GAIN and Industry Visit – Argonne National Laboratory, May 19-20, 2026

Department of Energy Office of Nuclear Energy

Advanced Materials and Manufacturing Technologies (AMMT) Program Overview

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Argonne NATIONAL LABORATORY
INL Idaho National Laboratory
Los Alamos NATIONAL LABORATORY
OAK RIDGE National Laboratory
Pacific Northwest NATIONAL LABORATORY

AMMT ADVANCED MATERIALS AND MANUFACTURING TECHNOLOGIES

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

AMMT Mission, Vision, Goals

AMMT is a crosscutting program that supports materials and manufacturing needs across diverse reactor systems.

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 for nuclear energy
- **Evaluate** materials performance in nuclear environments
- **Qualify**: enable rapid qualification
- **Deploy**: accelerate commercialization through technology maturation

AMMT 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

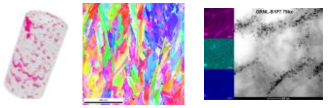
- Component Demonstration and Evaluation
- Codes, Standards & Licensing
- Scalable Manufacturing for Deployment

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

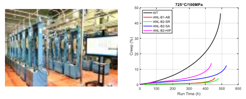
EXPERIMENTAL

Processing Experiments

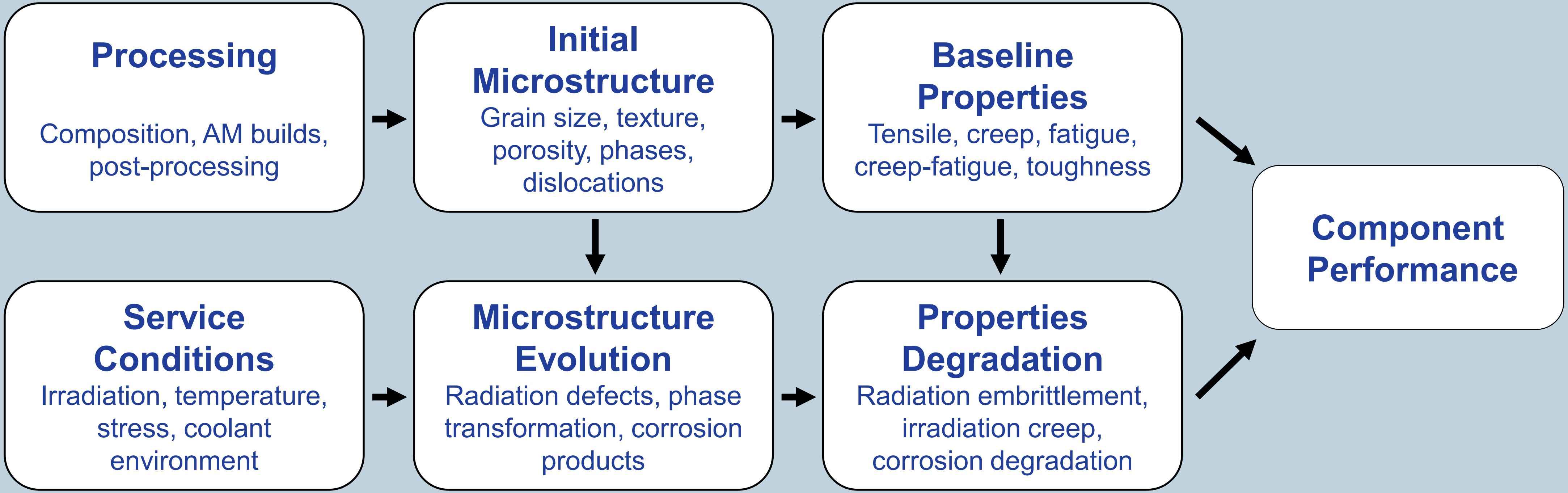
Microstructure Characterization



Property Testing



Component Testing



Processing
Composition, AM builds, post-processing

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

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

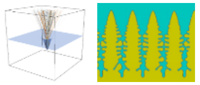
Service Conditions
Irradiation, temperature, stress, coolant environment

Microstructure Evolution
Radiation defects, phase transformation, corrosion products

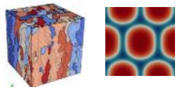
Properties Degradation
Radiation embrittlement, irradiation creep, corrosion degradation

Component Performance

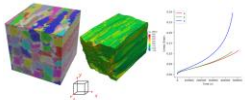
COMPUTATIONAL



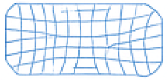
Processing Simulation



Microstructure Modeling



Property Prediction



Component Virtual Testing

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

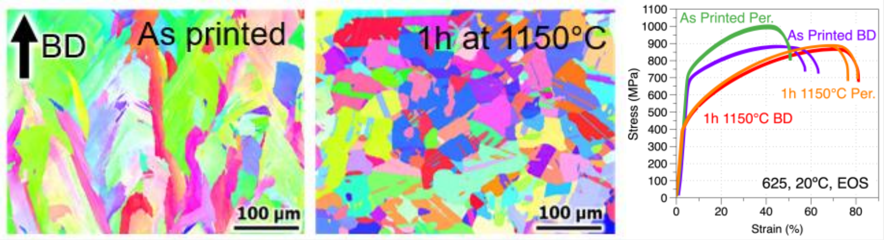
Manufacturing

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

Ni-based Alloys for Molten Salt Applications

Alloy 625

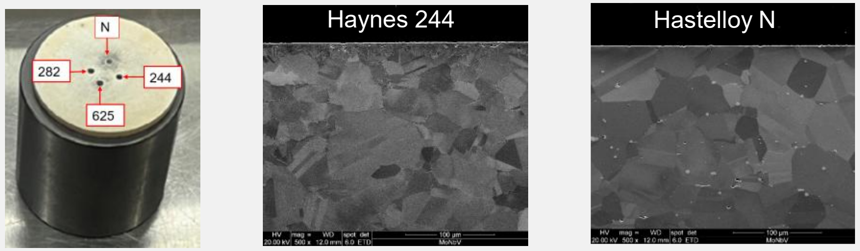
- **Application**
  - A **low-Co** alloy for reactor components.
  - Good high temperature strength and oxidation resistance, and weldability.
- **Advanced Manufacturing**
  - Additive manufacturing of Alloy 625 is a relatively mature technology.
  - Focus on mechanical properties and performance in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



Microstructure and tensile behavior of LPBF 625.

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.



Exposure in NaCl–$MgCl_2$ at for 1,000 h.

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

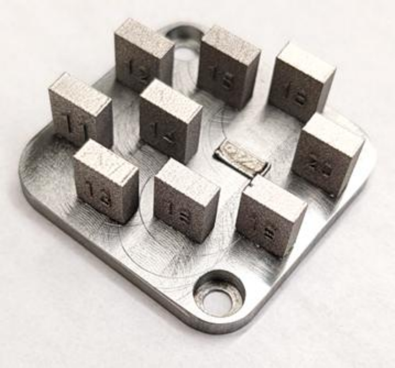
- LPBF 316H serves as a case study to develop and demonstrate a rapid qualification framework.
- LPBF 316H Sec III Div 5 Code Cases
- Neutron irradiation and PIE of LPBF 316
- Corrosion studies of LPBF 316

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.

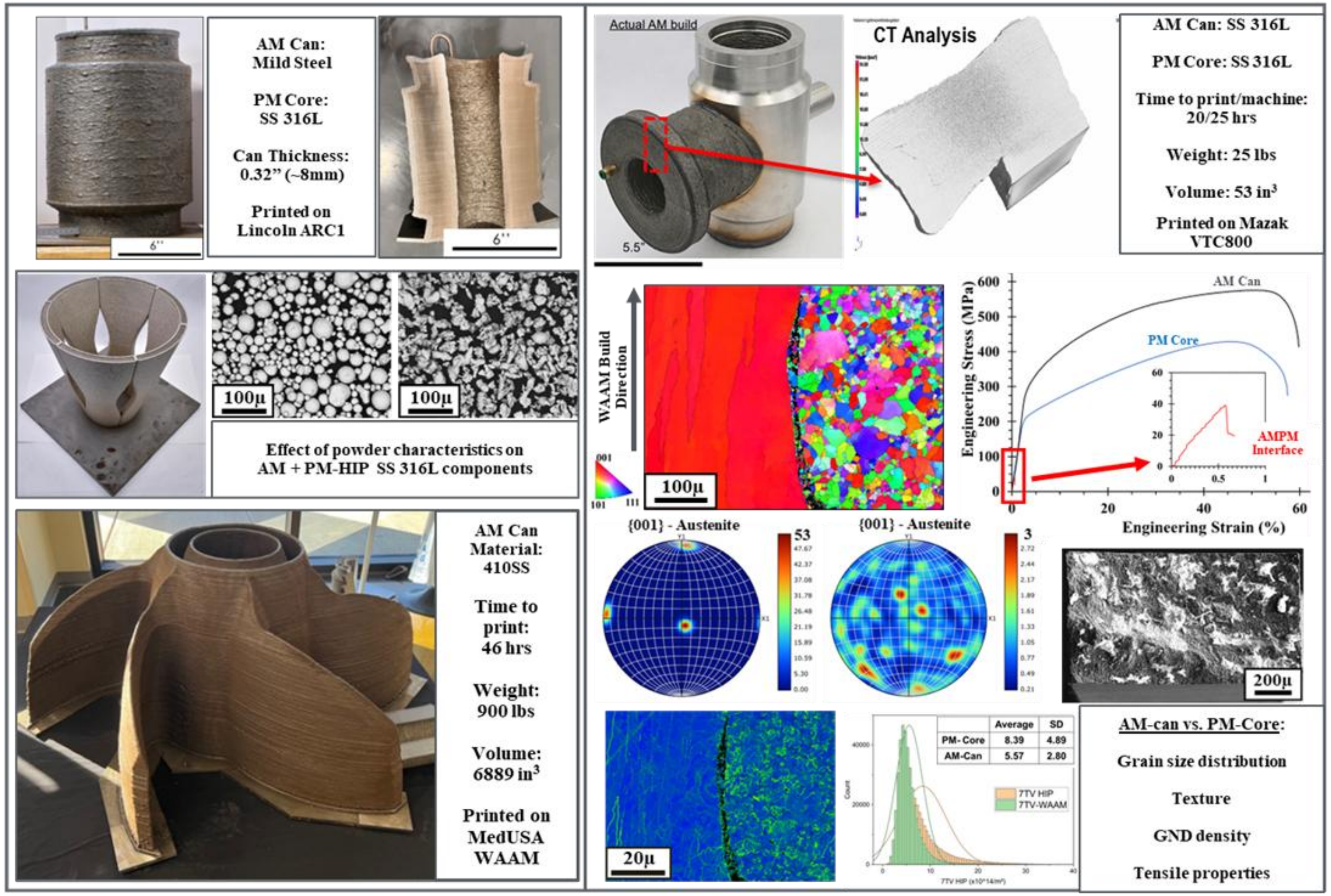
Nb1Zr build printed on the EOS M400 machine at LANL.



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

Large-Scale Component Fabrication (AM+PM)

- **Application**
  - Accelerate, scale-up PM-HIP for fabrication of large-scale nuclear components.
- **Use AM to manufacture HIP-cans**
  - Fabricate HIP cans (impeller and T-valve) using wire-arc additive manufacturing (WAAM) and hybrid AM (additive + substrative).
  - Understand sensitivity of powder shape and size on post-HIP microstructure and property.
  - Improve fabricability and post-processing of AM HIP-cans.
- **HIP Process**
  - Conduct powder filling, evacuation, and HIP to produce parts.
  - Demonstrate single-material and multi-material fabrication.
- **Incorporate in-situ monitoring and modeling**
  - Model deformation of HIP cans to improve geometry consistency.
  - Monitor and control stress evolution via in-situ DIC+IR.



	Average	SD
PM- Core	8.39	4.89
AM-Can	5.57	2.80

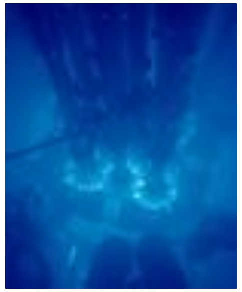
Fabricating structures with varying complexities across length-scales and understanding Processing-Structure-Property relationships to assist qualification of PM-HIP components.

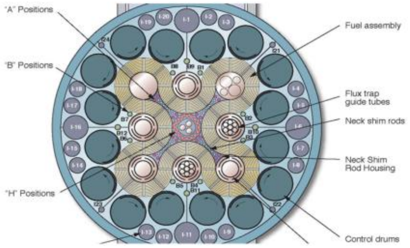
S. Nag, et. al. "Investigation of large-scale AM+PM parts for Nuclear Applications", Proceedings of Additive Manufacturing with Powder Metallurgy Conference 2024.

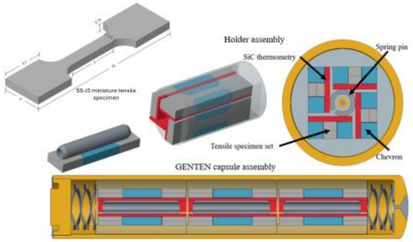
AMMT's Neutron Irradiation Campaigns

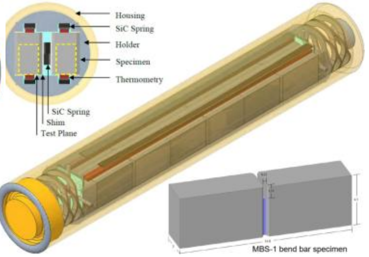
ATR and HFIR Irradiation

- **ATR** (Fast spectrum using shielded capsules)
  - Drop-in capsule design
  - SS-J and compact tension specimens
- **HFIR** (Mixed spectrum)
  - GENTEN capsules with SS-J tensile and mini-buttonhead specimens
  - MINBEN capsules with miniature bend bar specimens
- **Materials**: wrought and AM 316, A709
- **Irradiation conditions**: 300 - 800°C, up to 10 dpa









Performance Data & Design Needs

- **Irradiation Effects**
  - Hardening and embrittlement
  - Void Swelling
  - Irradiation creep
  - Helium & transmutation effects
  - Microstructural evolution & phase stability
  - Combined environmental effects
- **Mechanical Properties**
  - Tensile
  - Creep
  - Fatigue & creep-fatigue
  - Fracture toughness
  - Crack growth
- **Design Needs**
  - Design allowables & design rules
  - Constitutive models for inelastic behavior
  - Flaw tolerance & acceptance criteria
  - Degradation/damage mechanisms
  - Life prediction methods

Neutron Irradiation Collaborations

- **NEA FIDES-II:** (Second **F**ramework for **I**rradiation **E**xperiment**s**)
  - **INCREASE (In-Core Real-Time Mechanical Testing of Structural Materials)**
    - Phase I: In-core mechanical testing instrumentation design and testing at MITR to produce stress relaxation data
    - Phase II: Irradiation Campaign at High Flux Reactor (HFR) (the Netherlands) - AMMT provides materials for irradiation
  - **HITEC (High-Temperature Creep Testing)**
    - Irradiation campaign at High Flux Reactor (HFR) (the Netherlands)
    - Include instrumented in-pile creep tests and uninstrumented specimens (650°C 5 dpa)
    - AMMT provides materials for irradiation
- **AMMT-NSUF Collaboration**
  - NSUF SAM-3 neutron irradiation in ATR
  - AMMT provides materials for irradiation
- **JOYO Fast Reactor**
  - Collaborate with AFC as part of CNWG-FCWM sub working group
  - Include a limited number of AMMT-relevant samples

Sodium Compatibility

Argonne NATIONAL LABORATORY

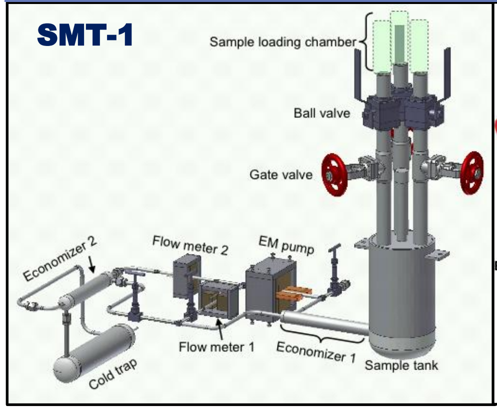
Material degradation mechanisms in liquid sodium

- Metallic Element Transfer
  - Controlled by the solubility of the element in liquid sodium.
  - Dissolution of metallic elements causes metal loss and phase transformation.

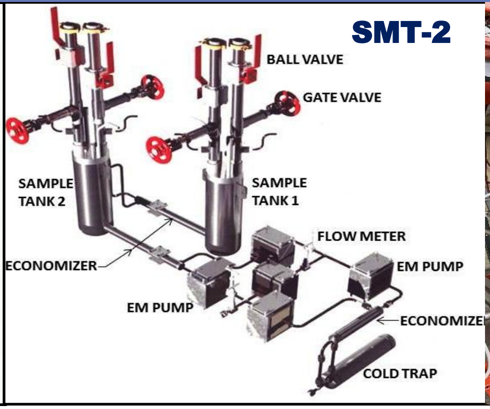
- Non-metallic Element Transfer (O, C, N, H)
  - Oxygen effect: has a strong effect on the corrosion rate of a material.
  - Carbon transfer: cause microstructural instability and mechanical property degradation.

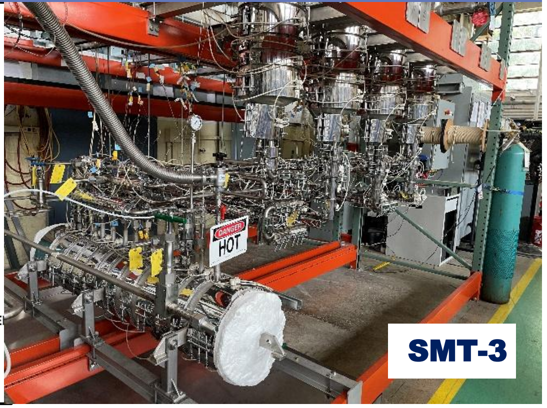
Argonne's Forced-Convection Sodium Materials Testing (SMT) Loops

SMT-1



SMT-2





SMT-3

Materials of Current Focus

- **316H austenitic stainless steel**
  - LPBF 316H
  - Wrought 316H as reference

- **Alloy 709 austenitic stainless steel**
  - Three commercial heats
  - Different heat treatments: PA & SA

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.

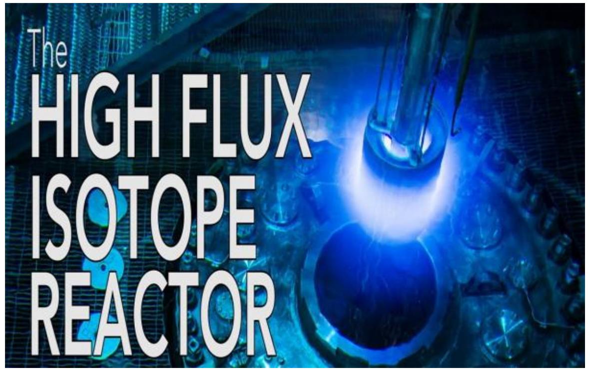
INL Idaho National Laboratory	Oak Ridge National Laboratory	Pacific Northwest National Laboratory
Corrosion of AM materials	Materials compatibility and lifetime predictions	Corrosion kinetics and interfacial interactions

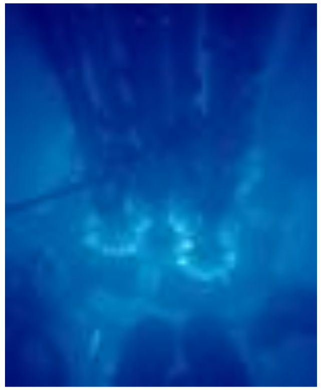
Combined Irradiation and Corrosion Effects of AM Components

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.





Reactor Material Qualification

"**Qualification**" refers to the process of systematically testing and evaluating materials to ensure their performance reliability under reactor operating conditions, such as high temperatures, mechanical load, radiation exposure, and corrosive environments.

Materials & Manufacturing

- Composition specifications
- Process control & repeatability
- Post-processing requirements

Material Properties

- Physical properties
- Mechanical properties (tensile strength, ductility, fatigue, toughness)
- High-temperature properties (creep, creep-fatigue)

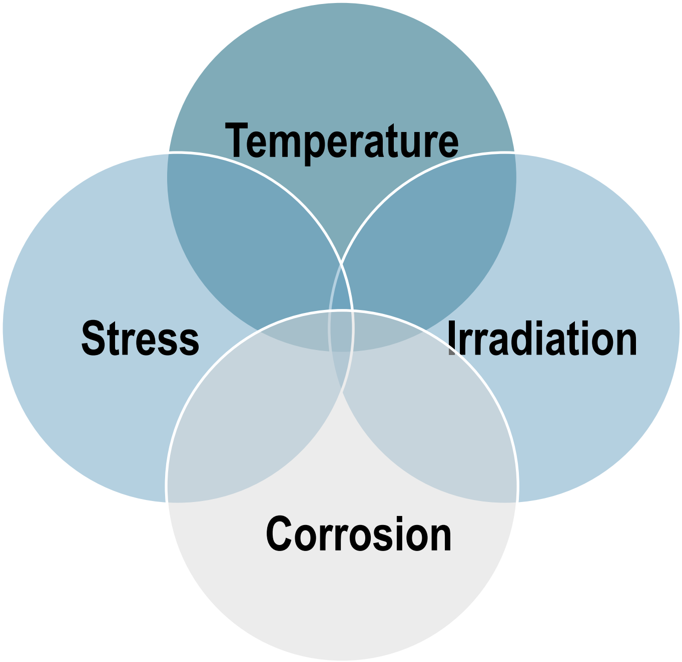
Environmental Performance

- Radiation resistance
- Chemical compatibility and corrosion resistance
- Long-term performance

Codes & Regulatory

- ASTM standards
- ASME Code (Section III)
- Regulatory compliance

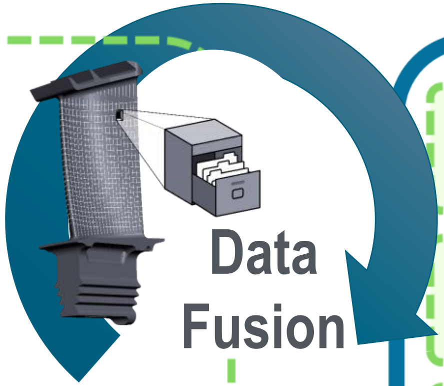
Nuclear Environment



Digital Qualification: Multi-Dimensional Data Correlation (MDDC)

Digital Twin

Spatially Tracked Data



Data Fusion

Manufacturing

Characterization

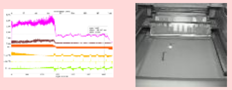
Process Parameters

Material Characterization

Feedstock Information

Non-Destructive Testing

In-Situ Data



Destructive Testing

Post Processing

Lifetime & Performance

MDDC

Twin 1

Twin 2

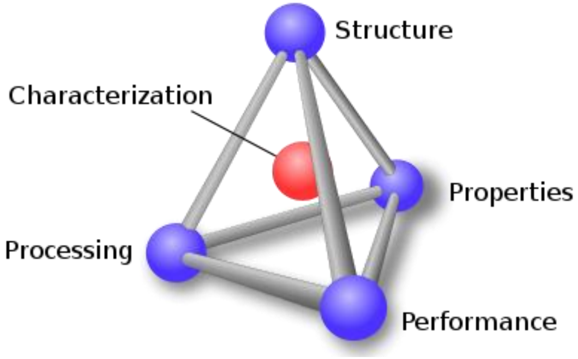
Twin 3

…

Twin n

Toolkit

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

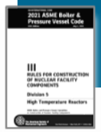


Digital Twins and MDDC Toolkit Accelerates Development

Demonstrations

3 years

Digitally Aided Qualification



2021 ASME Boiler & Pressure Vessel Code

III

RULES FOR CONSTRUCTION OF NUCLEAR FACILITY COMPONENTS

Division 5

High Temperature Reactors

5 years

AI Based Design

10 years

Improve Performance, Reliability and Lifetime of Nuclear Components

Qualification of Advanced Manufacturing - LPBF 316 SS

Multi-site, Multi-machine, Multi-batch powder builds

Renishaw AM400

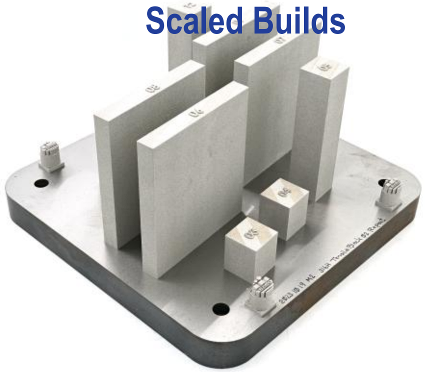
GE Concept Laser M2

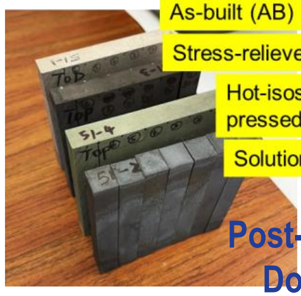
EOS M 290

	Material	316H SS	316H SS	316H SS	316H SS	ASTM Specification
	Vendor	Praxair	Praxair	PAC	Praxair	
	Lot #	2	3	AMP316H1001E	4	
Composition (wt %)	Fe	balance	balance	balance	Balance	balance
	Cr	16.8	17.0	16.94	16.7	16.0–18.0
	Ni	12.1	12.3	10.88	11.9	10.0–14.0
	Mo	2.5	2.3	2.23	2.6	2.00–3.00
	Mn	1.13	1.05	1.02	0.02	<2.00
	Si	0.48	0.07	0.37	0.04	<1.00
	Al	0.01	0.02	0.01	0.01	n/a
	N	0.01	0.012	0.05	0.01	n/a
	O	0.034	0.03	0.048	0.02	n/a
	P	<0.005	<0.005	0.031	<0.005	<0.045
	S	0.00	0.00	0.00	0.00	<0.03
	C	0.06	0.08	0.043	0.07	<0.03 (L) 0.04–0.10 (H)

Parametric Study Builds

Optimized Parameters Scaled Builds





As-built (AB)

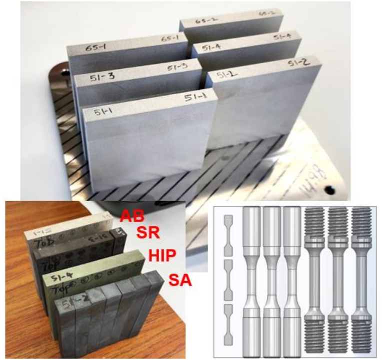
Stress-relieved (SR)

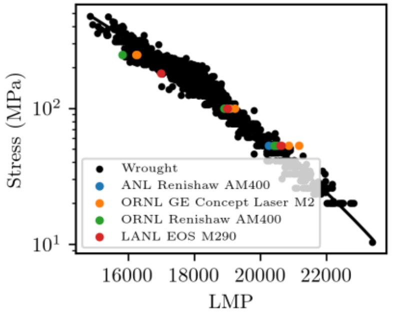
Hot-isostatic-pressed (HIP)

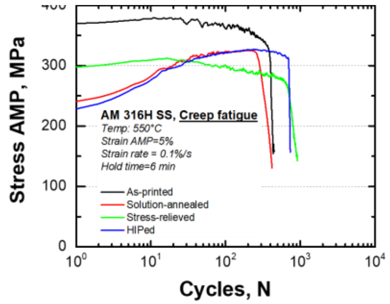
Solution-annealed (SA)

Post-built Treatment Down-selection

Mechanical Property Evaluation





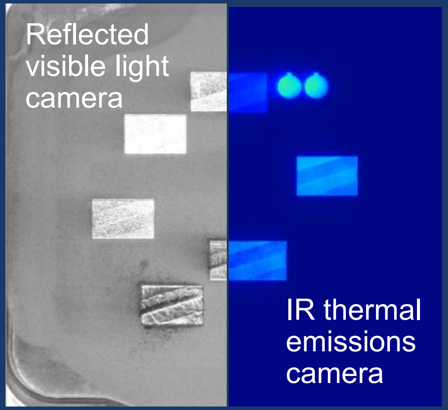


In situ Process Monitoring of AM Builds

In-situ monitoring is valuable when correlated with post-build NDE and component performance.

1

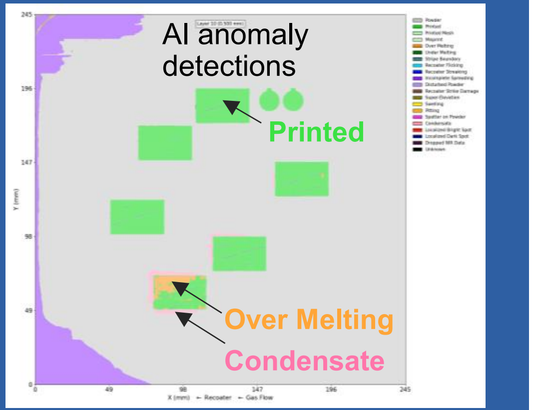
Collect



Collet in situ data for the entire build

2

Detect



AI algorithms detect and register them spatially to part locations

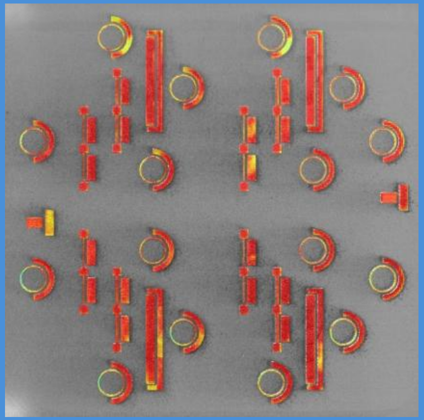
3

Correlate

Correlate in situ monitoring data with post-build NDE for part quality assessment

4

Qualify



Monitoring data used as QA tool within digital thread to reduce post-process NDE burden

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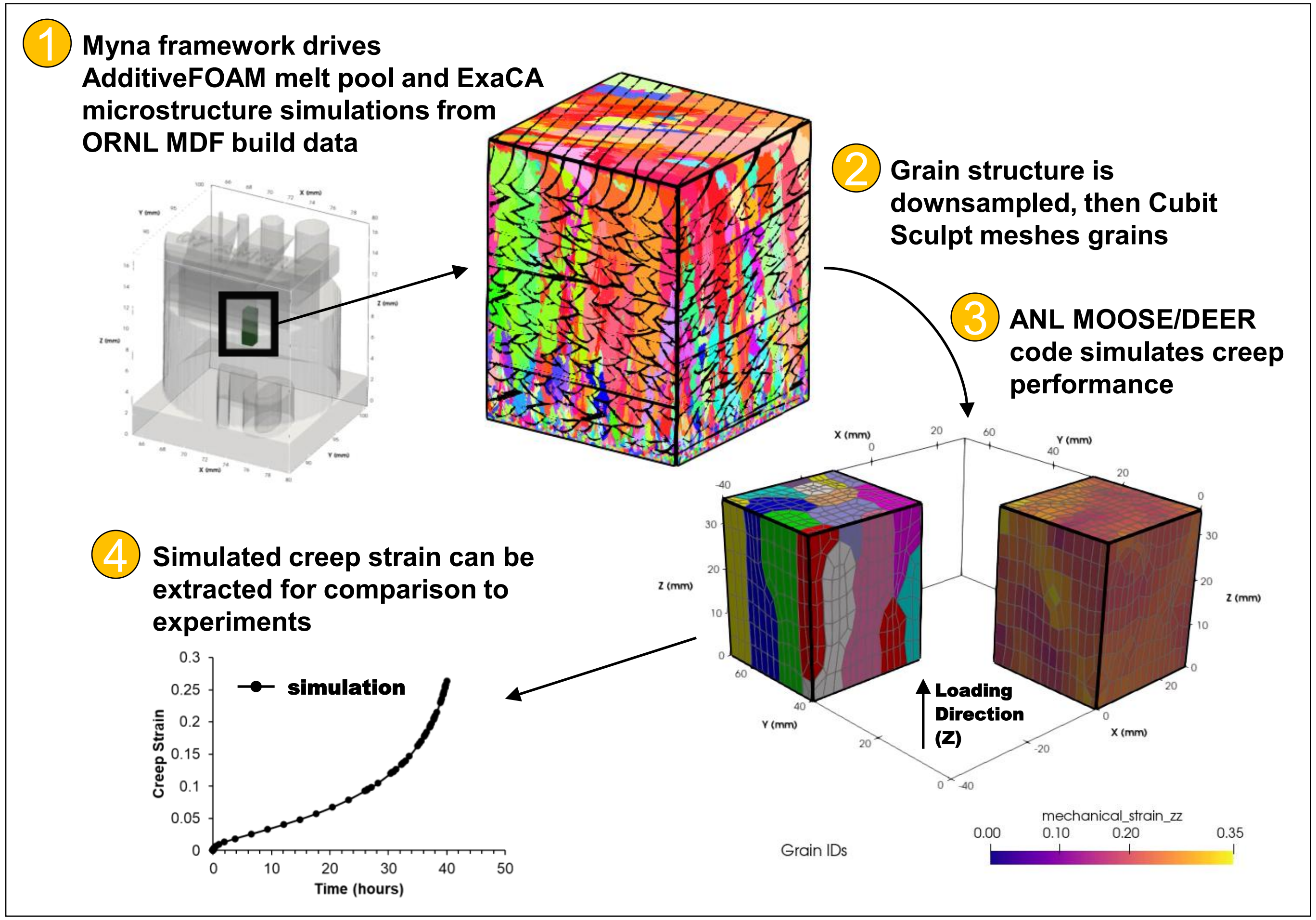
Processing-Structure-Creep Simulation Workflow

- 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.



① **Myna framework drives AdditiveFOAM melt pool and ExaCA microstructure simulations from ORNL MDF build data**

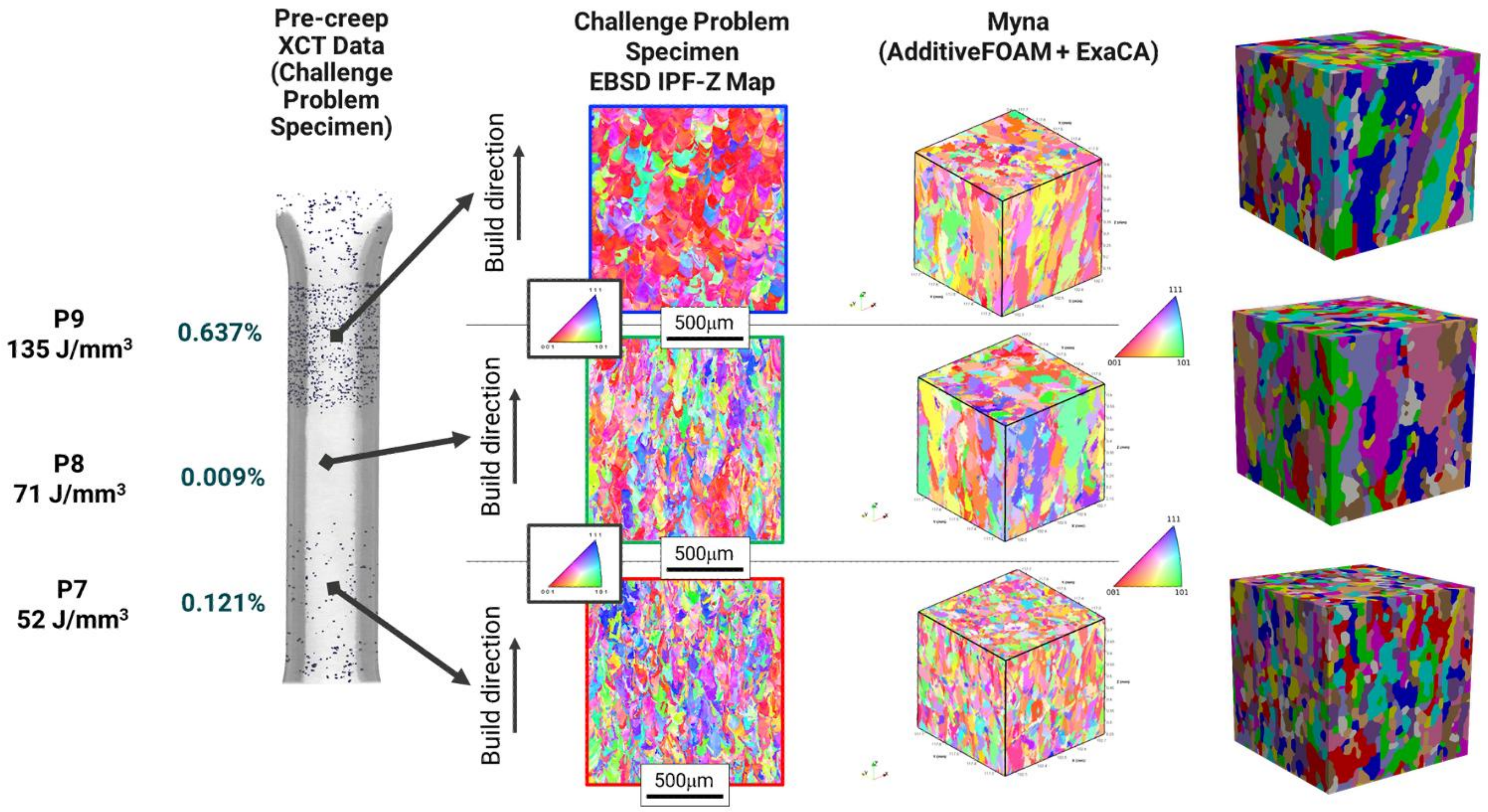
② **Grain structure is downsampled, then Cubit Sculpt meshes grains**

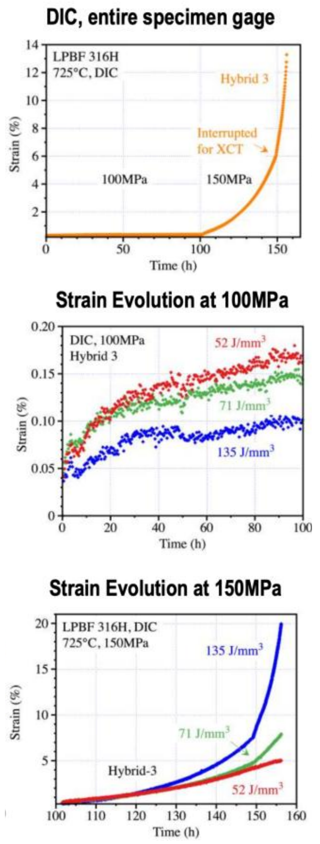
③ **ANL MOOSE/DEER code simulates creep performance**

④ **Simulated creep strain can be extracted for comparison to experiments**

Establish Defect – Performance Relationships

For AM nuclear components, the challenge is not only to detect defects - it is to establish whether those defects are acceptable for long-term service in harsh nuclear environments.





Accelerated Evaluation of Irradiation Effects

Apply a science-driven qualification strategy through the **Licensing Approach with Ions and Neutrons (LAIN)** framework, which integrates neutron and ion irradiations with physics-based modeling and AI.

Neutron Irradiation

- Provide critical performance data in reactor environments
- In-reactor experiments on combined irradiation+corrosion+temperature+stress effects

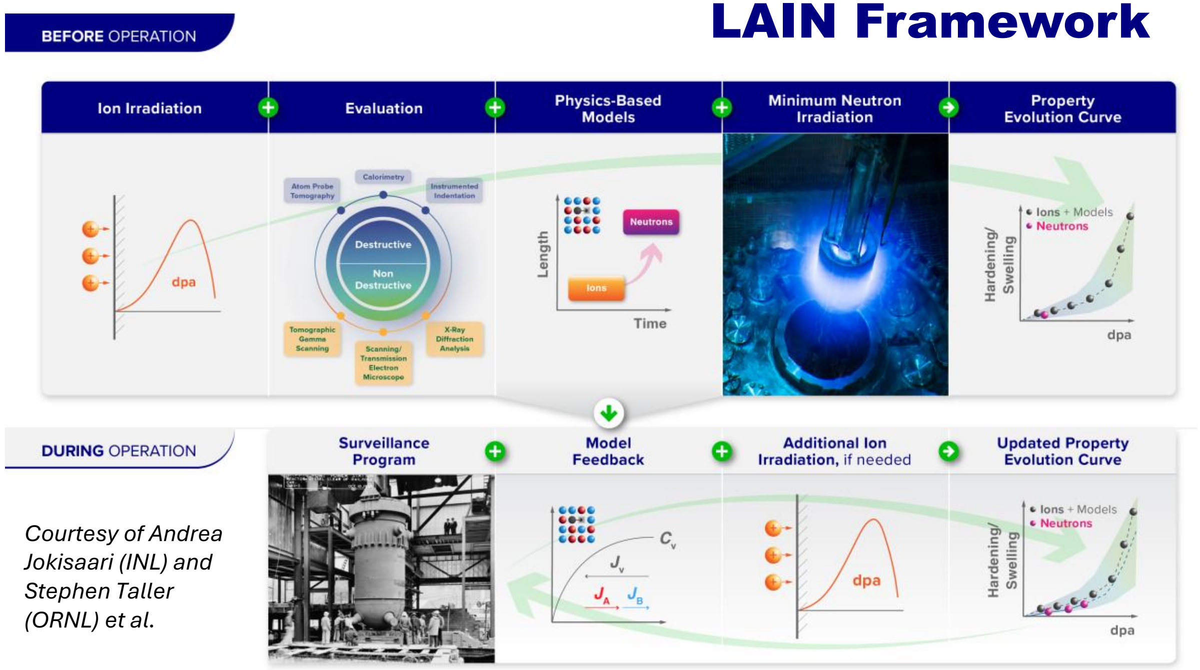
Ion Irradiation

- Serve as an accelerated, complementary tool to explore a wide parameter space
- Support studies of
  - Metallurgical variables (composition, processing parameters, heat treatment conditions)
  - Irradiation Variables (temperature, dose, dose rate, energy spectrum, transmutation)
- Identify irradiation degradation mechanisms

Modeling and Simulation

- Support understanding the underlying physics
- Predict material performance beyond testing conditions.

LAIN Framework

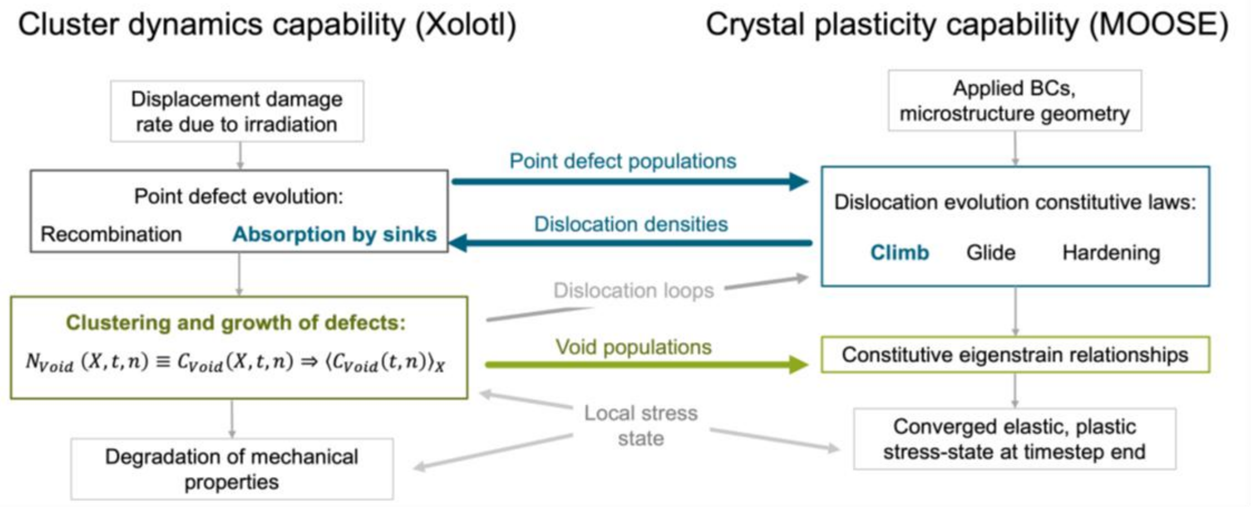


Courtesy of Andrea Jokisaari (INL) and Stephen Taller (ORNL) et al.

Irradiation Creep Modeling

Modeling Approach

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



Cluster dynamics capability (Xolotl)

Crystal plasticity capability (MOOSE)

Displacement damage rate due to irradiation

Point defect evolution:

Recombination

Absorption by sinks

Clustering and growth of defects:

$N_{Void}\,(X,t,n) \equiv C_{Void}(X,t,n) \Rightarrow \langle C_{Void}(t,n)\rangle_X$

Degradation of mechanical properties

Point defect populations

Dislocation densities

Dislocation loops

Void populations

Local stress state

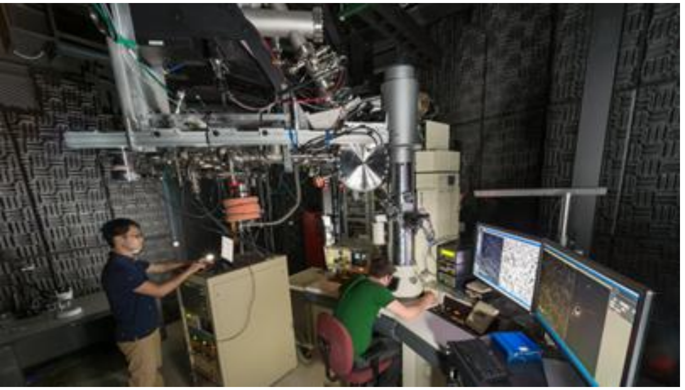
Applied BCs, microstructure geometry

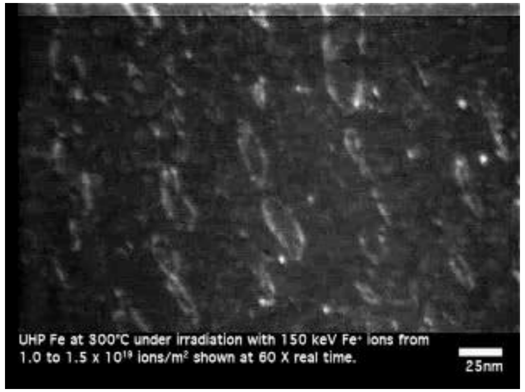
Dislocation evolution constitutive laws:

Climb Glide Hardening

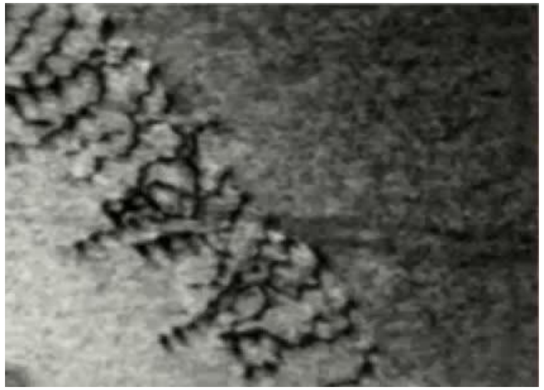
Constitutive eigenstrain relationships

Converged elastic, plastic stress-state at timestep end





UHP Fe at 300°C under irradiation with 150 keV Fe+ ions from 1.0 to 1.5 x 10^{19} ions/m² shown at 60 X real time.



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.

Technology Maturation

Goal is to advance a technology by increasing its TRL to accelerate the adoption of advanced materials and manufacturing processes in nuclear applications.

Component Fabrication and Evaluation for Technology Demonstration

- Demonstrate the fabrication feasibility of reactor components using new materials or AM technologies.
- Evaluate the component performance in relevant reactor environments.

Codes and Standards

- Introduce new materials and manufacturing methods into ASME Code.
- Incorporate the rapid qualification framework and methods into Codes and Standards.

Regulatory Acceptance and Licensing

- Establish design and operational limits and guidance to support advanced reactor licensing applications.
- Develop material surveillance programs to monitor material degradation during service.

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.

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

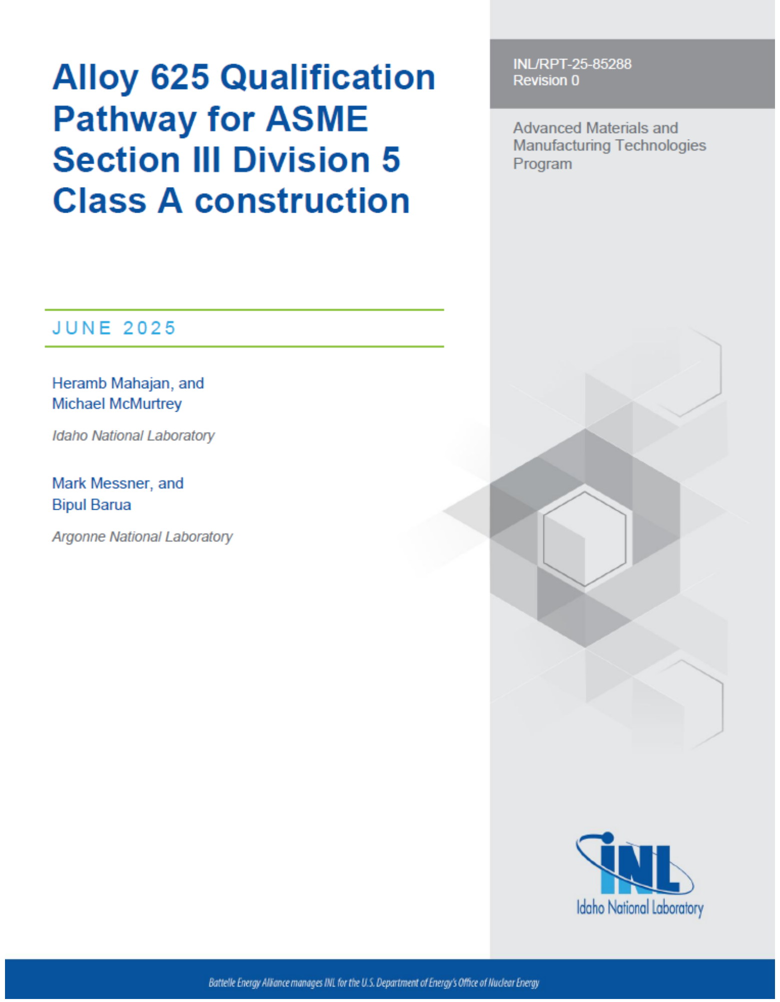
- Totaling about 45,000 lbs

Photograph of 2nd commercial heat in solution-annealed condition

Photograph of 3rd commercial heat in solution-annealed condition

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.



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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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Michael McMurtrey

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

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

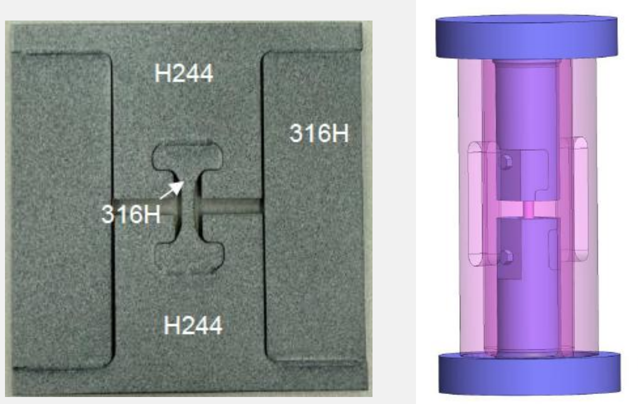
- Survey international standards (e.g., RCC-MRx, Japan) that address environmental impacts.
- Evaluate post-irradiation creep rupture data of 316 SS.
- Evaluate the damage fraction model

Impact

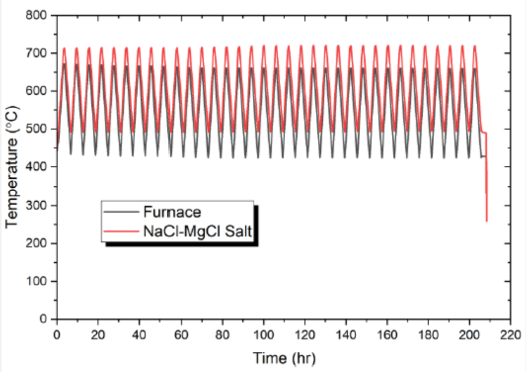
- Fills a critical gap for U.S. nuclear vendors.
- Supports unified approaches for licensing.
- provides an alternate method for rapidly providing R&D results to vendors.

Advanced Reactor Surveillance Technology Development

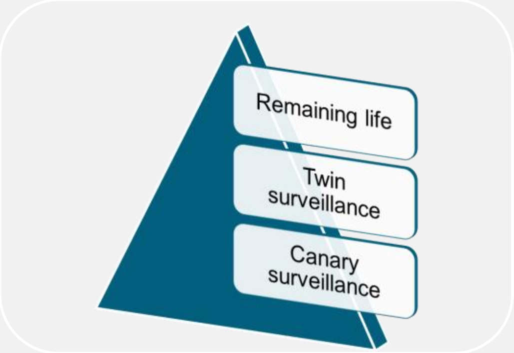
- A material surveillance program is necessary to monitor material degradation in service to mitigate the risk posed by the limited up-front test data.
- AMMT is developing surveillance test articles aimed at assessing material degradation in reactor relevant environments.
- Current effort focuses on 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.



Test article design



Testing in Air and Molten Salt


Remaining life

Twin surveillance

Canary surveillance

Acceptance procedure

2026 AMMT Program Review Meeting (Hybrid 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.
- All attendees need to register via our meeting registration form by May 31, 2026.

U.S. DEPARTMENT
of ENERGY

Office of
Nuclear Energy

AMMT website: https://ammt.anl.gov/