Advanced Materials and Manufacturing

Optimize & Manufacture Existing Materials

- Optimize current reactor material for advanced manufacturing for nuclear applications

Ongoing activities
- Prioritization of current reactor materials for advanced manufacturing (ANL, INL, PNNL)
- Improve and optimize LPBF 316 SS to improve heterogeneity in AM material (ORNL)
- Develop 316H and ODS steels by solid-state manufacturing processes (PNNL)

Develop & Manufacture New Materials

- Develop new reactor material through advanced manufacturing to achieve superior performance in nuclear environments

Ongoing activities
- Preliminary feasibility studies of new materials for advanced manufacturing (LANL, ORNL, PNNL)
- Develop 316H and ODS steels by solid-state manufacturing processes (PNNL)

Large-Scale Additive Manufacturing

- Fabrication of large-scale nuclear components with advanced manufacturing technologies

Ongoing activities
- Large scale additive manufacturing for nuclear applications (ORNL)

Critical Minerals

- Address the supply of critical minerals, decrease the supply risk, increase cost effectiveness via advanced manufacturing

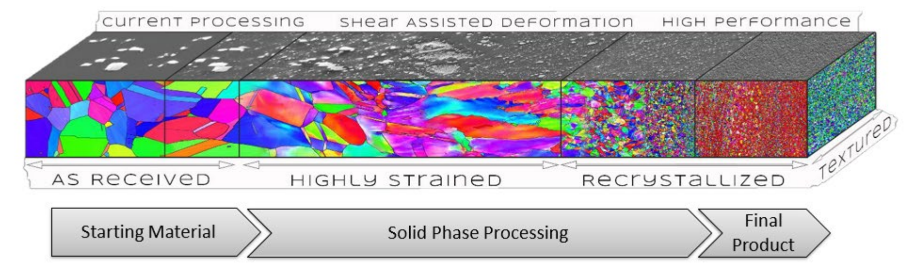
Ongoing activities
- Critical minerals (PNNL)

Milestone 1: Optimize current reactor material for advanced manufacturing to achieve improved performance in nuclear environments (2026)
Milestone 2: Develop new reactor material for advanced manufacturing to achieve superior performance in nuclear environments (2027)

Optimize and Manufacture Existing Materials

Improve and Optimize 316 SS

- Develop optimized AM 316 SS to minimize microstructural heterogeneity.
- Modify AM 316 SS with tailored microstructures for improved radiation, corrosion, and high-temperature resistance.
- Solid-state manufacturing of 316H stainless steel.



Improve and Optimize Steel/Ni Alloys

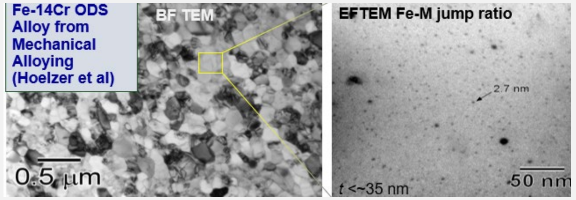
- Down-select high-performance, high-impact steels and Ni-based alloys for AM technologies.
- Consider the significance to nuclear industry, material processability via AM technologies, and improved performance in nuclear reactor environments.
- Prioritize existing reactor materials for AM technologies.
- Optimize selected materials for AM to achieve improved performance in nuclear environments.

Develop and Manufacture New Materials

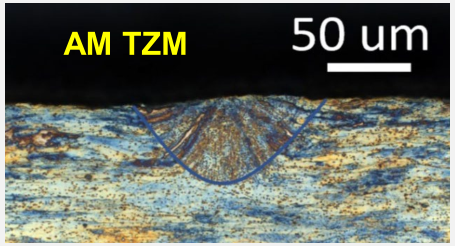
- To explore new materials and feasible manufacturing routes to achieve superior high-temperature, radiation and corrosion resistance.
  - Corrosion-resistant cladding/coatings
  - Metal/ceramic composites
  - Refractory alloys
  - High entropy alloys
  - Functionally graded materials

Preliminary Feasibility Studies of New Materials for Advanced Manufacturing

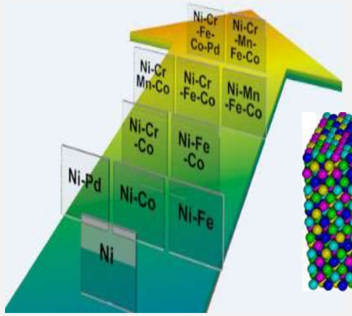
ODS Alloys

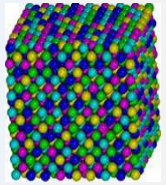


Refractory & Composites



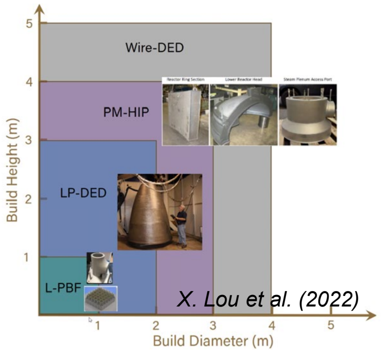
High Entropy Alloys

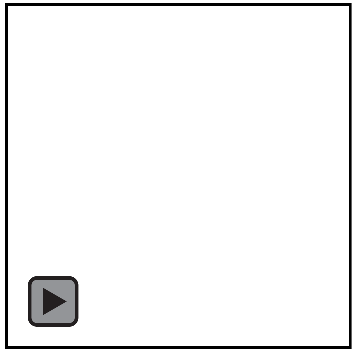




- Down-select material and alloy systems.
- Explore feasibilities of their processing routes for practical applications.
- Provide a prospective of nuclear application and future direction.

Large-Scale Additive Manufacturing





Challenge

- Large-scale additive manufacturing technologies like direct energy deposition (DED) can fabricate components on the size scale of meters such as valves, pumps, impellers, etc., that are challenging or difficult to source, especially when developing new systems or replacing obsolete components.

Objectives

- Understand the current state of large-scale DED technology for the deposition of mild steel (HIP cans) and 316 SS (final components).
- Determine methods for *in-situ* monitoring that could be incorporated into the MDDC platform for quality control.
- Perform microstructure and mechanical property evaluation on the printed materials.

Milestones

- Demonstrate PM-HIP can technology fabricated from mild steel.
- Fabricate large-scale components using DED technology.
- Outline potential path for certification and qualification.

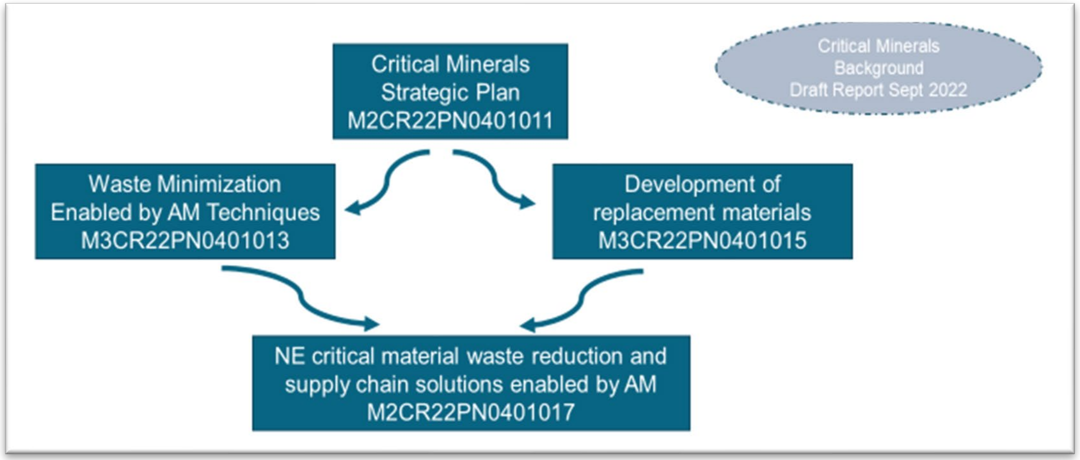
Critical Minerals

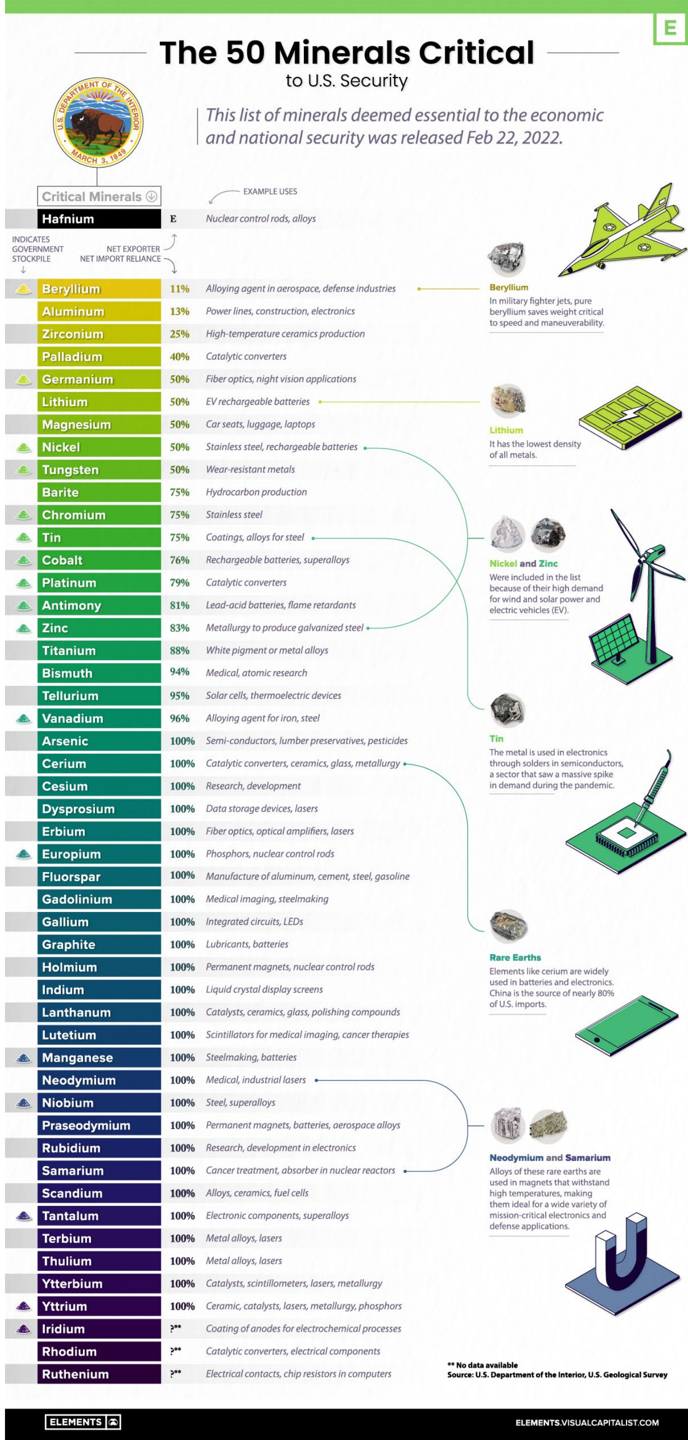
WHAT ARE CRITICAL MINERALS?

Elements that are "*vital for the economic well-being of the world's major and emerging economies, yet whose supply may be at risk due to geological scarcity, geopolitical issues, trade policy or other factors.*"

Scope and Milestones

- Provide a summary of how advanced manufacturing can impact critical minerals waste and supply chain.
- Develop a supply solution through application of replacement material design and development enabled by advanced manufacturing.





Rapid Qualification of AM Materials/Components

Process Understanding & in situ Process Monitoring

- Understand the manufacturing process, integrate in situ process monitoring data, and generate AM material property data.

Ongoing activities
- Processing understanding for qualifying LPBF 316 SS (ANL, LANL, ORNL)
- Uncertainty reduction in AM qualification and certification (ORNL)
- Accelerate creep testing (ANL)

Post-process NDE

- Develop advanced reliable, high-resolution NDE techniques for AM components with complex geometries.

Ongoing activities
- Post-process NDE (INL, PNNL)

Process-Structure-Property Relationship

- Understand the Process-Structure-Property relationship to accelerate qualification.

Ongoing activities
- Process modeling and variability in AM 316 SS (ORNL)
- Modeling microstructure-property relationship in AM 316 SS (LANL)
- Mechanistic modeling of creep and aging for time extrapolation in LPBF 316 SS (ANL, INL, LANL)

Multi-Dimensional Data Correlation (MDDC) Platform

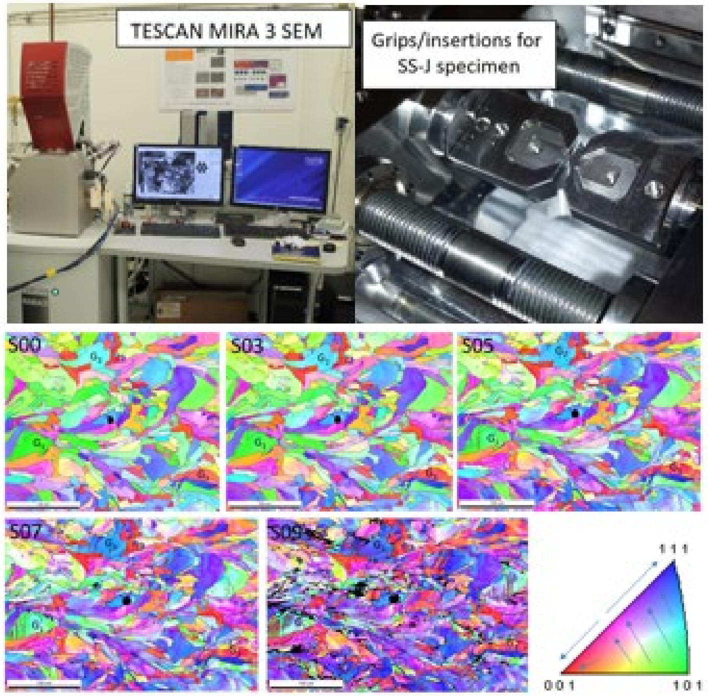
- MDDC platform integrates manufacturing, characterization, testing and modeling data for materials/component qualification.

Ongoing activities
- Unified software architecture for AMMT data management and processing (ORNL)
- MDDC platform: multi-length scale data integration (ANL, INL, LANL, ORNL, PNNL)

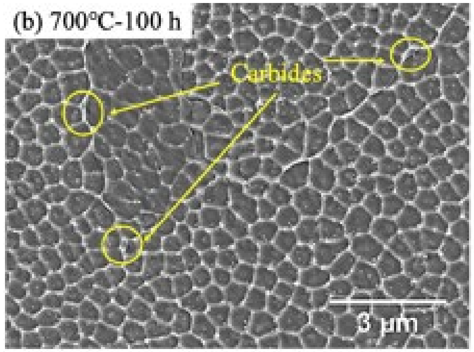
Milestone 1: Demonstrate process-informed qualification for AM (2024)
Milestone 2: Demonstrate NDE techniques capable of detecting defects and various microstructural features (2025)
Milestone 3: Establish the MDDC framework and demonstrate its application to the qualification of LPBF 316SS (2026)
Milestone 4: Complete ASME Code qualification experiments and demonstrate accelerated model-based qualification (2027)

Processing Understanding for Qualifying LPBF 316 SS

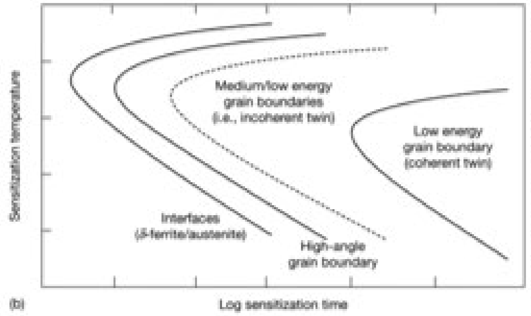
- Understand the effects of processing and post-processing conditions on residual stress, porosity and microstructure of AM 316H SS.
- Identify the key process parameters and postprocessing conditions that have the most influence on component performance.
- Conduct a round robin style testing campaign across the ORNL, ANL and LANL teams to understand material quality/repeatability requirements.
- **Make prerequisite decisions to support Code qualification of LPBF 316H SS for use in high temperature reactors.**



M. Gussev et al., ORNL/TM-2020/1574



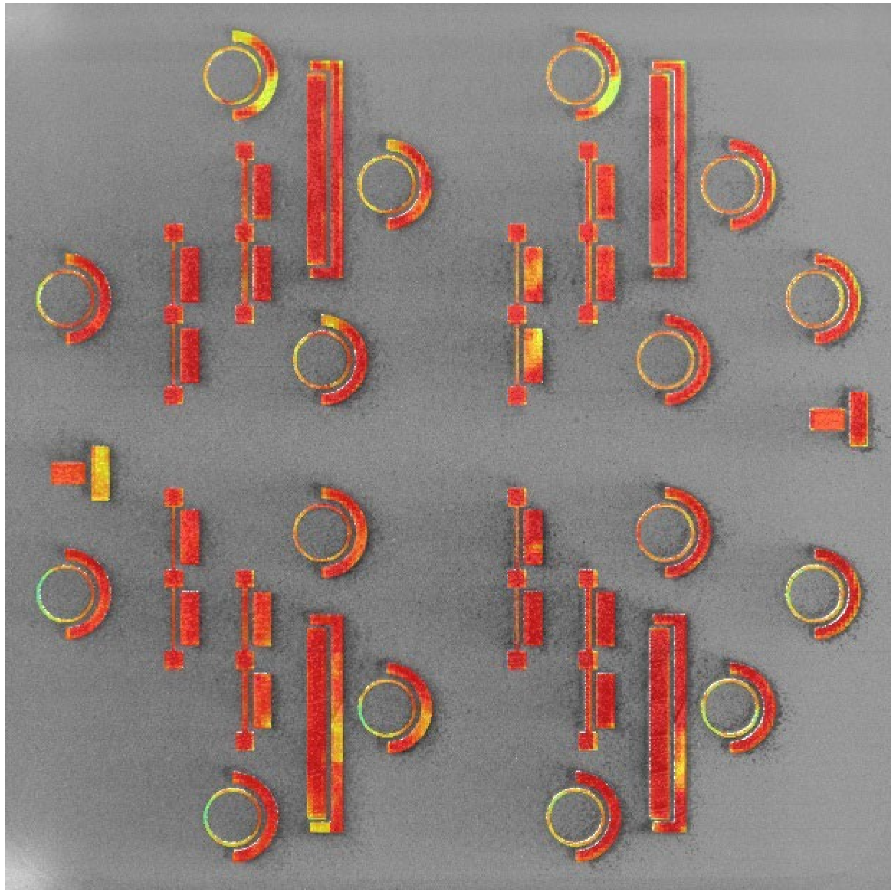
H. Yin, Additive Manufacturing, 2021



D.L.Engelberg, Shriers Corrosion, 2010

Uncertainty Reduction in AM Qualification/Certification

- Develop *in situ* sensing to mitigate the risks associated with material qualification and reduce the reliance on exhaustive testing.
  - Develop novel sensors for evaluating melt pool solidification and residual strain during manufacturing and the range of resulting microstructures for a given material system and set of process parameters
  - Identify instrumentation that can provide higher-fidelity information regarding material properties and performance during manufacturing
- Integrate *in situ* process monitoring data with characterization and testing data.
- Ultimate goal is to qualify nuclear components by mapping properties to *in situ* processing data.



AI-based prediction of mechanical performance based on *in situ* processing data (colors represent mechanical property values; the shapes are parts within the printing layer).

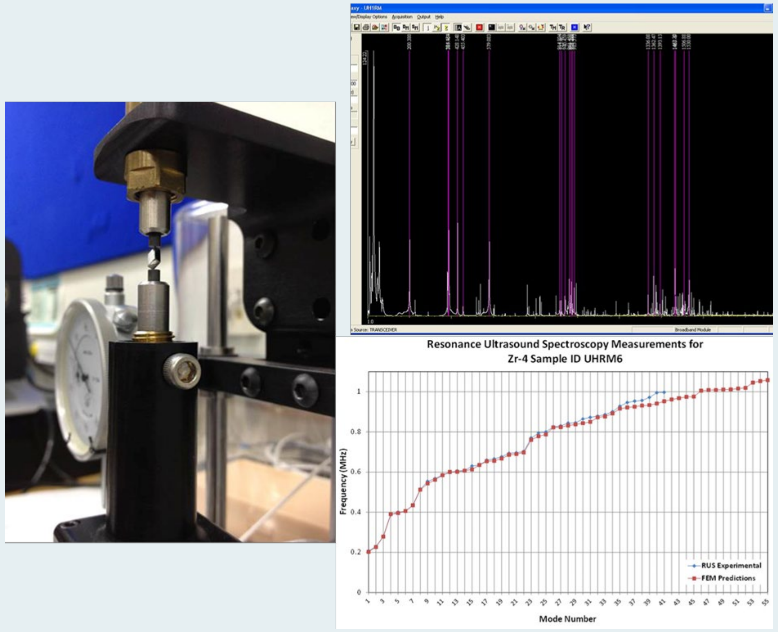
Post-Process NDE

Objectives

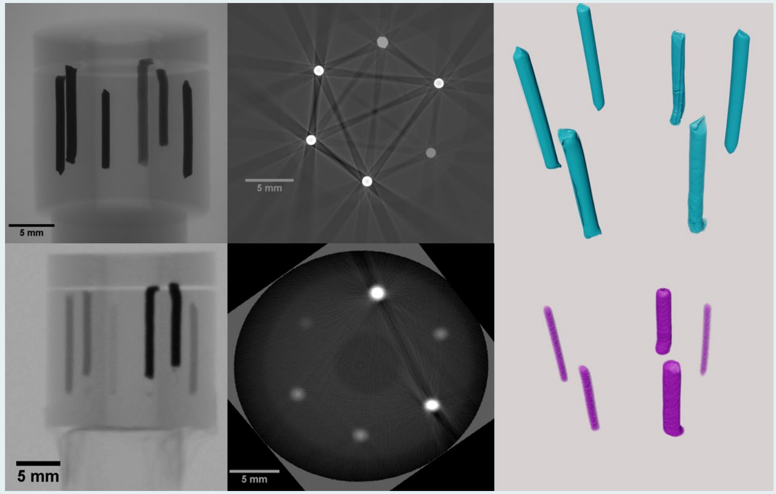
- Identify and address unique challenges associated with NDE applied to AM components.
- Determine technical basis for identification and development of advanced, reliable and high-resolution NDE techniques.
  - Complex geometries
  - Defect sensitivity
  - Materials elastic properties

Outcome

- Establish capability of resonant ultrasound spectroscopy (RUS) to confirm elastic properties of AM components.
- Increase ability to interrogate AM materials using combined neutron and X-ray computed tomography.
- Support qualification of AM materials and components with NDE techniques.



Resonant Ultrasound Spectroscopy - PNNL



Neutron and X-ray Computed Tomography - INL

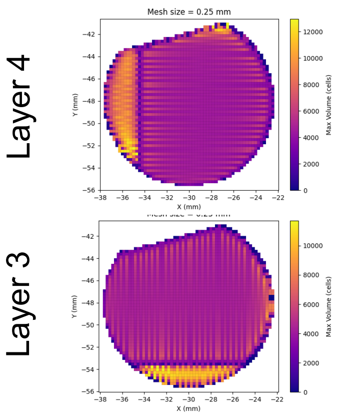
Processing Modeling and Variability in AM 316 SS

Process-Structure Relationship:

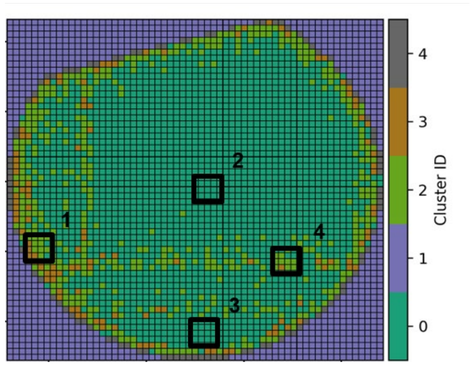
Understand the impacts of process parameters on microstructural features resulting from AM processes.

- Focus on a multitude of modeling techniques
  - Thermal and mass transport
  - Solidification modeling
  - Grain structure modeling
  - Residual stress modeling
- Work closely with experiments for model calibration and validation
  - Scan path information for geometries of interest
  - Melt pool and microstructural data
- Link to properties modeling and the MDDC platform

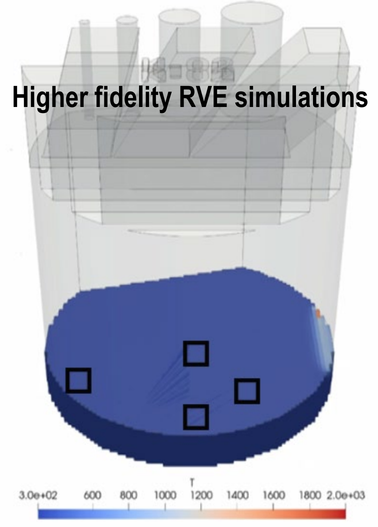
Leveraging previous DOE investment: AMO/OE 3DThesis, ASCR ECP ExaAM

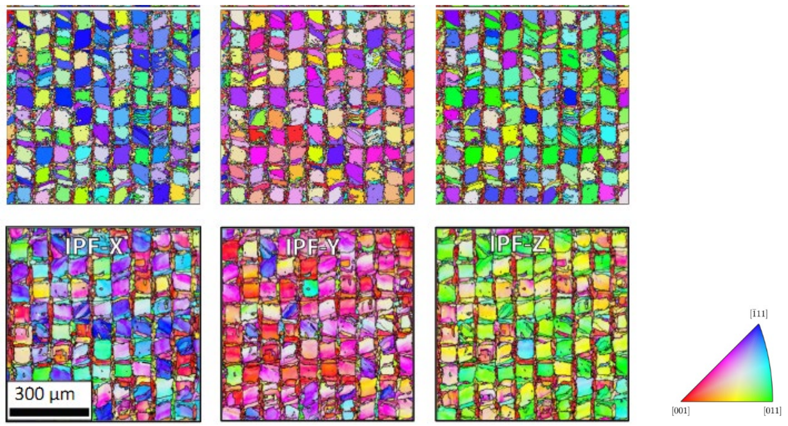


Reduced order thermal estimate



Cluster analysis to identify RVEs





Microstructure simulation

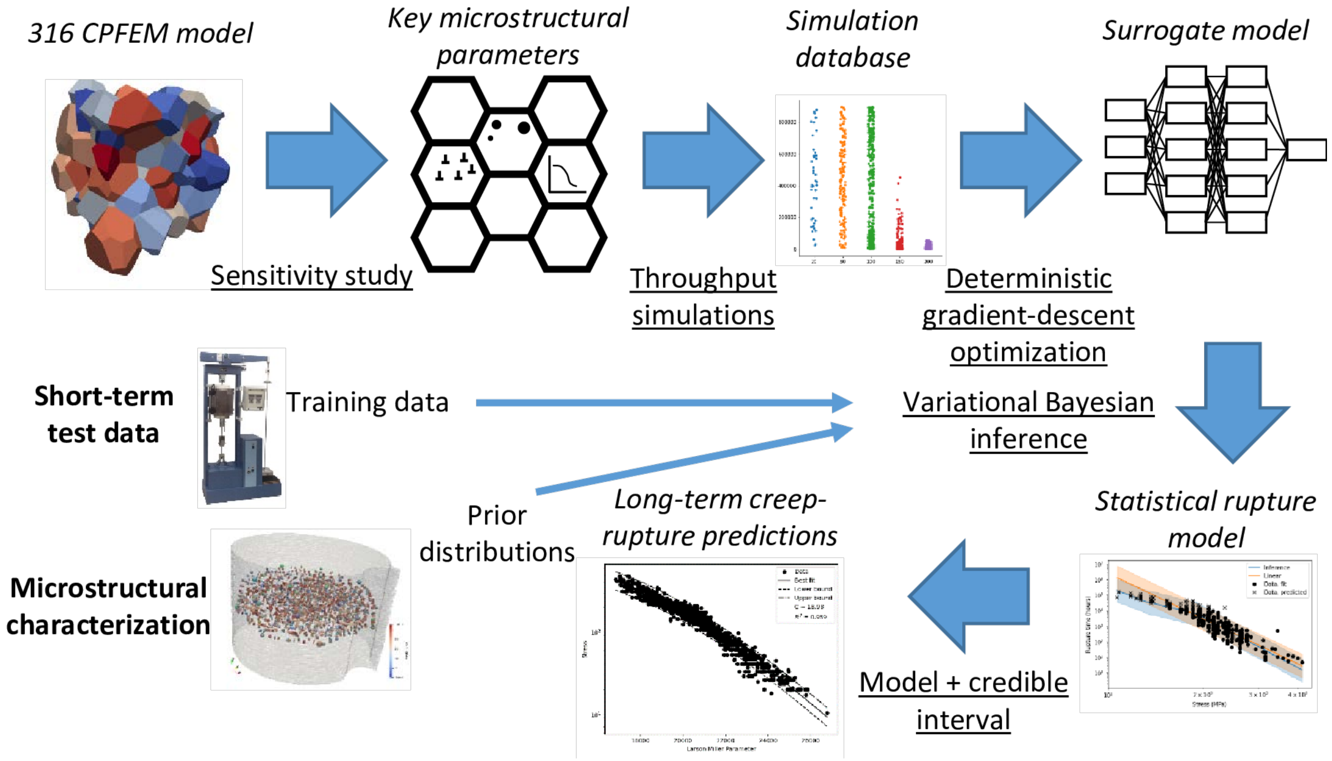
Mechanistic Modeling for Accelerated Qualification

Structure-Property-Performance Relationship:

Model the correlation of mechanical properties with microstructural parameters and environmental effects with uncertainty quantification.

- Modeling microstructure-property relationship in AM 316 SS
  - Quantify the correlation and impacts of AM microstructure on tensile properties
- Mechanistic modeling of creep and aging for time extrapolation in AM 316 SS
  - Model aging kinetics and precipitation behavior during long-term thermal exposures
  - Develop mechanistic models for creep and aging response of AM 316H SS
  - Work toward Bayesian model for extrapolating short-term creep/aging data to long-term predictions
  - Include radiation effects to model irradiation creep behavior

Predicting Long-term Creep Rupture Strength



MDDC Platform: Multi-length scale Data Integration & Unified Software Architecture

Multi-length Scale Data Integration

- A multi-lab effort involving ANL, INL, LANL, ORNL, PNNL.
- Each laboratory will provide input regarding materials processing, characterization, testing, and modeling data spanning from the micro, meso, and macro scale.
- Establish required procedures governing data collection, data transfer, and recording at each lab.
- Establish a data integration plan to be incorporated with the MDDC platform.

Unified Software Architecture

- Determine data architectures required to address the handling of the multilength scale data needed for informed certification and qualification of nuclear components.
- Define a data management strategy to collect, store, and share data between all AMMT program contributors and collaborators.
- Design a unified software architecture that can be transferred across all partners within the AMMT program using AM technologies.

Material Performance Evaluation

Neutron Irradiation and PIE

- Conduct neutron irradiation and PIE to establish a technical basis for regulatory acceptance of AM 316 SS

Ongoing activities
- Neutron irradiation and PIE for AM 316 SS and novel materials (INL)
- Neutron irradiation for accelerated qualification (ORNL)

Ion Irradiation and Computer Modeling

- Conduct ion irradiation for fast screening of new materials and for supporting regulatory acceptance of AM materials with combined ion, neutron irradiation and computer modeling

Ongoing activities
- Ion irradiation and computer modeling of AM materials (ANL, INL)
- White paper for addressing material qualification using combined neutron and ion irradiation data (ANL, INL)

Corrosion Testing of AM Materials

- Determine the corrosion responses of AM materials in nuclear reactor environments

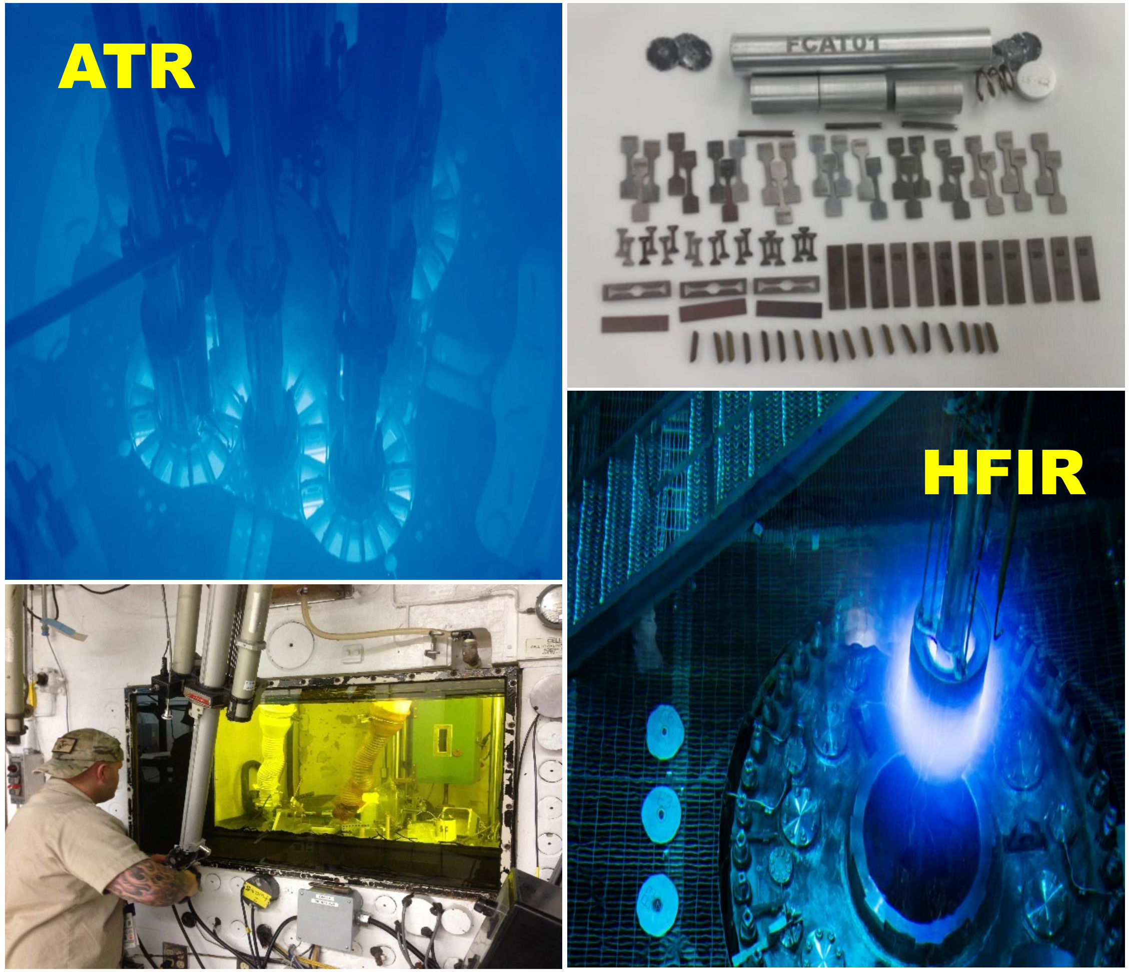
Ongoing activities
- Survey corrosion testing methodologies for AM materials (ANL, INL, PNNL)

Milestone 1: Ion/neutron regulatory acceptance white paper (2023)
Milestone 2: Demonstrate acceptable performance in irradiation environments using combined ion/neutron testing data and modeling results (2027)

Neutron Irradiation and PIE

Generate a database of irradiated material properties

- Perform neutron irradiation experiments at the Advanced Test Reactor (ATR) and High Flux Isotope Reactor (HFIR) and post-irradiation examination (PIE).
- Link irradiation data of the selected materials to AM builds with high-pedigree digital signatures and well-characterized local microstructures.
- Evaluate the performance of new materials in nuclear reactor environments.
- Establish a technical basis for qualification of AM materials.



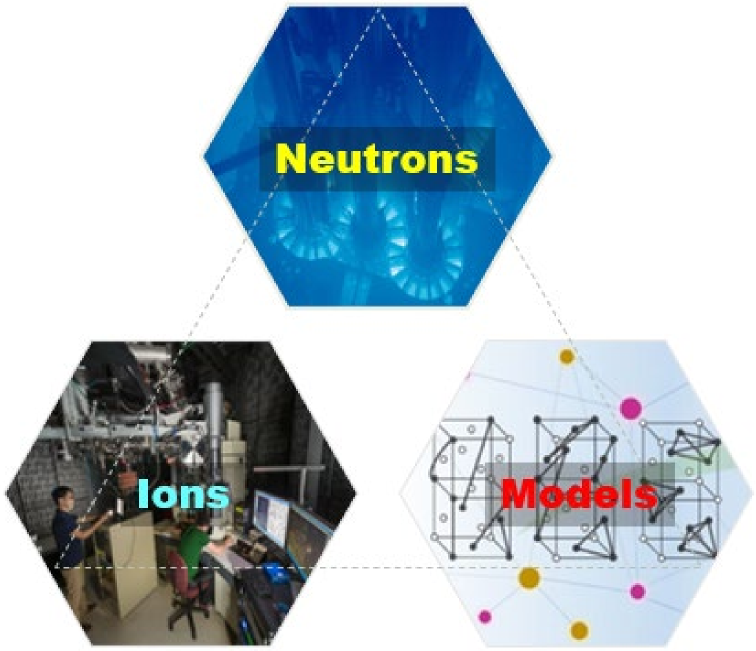
Ion Irradiation and Computer Modeling

Motivation

- Both neutron and ion irradiation tools have their advantages and limitations.
- Each irradiation tool can provide unique and complementary information.
- Use the collective neutron and ion irradiation information coupled with physics-based modeling to establish a technical basis to accelerate material's qualification.

Objectives

- Perform ion irradiation experiments to develop microstructure-based understanding of irradiation behavior of AM materials.
- Perform ion irradiation experiments to provide high-fidelity data for model refinement and validation.
- Perform modeling and simulation to interpret the ion and neutron data and predict damage behavior for various irradiation conditions.



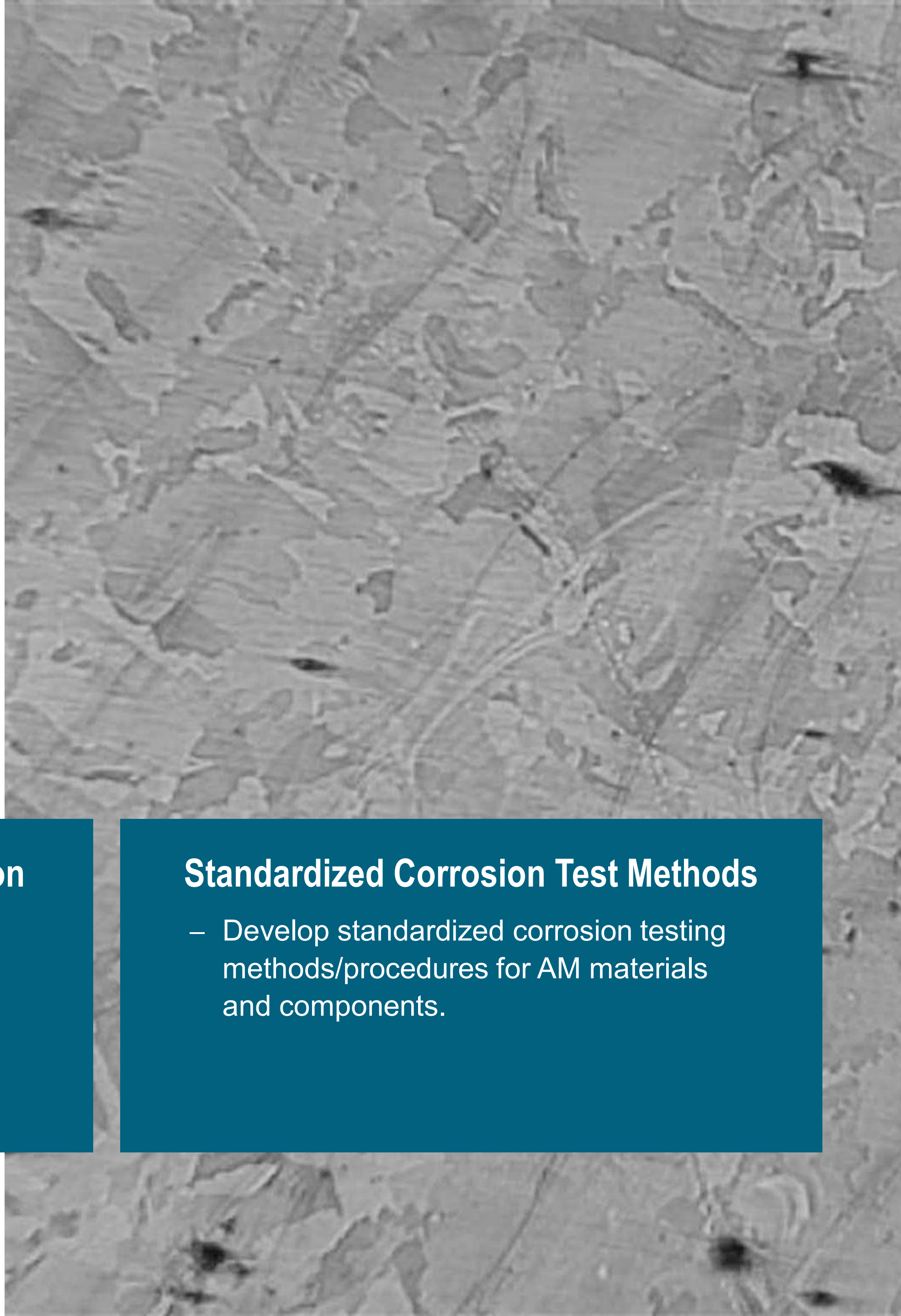
White Paper to Address Material Qualification using Combined Neutron & Ion Irradiation Data

- Provide a path forward for promoting the regulatory acceptance of using combined ion and neutron irradiation data supported by modeling and simulation.
- Leverage previous and ongoing research efforts (e.g. SNAP project).
- Focus on unique aspects of different irradiation tools to provide complementary data of a material's radiation behavior rather than direct correlation between ion and neutron irradiation data as done in the previous work.

Corrosion Testing of AM Materials

Survey corrosion testing needs and methodologies for AM materials

- Determine the basic needs and concerns specific to corrosion of AM materials for applications in nuclear reactors environments and support future AMMT corrosion testing efforts.



Evaluation of Corrosion Performance

- Evaluate the corrosion performance of AM materials and components in nuclear environments.

Microstructure-Corrosion Correlation

- Influence of surface roughness, porosity, residual stresses.
- Influence of melt pool boundaries.
- Influence of microstructural anisotropy.

Standardized Corrosion Test Methods

- Develop standardized corrosion testing methods/procedures for AM materials and components.

Technology Demonstration

Component Fabrication and Demonstration

- Engage with industry partners to identify, fabricate components using AM and demonstrate their performance

Ongoing activities
- Component Fabrication and Demonstration of AM 316 SS (ORNL)
- Manufacturing Quality Assurance (ORNL)

ASME Engagement for Materials Code Qualification

- Establish a Code Case for LPBF 316 SS to demonstrate the accelerated qualification framework

Ongoing activities
- ASME Engagement (ANL, INL, ORNL, PNNL)
- ASME Code qualification plan for LPBF 316 SS (ANL, INL, ORNL, PNNL)

Qualification Process Evaluation

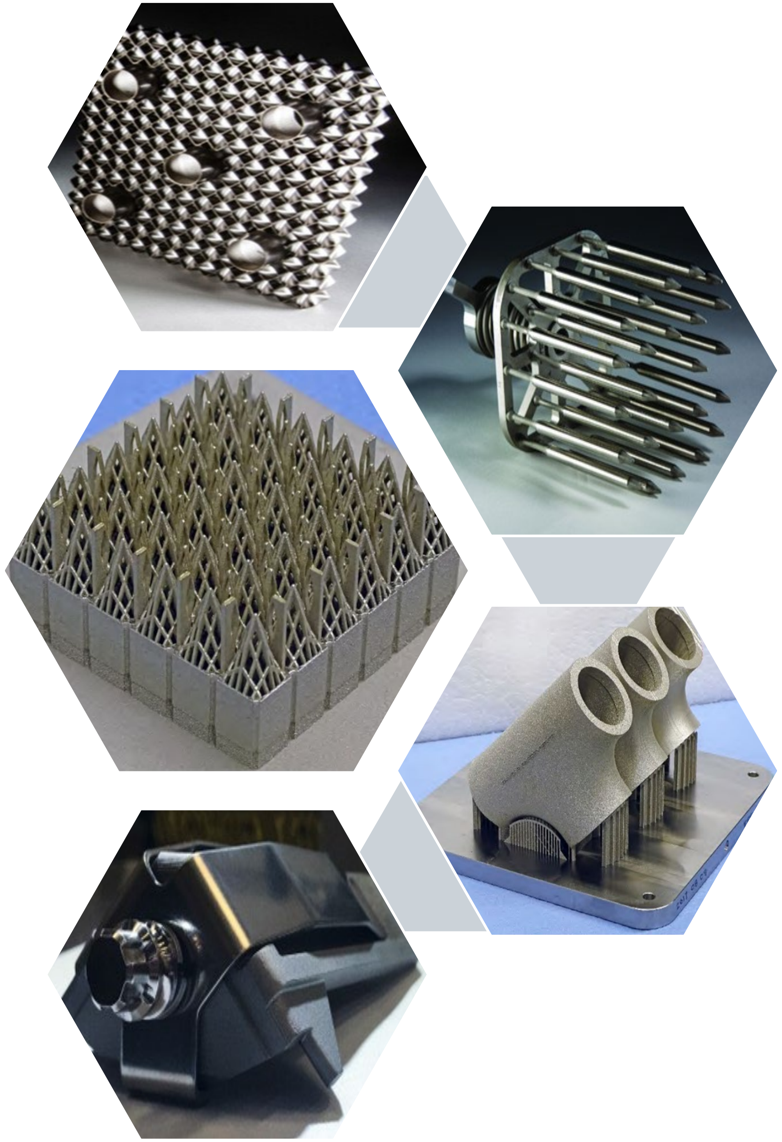
- Survey qualification methodologies adopted by other industries and develop a long-term qualification strategy

Ongoing activities
- Qualification process evaluation (PNNL)

Milestone 1: Demonstration of AM components by utilizing a rapid qualification approach (2026)
Milestone 2: Complete submission package for ASME Code Cases for LPBF 316 SS (2027)

Component Fabrication and Demonstration

- Engage with industry partners to identify components for potential demonstration projects.
- Manufacture selected components using AM technologies.
- Perform and benchmark demonstration analyses against modeling and simulation results.
- Include both modeling and *in situ* data in the MDDC platform.
- Apply lessons-learned from the demonstrations to complete a roadmap for demonstration of other advanced materials and manufacturing techniques.



ASME Engagement for Material Code Qualification

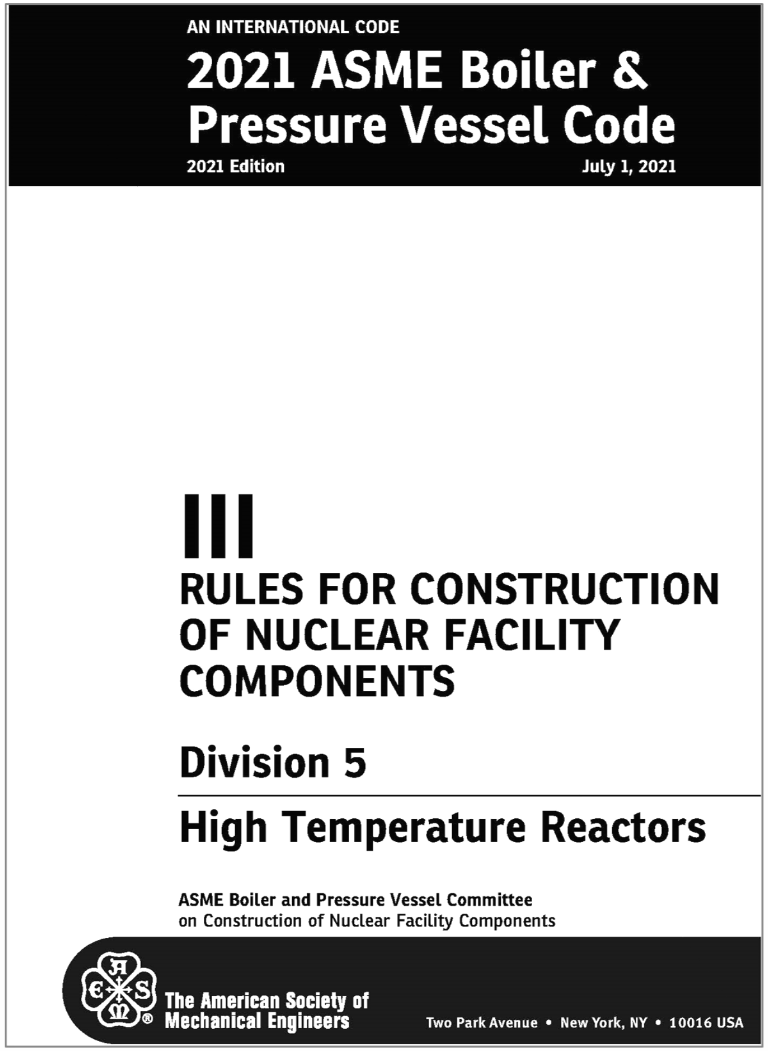
ASME Engagement

- Attend ASME Code Week meetings (4x per year) to push forward AM 316H qualification.

ASME Code Qualification Plan

- Develop a plan to qualify LPBF 316H SS for use with ASME Section III, Division 5 rules via a Nuclear Code Case.
  - Address key differences between AM materials and conventional materials.
  - Include a strategy for engaging with ASME Code Committees.
  - Develop a test plan to qualify the material using existing qualification approaches.
  - Describe opportunities for accelerating the ASME qualification process.

M2 Milestone: ASME Code Qualification Plan for LPBF 316 SS (2023)



Qualification Process Evaluation

- Survey qualification methodologies adopted by other industries.
- Identify emerging qualification strategies.
- Summarize international nuclear industry qualification efforts.
- Summarize current and planned activities under the codes and standards organizations.
- Provide gap analysis and recommendations.
- Provide a qualifications strategy for advanced material and manufacturing technologies.

ASTM International	International Organization For Standardization	American Society of Mechanical Engineers
SAE International	American Welding Society	Institute of Electrical and Electronics Engineers
American Petroleum Institute	MITA Medical Imaging & Technology Alliance	Association for the Advancement of Medical Instrumentation
Metal Powder Industries Federation	Underwriters Laboratories, Inc.	IPC - Association Connecting Electronics Industries

Capability Development & Transformative Research

Advanced Experimental Techniques

- Develop accelerated testing, high-throughput characterization techniques critical and unique to AMMT

Ongoing activities

- Automated, high-throughput materials characterization techniques (ORNL)
- Computer vision enabled automated microstructural quantification (ANL, PNNL)
- Accelerated creep testing techniques for Code use (ANL, INL)
- Rapid testing and characterization (INL)

Computational Capabilities for Qualification

- Develop application-specific computational capabilities for accelerated development and qualification

Ongoing activities

- Physics models and data analytics (INL)

Transformative Research

- Perform transformative research to build a pipeline of future capabilities and discoveries

Ongoing activities

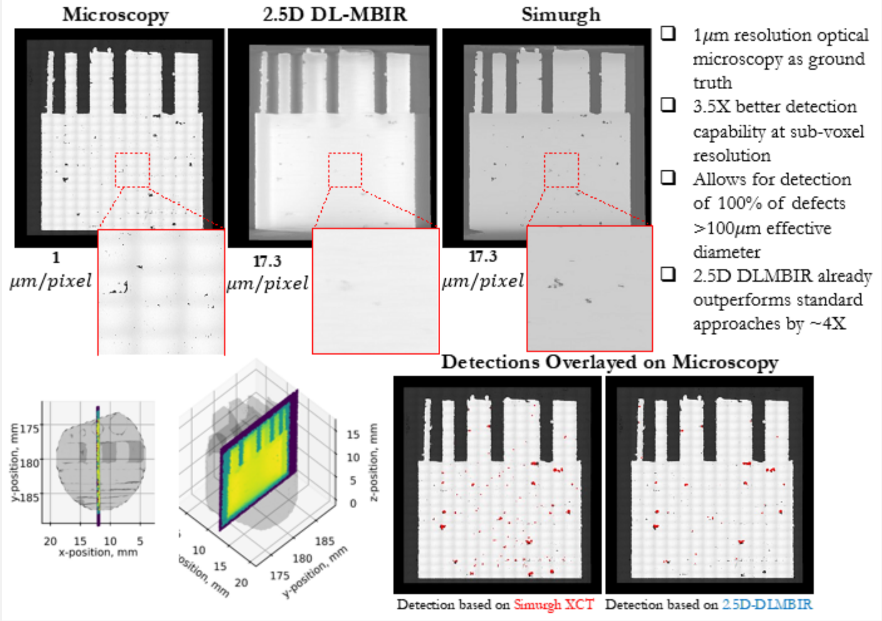
- Scientifically-guided AI methods for material development and qualification (INL)

Milestone 1: Demonstrate accelerated creep testing techniques for use in Code qualification (2025)
Milestone 2: Develop computer vision and machine learning-enabled automated microstructural characterization and quantification tools for in-situ studies (2027)
Milestone 3: Exercise multiscale and machine learning modeling for microstructure prediction and engineering during additive manufacturing (2026)
Milestone 4: Apply data science methodologies for multi-scale integration and robust extrapolation in support of accelerated qualification (2027)
Milestone 5: Demonstrate scientifically-guided AI-based thermodynamic, kinetic, and defect engineering capability for developing high-performance nuclear reactor materials (2027)

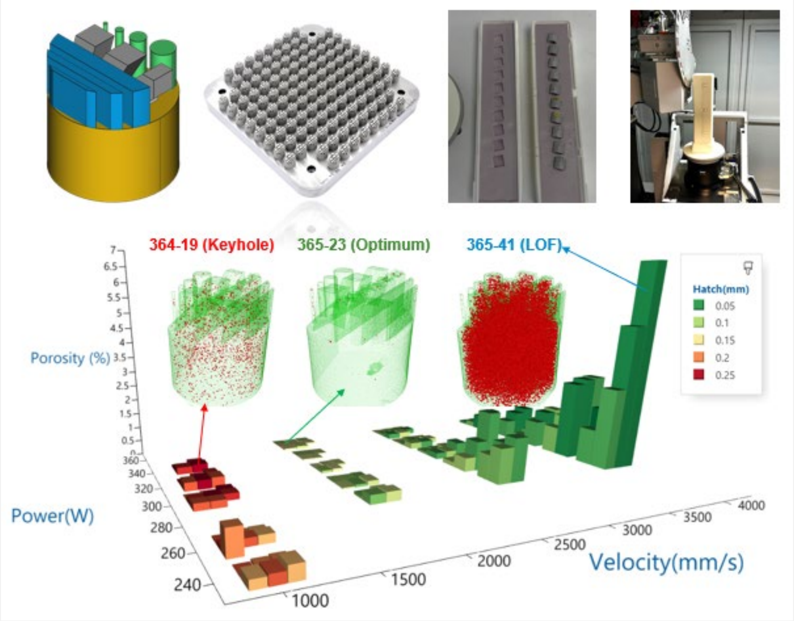
Automated Microstructural Characterization & Quantification

- Automation of microstructural characterization is important to the material development and qualification, which requires a large amount of characterization at various length and time scales.
- Quantified microstructural data is essential for establishing the relationships of the process-structure-property-performance.
- Computer vision-enabled automated microstructural analysis and quantification will be applied to a suite of microstructural characterization techniques that spans from atomistic scales (e.g., TEM) to meso scales (e.g., optical microscopy).

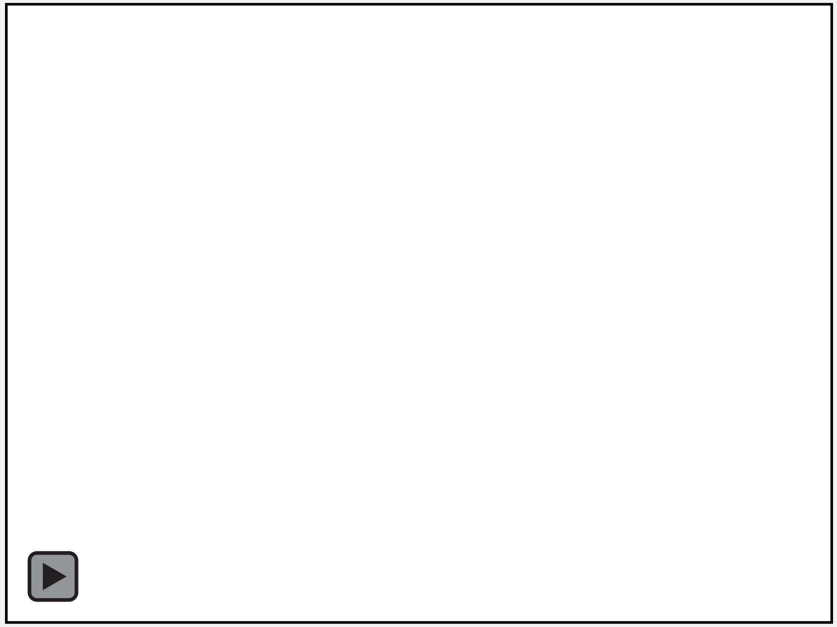
Automated Optical Microscopy



Rapid Pedigree X-ray CT Data Pipeline

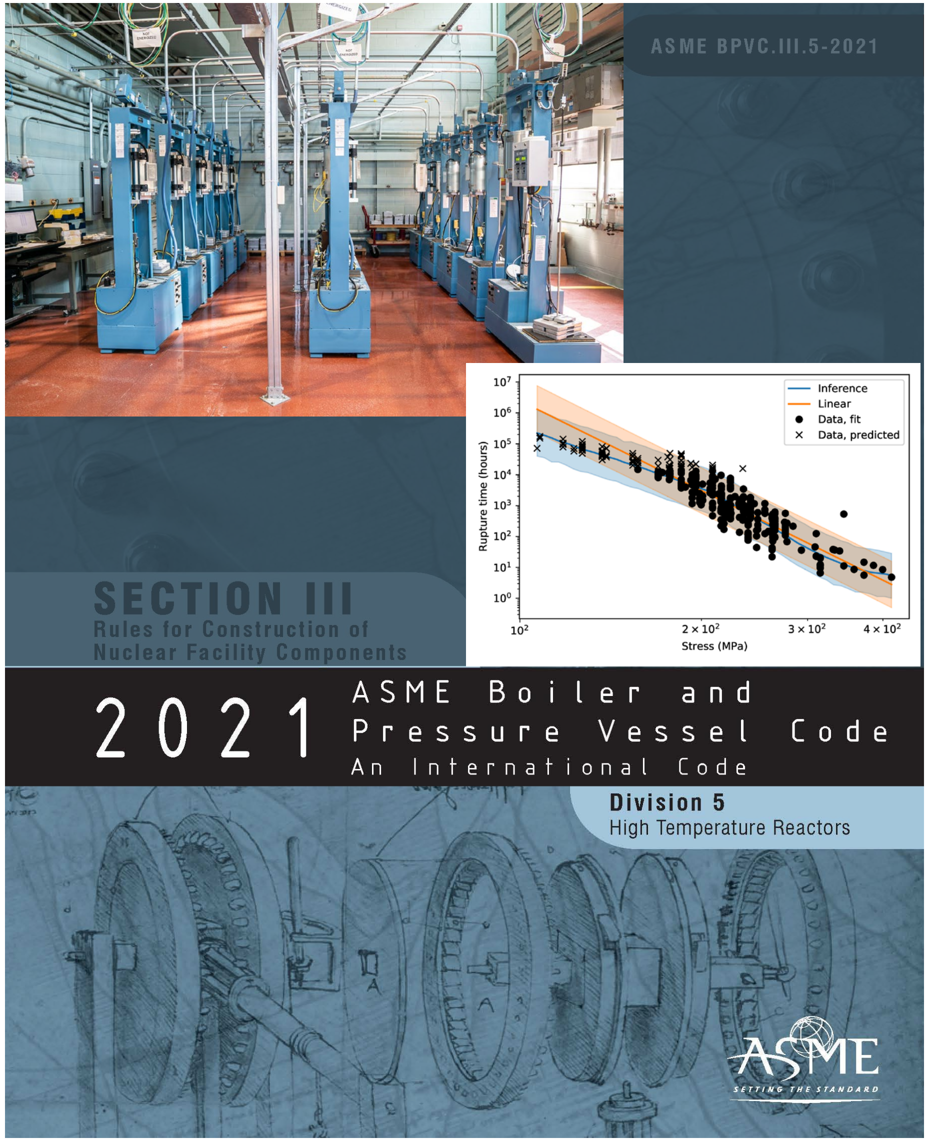


AI-based TEM Irradiation Defect Quantification



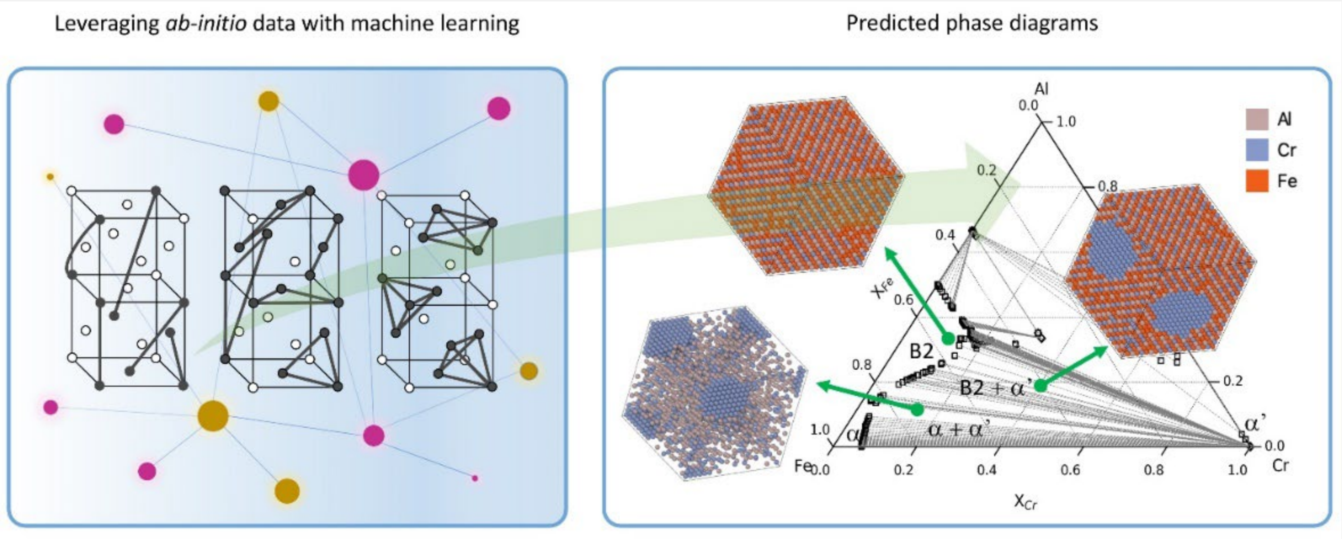
Accelerated Creep Testing for Code Use

- Overall objective is to decrease the time required for code qualification.
- A multi-pronged approach
  - Feasibility of increasing the throughput of creep testing through equipment, testing setup, specimen geometries.
  - Use of advanced instrumentation and measurement techniques to increase the relevant data.
- Concurrent effort on creep modeling.
- Interaction with relevant ASME Code Committees (e.g. Allowable Stress Criteria Working Group) for ASME Code committee acceptance.
- **Expected outcome:** Recommendations for accelerated creep testing methods for AMMT and assessment of ASME code committee reactions.



Physics Models and Scientifically-guided AI for Material Development

- Integrating ML/AI and physics-based modeling for material development by taking an ICME-based approach for manufacturing and environmental performance.
- Complete proof-of-principle of integrated multiscale mechanistic and machine learning models for AM material prediction.



Integrating physics-based modeling with machine learning to predict the energetics of atomic-scale composition variation enables calculation of multicomponent phase diagrams without experimental data.