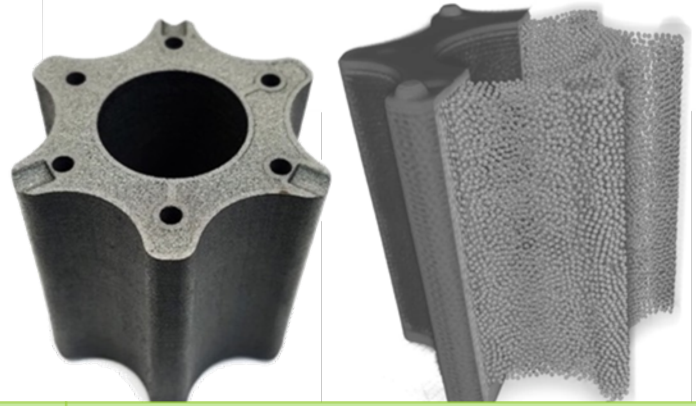
Using AI to navigate an unconstrained design space and realize superior performance

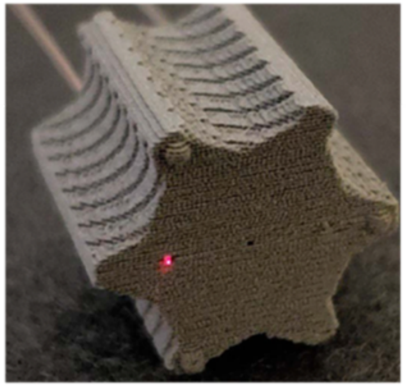
Leveraging AM to arrive at high-performance materials in complex geometries

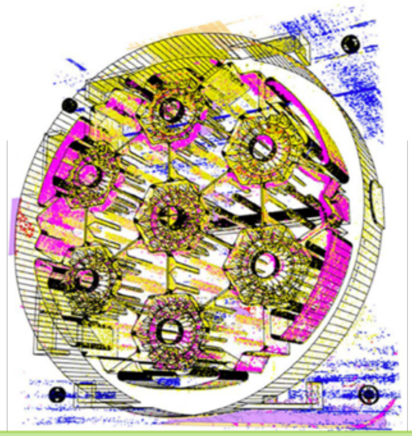
Exploiting AM to incorporate integrated and distributed sensing in critical locations

Using AI to assess critical component quality through in situ manufacturing signatures





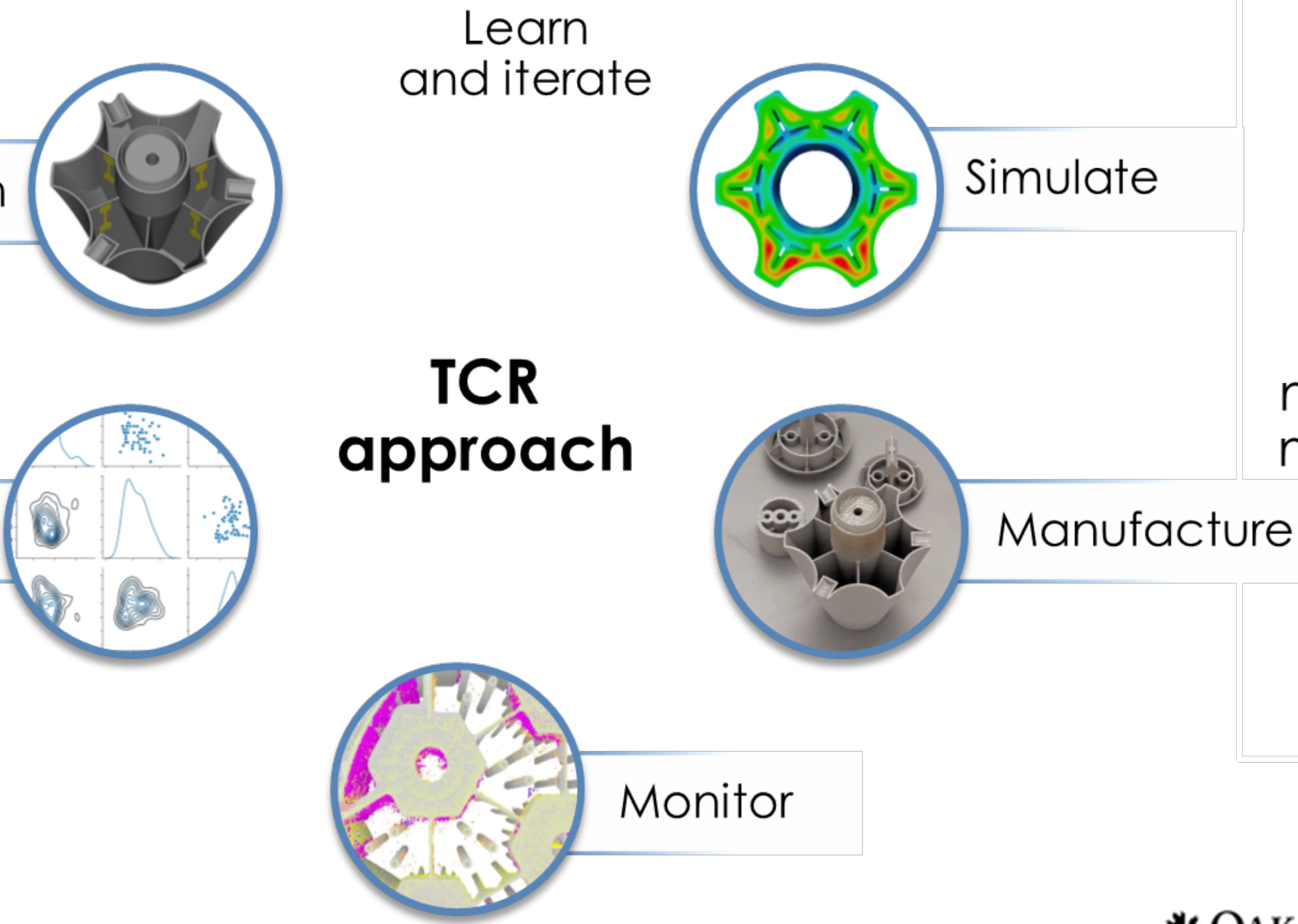




AI-informed Design	Advanced Materials	Integrated Sensing and Control	Digital Platform

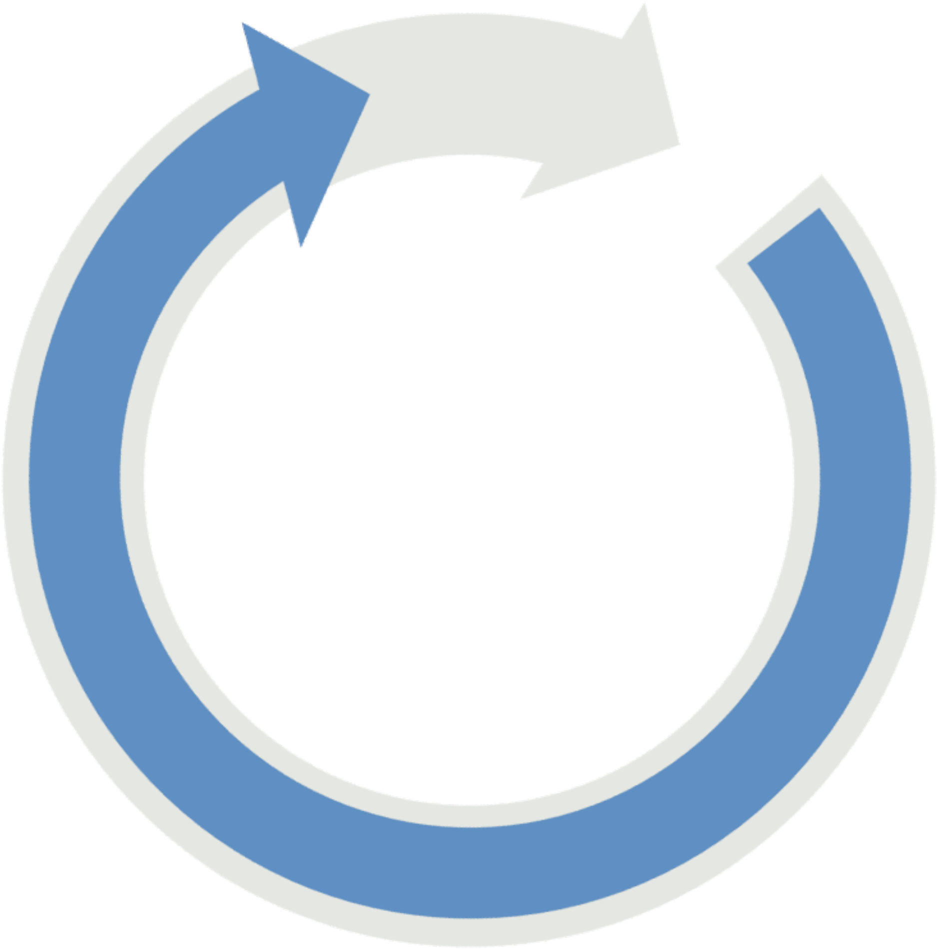
The agile design and development approach employed by TCR is intended to accelerate deployment

Agile approach breaks with traditional linear development models to exercise an iterative, dynamic development process



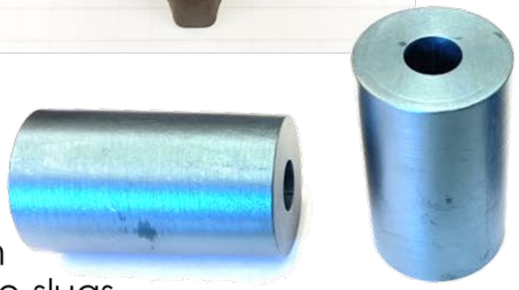
This approach lends itself to complex projects, in which a large, multilaboratory, multidisciplinary team works closely to complete a product

The agile design and development approach employed by TCR is intended to accelerate deployment

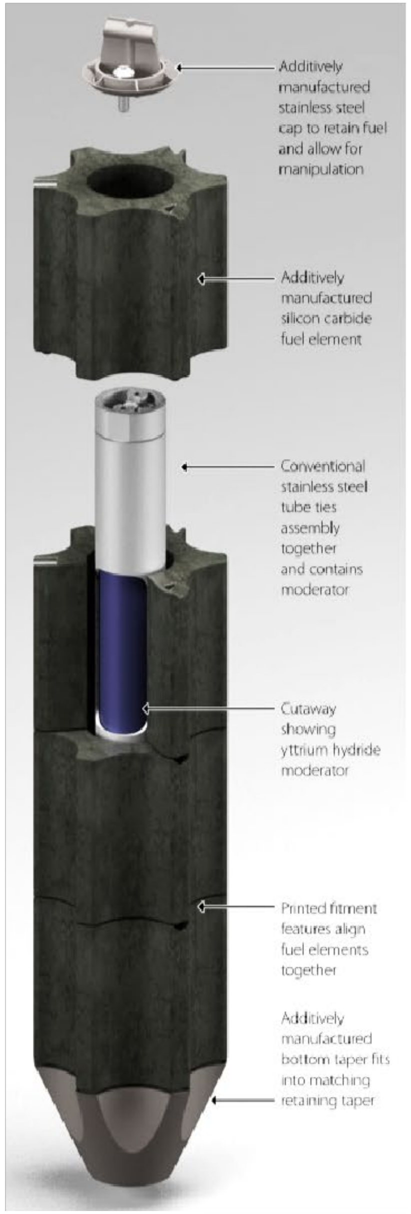


TCR core is composed of highly advanced, safe and robust constituents

- TCR fuel has multiple inherent barriers to radionuclide release and is encapsulated in refractory and oxidation resistant SiC
- TCR uses the H-bearing moderator with highest known thermal stability
- Additively and conventionally manufactured Grade 316 stainless steel act as the hydride sheath and provides assembly structure

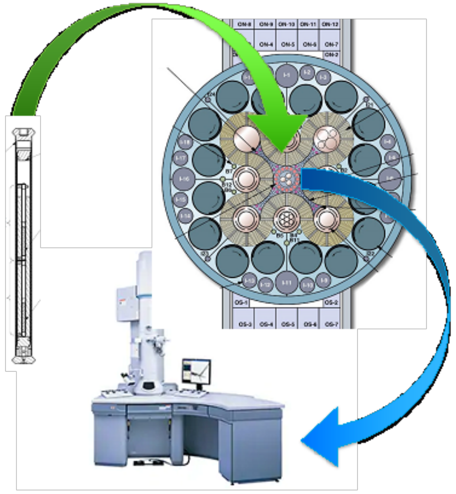


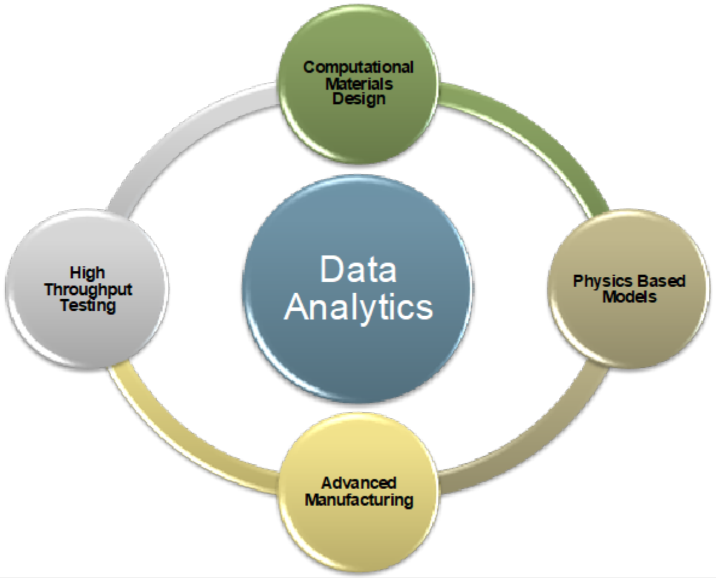
Fully densified and assembled fuel assembly



For nuclear energy applications, the environmental and irradiation conditions must be correlated to materials' evolution and degradation in service

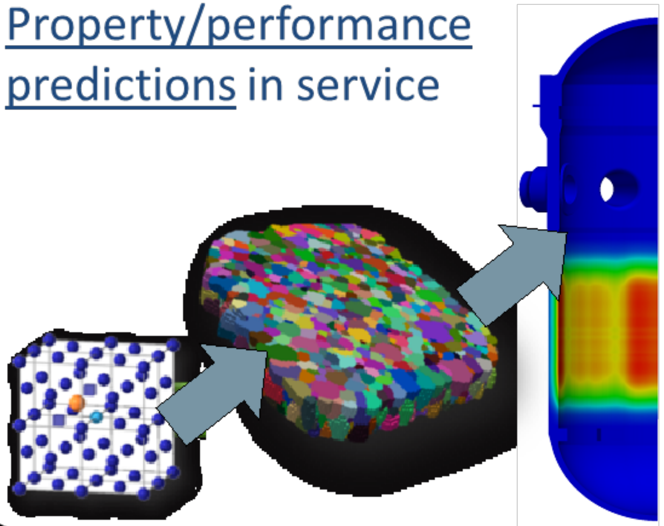
Physics-based modeling and rapid testing & characterization links microstructures & service conditions to properties





Machine learning to harness data in new ways for improved physics-based predictions

Property/performance predictions in service



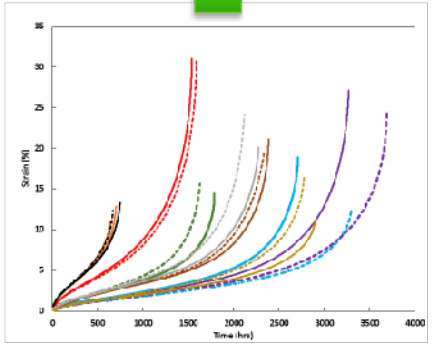
NMDQi Nuclear Materials Discovery and Qualification Initiative

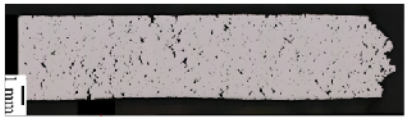
Allen Roach TMS 2021 presentation

FY-21 NMDQi Plans for Rapid Qualification

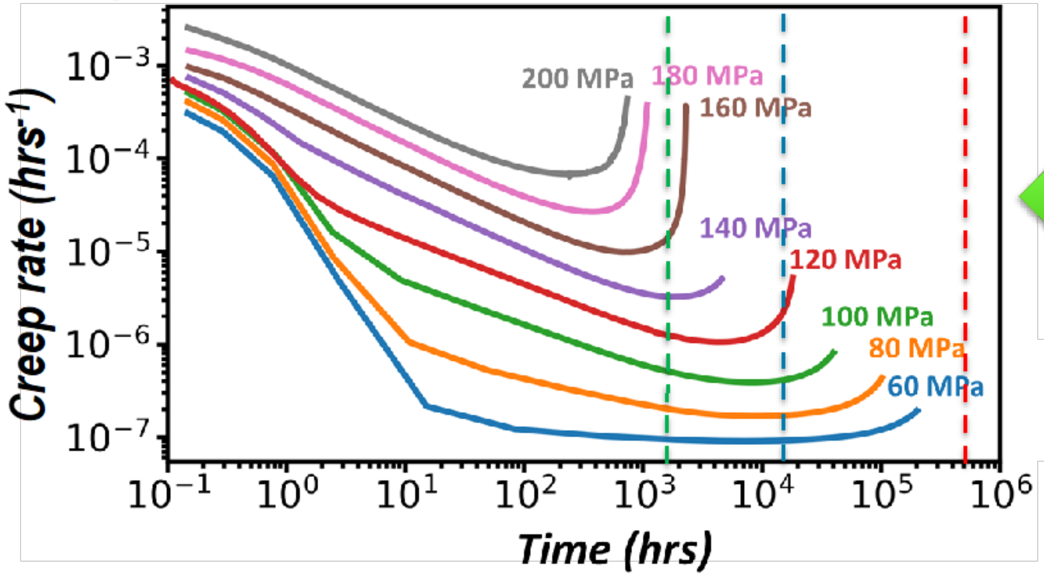
INL/CON-21-61741

Focus: Strategy development for how to approach a new qualification paradigm using enabling physics-based modeling, data analytics, high-throughput testing and characterization



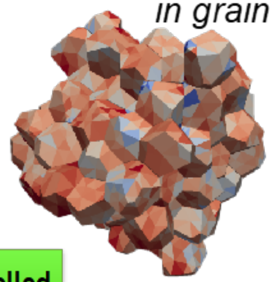


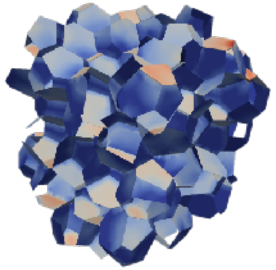
Experimental validation for 1, 10, 30 year design life



Long term modelled design properties

Effective stress in grain bulk





Creep cavity density on grain boundaries

Staggered qualification for structural materials

Michael McMurtrey, Mark Messner, Allen Roach

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
- Large component fabrication and welding, Size limitations (Scalability – size, volume)
- Sensors:
  - Radiation tolerant sensors
  - Wireless sensors
  - Embedded
  - Miniaturization
  - Multi-properties
  - Real time
  - Integrated manufacturing processes
- Thermal barrier coatings: Interface designs to prevent scaling, functional materials, isolation

Conclusions

- Bring together **diverse set of manufacturing methods and materials** with harsh environmental working capabilities to identify **common barriers, technical pathways** to addressing these challenges.

- How do we measure or gauge applications of new advanced manufacturing methods?
  - ✓ Technology readiness level
  - ✓ Qualification routes
  - ✓ Standards/Codes
  - ✓ Risks

- Determining requirement & performance specifications

- How do we measure & communicate the impact of our research

- Learn from other industries and countries

Manufacture product and material simultaneously

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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.

Upcoming Webinars

Date	Title	Presenter
24 June 2021	In Service Inspection and Repair Developments for SFRs and Extension to Other Gen4 Systems	Mr. François Baque, CEA, France
27 July 2021	Evaluating Changing Paradigms Across the Nuclear Industry	Ms. Jessica Lovering, Carnegie Mellon University, USA
26 August 2021	Graded Approach: Not just Why and When, but How	Mr. Vince (Alois) Chermak, INL, USA