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AMMT Overview

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DOE-NE AMMT Industry Workshop, May 23-24, 2023

AMMT Leadership Team

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Materials Development

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Advanced Manufacturing

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Environmental Effects

NTD: National Technical Director; TAL: Technical Area Lead

AMMT Mission, Vision and Goals

Mission

- To develop cross-cutting technologies in support of a broad range of nuclear reactor technologies.
- To maintain U.S. leadership in materials & manufacturing technologies for nuclear energy applications.

Vision

To accelerate the development, qualification, demonstration and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy.

Goals

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

AMMT Program

Program Elements

Development, Qualification and Demonstration

- Advanced Materials & Manufacturing
- Rapid Qualification
- Material Performance Evaluation
- Technology Demonstration

Capability Development & Transformative Research

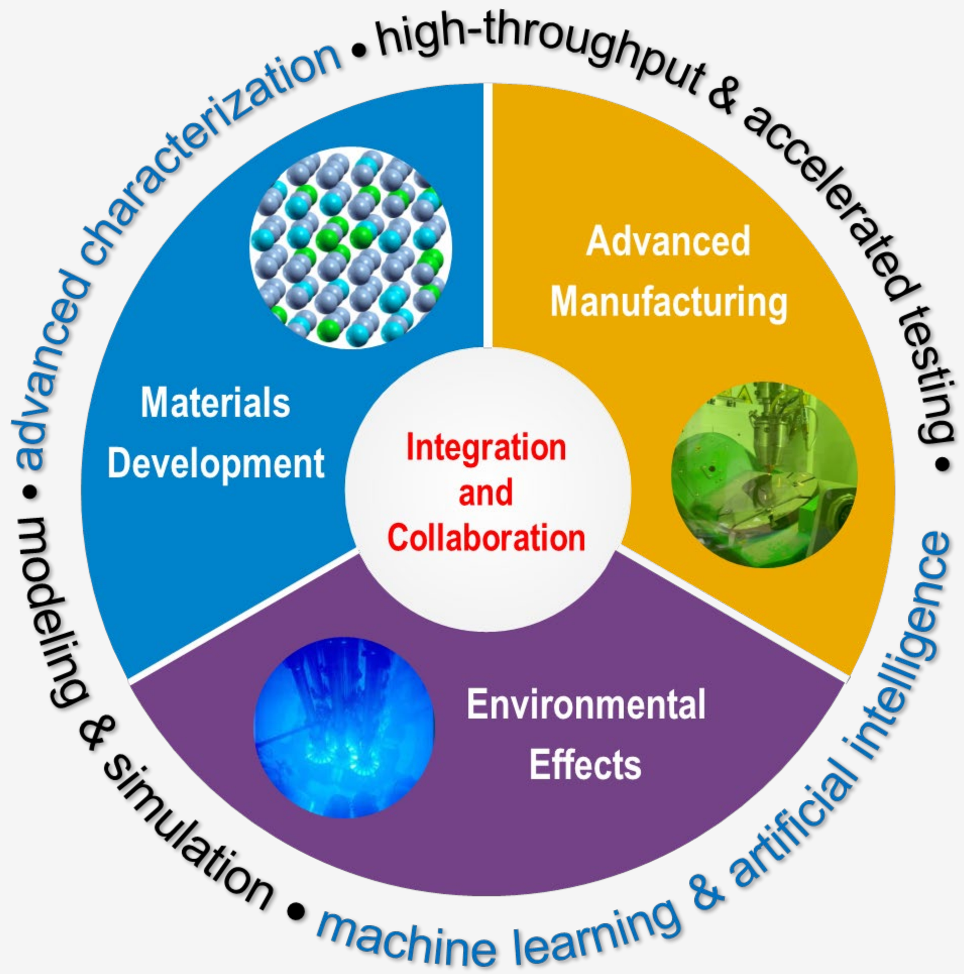
- Advanced Experimental Tools
- Advanced Computational Tools
- Transformative Research to Explore New Materials Design & Processes

Collaborative Research and Development

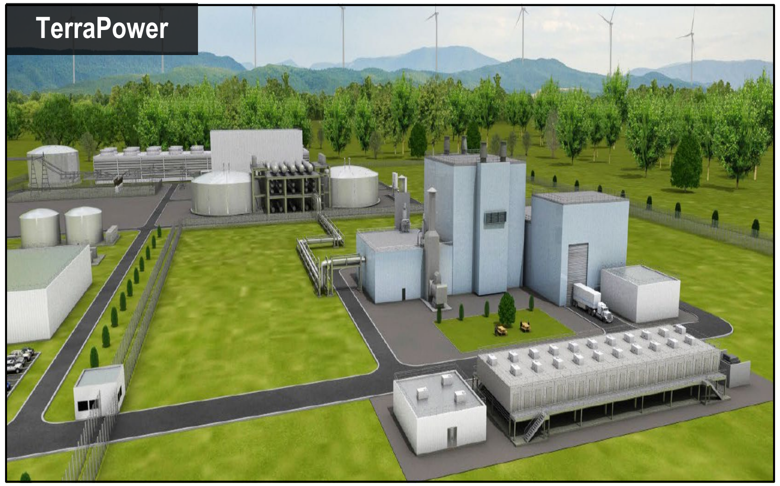
- Collaboration & partnership to address diverse needs of the nuclear community

- Investigate a broad range of technologies
- Leverage and collaborate on capability development
- Provide near-term solutions to nuclear industry

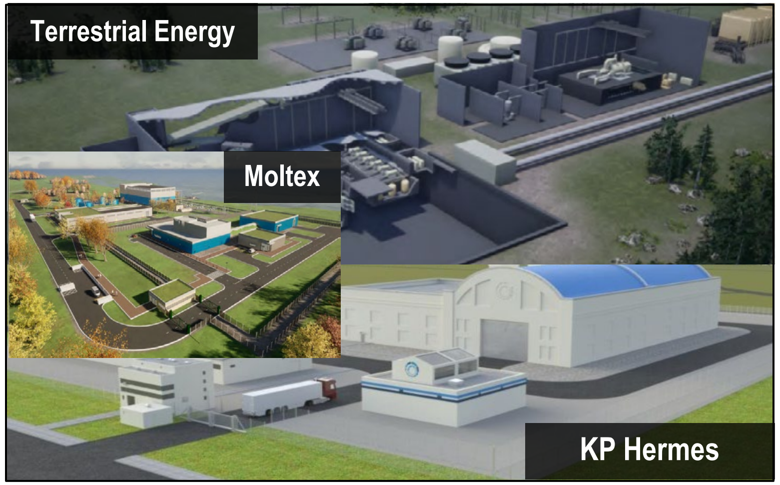
Execution Strategy



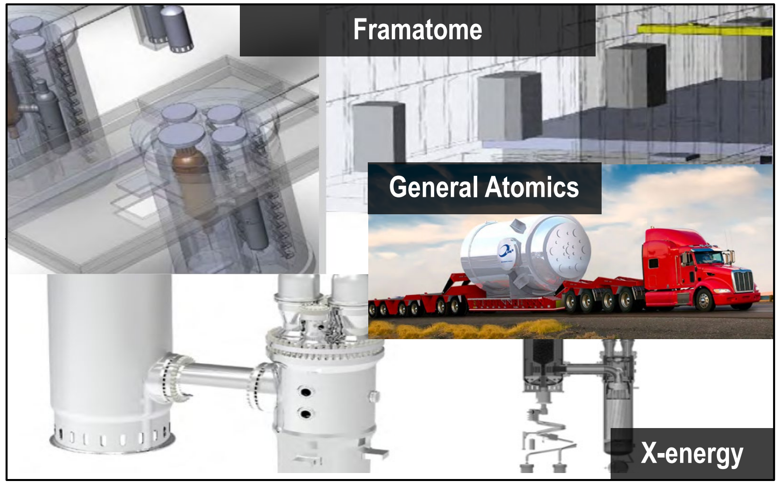
AMMT: Cross-cutting Technology



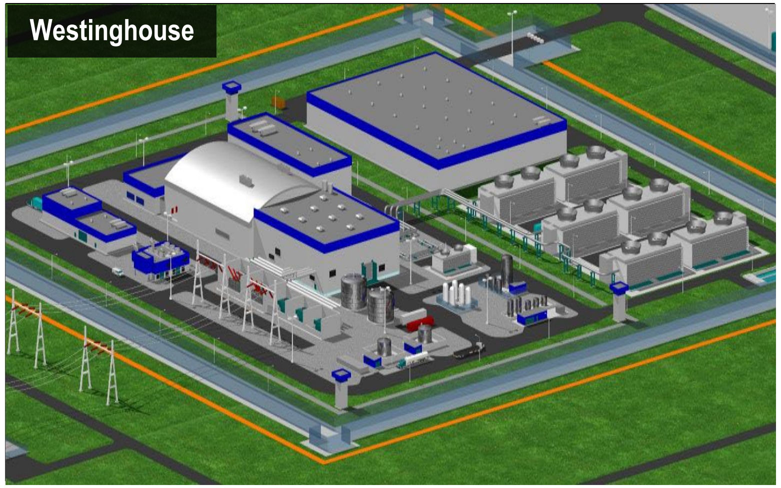
Sodium-cooled Fast Reactor (SFR)



Molten Salt Reactor (MSR)



High-temp Gas-cooled Reactor (HTGR)



Lead-cooled Fast Reactor (LFR)

Light Water Reactor (LWR)/
Small Modular Reactor (SMR)

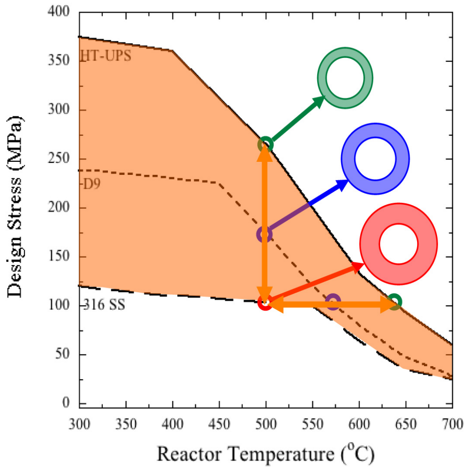
Micro-reactor

Nuclear Innovation Alliance (2021), "Advanced Nuclear Reactor Technology: a primer."

AMMT: Enabling Technology

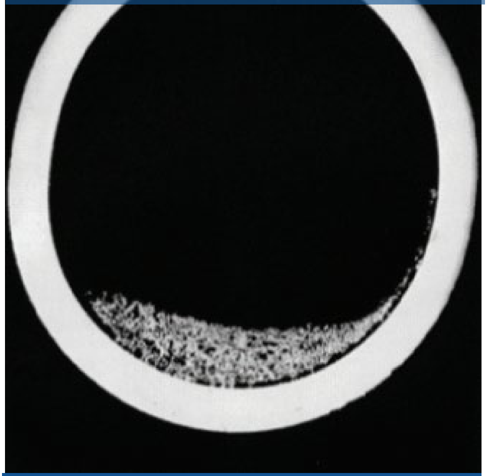
Industry Benefits

Heat Resistance



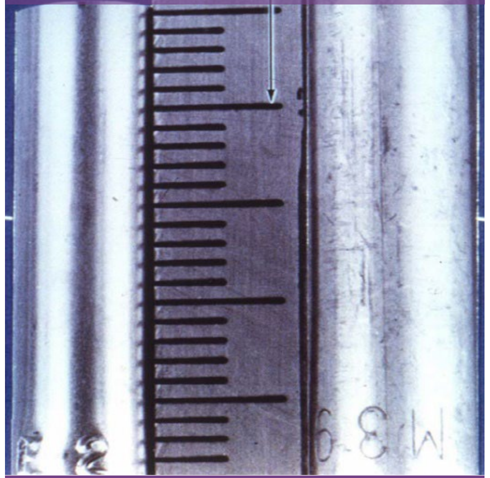
- Higher operating temperature
- Greater thermal efficiency
- Improved safety
- Cost reduction

Corrosion Resistance



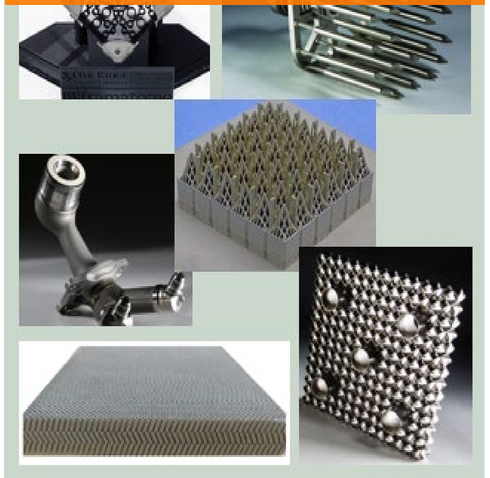
- Enable a wide range of reactor technologies
- Enable new reactor concepts
- Reduce maintenance cost

Radiation Resistance



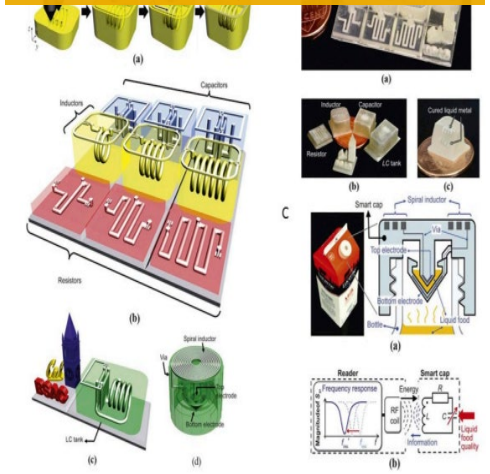
- Long lifetime
- Less inspection and maintenance cost
- Fewer component replacements

Innovative Design



- Performance enhancement
- Design flexibility
- Reduce supply chain risks and costs
- Lower fabrication costs

Embedded Sensing

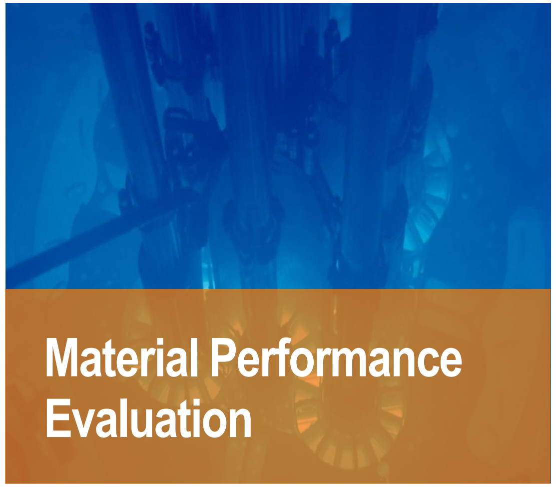


- Enhance system control
- Enable health monitoring
- Allow for autonomy

Rapid qualification *will shorten the development cycle and time-to-market.*

J. Busby (unpublished); Molten Salt Chemistry Workshop (2017); Straalsund et al. JNM 108&109 (1982) 299.

Research Focus Areas



Capability Development & Transformative Research

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Advanced Materials and Manufacturing

Advanced Materials and Manufacturing

Materials development as an integrated part of advanced manufacturing
– develop new materials and processes for advanced manufacturing technologies.

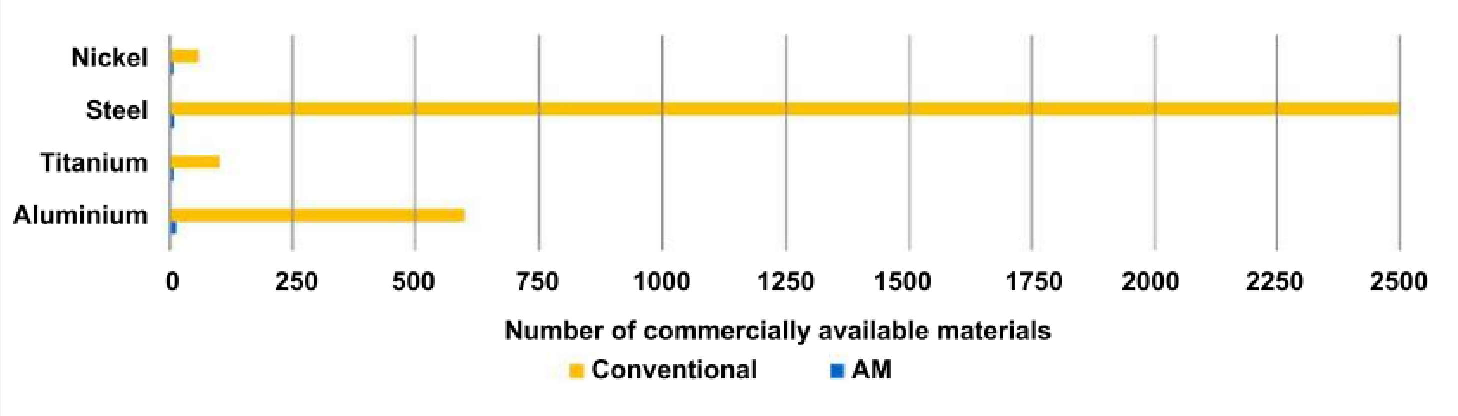
Existing reactor material optimization for AM	Innovative new material development through AM	AM process understanding and development	Large-scale advanced manufacturing for nuclear applications
AM component design optimization	Integrated design of materials, manufacturing processes, and products	Multifunctional, multi-material component designs and fabrication	Design of embedded sensor for reactor in-service monitoring

AM Material Development

Optimize and Manufacture Existing Reactor Materials

Optimize and improve existing reactor materials that are compatible with advanced manufacturing processes to expand their applications. Initial focuses are:

- **Ferritic-martensitic steels**
- **Austenitic stainless steels**
- **Ni-based alloys**



The number of alloys currently commercially available for metal additive manufacturing is significantly smaller than ones available for conventional manufacturing processes. (D. Beckers 2019)

Develop and Manufacture New Reactor Materials

Advanced manufacturing can enable new material designs (compositional, microstructural) currently unavailable or limited possibilities using conventional manufacturing.

- **ODS alloys**
- **High entropy alloys**
- **Refractory alloys**

- **Composites**
- **Functionally graded materials**
- **Coatings/claddings**

Advanced Manufacturing Technologies

NRC Definition: Techniques and material processing methods that have not been: (1) traditionally used in the U.S. nuclear industry, or (2) formally standardized/codified by the nuclear industry.

NRC initial focus areas:

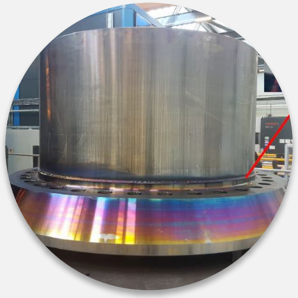
- Laser powder bed fusion (LPBF)
- Directed energy deposition (DED)
- Powder metallurgy hot isostatic pressing (PM-HIP)
- Electron beam welding (EBW)
- Cold spray

AMMT initial focus areas:

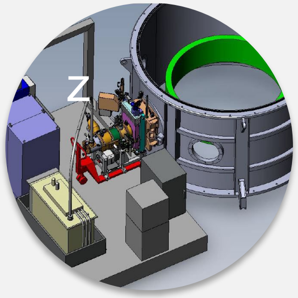
- Laser powder bed fusion (LPBF): A test case to establish a rapid qualification framework.
- Directed energy deposition (DED): Large-scale additive manufacturing for nuclear applications.

PM-HIP and EBW *are being developed and demonstrated by nuclear industry funded by DOE-NE*.

SMR PM-HIP



SMR EBW



Modular in-chamber EBW

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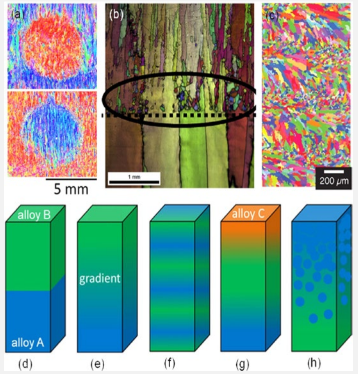
Rapid Qualification

Rapid Qualification

Unique Challenge - AM Qualification for High-temperature Nuclear Structural Applications.

AM Materials Qualification

- Additive manufacturing (AM) is a domain-by-domain, **highly-localized** process.
  - Microstructure and property variations: location, orientation-dependent
  - Compositional variations: functionally graded materials
  - Defect variations: geometry and process dependent defect formation



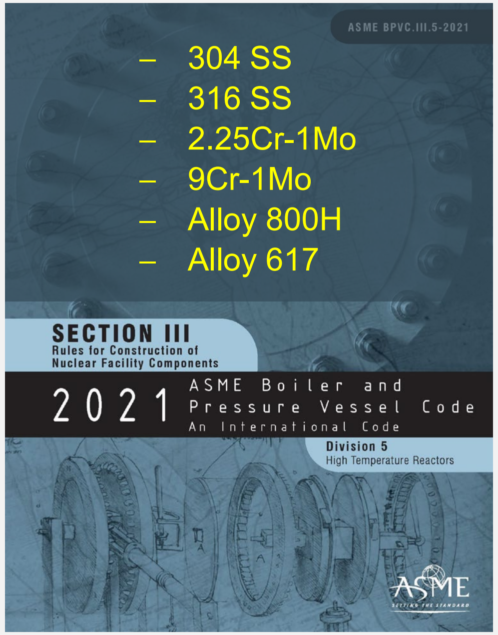
Site-specific microstructures of (a-c) single- and (d-h) multi-material alloy obtained by additive manufacturing.

- Materials and components are formed **simultaneously** in additive manufacturing vs. **sequentially** in conventional manufacturing.
- AM qualification involves materials, equipment, operators, processes, components.

High-Temperature Material Code Qualification

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

Only **six materials** have been approved for elevated-temperature nuclear construction in ASME Code.



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

Time-dependent Behavior

- Shorten/optimize creep and creep-fatigue testing
- Predict long-term thermal aging, creep and creep-fatigue properties

Z. Liu, et al., J. Mater. Sci. & Tech. 100 (2022) 224.

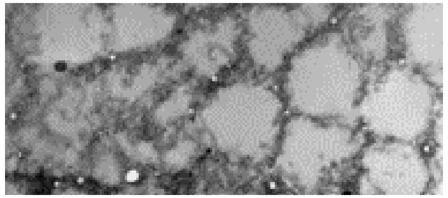
Rapid Qualification

Develop Processing-Structure-Property-Performance based Qualification Framework

To address the challenges posed by advanced manufacturing that cannot be easily handled by traditional qualification approaches, we will develop a P-S-P-P based qualification framework by integrating materials development, advanced manufacturing, environmental effects.

Use integrated experimental, modeling and data-driven tools

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



Establish new qualification framework through qualifying LPBF 316H SS

Additively-manufactured 316 stainless steel (AM 316 SS) will serve as a case study for the development and demonstration of a new qualification framework.

Ensure new qualification framework applicable to other materials systems

Develop an agnostic qualification approach applicable to a variety of material systems, e.g. metallic, ceramic and composites, as well as a variety of advanced manufacturing techniques.

Laser Powder Bed Fusion (LPBF)

Selected LPBF as the process for development of a new qualification framework.

Process Understanding

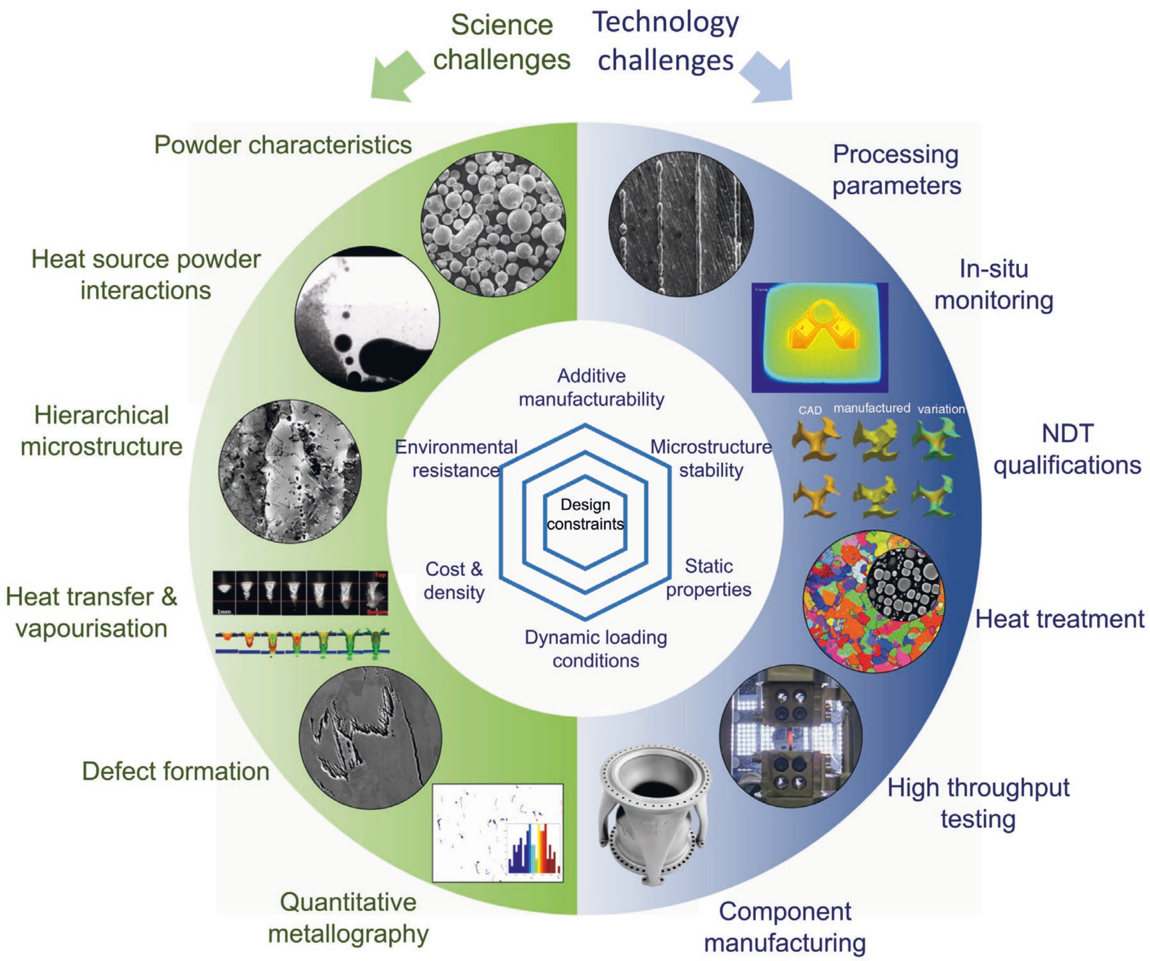
- Powder characteristics
- Thermal transport
- Defect formation
- Multi-scale microstructure
- High-throughput characterization

In-process and Post-process NDE

- In situ sensing and measurements
- High-resolution NDE techniques
- Defect acceptance criteria
- Processing-microstructure relationship

Digital Manufacturing

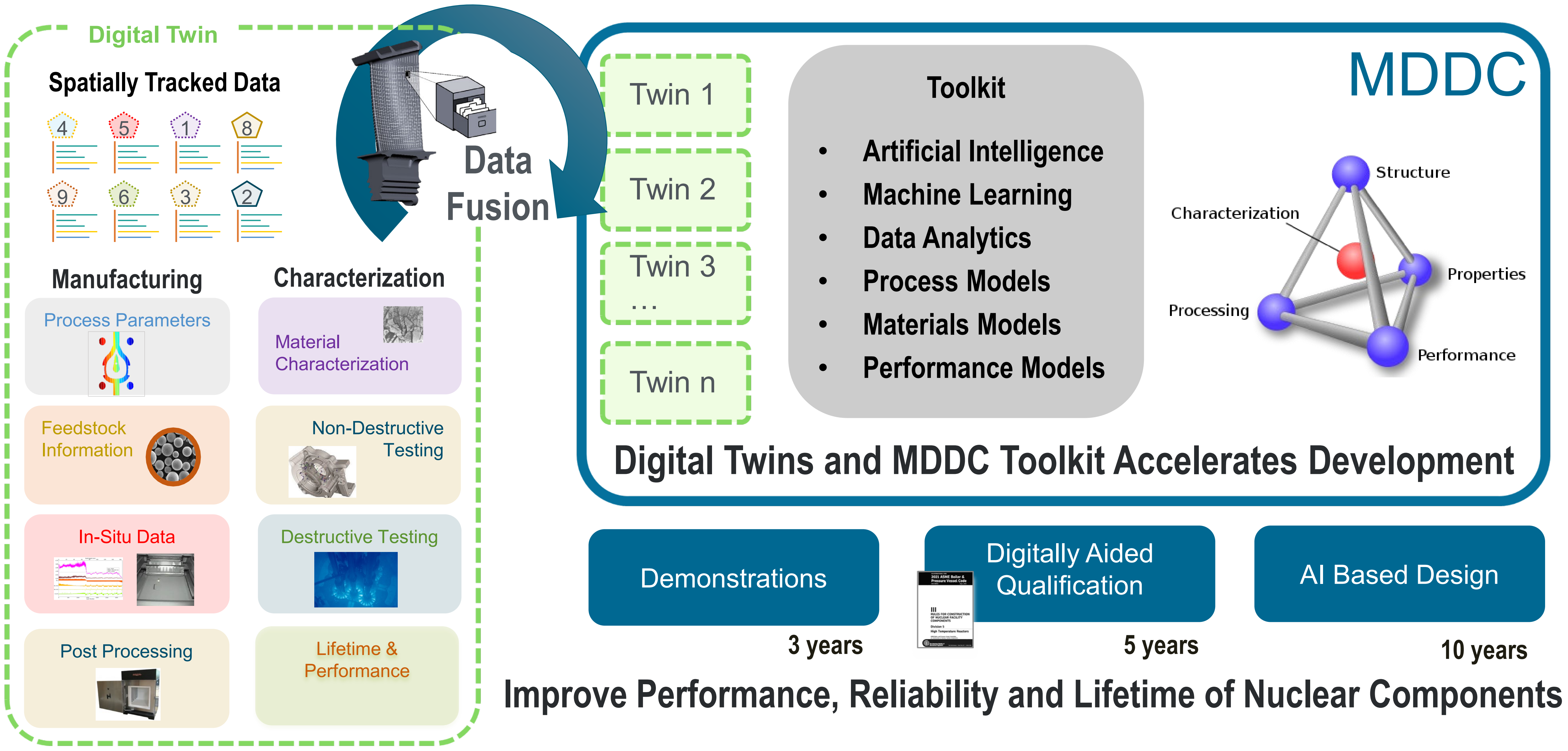
- Data analytics
- Machine learning/artificial intelligence
- Modeling and simulations
- Digital twins



"Fundamental understanding of the processing science includes powder flowability and powder shape distribution, interaction with heat source, hierarchical microstructure formed, defects mitigation and better quantification of metallurgical features. Challenges on the technology perspective includes parametric optimization of processing, real-time monitoring, establishment of qualification standard, high throughput testing and manufacturing of scaled-up components."

C. Panwisawas, et al. Nature Communications (2020)

Multi-Dimensional Data Correlation (MDDC) Platform



Rapid Qualification: Phased Approach

Consider multiple qualification pathways and take a phased approach.

Statistical/Equivalence-based Qualification

Require extensive testing and empirical modeling to demonstrate a new material or process is equivalent to a previously qualified one.

In-situ Data based Qualification

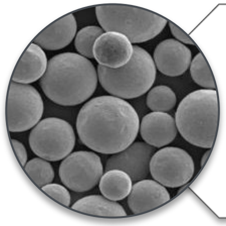
Use in-situ measurement data and understanding of the Processing-Structure-Property-Performance relationship.

ICME-based Qualification

Demonstrate the performance in computer models with the Processing-Structure-Property-Performance relationship and verify it with minimal testing.

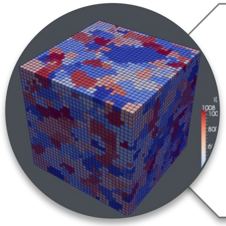
ASME Code Case for LPBF 316H SS

Qualify LPBF 316H SS for use with ASME Section III, Division 5, High Temperature Reactors via a ASME Code Case.

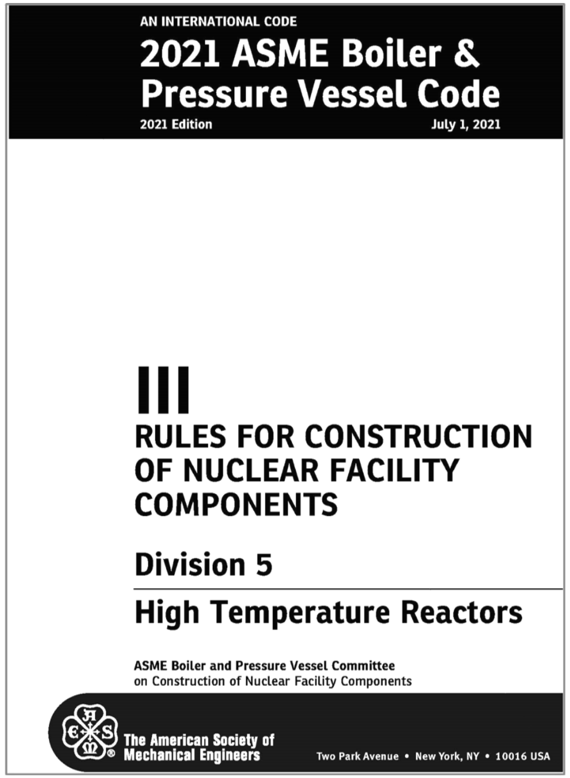


Address key differences between LPBF 316H SS and regular 316H SS.

Establish AM 316 SS property data package including tensile, creep and creep-fatigue, and thermal aging data for high-temperature operating environments.



Use traditional qualification approaches while developing/implementing accelerated experimental and computational qualification techniques.



FY23 M2 Milestone: ASME Code Qualification Plan for LPBF 316H SS.

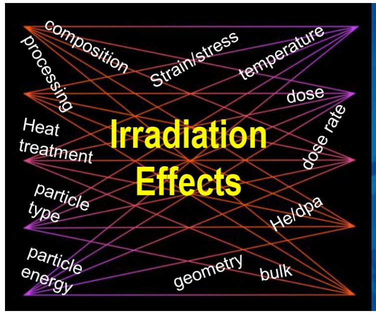
Material Performance Evaluation

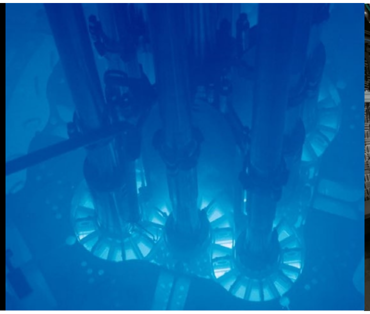
Material Performance Evaluation

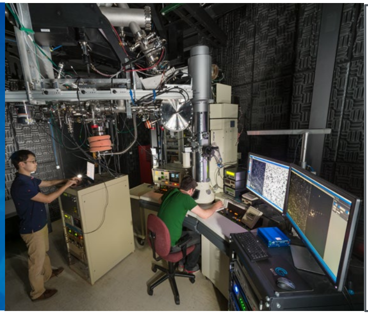
Evaluate long-term performance in nuclear reactor environments, currently focusing on AM 316H SS.

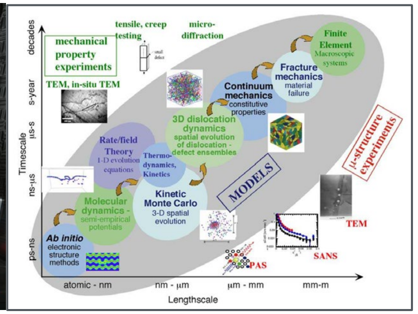
Irradiation Effects

- Ion irradiation for rapid screening and basic understanding
- Neutron irradiation for performance verification
- Qualification of AM materials with combined ion & neutron irradiation and computer modeling









Corrosion Effects

- Understand the effects of AM defects and microstructural heterogeneities on corrosion behavior
- Evaluate the corrosion performance of AM materials in nuclear environments

Processing
Feedstock, printing parameters, post-processing conditions, etc.

→

Microstructure
Porosity, residual stress, surface roughness, anisotropy, chemical segregation, grain structure, dislocation structure, etc.

→

Corrosion Behavior
General corrosion, SCC, IASCC, corrosion fatigue, intergranular corrosion, mass transfer, etc.

Corrosion test method standardization

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Technology Demonstration

Technology Demonstration

Objectives

- Identify, fabricate and test nuclear components based on specific reactor applications.
- Work closely with industry partners to develop supply chains and qualification requirements.

Component Selection

Identify specific reactor components that could take advantage of new materials or AM technologies for demonstration.

Component Testing

Evaluate component performance in representative operating environments to gain engineering experience.

Codes and Standards

Develop Codes and Standards to enable the adoption of advanced manufacturing technologies.

Supply Chain

Identify potential nuclear vendors, manufacturers, and consider vendor qualification, NQA-1 certification requirements.

Stakeholder Interaction

Interact with advanced reactor campaigns, NRIC, NRC, reactor developers and vendors, and non-nuclear commercial partners.

Knowledge Transfer

Transfer knowledge and experience to industry vendors, supply chain, owners.

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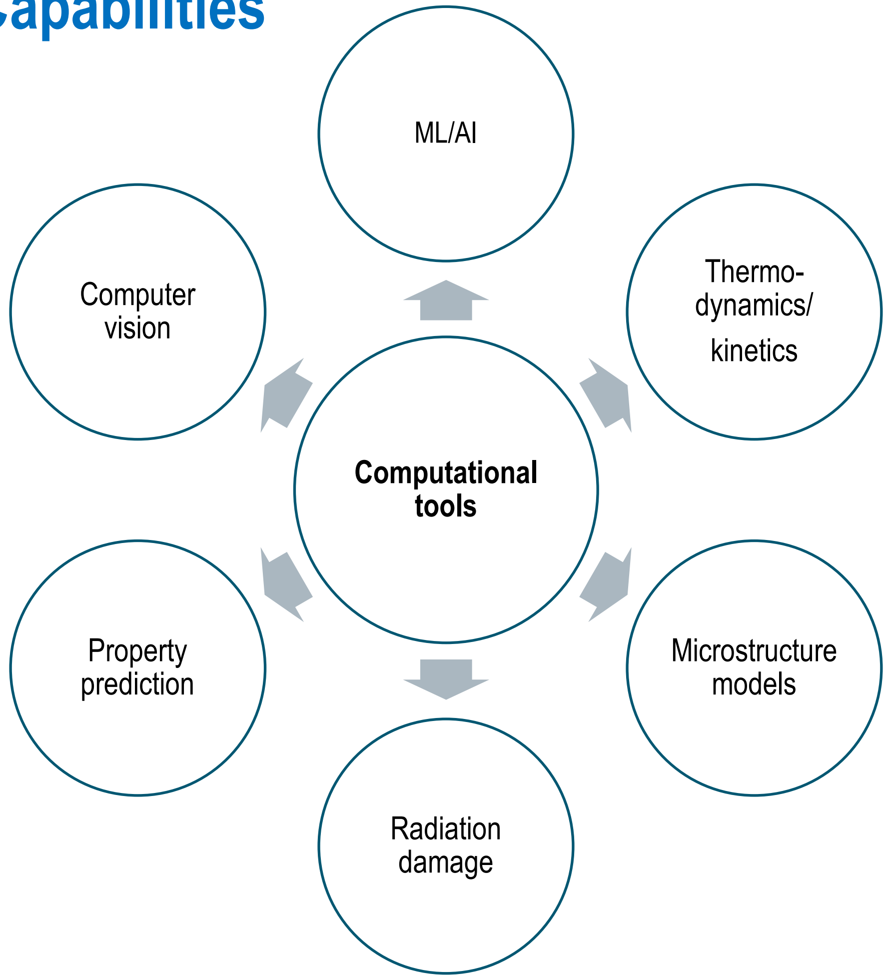
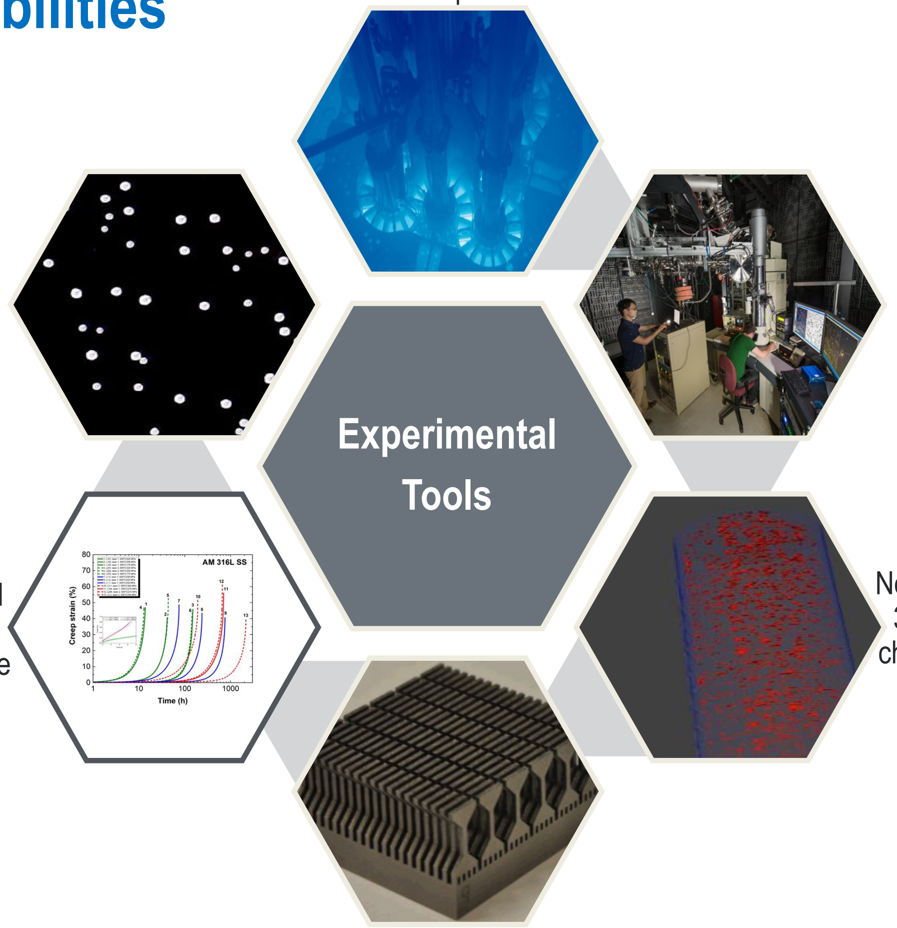
Capability Development & Transformative Research

Capability Development

Computational Capabilities



Experimental Capabilities



Transformative Research

Focus on fundamental understanding and exploratory materials and process development.

- Leverage material design capabilities developed within the AMMT program and by others (e.g. MGI and ICME) with focus on nuclear reactor considerations.
- Design materials with targeted properties through understanding of the Processing-Structure-Property-Performance relationships.
- Enable modification of existing material classes to improve radiation, corrosion, and heat resistance.
- Design and manufacture new materials incorporating understanding of new processes.
- Develop a high-dimensional, nonlinear design strategy to achieve multi-attribute optimization.
- Establish an agnostic material/component design and development integrated process.

Collaborative Research and Development

Develop collaboration & partnership to address diverse needs of the nuclear community.

Development of advanced materials and manufacturing is a cross-cutting field with many scientific and technological challenges that are not unique to nuclear energy systems. Addressing these complex problems will require collaborations and partnerships for success.

Collaborative R&D supports research in all the focus areas. In addition, it allows us to

- Investigate a broad range of technologies
- Leverage and collaborate on capability development
- Provide near-term solutions to nuclear industry

We are working with other DOE programs, funding agencies, industry partners, and universities to identify common interests and establish mechanisms for collaborations.

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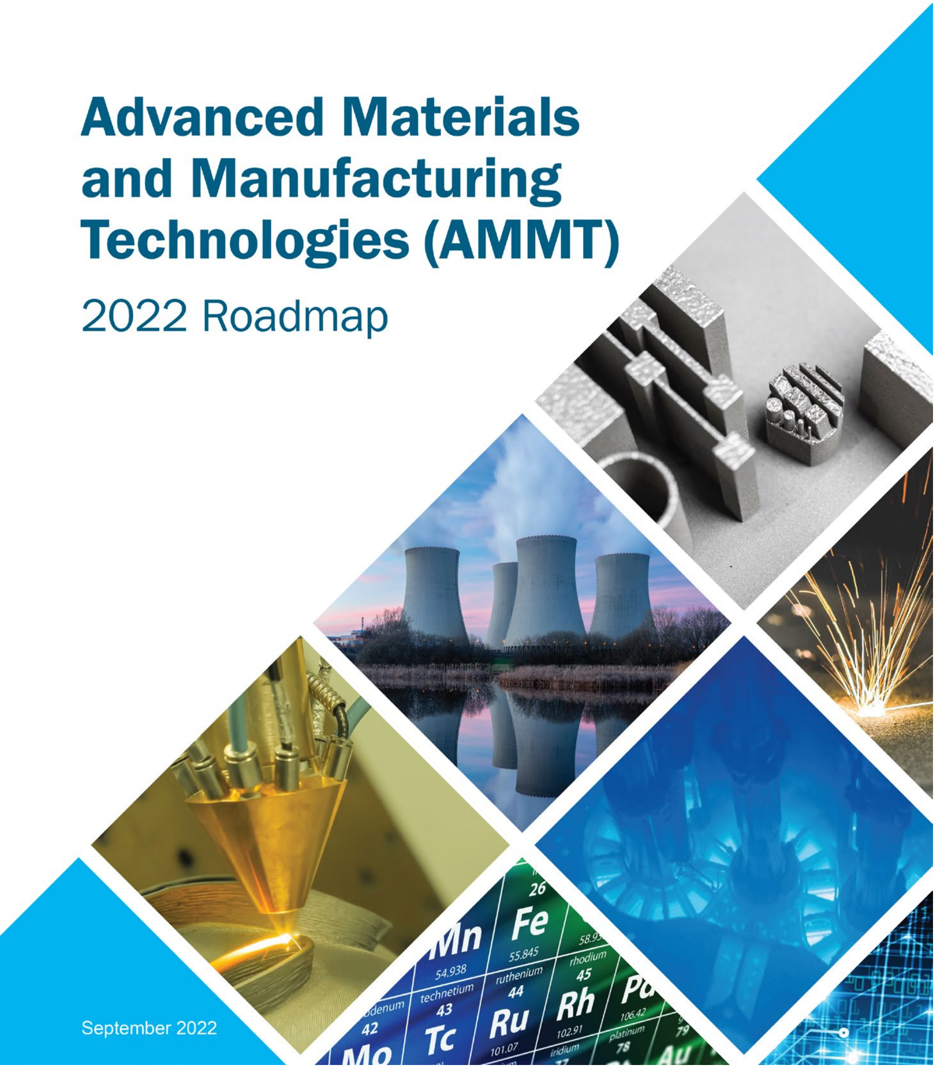
Advanced Materials and Manufacturing Technologies (AMMT)

2022 Roadmap



September 2022

Year 1	Year 2	Year 3	Year 4	Year 5

Development, Qualification and Demonstration

Advanced Materials and Manufacturing

- Optimize current reactor material for advanced manufacturing to achieve improved performance in nuclear environments
- Develop new reactor material for advanced manufacturing to achieve superior performance in nuclear environments

Rapid Qualification

- Demonstrate process-informed qualification for AM
- Demonstrate NDE techniques capable of detecting defects and various microstructural features
- Establish the MDDC framework and demonstrate its application to the qualification of LPBF 316SS
- Complete ASME Code qualification experiments and demonstrate accelerated model-based qualification

Material Performance Evaluation

- Ion/neutron regulatory acceptance white paper
- Demonstrate acceptable performance in irradiation environments using combined ion/neutron testing data and modeling results

Technology Demonstration & Deployment

- Demonstration of AM components by utilizing a rapid qualification approach
- Complete submission package for ASME Code Cases for LPBF 316 SS

Capability Development and Transformative Research

Advanced Experimental Techniques

- Demonstrate accelerated creep testing techniques for use in Code qualification
- Develop computer vision and machine learning-enabled automated microstructural characterization and quantification tools for in-situ studies

Modeling Capabilities for Qualification

- Exercise multiscale and machine learning modeling for microstructure prediction and engineering during additive manufacturing
- Apply data science methodologies for multi-scale integration and robust extrapolation in support of accelerated qualification

Transformative Research

- Demonstrate scientifically-guided AI-based thermodynamic, kinetic, and defect engineering capability for developing high-performance nuclear reactor materials

Collaborative Research and Development

- Working with DOE programs, NRC, industry, and universities, etc.

Summary

Advanced Materials & Manufacturing

- Optimize existing materials and develop new materials for advanced manufacturing.

Question –
What new materials and manufacturing technologies would have the highest impact on the nuclear industry and for what applications?

Material Performance Evaluation

- Evaluate irradiation and corrosion behavior of advanced materials, currently focusing on LPFB 316H SS.

Question –
What irradiation and corrosion data are needed for AM materials?

Rapid Qualification

- Establish a rapid qualification framework via qualifying LPBF 316H SS.

Question –
What strategies and new methods do you recommend to accelerate the LPBF 316H SS ASME Code Case development?

Technology Demonstration

- Accelerate commercialization through technology demonstration.

Question –
What are the most promising advanced manufacturing technologies and/or reactor components that could be demonstrated with nuclear industry?

Questions?

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