ADVANCED NUCLEAR MATERIALS AND MANUFACTURING

Pacific Northwest NATIONAL LABORATORY

Integrating material design, development, and qualification through the complete nuclear material lifecycle

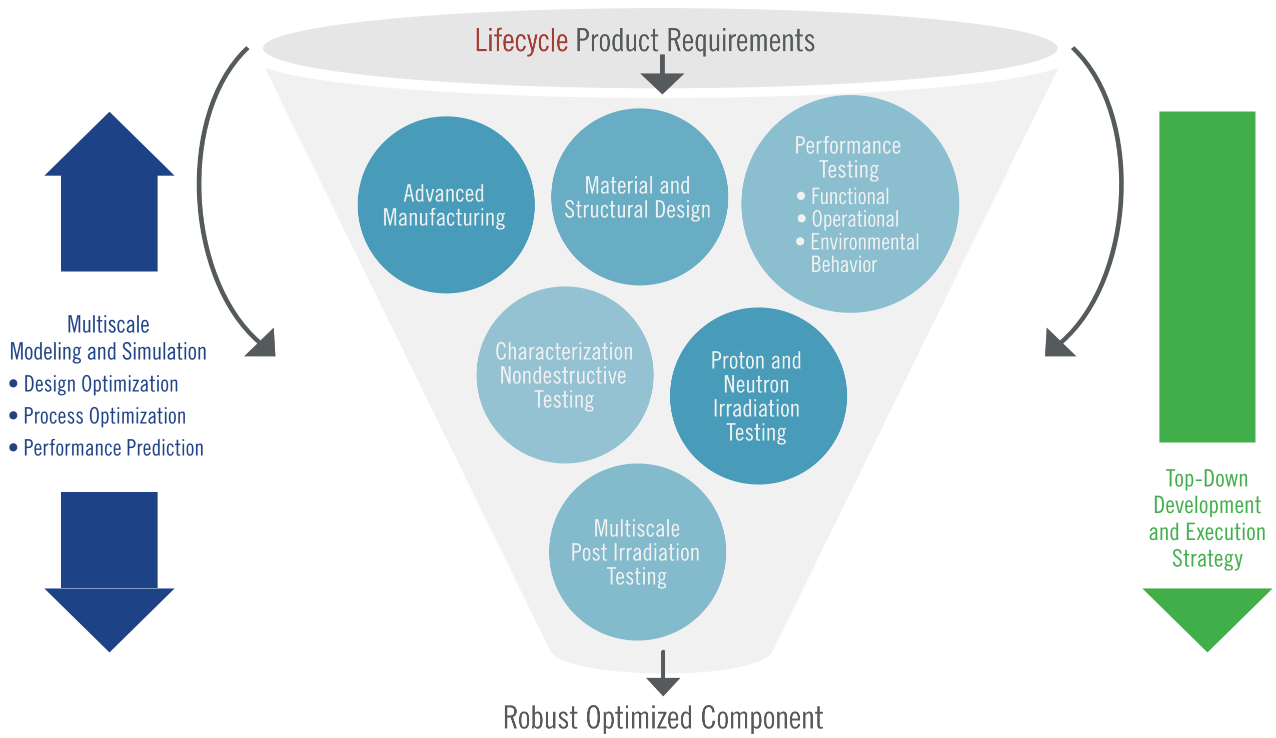
U.S. DEPARTMENT OF ENERGY

ADVANCED MANUFACTURING FOR NUCLEAR ENERGY

To meet growing energy demands, the nuclear industry needs innovative, trustworthy materials that can keep up with rapid developments in fuel and reactors. Developing new materials provides avenues for innovative reactor improvements and understanding how current material performance sustains and extends the lifetime of a nuclear facility.

Pacific Northwest National Laboratory (PNNL) streamlines the time it takes for new materials to move from design to deployment by integrating knowledge and tools to holistically address material property needs, production contingencies, development constraints, and performance quantification. Understanding a material's entire lifecycle from designing new materials through performance testing, efficient production, and successful operation allows us to more quickly create robust materials that address today's challenges and prepare for future nuclear systems that operate more safely and economically.

Integrated Reactor Material Development and Qualification Enabled by Advanced Manufacturing Technologies



Our top-down development and execution strategy allows us to manufacture a material and component simultaneously.

SOLUTION-DRIVEN MATERIAL SYSTEMS

Historically, the path from material discovery to market was a sequential process, but PNNL researchers integrate previously linear steps into a concurrent process though harnessing materials science advances. Our tools, capabilities, and expertise inform one another as they create advanced material systems to solve industry challenges throughout the entire material lifecycle.

We consider beyond the initial discovery of materials to the design, development, and qualification of components for long-term performance within any environment. As we fabricate complex and micro materials for extreme environments, our researchers can tune microstructural features to be locally designed for specific performance. We use modeling, corrosion testing, and nondestructive examination to link material performance with microstructure consistency and process repeatability for each component at each stage of a material system.

THE FOREFRONT OF TOOLS THAT ENABLE RESEARCH

Our advanced nuclear materials and manufacturing approach leverages a nexus of PNNL capabilities in materials science and engineering, physics-based computational sciences, interfacial chemistry, metrology, and data analytics. Our access to state-of-the-art materials characterization tools validates modeling methods and allows us to train machine learning algorithms against ground truth. Our unique facilities allow us to conduct experiments at pilot-scale—filling a niche between fundamental research and full-scale production.

ENHANCED TECHNOLOGY READINESS

We help developers identify ways to improve the current and future advanced material supply chain through our holistic approach. Unlike other material design approaches that create theoretical materials on a computer, we focus our materials system development with the end goal to fabricate components with obtainable materials using well-defined production processes that are ready to scale. Our approach integrates processes and communications between all stakeholders within a materials system, from component and material design through production and scalability, to create robust materials systems that deliver results that are immediately ready for the production environment. Our holistic approach also enables us to find specific solutions to identify and address customer needs beyond design and production through the long-term effects and performance of a material in situ.

ROBUST OPTIMIZED COMPONENTS

Our top-down development and execution strategy allows us to develop material systems that enable simultaneous manufacturing of a material and a component. Through multiscale modeling and simulation, we optimize manufacturing processes and designs to create robust component prototypes with superior performance that can then be made to scale using the procedures and materials we develop. We apply our expertise and equipment to identify and predict how materials degrade in extreme environments, particularly before macroscopic damage propagates and leads to the failure of structures, systems, and components important to safety. We focus on advancing the understanding of how materials age and degrade using a host of capabilities, including atomic-resolution electron microscopy, materials testing in realistic environments, mechanical design, material qualification, and multiscale modeling.

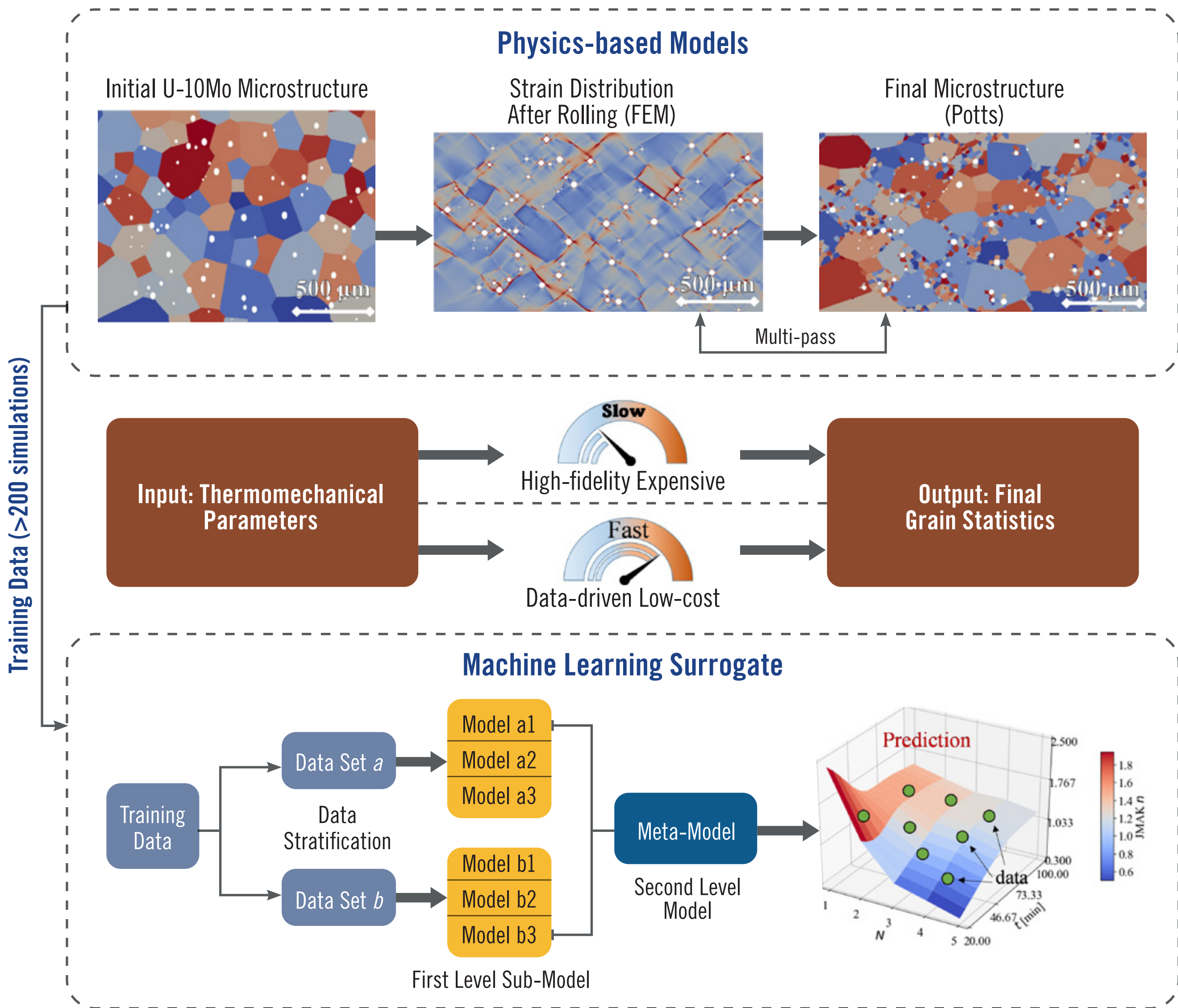
Deeper understanding of the relationships between material design, production process, material microstructure, and performance properties accelerates material systems development.

ADVANCED MODELING AND SIMULATION THROUGHOUT MATERIAL AND COMPONENT LIFE CYCLE

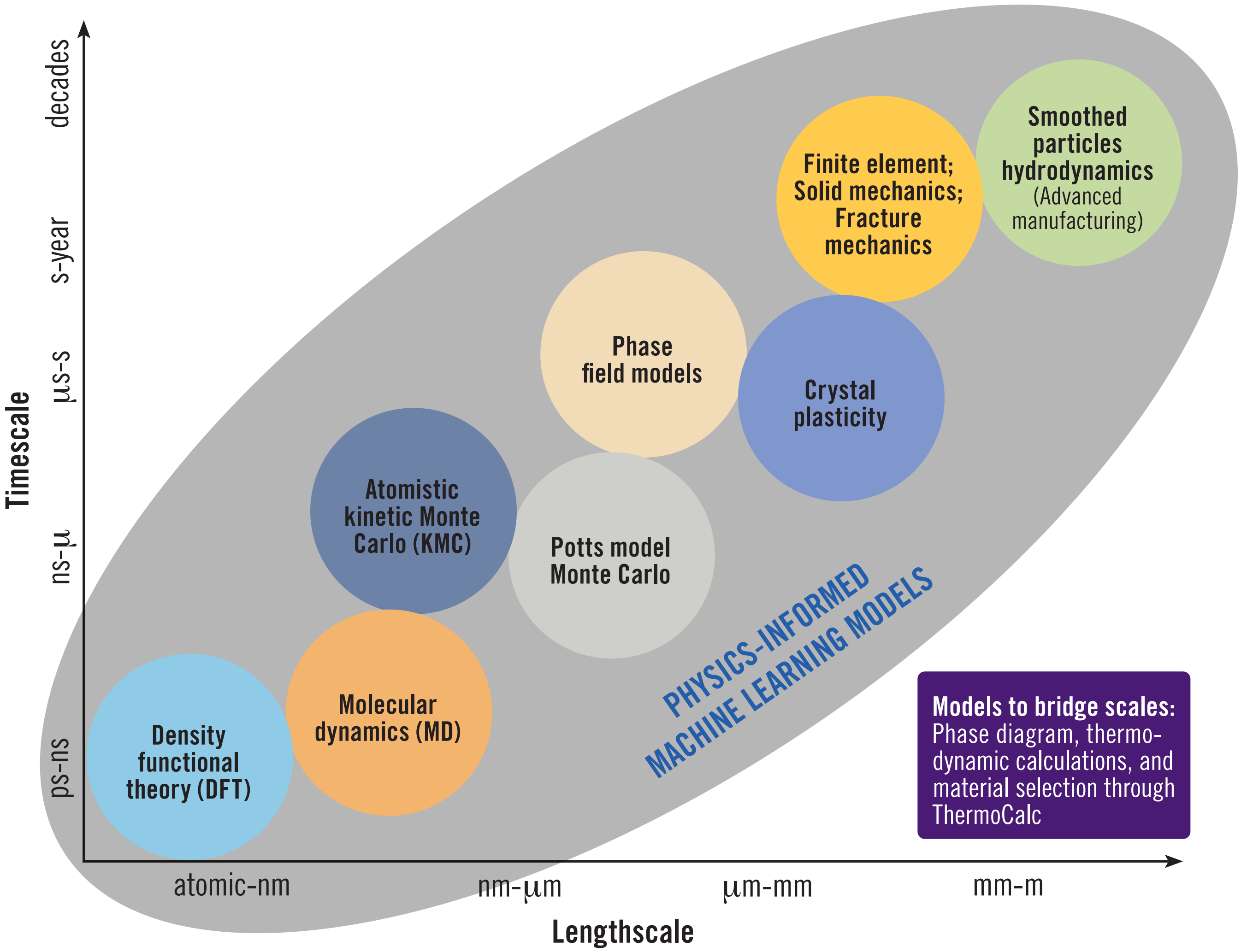
Current approaches to qualify materials and processes rely on extensive empirical testing, which limits the number of trustworthy materials for use in nuclear reactors. These high-temperature, extreme environments demand incredibly sensitive but robust components with highly specific performance requirements. When a difference of even few millimeters, minutes, or degrees during the manufacturing process can mean the difference between material success or failure, modeling can be used as a less expensive predictive tool to understand how even slight changes can affect the microstructures that determine performance.

Our modeling capabilities investigate a fundamental mechanistic understanding of materials, microstructures, and performance—ranging from the atom arrangement to the lifetime performance of entire components. Because of how precisely our models can be tuned, these powerful tools shorten development and qualification time for materials, components, and manufacturing techniques. And after components are created and qualified, our modeling capabilities continue to provide insight into component performance over time, informing both reactor design and ongoing operation considerations.

PNNL MODELS AND MACHINE LEARNING SURROGATES IDENTIFY INFLUENTIAL PROCESSING PARAMETERS, GUIDE EXPERIMENTAL DESIGN, AND PREDICT FINAL MATERIAL CONDITIONS



EXPERT MODELING FROM ATOMIC TO ENGINEERING SCALE



SCALE LENGTHS OF OUR IN-DEPTH AND DIVERSE MODELING CAPABILITIES

Atomistic models for irradiation damage, performance, and manufacturability

- Density functional theory (DFT)
- Molecular dynamics (MD)
- Atomistic kinetic Monte Carlo (KMC)

Grain-level meso-scale models for structural deformation of material during manufacturing and solid phase processing

- Potts Model Monte Carlo
- Phase field models
- Crystal plasticity

Component-level models

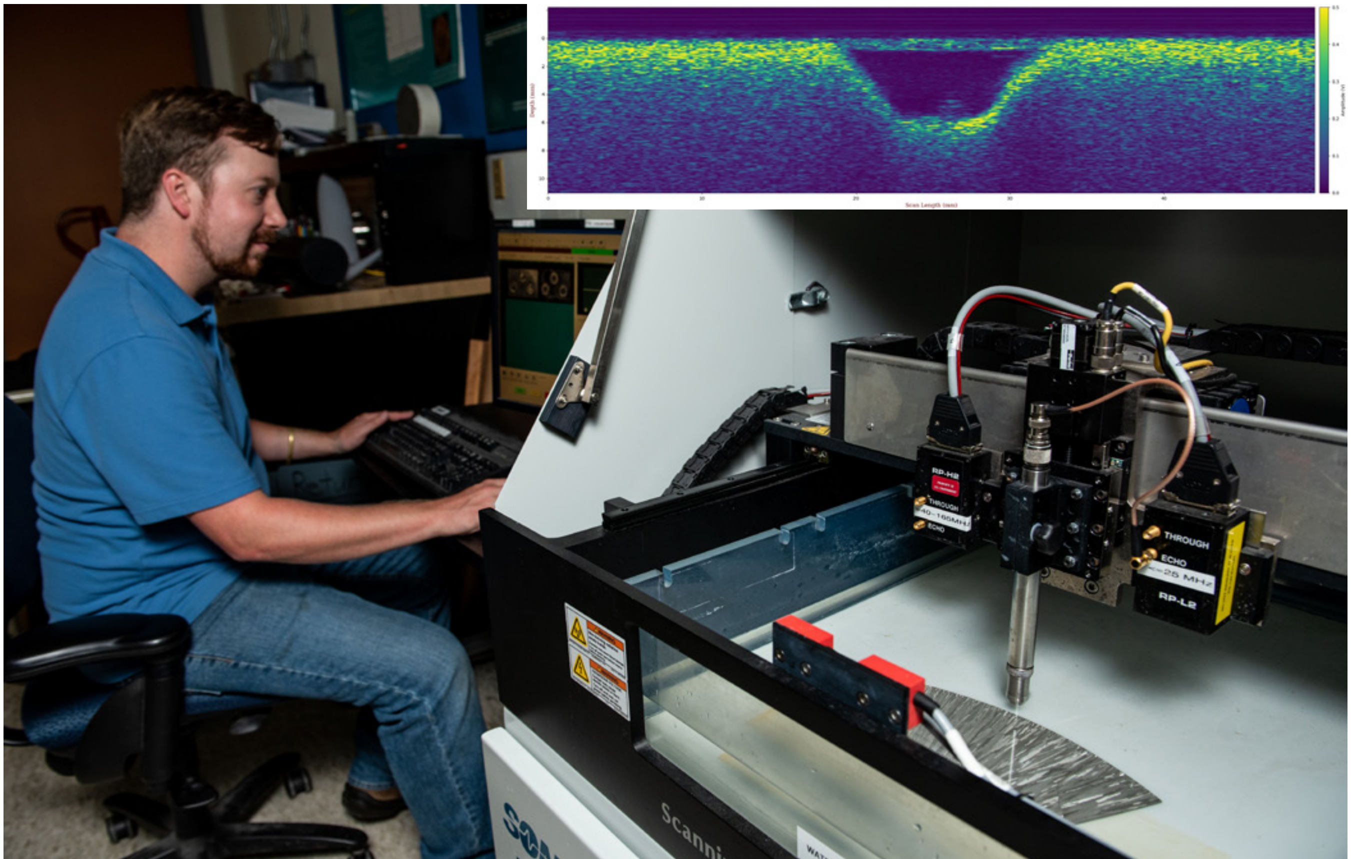
- Finite element; Solid mechanics; Fracture mechanics
- Smoothed particle hydrodynamics (advanced manufacturing)

Models to bridge and connect across scales

- Physics-informed machine learning models for material microstructure predictions during processing

ThermoCalc for materials selection

- Predict thermodynamics, kinetics, properties throughout the material lifecycle



Acoustic microscope used to investigate the microstructure of a metal sample. The inset image shows the results of ultrasonic imaging of material grain size within the base metal and the friction stir zone (central dark area) for a cross-sectional view of the processed region.

NEXT GENERATION NONDESTRUCTIVE EXAMINATION

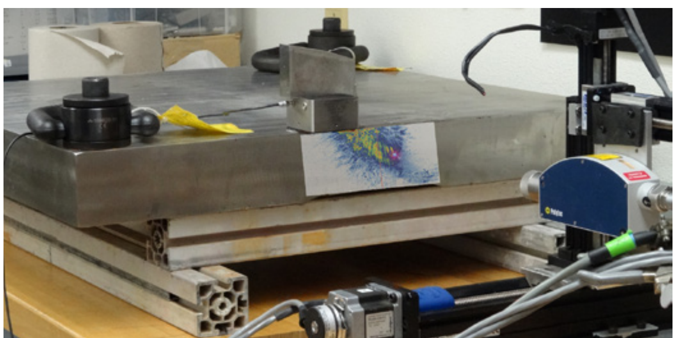
Advanced materials systems and component structural designs challenge conventional nondestructive examination (NDE). By building on our decades-long laboratory and in-plant expertise in traditional NDE, we are developing the next generation of NDE tools to qualify and monitor the structural integrity of components fabricated using advanced manufacturing technologies for advanced reactors. Our researchers are locating new areas to understand and monitor components as they are fabricated using additive manufacturing and other advanced manufacturing techniques.

NDE plays a critical role in generating information to understand a material system during manufacturing, post-fabrication, and in situ operation. Our capabilities include detection, characterization, and monitoring of component and material conditions throughout the material system lifecycle using a vast array of nondestructive interrogation techniques. These evaluations help to provide an in-depth understanding of the material condition during fabrication, post fabrication, and in operation when knowing the degraded state of a component can provide information on the remaining useful life, and inform mitigation, repair, or replacement activities. In addition, we are creating a robust sensing technology that can be attached to components and withstand the extreme environments of a nuclear reactor to monitor material changes during longer periods of use without down time.

PNNL's NDE experts steward state-of-the-art research facilities that house advanced NDE instrumentation, probes and sensors, an extensive inventory of vintage nuclear power plant materials and components, and the latest multiphysics-based modeling and simulation capabilities. PNNL staff are actively engaged in national and international codes and standards and have been instrumental in crafting significant improvements to the use of NDE in the nuclear power industry.

NDE TECHNIQUES AND RESOURCES

- Linear and nonlinear ultrasonic techniques
- Ultrasonic laser imaging
- Acoustic microscope
- Eddy current and electromagnetic methods
- Time and frequency domain reflectometry
- Infrared thermography
- Mechanical testing including load frames and ovens
- Computational modeling of physical processes on inspection signals
- Digital radiography
- Micro/mm-waves
- Dielectric spectroscopy
- Automated data analysis
- Inspection systems modeling and simulation with structural material and flaw interaction
- Physics-based representation of degradation mechanisms
- More than 10,000 sq ft of indoor and outdoor laboratory facilities
- Hundreds of structural specimens and mockups built and maintained for clients and including material harvested from nuclear power plants
- Photon-based interrogation techniques including microtomography for microstructural information, transmission radiography, computed tomography of components, and emission tomography of irradiated components



Ultrasonic laser imaging for nondestructive evaluation using linear and nonlinear ultrasonic techniques.

Accelerated cable degradation capabilites.

MAXIMIZING EXISTING MATERIALS

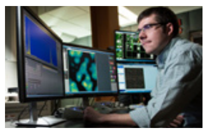
In addition to developing new reactor material to keep up with changed corrosion behavior and requirements, we can also improve and optimize the limited number of already approved reactor materials. Each material and manufacturing process pair creates specific properties, and the industry will need qualification methodology for new material properties created through the microstructural changes inherent in a new technique using a conventional material. We continue to implement technology to understand the link between desired performance parameters and tunable steps in the manufacturing process through our in-process monitoring and computer vision capabilities for microstructural analysis. We can build on this foundation to provide the technical basis for regulatory acceptance through manufacturing process understanding, in-process monitoring, post process evaluation, and environmental effects.

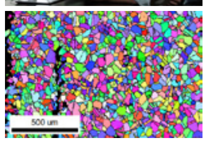
NUCLEAR MATERIALS AND MATERIALS PROCESSING EXPERTISE

PNNL's deep expertise in nuclear materials and in nuclear materials synthesis and manufacturing uniquely situates us to decrease the qualification cycle, shorten the development cycle, and condense time to market for advanced materials and manufacturing technologies that support a broad range of nuclear reactor technologies. Additionally, while driving innovation and working with industry and other partners, we maintain and protect proprietary information.

Our materials science expertise integrates advanced characterization, modeling and simulation, machine learning and artificial intelligence in materials properties, materials development, and qualification. Through this, we help the nuclear industry embrace new manufacturing processes for nuclear material by identifying potential risks for production and deployment as we qualify materials for use in these extreme environments.

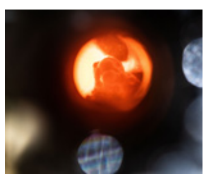
Accelerated Material Design and Development





- Material System Identification and Design
- Enabling Synthesis
- High-Resolution, Customized Characterization
- Design Qualification Methodologies
- Artificial Intelligence and Machine Learning

Radiological Materials

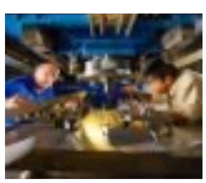


- Wasteform Development
- Thermal Processing
- Process Engineering

Nuclear Chemistry & Engineering

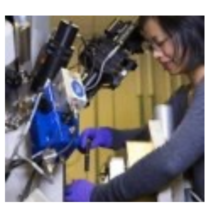
- Separations
- Radiochemistry
- Irradiated Materials Characterization
- Actinide Sciences

Reactor Materials & Mechanical Design



- Stress Corrosion Cracking
- Radiation Effects
- Materials Modeling
- Nano Materials Science
- Mechanical Testing
- Post Irradiation Examination
- Nondestructive Examination

Irradiation Sciences

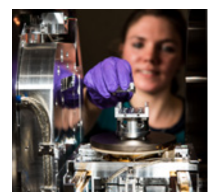


- Neutron Metrology
- Radiation Effects on Materials
- Radiation Dosimetry and Measurement

Applied Materials & Manufacturing

- Materials Development, Processing, and Performance Testing
- Synthetic Chemistry
- Polymers
- Rapid Prototyping
- Additive Manufacturing

Nuclear Engineering & Analysis



- Core Design
- Criticality Safety Assessment
- Radiation Shielding Analysis
- Fuels and Materials Performance Analysis

Solid Phase Manufacturing Processes

- Shear Assisted Processing and Extrusion (ShAPE) Process
- Cold Spray
- Friction Stir Welding and Processing
- Friction Stir Additive Manufacturing

Contacts:

Isabella J. van Rooyen
Senior Technical Advisor, Advanced Material Systems
(509) 375-2624 | isabella.vanrooyen@pnnl.gov

Mark Nutt
Nuclear Market Sector Manager
(509) 375-2984 | mark.nutt@pnnl.gov

Ali Zbib
Nuclear Industry Program Manager
(509) 372-4034 | ali.zbib@pnnl.gov