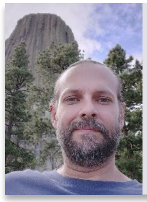
Department of Energy Office of Nuclear Energy

Advanced Materials and Manufacturing Technologies (AMMT) Program Overview

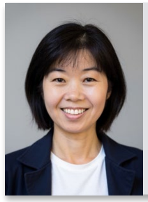
Meimei Li
National Technical Director
Argonne National Laboratory

Program Leadership



Dirk Cairns-Gallimore (DOE)

Federal Program Manager



Meimei Li (ANL)

National Technical Director

Isabella van Rooyen (PNNL)

Technical Area Lead

Advanced Mater. & Manuf.

Stephanie Pitts (INL)

Technical Area Lead

Environmental Effects

Caleb Massey (ORNL)

Technical Area Lead

Rapid Qualification

Ryan Dehoff (ORNL)

Technical Area Lead

Technology Maturation

Mission, Vision, Goals

Mission

Accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies in support of U.S. leadership in a broad range of nuclear energy applications.

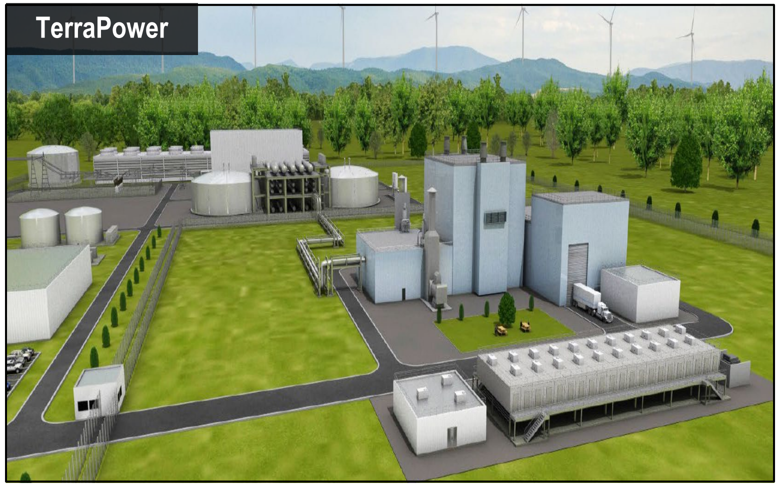
Vision

Expansion of reliable and economical nuclear energy enabled by advanced materials and manufacturing technologies.

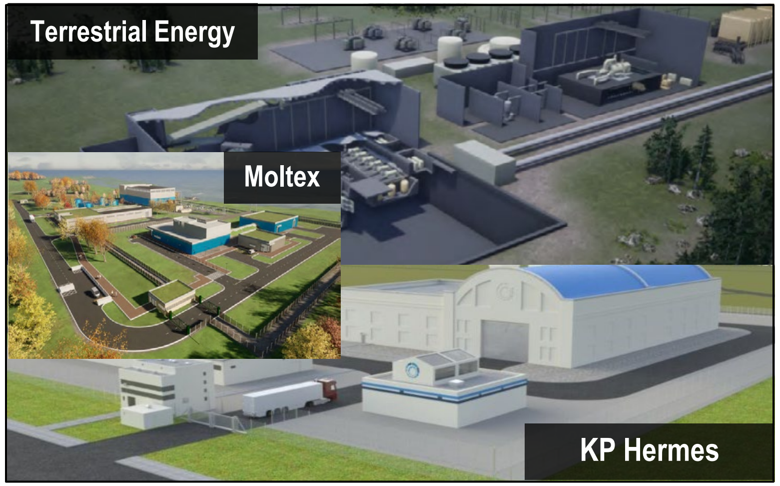
Goals

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

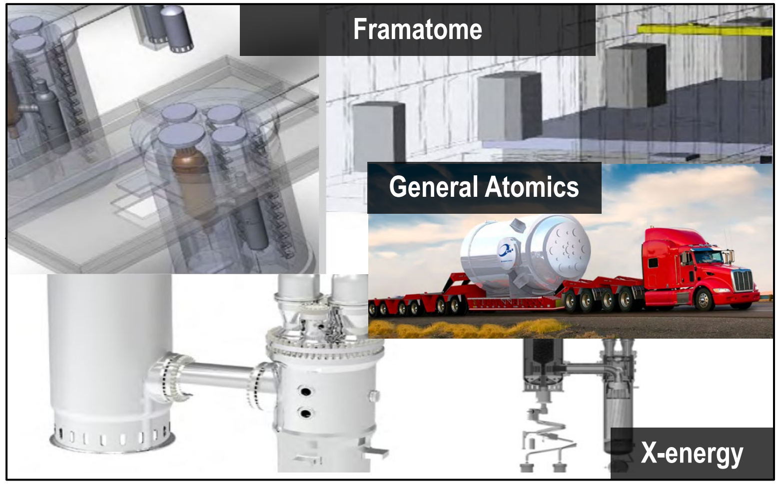
AMMT Supports a Broad Range of Reactor Technologies



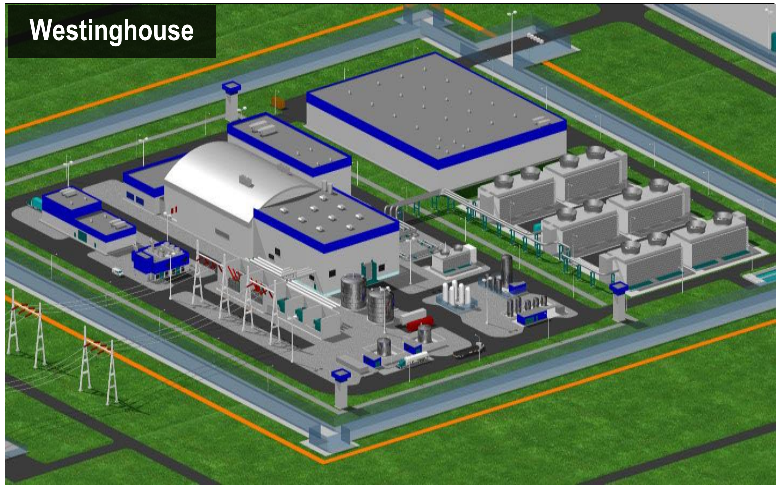
Sodium-cooled Fast Reactor (SFR)



Molten Salt Reactor (MSR)

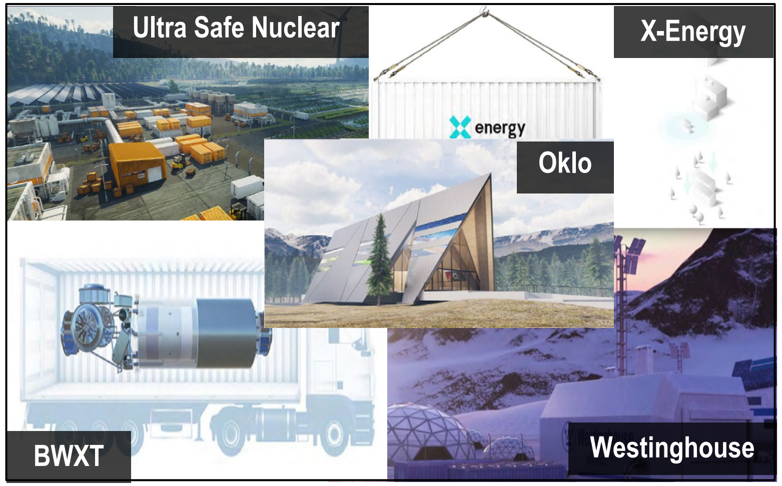


Gas-cooled Reactor (GCR)



Lead-cooled Fast Reactor (LFR)

Advanced Light Water Reactor (ALWR)



SMR & Microreactor

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

Technical Areas

Advanced Materials & Manufacturing

- Advanced Metallic Materials
- Advanced Manufacturing Technologies
- Traditional Manufacturing Integration

Environmental Effects

- Irradiation Effects in Materials
- Coolant Corrosion of Materials
- Accelerated Evaluation of Environmental Effects

Rapid Qualification

- Data-driven Qualification Methods
- High-temperature Materials Qualification for Nuclear Environments
- Advanced Manufacturing Qualification for Nuclear Environments

Technology Maturation

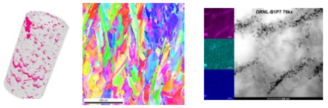
- Component Demonstration and Evaluation
- Codes, Standards & Licensing
- Scalable Manufacturing for Deployment

Foundation: Processing-Structure-Property-Performance Relationships for Reactor Materials

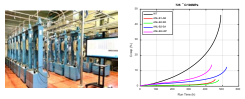
EXPERIMENTAL

Processing Experiments

Microstructure Characterization



Property Testing



Component Testing

Processing
Composition, processing, post-processing

→

Initial Microstructure
Grain size, texture, porosity, phases, dislocations

→

Baseline Properties
Tensile, creep, fatigue, creep-fatigue, toughness

Service Conditions
Irradiation, temperature, stress, coolant environment

→

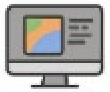
Microstructure Evolution
Radiation defects, phase transformation, corrosion products

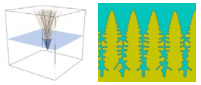
→

Properties Degradation
Radiation embrittlement, irradiation creep, corrosion degradation

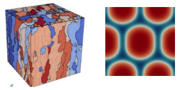
Component Performance

COMPUTATIONAL

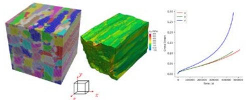




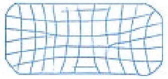
Processing Simulation



Microstructure Modeling



Property Prediction



Component Virtual Testing

Materials Challenges in Molten Salt Reactors

Operating Environment

Materials are exposed to:

- **Corrosive fluoride/chloride salts**
- High temperatures
- Thermal gradients
- Mechanical loading
- Neutron irradiation
- Long service lifetimes.

The challenge is the combined effect of **corrosion + temperature + stress + irradiation + time**.

Qualification Requirements

Materials must demonstrate:

- Mechanical integrity
- Environmental compatibility
- Fabricability and weldability
- Inspectability
- ASME Code approval
- Licensing acceptance

Selection Criteria

Important attributes include

- Tensile strength
- Creep & creep-fatigue resistance
- Facture/cracking resistance
- Thermal aging resistance
- Corrosion compatibility
- Irradiation tolerance
- Fabricability and weldability
- Inspectability
- ASME Code approval
- Licensing pathway

*A successful MSR structural material must be **scientifically understood**, **engineering-qualified, manufacturable at scale & licensable.***

Advanced Manufacturing as an Enabling Technology

Methods & Benefits

Methods of Interest

- Laser Powder Bed Fusion (LPBF)
- Directed Energy Deposition (DED)
- Powder Metallurgy HIP (PM-HIP)
- Coating & cladding
- Advanced joining methods

Potential Benefits for MSRs

- Complex geometries (e.g. compact heat exchangers)
- Increased design flexibility
- Reduced supply chain vulnerability
- Faster low-volume fabrication

Risks & MSR Relevance

Advanced Manufacturing - Specific Concerns

- Surface roughness
- Porosity
- Residual stress
- Chemical heterogeneity
- Process-induced microstructure variability
- Anisotropy

Why Matters in MSRs

- Accelerated corrosion behavior
- Crack initiation at defect sites
- New degraded mechanisms in nuclear environments
- Reduced long-term reliability

Advanced manufacturing can enable MSR designs that are difficult or impractical using conventional methods, but qualification must address AM-specific defects and microstructural variability.

AMMT's Advanced Materials & Manufacturing Development

- **Apply advanced manufacturing to existing reactor materials**
  - Expand the use and improve the performance of existing materials through advanced manufacturing techniques.
  - Code-approved materials or those with sufficient knowledge in nuclear environments
  - Optimize manufacturing processes for these materials.
- **Transition non-nuclear commercial materials for nuclear applications**
  - Leverage industry advancements to reduce development time and costs, expanding nuclear material options.
  - Optimize materials for nuclear use through composition refinement or manufacturing processes for enhanced resistance to nuclear environments.
- **Develop innovative new materials**
  - Explore novel material design concepts, e.g. ODS, HEAs
  - Use advanced manufacturing to engineer materials with tailored properties, e.g. functionally graded materials.

Materials

- Fe-based alloys
- Ni-based alloys
- Refractory alloys
- Innovative new materials

Manufacturing

- LPBF, DED, PM-HIP
- Hybrid techniques
- *Coating/Cladding techniques*
- *Welding/Joining techniques*

Ni-based Alloys for Molten Salt Applications

Alloy 625

- **Application**
  - A **low-Co** alloy for reactor components.
  - Good high temperature strength and oxidation resistance, and weldability.
- **Advanced Manufacturing**
  - Additive manufacturing of Alloy 625 is a relatively mature technology.
  - Focus on mechanical properties and performance in nuclear environments.

Alloy 244

- **Application**
  - A **low-Cr** alloy expected to be molten salt compatible.
  - A new Ni-Mo-Cr-W alloy developed for advanced gas turbine engine application.
- **Advanced Manufacturing**
  - Processing studies of Alloy 244 by laser powder bed fusion and directed energy deposition.

Work will be presented:

4:50 PM	5:10 PM	Ni-based alloys for molten salt applications	Sebastien Dryepondt/ORNL

Fe-based Alloys

Alloy 709 SS

- Wrought Alloy 709 Sec III Div 5 Code Cases
- LPBF and DED optimization of Alloy 709
- Neutron irradiation and PIE of Alloy 709
- Corrosion studies of Alloy 709

G91/G92 F-M Steel

- Grade 91 is a Code-approved Sec III Div 5 material
- Grade 92 is an improved variant
- LPBF and DED process optimization for G91/G92

PM-HIP 316 SS

- Advance PM-HIP 316 for high-temperature reactor service
- Correlate powder conditioning, HIP processing, microstructure to high-temperature property.
- Improve creep and creep-fatigue resistance

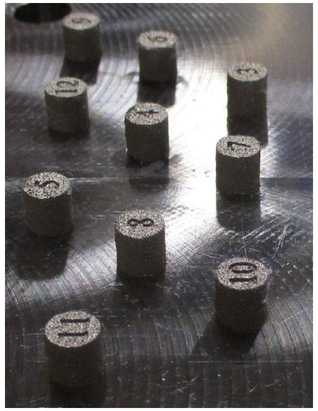
LPBF 316 SS

- LPBF 316H serves as a case study to develop and demonstrate a rapid qualification framework.
- LPBF 316H Sec III Div 5 Code Cases
- Neutron irradiation and PIE of LPBF 316
- Corrosion studies of LPBF 316

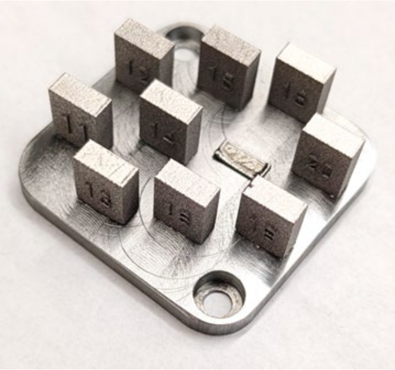
Refractory Alloys

- Refractory alloys are being considered to provide material option with higher operating temperatures.
- It is difficult and costly to fabricate complex components from refractory alloys using traditional manufacturing techniques.
- Explore additive manufacturing of refractory alloys to overcome difficulty in conventional fabrication in support of microreactor applications.
- Current focus is on LPBF of TZM and Nb1Zr alloys.

Seven-hole core block sample fabricated from TZM alloy at LANL.



Nb1Zr build printed on the EOS M400 machine at LANL.



Printed Nb-1Zr cubes on Mo build plate at ORNL.

Molten Salt Corrosion: Coupled Salt-Material-Environment Effects

Governing Factors

- **Salt Chemistry**
  - Salt type, redox conditions, impurity content
- **Environmental Conditions**
  - Temperature, thermal gradients, flow conditions, irradiation
- **Metallurgical Conditions**
  - Alloy composition, microstructure, surface state

Degradation Mechanisms

- Selective dissolution & dealloying
- Interfacial elemental transport
- Surface compositional changes
- Therma-gradient-driven mass transfer
- Corrosion product formation & redistribution

Performance Impact

- Wall thinning and roughening
- Microstructural & microchemical degradation
- Reduced ductility and strength
- Property degradation
- Uncertainty in component life

Corrosion in molten salts is a coupled salt-material-environment problem that directly affects mechanical properties and component life.

Molten Salt Corrosion Studies: Current Activities

Current Focus: 316H, 709 stainless steels, Alloys 625, 244 Ni alloys (wrought and AM).

- Corrosion behavior and mechanical properties in molten fluoride and chloride salts.
- Corrosion of advanced manufacturing alloys in molten salt environments.
- Corrosion kinetics and speciation in fueled molten chloride salt.

Work will be presented:

2:15PM	2:45 PM	The critical role of alloy chemistry and microstructure on the corrosion behavior and mechanical properties of structural alloys in molten halide salts	Rishi Pillai/ORNL
2:45 PM	3:05 PM	Challenges of additively manufactured materials under molten salt corrosion	Jahangir Lodhi/INL
3:05 PM	3:25 PM	Corrosion kinetics of structural materials in molten chloride environments	Thomas Hartmann/PNNL
3:40 PM	4:10 PM	Chloride salt flow loop and corrosion studies	Ruchi Gakhar/INL

Irradiation Effects in Molten Salt Reactors

Damage Modes

- Radiation hardening and embrittlement
- Irradiation creep
- Void swelling
- Helium embrittlement

These effects reduce strength, ductility, and dimensional stability, limiting component lifetime and safety margin.

Combined Effects

Radiation damage is tightly coupled with high-temperature corrosion.

Main Challenges

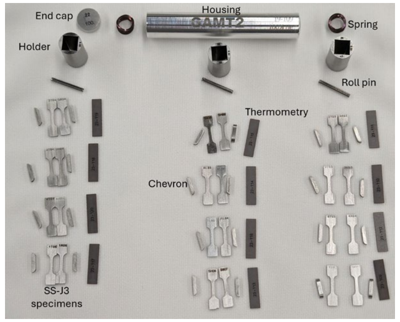
- Limited irradiation data
- Long-term prediction difficulty
- Microstructure sensitivity
- Evolving licensing pathways

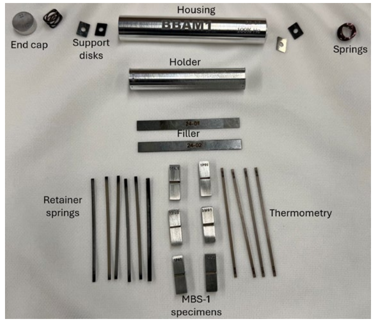
MSR materials must be qualified for combined effects of irradiation, salt chemistry, and high-temperature.

Neutron Irradiation and PIE of LPBF 316H SS

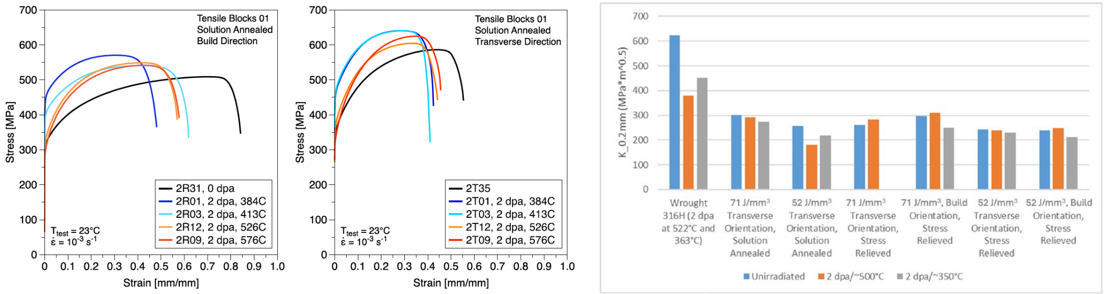
Neutron Irradiation at HIFR

- Specimens fabricated with LPBF process
  - Two different energy depositions (71 and 52 J/mm^3)
  - Two different post-build heat treatments (SR and SA)
  - Two directions (BD and TD)
- Irradiation temperature: 400, 600°C
- Irradiation doses: 2, 10 dpa
- 20 irradiation capsules:
  - 8 GENTEN capsules (SS-J3 tensile specimens)
  - 12 MINBEN capsules (miniature bend bar specimens)





Post-Irradiation Examination of 2 dpa Capsules



Tensile and fracture toughness tests of 2 dpa irradiated specimens.

Neutron Irradiation at ATR

- Provide additional mechanical property data
- Irradiation temperatures: 400, 600°C
- Irradiation doses: 1, 2 dpa
- PIE: tensile, creep, creep crack growth
- Neutron irradiation is in preparation

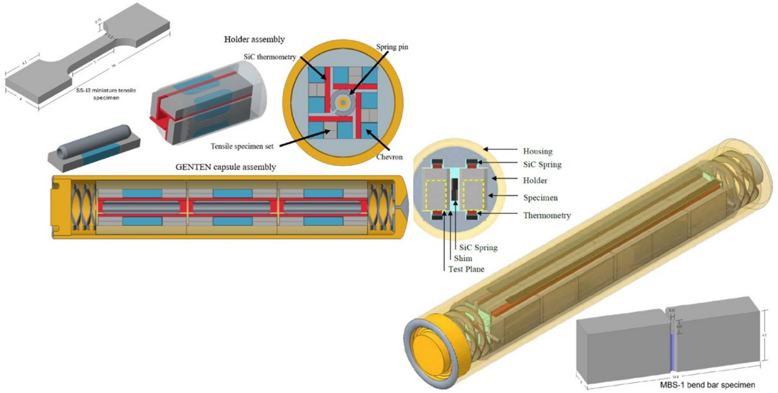
Neutron Irradiation and PIE of Alloy 709

A709 Commercial Heats

- Three commercial-scale heats in plate form, each ~40,000-45,000 lbs.
- Two heat treatments (SA & PT)
- Goal is to develop the design data for establishing end-of-life design parameters to support the deployment of A709 reactor structural components.

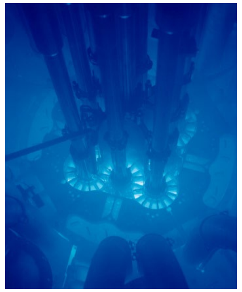
HIFR Irradiation

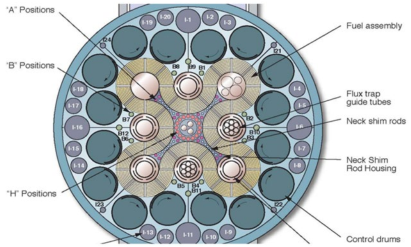
- Irradiation experiments at HFIR:
  - Mixed neutron spectrum
  - Temperature: 300 - 800°C
  - Doses: up to10 dpa
  - Specimens for tensile, creep and fracture toughness testing.



ATR Irradiation

- Irradiation experiments at ATR:
  - Fast neutron spectrum using shielded capsules
  - Temperature: 300 - 800°C
  - Doses: 1, 2 dpa
  - Specimens for tensile, creep and fracture toughness testing.

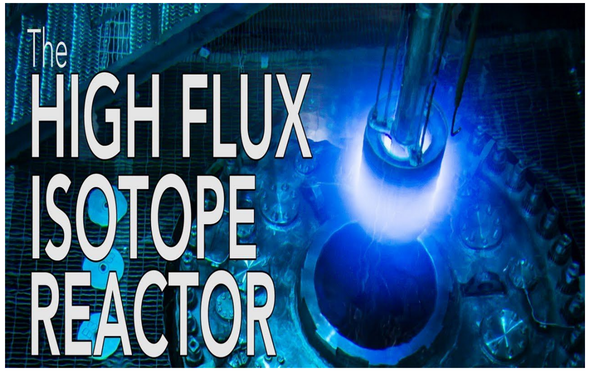




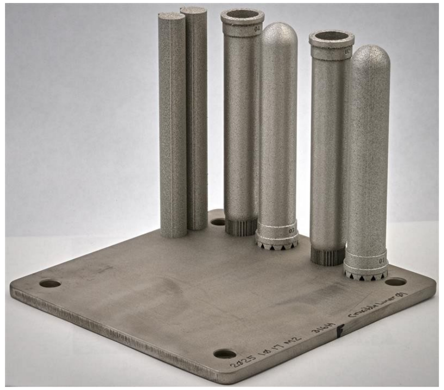
Combined Irradiation and Corrosion Effects of AM Components

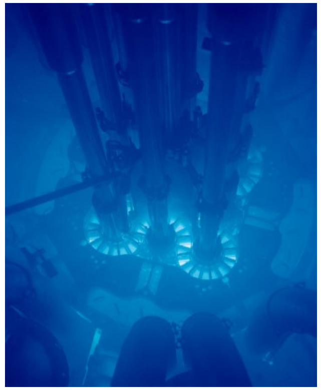
3D Printed 316 SS Irradiation Capsules for tests in High Flux Isotope Reactor (HFIR) and Advanced Test Reactor (ATR)

- ORNL designed, printed, and successfully tested irradiation capsules in High Flux Isotope Reactor (HFIR).
- Post-irradiation examination of AM irradiation capsule provided initial critical data for use of AM in safety critical applications.



- 3D printed 316 SS irradiation capsules filled with nuclear fuel salt will be tested in Advanced Test Reactor (ATR), providing valuable data on the combined effects of irradiation and corrosion.
- Collaboration between AMMT & AFC programs.





Requirements for Complete MSR Material Qualification

Qualification Requirements

- Baseline high-temperature mechanical properties
- Thermal aging effects
- Salt compatibility
- Irradiation effects
- Long-term degradation
- Life prediction methods
- Design allowables and acceptance criteria
- Advanced manufacturing qualification

Current Gaps

Current code basis
ASME Section III, Division 5 High Temperature Reactors

Present limitations
- Few Code-approved materials
- MSR-specific environmental effects not directly covered

Key gaps
- Environmental performance data
- Irradiation-corrosion interaction
- Validated life prediction models
- Advanced manufacturing effects
- Design guidance beyond existing code rules

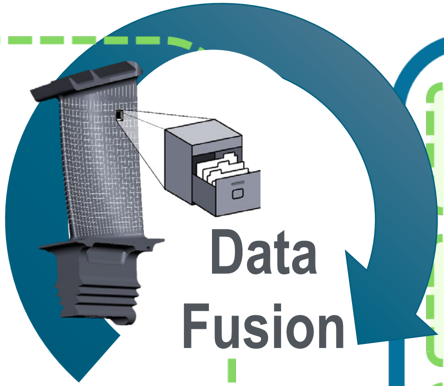
Full MSR material qualification requires an integrated, environment-aware framework that consider corrosion, irradiation, temperature, stress and time effects.

Digital Qualification: Multi-Dimensional Data Correlation (MDDC)

Digital Twin

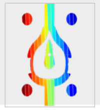
Spatially Tracked Data

4 5 1 8
9 6 3 2

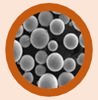


Manufacturing

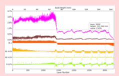
Process Parameters



Feedstock Information



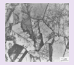
In-Situ Data



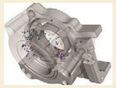
Post Processing

Characterization

Material Characterization



Non-Destructive Testing



Destructive Testing

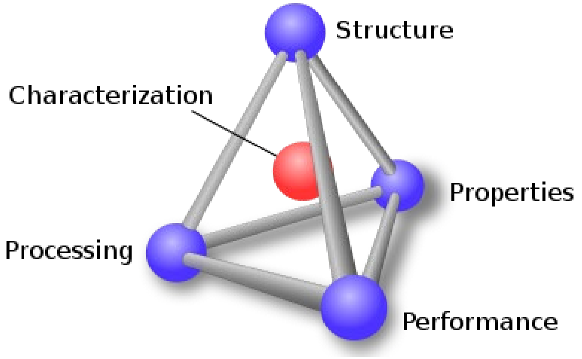
Lifetime & Performance

MDDC

Twin 1
Twin 2
Twin 3
…
Twin n

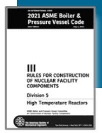
Toolkit

- Artificial Intelligence
- Machine Learning
- Data Analytics
- Process Models
- Materials Models
- Performance Models



Digital Twins and MDDC Toolkit Accelerates Development

Demonstrations — 3 years



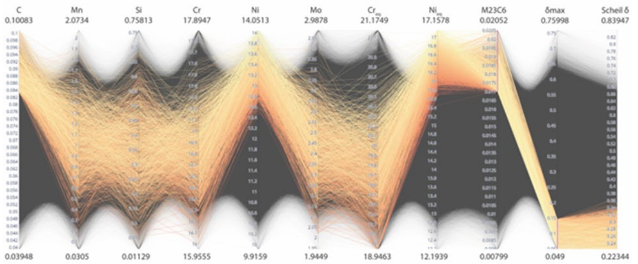
Digitally Aided Qualification — 5 years

AI Based Design — 10 years

Improve Performance, Reliability and Lifetime of Nuclear Components

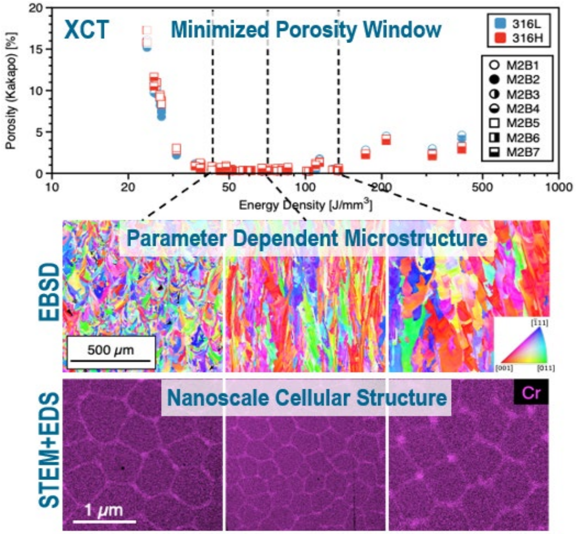
Qualification of Advanced Manufacturing - LPBF

Feedstock Chemistry



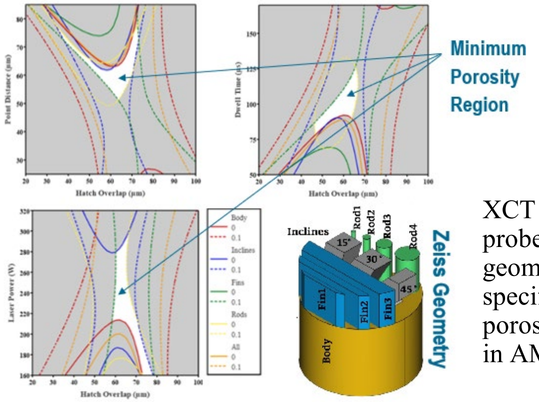
Chemistry on sensitivity to energy density, and data mining highlighting 316H chemistries to maximize carbides and minimizing δ-ferrite.

Process Variables



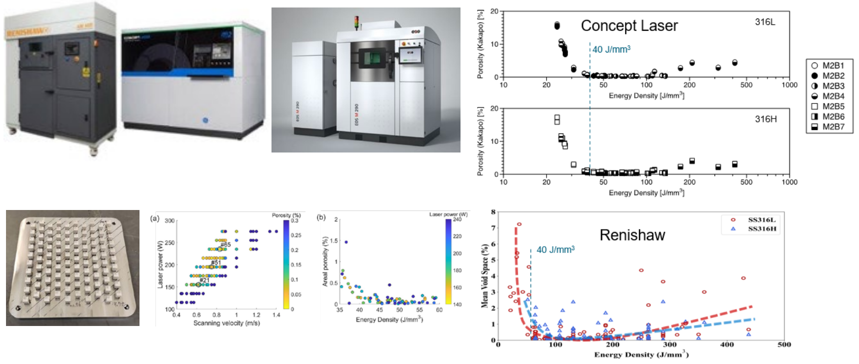
Multiscale reveals variations in porosity, grain structure, & nanoscale segregation as a function of varying processing parameters.

Geometry Effects



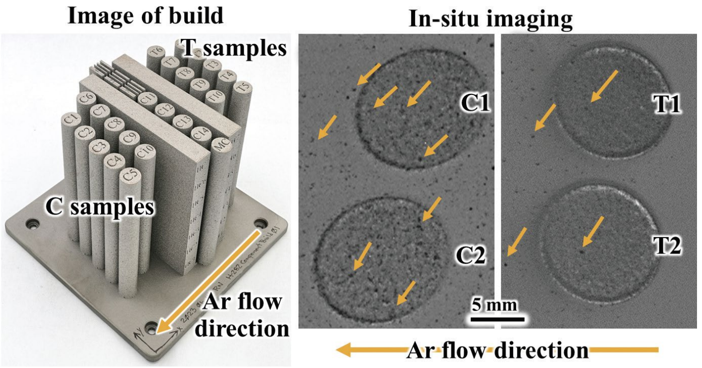
XCT used to probe geometry-specific porosity trends in AM parts.

Machine Variability



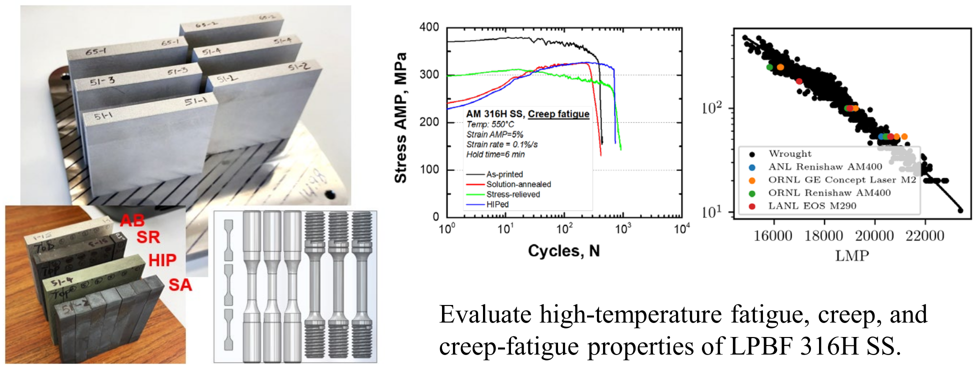
- Volumetric energy density provides a reasonable first-pass optimization parameter for porosity minimization.
- Investigate the "windows" of optimal parameters between machines.

In-situ Process Monitoring



- Integrate in-situ monitoring capabilities with Peregrine software to detect process anomalies during AM builds.
- Combination of techniques offers a valuable framework for evaluating the quality of AM components.

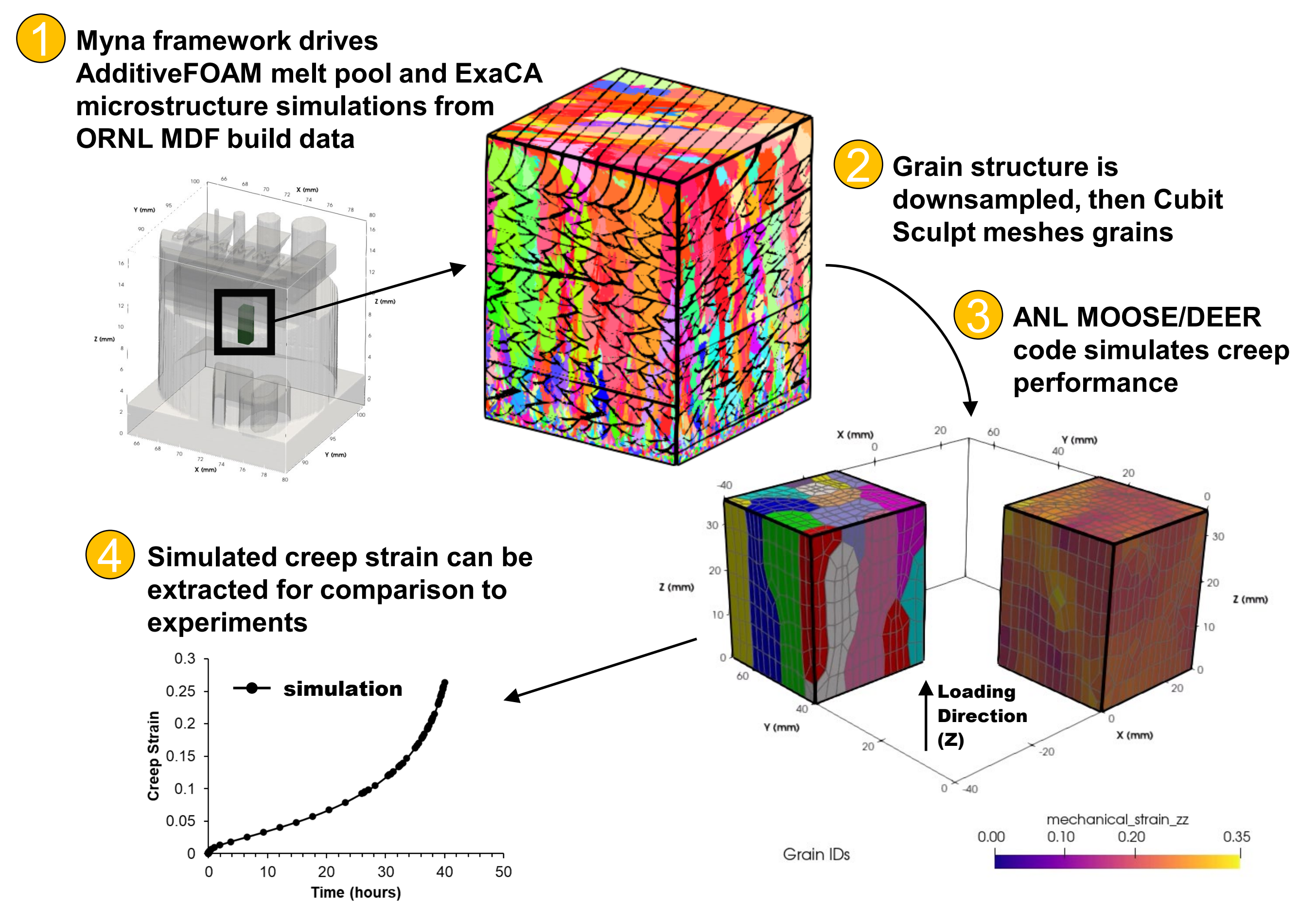
Mechanical Property Evaluation



Evaluate high-temperature fatigue, creep, and creep-fatigue properties of LPBF 316H SS.

Processing-Structure-Creep Simulation Workflow

- Coupling powder bed fusion manufacturing data with processing-structure-property modeling tools to simulate creep behavior in AM.
- Use ORNL simulation tools Myna (data management, workflow), AdditiveFOAM (melt pool), and ExaCA (microstructure), as well as the ANL-developed DEER module (creep) within the MOOSE framework.
- Demonstrate the capability to execute all codes on the Oak Ridge Leadership Computing Facility (OLCF) Frontier supercomputer, enabling large-scale creep simulations on AM microstructure.



Accelerated Evaluation of Irradiation Effects

Apply a science-driven licensing strategy, so called the **Licensing Approach with Ions and Neutrons (LAIN)** framework that combines neutron and ion irradiations with physics-based modeling to accelerate material qualification.

Neutron Irradiation

- Provide critical performance data in nuclear reactor environments.
  - Neutron irradiation and post irradiation examination (PIE)
  - In-reactor experiments including combined irradiation and corrosion effects

Ion Irradiation

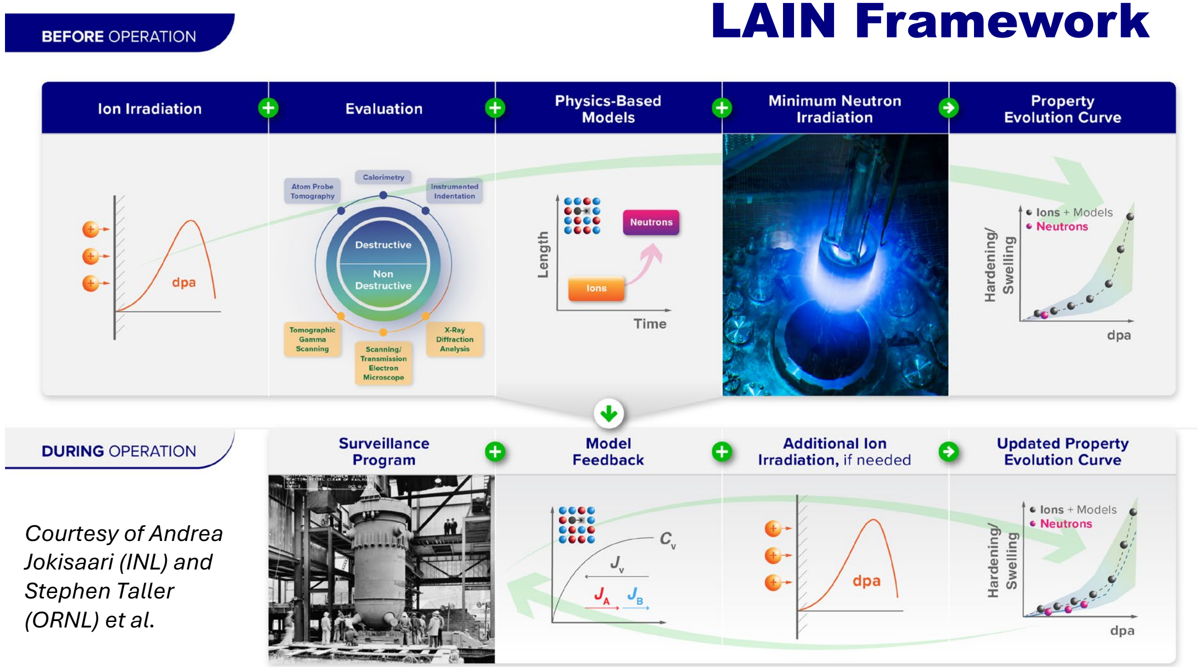
- Use ion irradiation as an accelerated tool to provide complementary data to cover a wide parameter space.
  - Metallurgical variables, e.g. heat variation, product form, heat treatment, etc.
  - Irradiation parameters, e.g. temperature, dose, dose rate, energy spectrum, transmutation, etc.
- Identify degradation mechanisms under irradiation.

Modeling and Simulation

- Understand the underlying physics and predict material performance beyond testing conditions.

Qualification must move from a purely empirical approach to an integrated experiment–model–data framework.

LAIN Framework

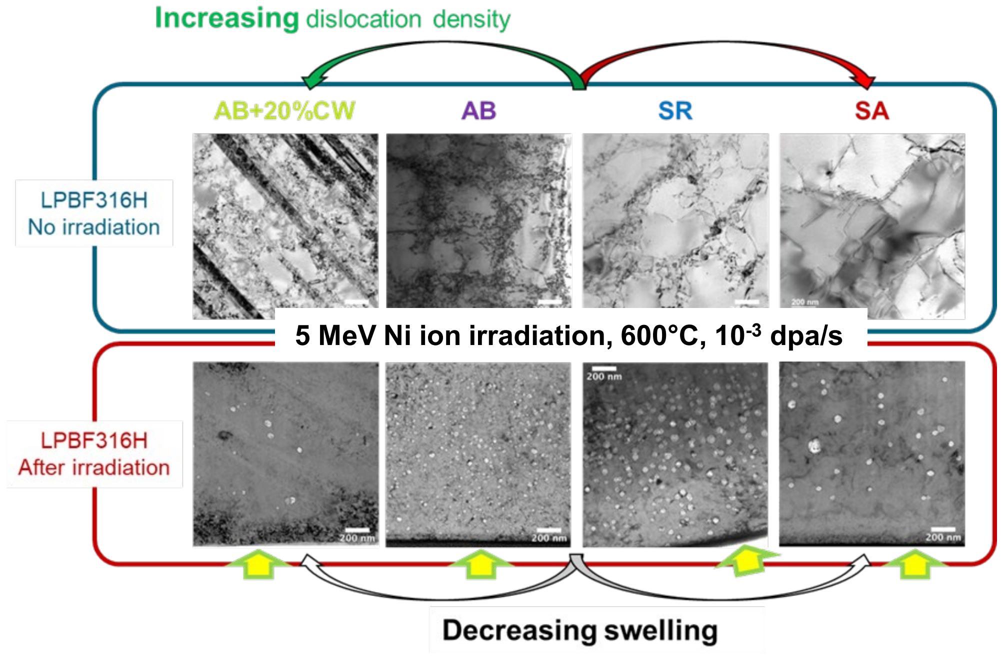


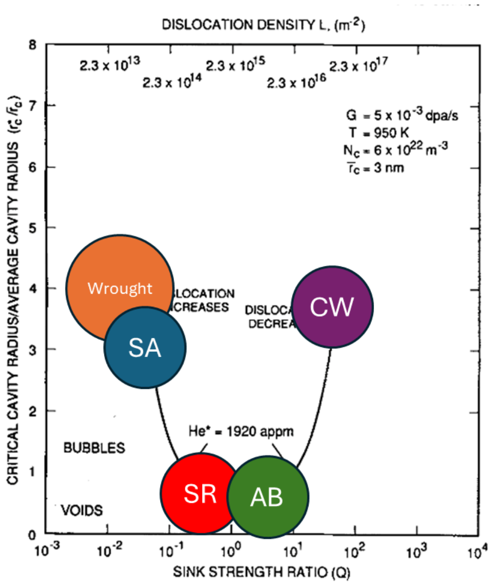
Courtesy of Andrea Jokisaari (INL) and Stephen Taller (ORNL) et al.

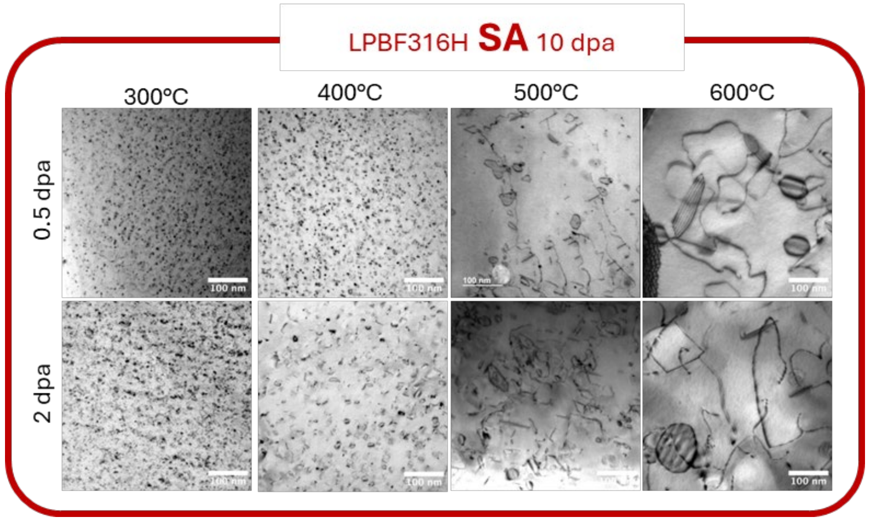
Irradiation Damage in LPBF 316 SS

Effect of Thermal-Mechanical Processing Conditions on Void Swelling

- The initial dislocation density continues to evolve under irradiation which will also affect the overall defect evolutions.
- Initial dislocation density resulting from processing conditions affects void swelling in LPBF 316 SS.



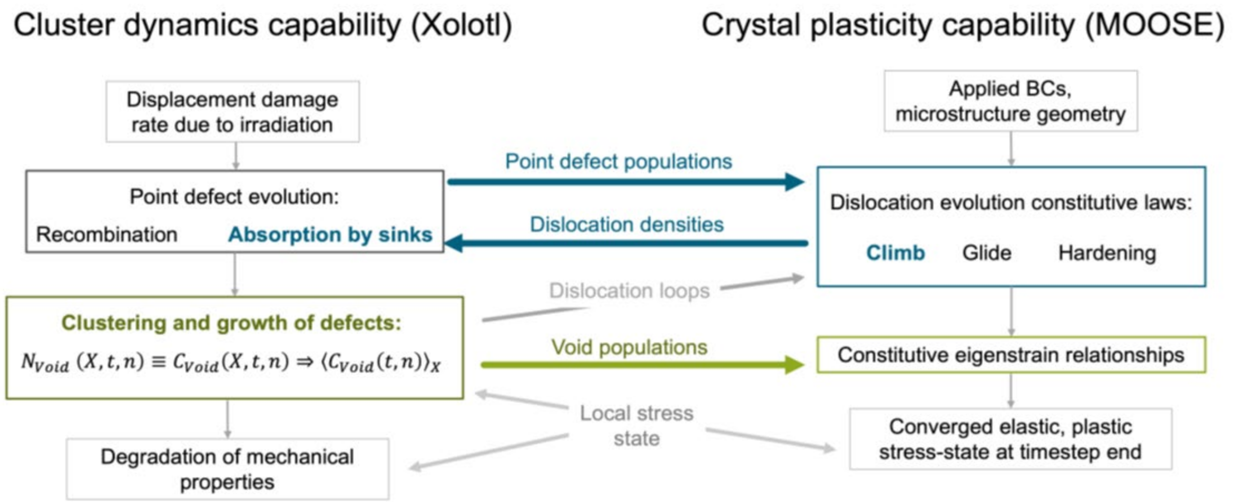


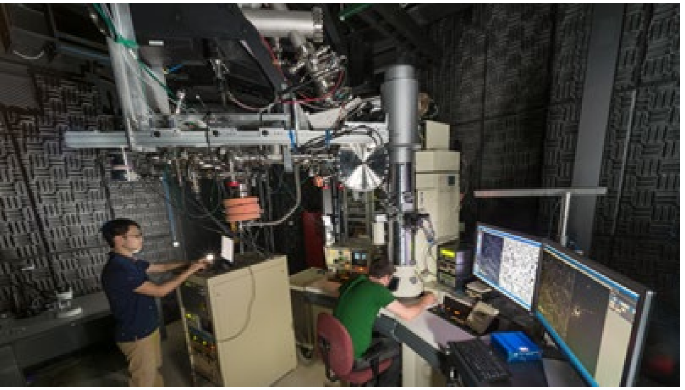


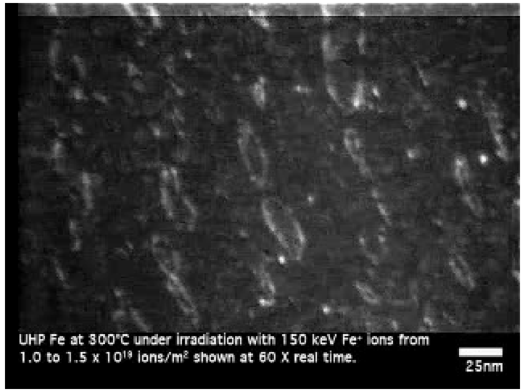
Irradiation Creep Modeling

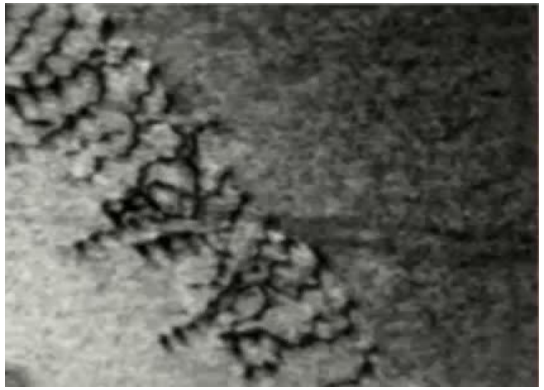
Modeling Approach

- Cluster dynamic simulation of radiation defect formation and evolution.
- Crystal plasticity modeling of irradiation creep informed by defect evolution.







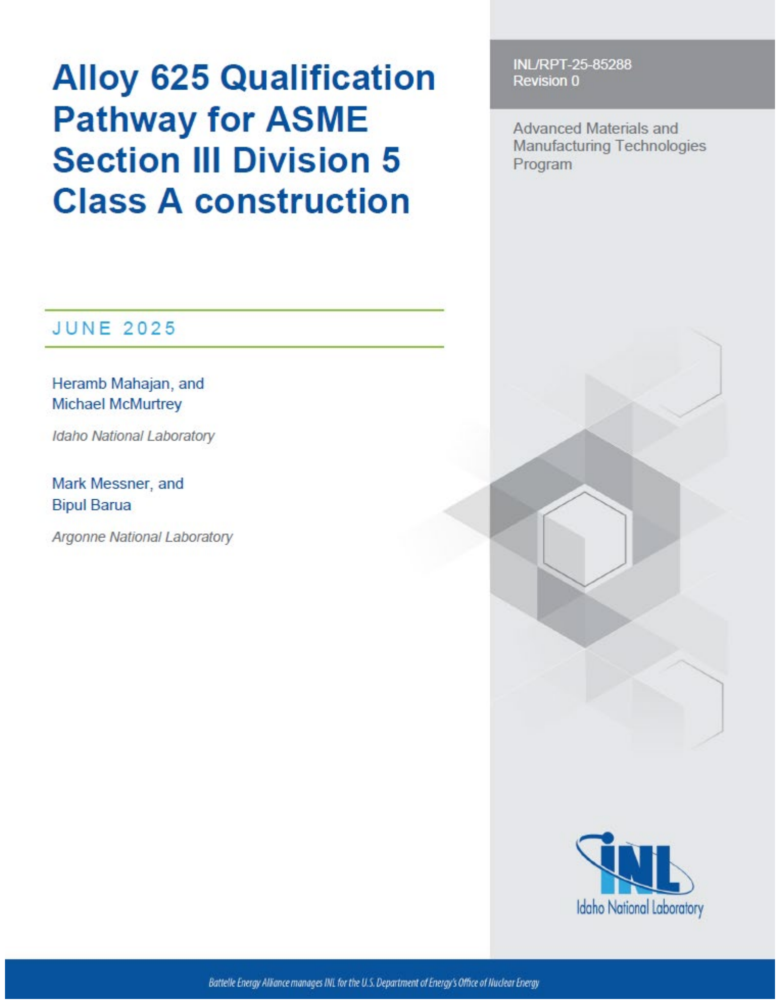


In situ ion irradiation with TEM

- Provide real-time observations of defect formation, motion, and interaction.
- Provide high-fidelity experimental data to refine and validate models.

Alloy 625 Sec III Div 5 Code Case

- AMMT helped initiate the formation of a task group within ASME for the inclusion of Alloy 625 in Section III, Division 5.
- The task group comprises several domestic and international reactor developers.
- AMMT released a white paper to guide vendors on what data exists and what testing gaps remain to Code-qualify Alloy 625.
- Aim to demonstrate a community code case development approach through qualification of Alloy 625 in collaboration with nuclear vendors.
  - Incorporate industry test plans into required test matrix and identify gaps in testing for material qualification.
  - Initiate limited testing as gaps are identified.
  - Collaborate with vendors in ASME BPVC Task Group to begin drafting code case.



INL/RPT-25-85288
Revision 0

Advanced Materials and Manufacturing Technologies Program

Alloy 625 Qualification Pathway for ASME Section III Division 5 Class A construction

JUNE 2025

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Idaho National Laboratory

Mark Messner, and
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Argonne National Laboratory

Idaho National Laboratory

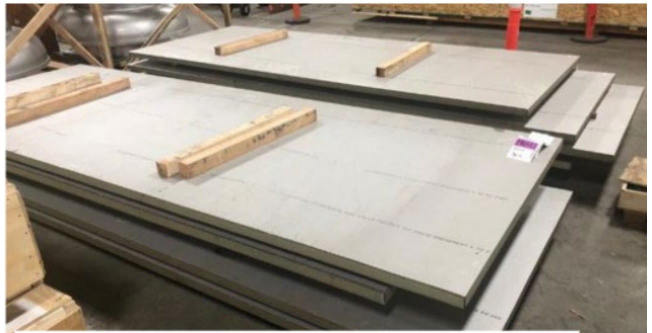
Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

Alloy 709 Sec III Div 5 Code Cases

- **Wrought Alloy 709 Code Cases for Class A Components in Section III Division 5.**
  - Develop Alloy 709 100,000 h Code Case for plate forms
  - Include additional product forms of Alloy 709, such as bar, pipe and forging
  - Develop longer-term Code Cases (300,000 h and 500,000 h)

Photograph of 1st commercial heat A709 plates in as-rolled condition

- Totaling about 45,000 lbs



Photograph of 2nd commercial heat in solution-annealed condition

Photograph of 3rd commercial heat in solution-annealed condition

LPBF 316H Sec III Div 5 Code Case

Develop a 100,000 h Code Case for LPBF 316H as Class A material in Sec III, Div 5.

- **Purpose**
  - Use the Code Case as a test bed to explore and test innovative qualification methods.
  - Drive the adoption of innovative methodologies in ASME Code development and application.
- **Significance**
  - First-time introduction of additively-manufactured material in Section III Division 5.
  - Critical step for AM technologies in advanced reactor designs.
- **Engagement**
  - Continuous interaction with ASME.
  - Advocate innovative approaches for Code and regulatory acceptance.

Environmental Effects Design Guide

Challenge

- ASME Section III, Division 5 does **not account for environmental effects (corrosion and radiation)** on metallic components.
- No standardized methodology exists for evaluating environmental impacts on material durability.
- Responsibility left to vendors, creating inconsistencies and barriers to licensing.

Ongoing Activities

- Survey international standards (e.g., RCC-MRx, Japan) that address environmental impacts.
- Evaluate post-irradiation creep rupture data of 316 SS.
- Evaluate the damage fraction model

Impact

- Fills a critical gap for U.S. nuclear vendors.
- Supports unified approaches for licensing.
- provides an alternate method for rapidly providing R&D results to vendors.

Advanced Reactor Surveillance Technology Development

- A material surveillance program is necessary to monitor material degradation in service to mitigate the risk posed by the limited up-front test data.
- AMMT is developing surveillance test articles aimed at assessing material degradation in reactor relevant environments.
- Current effort focuses on generating thermal cycling data in molten salt for establishing acceptance criteria of MSR materials surveillance program in support of NRC staff guidance on materials compatibility.

Work will be presented:

4:10 PM	4:30 PM	Surveillance testing program for advanced reactors	Xinchang Zhang/INL
4:30 PM	4:50 PM	Materials surveillance technology development	Bipul Barua/ANL

Summary

- MSRs offer significant performance advantages for advanced nuclear energy, but materials remain a key constraint on deployment readiness.
- Candidate Ni-based alloys, Fe-based alloys, refractory alloy, and advanced-manufactured materials are under active development.
- Candidate alloys and AM routes are promising, but data gaps remain large.
- Qualification challenged by coupled effects: High temperature + Corrosive salts + Irradiation + stress + Long service life.
- Existing ASME pathways are necessary but not sufficient for full MSR environmental qualification
- Accelerated qualification requires:
  - Integrated experiments, advanced characterization, mechanistic modeling, and AI/digital tools
  - Integration of R&D, Code development and licensing

2026 AMMT Program Review Meeting

- The DOE-NE AMMT Program Review Meeting will be held at June 23-25, 2026, at Spaces - Penthouse Conference Room, 800 Maine Ave SW, Washington, DC 20024.
- The AMMT Program Review will cover the full range of R&D activities currently being conducted within the AMMT program.
- The meeting will be in-person, with a virtual option available for those unable to travel.
- All attendees need to register via our meeting registration form by May 31, 2026.

U.S. DEPARTMENT *of* ENERGY | Office of Nuclear Energy