Advanced Materials and Manufacturing Technologies (AMMT) Program

Overview of Materials Interaction with Molten Salts

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AMMT Program: 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.
- Establish and demonstrate a rapid qualification framework.
- Evaluate materials performance in nuclear environments.
- Accelerate commercialization through technology maturation.

AMMT Program: Technical Areas

Advanced Materials & Manufacturing

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

Rapid Qualification

- Rapid Qualification Framework
- High-temperature Materials Qualification
- Advanced Manufacturing Qualification

Environmental Effects

- Neutron Irradiation & Post-irradiation Examination
- Accelerated Qualification for Radiation Effects
- Corrosion Effects in Nuclear Environments

Technology Maturation

- Component Fabrication & Evaluation
- Codes and Standards
- Regulatory Acceptance & Licensing

Impact: The AMMT program will provide the nuclear industry with next-generation high-performance materials and advanced fabrication methods for expanded supply chains and demonstrate new technologies within the next decade.

Technical Area: Environmental Effects

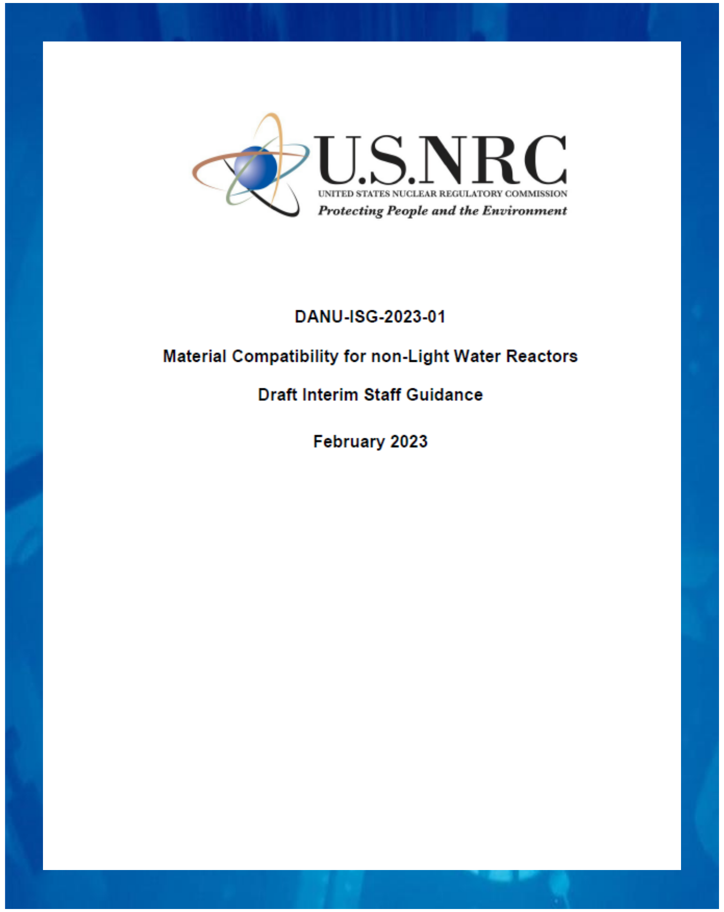
Environmental Effects addresses materials degradation issues, such as corrosion and irradiation effects.

Goals:

- First-of-a-kind performance data on new materials in reactor environments
- Effect of microstructural variability on material degradation
- Rapid and effective qualification on materials performance and degradation
- Contributing to a technical basis for regulatory acceptance

Topics:

- Neutron irradiation and post-irradiation examination to evaluate materials performance
- Accelerated qualification for radiation effects through combined ion, neutron irradiation and computer modeling
- Evaluate material corrosion performance in various reactor coolant environments (e.g. molten salt, sodium, helium) to determine their performance limits


U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

DANU-ISG-2023-01

Material Compatibility for non-Light Water Reactors

Draft Interim Staff Guidance

February 2023

Technical Area: Advanced Materials & Manufacturing

Our materials development strategy is to develop advanced materials through integration with manufacturing processes.

- **Apply advanced manufacturing to existing reactor materials**
  - Expand the use of nuclear reactor materials through advanced manufacturing techniques.
  - Optimize manufacturing processes for existing reactor materials (Code-approved materials or those with sufficient data in nuclear environments).
- **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 new material design concepts, e.g. ODS, HEAs
  - Use advanced manufacturing to develop innovative materials, e.g. functionally graded materials, cladding, etc.

Materials of Interest

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

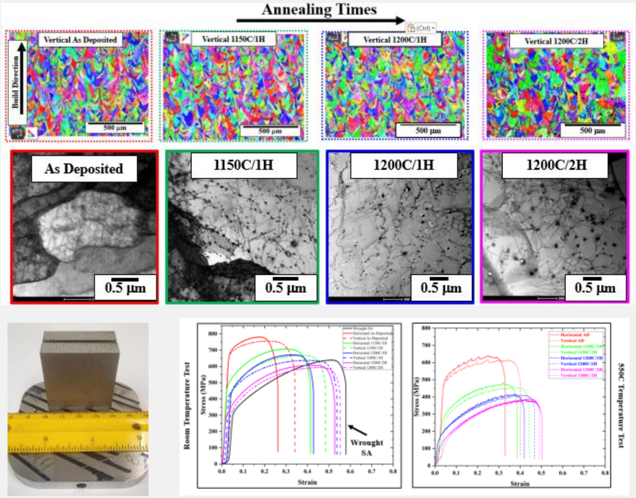
Manufacturing Processes

- Advanced manufacturing
- Traditional manufacturing
- Hybrid manufacturing
- Joining techniques

Development of Fe-based Alloys

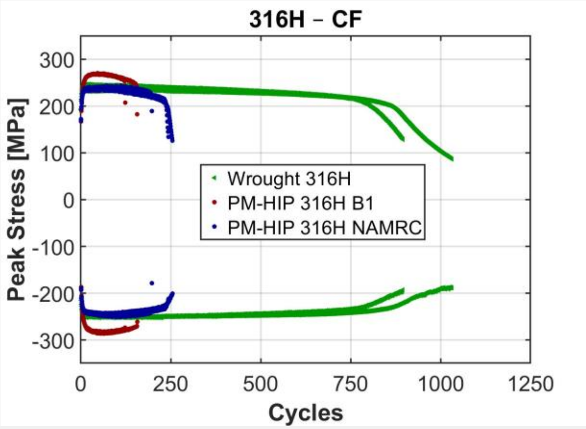
AM 316H, A709, G91, G92

- Enable additive manufacturing of current reactor materials.
- Optimize LPBF and DED processes and post-process treatments to achieve high temperature properties.



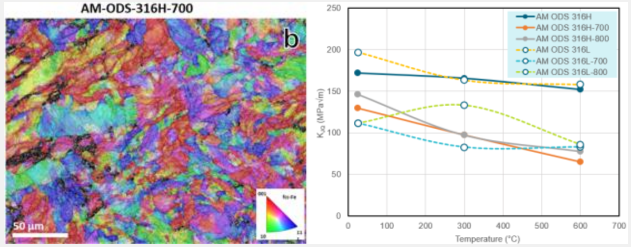
PM-HIP 316H

- Support microreactor high-temperature structural component fabrication.
- Achieve high temperature mechanical properties of PM-HIP comparable to or better than wrought materials.



ODS 316 SS

- Demonstrate high-quality ODS alloys can be manufactured using alternative processing routes without the need for mechanical milling.
- Successfully demonstrated the LPBF processing of 316Y + oxide mixture.

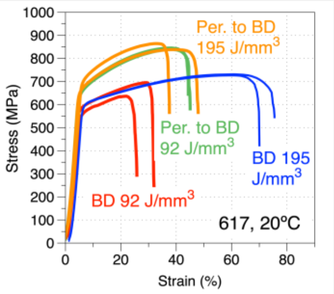


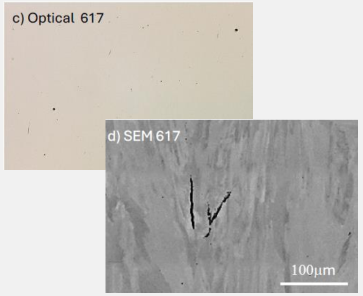
S. Mantri, et al. (ANL); M. McMurtrey (INL), T. S. Byun et al. (ORNL), I. van Rooyen, et al. (PNNL)

Development of Ni-based Alloys

Alloy 617

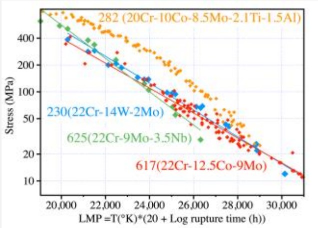
- An ASME Code-approved Class A material for high temperature nuclear applications.
- Good high temperature strength and oxidation resistance.
- Optimize additive manufacturing processing parameters & post-process treatment.



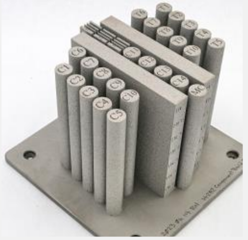


Alloy 625

- A low-Co alloy considered for reactor internal applications.
- Good high temperature strength and oxidation resistance, and weldability.
- Optimize additive manufacturing processing parameters & post-process treatment.



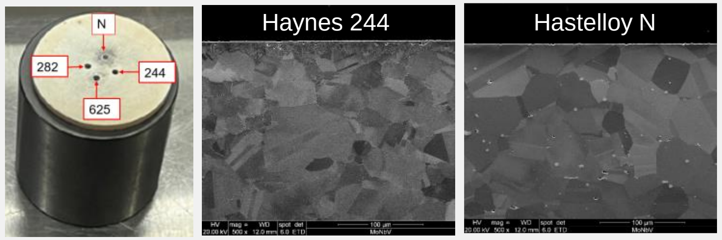
Larson–Miller plot comparing the creep resistance of wrought Ni-based alloys.



LPBF builds of mechanical test specimen blanks.

Alloy 244

- A new Ni-Mo-Cr-W alloy developed for static parts in advanced gas turbine engines.
- A low-Cr alloy expected to be molten salt compatible.
- Perform static molten salt corrosion tests of wrought 244 to evaluate the compatibility.
- Explore the printability of Alloy 244 by LPBF and DED.



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

AMMT Molten Salt Corrosion Studies

Current Focus: 316H, 709 stainless steels, Alloys 625, 617, 244 Ni alloys (wrought and AM).

Idaho National Laboratory | Oak Ridge National Laboratory | Pacific Northwest National Laboratory

Processing - structure - performance studies

Materials compatibility and lifetime predictions

Corrosion kinetics and interfacial interactions

Materials Interaction with Molten Salts

MSR materials choices are currently driven by legacy knowledge.

Lessons learned

- Salt purity
- Corrosion susceptibility correlated to Cr content
- Alloy development for improved performance in molten salt (Hastelloy N in FLiBe)
- Existence of embrittlement mechanisms (Te and He)
- Molten Salt Reactor Experiment (MSRE) temperature range for FLiBe: 650°C

Transitioning to new materials and manufacturing technologies

- What are the role of alloying elements in mitigating corrosion?
- How will materials perform long-term in different salts? Can we predict?
- What is the role of impurities?
- What are the synergistic effects of stress, corrosion, thermal aging, and irradiation?

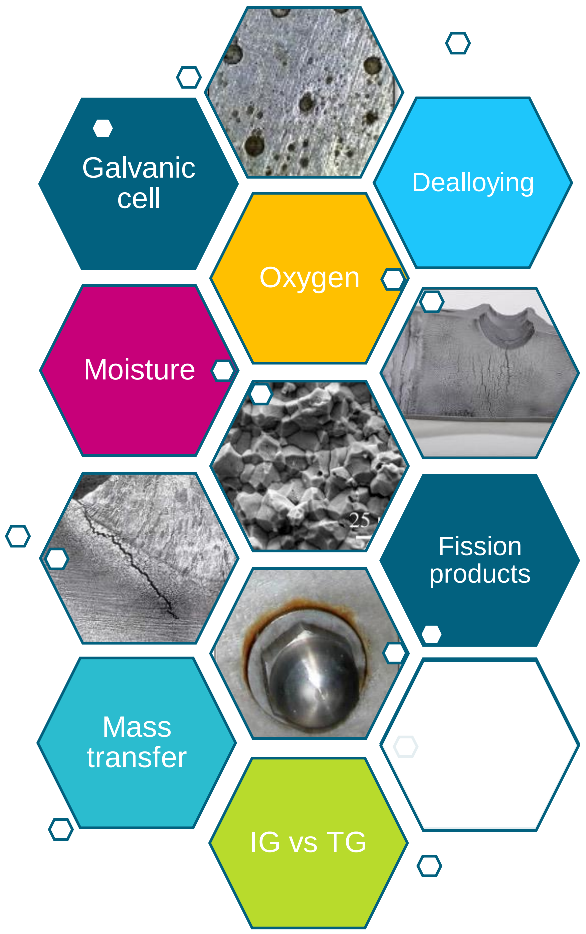
Operating and Regulatory Concerns for MSR Materials

Operating concerns

- Surface area
- Reduction in operating lifetime
- Salt impurities
- Corrosion of wrought alloys
  - Dealloying
  - Fission products
  - Moisture / oxygen
  - Preferential-intergranular
  - Galvanic effects
- Additional concerns for AM alloys
  - Dendritic as-solidified structures and microsegregation
  - High-temperature/secondary phases
  - Surface condition
  - Porosity / defects

Regulatory concerns

- Standards (e.g., ASTM) help NRC systematically evaluate licensing concerns related to corrosion of structural materials.
- No ASTM standard exists that is specific for corrosion testing AM materials.
- **An internal standardized methodology for testing is critical, establishing a foundation to advocate for a new ASTM standard.**



Evaluation of Fe- and Ni-based Alloys in Molten Fluoride and Chloride Salts

- Provide data of general corrosion and creep rupture lifetime in molten fluoride and chloride salts for 316H SS, Alloy 709, Alloy 617.
- Investigate the compatibility of Alloy 244 in NaCl-$MgCl_2$.
- Develop a validated physics-based approach to predict molten salt corrosion in multicomponent and multiphase alloys under static and flowing conditions.

Purification + testing	Mass Transfer	Long-term operation
• Salt chemistry • Fuel salt vs coolant salt • Allowable impurities • Redox control	• Corrosion • Deposition • Temperature dependence • Sensor Technology	• Transmutation performance • Salt chemistry changes • Redox control (how much?) • Useful predictive models

Creep Behavior in Molten Salt Environment

Materials

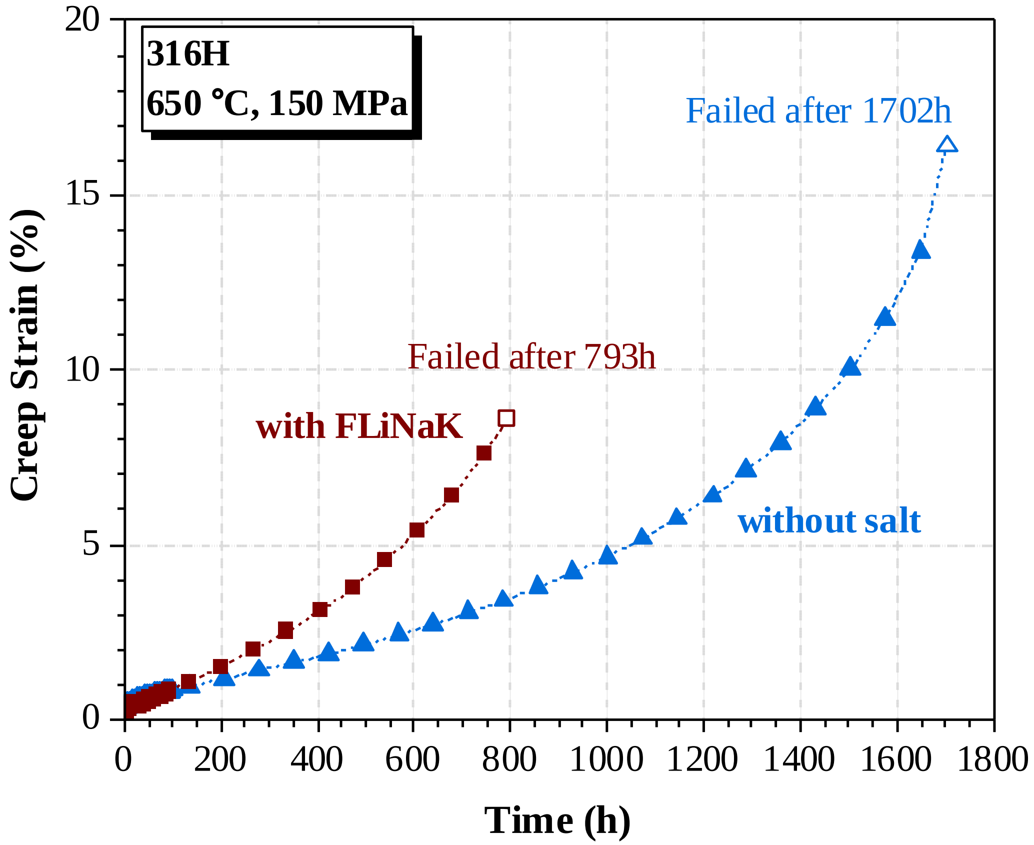
Alloy	Fe	Cr	Ni	Mn	Si	Mo	C	Co	Al	Ti	Other
316H	Bal.	16.6	10.3	1.6	0.3	2.0	0.04	0.2	-	-	Cu 0.4, N 0.03
709	Bal.	20.0	24.6	0.9	0.4	1.5	0.08	-	-	-	Nb 0.2, N 0.2
617	1.6	22.2	Bal.	0.1	0.1	8.6	0.05	11.6	1.1	0.4	Cu 0.04

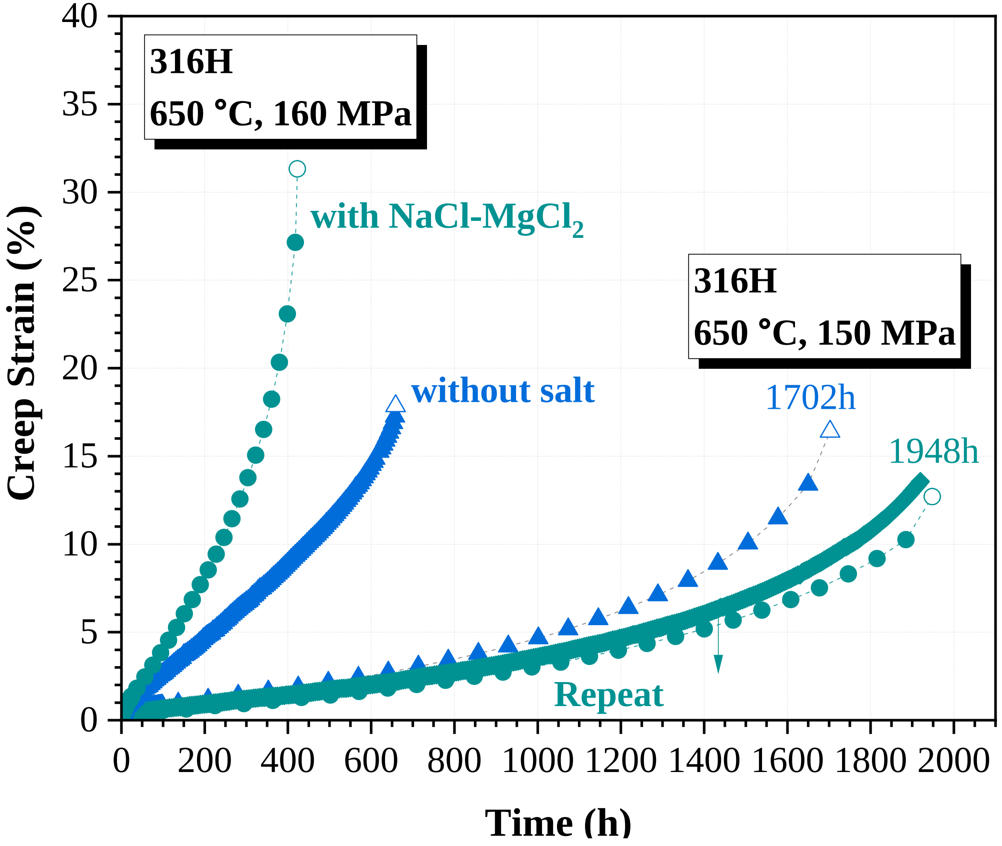
Testing conditions

	Wrought SA 316H 650°C, 150 MPa	**Wrought SA 709 700°C, 158 MPa**	**Wrought SA617 750°C, 146 MPa**
Baseline (no salt)	Completed	Completed	Completed
FLiNaK	Completed	Completed	Completed
$NaCl$-$MgCl_2$	Completed		

Creep Behavior of 316H in Molten Salt Environment

- Considerable impact of molten salt environment on creep behavior of wrought 316H.

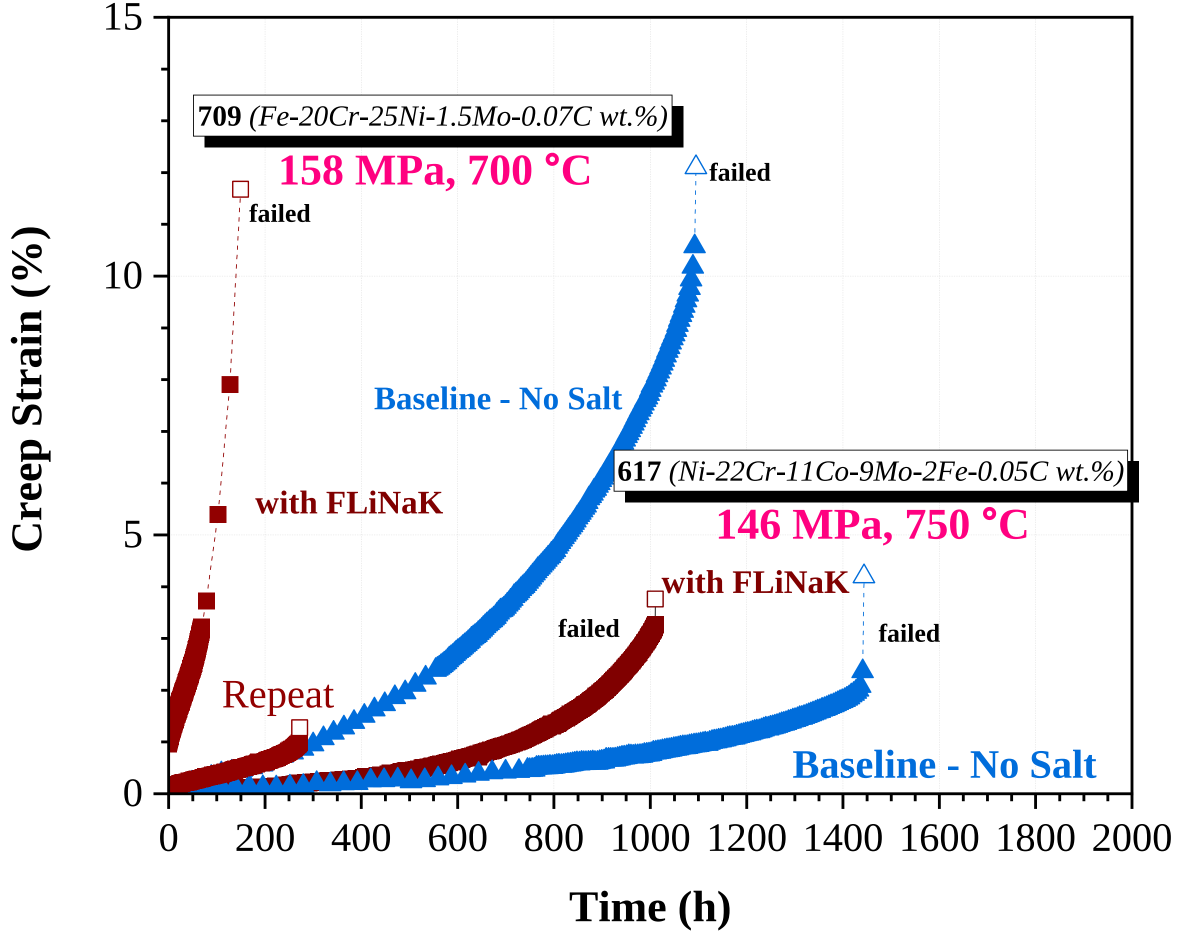




Lower stresses → longer creep rupture times → stronger impact of corrosion on microstructure.

Creep Behavior of 709 and 617 in Molten Salt Environment

- **Molten salt environment impacts creep rupture lifetimes of Alloys 709 and 617.**



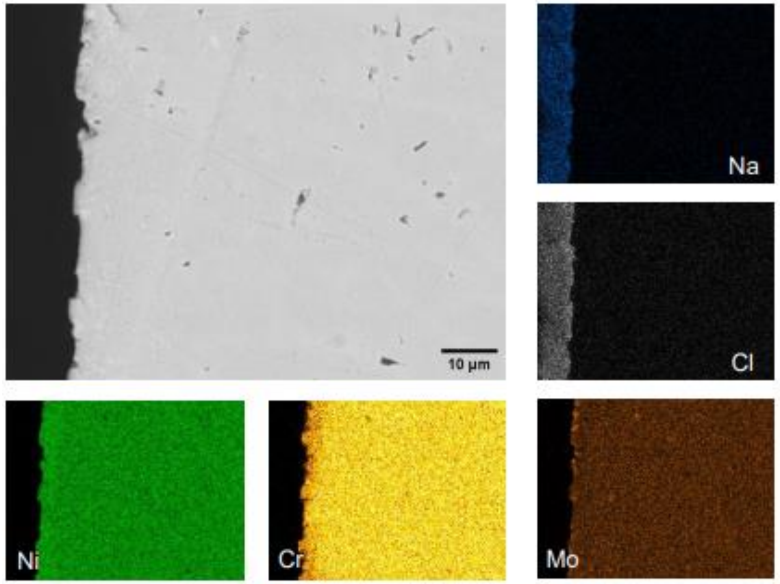
Work in Progress

- Continue creep testing of 316H, 709 and 617 in molten fluoride and chloride salts at different stresses.
- Improve mechanistic understanding of creep-corrosion interactions including
  - Salt chemistry analyses
  - Detailed microstructural characterization
- Evaluate corrosion behavior of Haynes 244 in molten chloride salts.

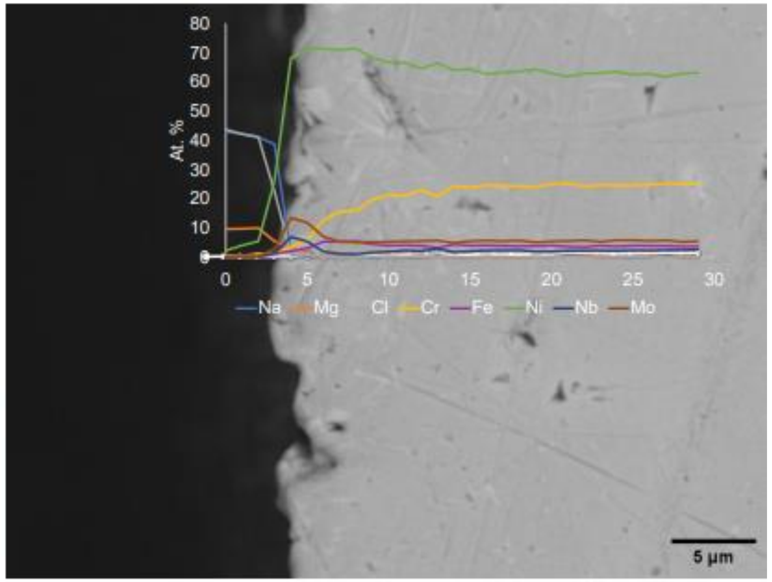
Corrosion Kinetics and Interfacial Interactions

- Conducted sealed capsule tests in molten NaCl-$MgCl_2$ for wrought alloys (Alloys 625, 617, 244 and 316H SS)
- Determine corrosion kinetics and speciation using SEM-EDS, X-ray Absorption Spectroscopy.

Alloy 625 after 30 days at 650ºC in eutectic NaCl-$MgCl_2$

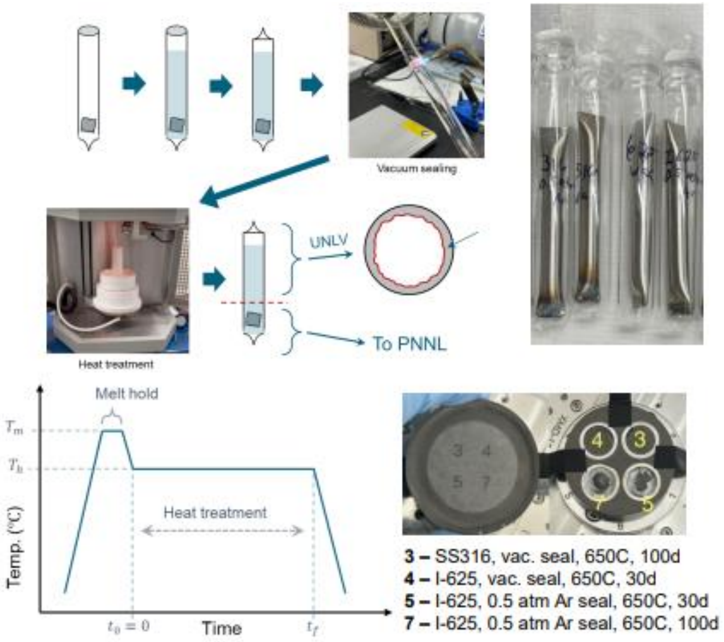


SEM Backscattered-electron image and EDS elemental color map.



SEM Backscattered-electron image and EDS Quantitative Linescan.

Experimental schematic



Findings and Work in Progress

Findings

Inconel 625

- Cr depletion observed at the surface (~5 µm after 30 days, and ~10 µm after 100 days).
- Surface enrichment of Ni, Mo, and Nb within a 2-3 µm layer.
- Color mapping indicates Cr, Ni, and Mo penetration approximately 3 µm into the salt.

316 SS

- Color mapping reveals Mg and Cl penetration 20-30 µm into the steel, forming localized pitting type spots.
- Na penetration is not observed.
- Mg and Cl infiltration is also confirmed in quantitative line scan.

Work in Progress

	1 month	2 months	8 months
550ºC	625, 316	625, 316	625, 316
650ºC			625
750ºC	617, 244	617, 244	617, 244
850ºC	617, 244	617, 244	617, 244

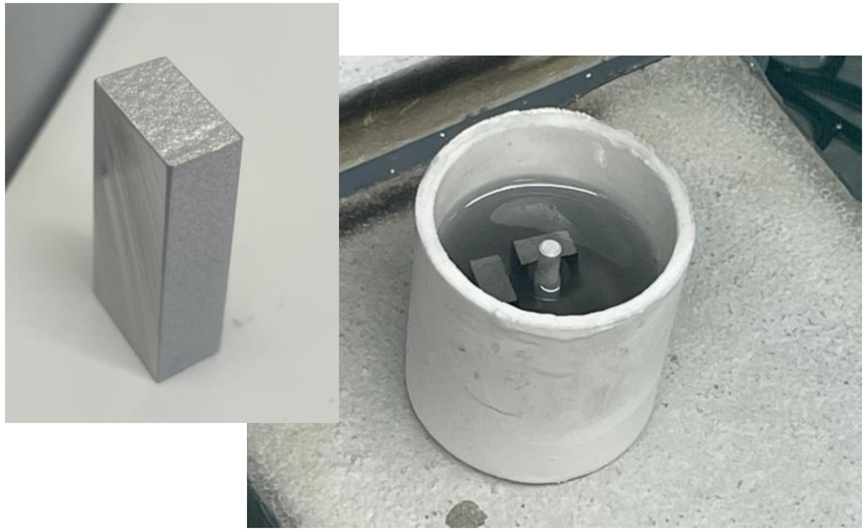
Corroded foils of IN 625 and SS 3316 will be analyzed at PNNL by XAS.

Future Work

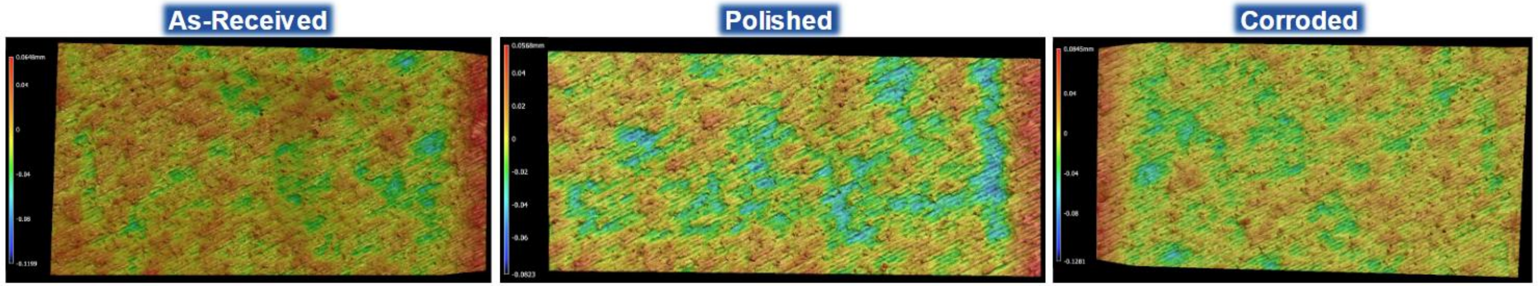
- Longer term corrosion tests of IN617 and Haynes 244.
- Corrosion in ternary eutectic Na-Mg-U chloride salt melts.

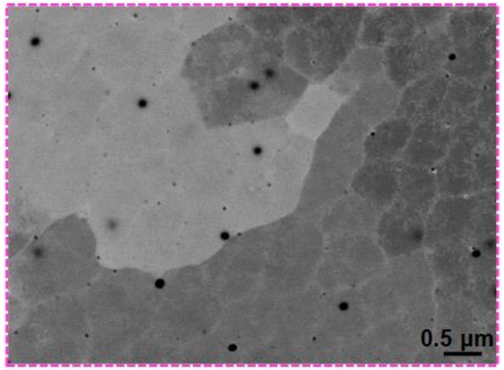
Evaluating Performance of LPBF 316H in Molten NaCl-$MgCl_2$

- **Additively manufactured materials have some unique considerations for corrosion behaviors.**
  - Fabrication parameters and build direction
  - Surface finish (i.e. acid pickling of as-built surface, machined surface)
- **Performing a comparison study with wrought 316H specimens**
  - 550°C, 500 h, capsule tests
- **Characterization includes**:
  - Weight change and estimated rate of corrosion
  - Surface characterization before and after corrosion: laser profilometry, SEM/EDS/EBSD



LPBF 316H specimen after pickling and immersed in molten NaCl-$MgCl_2$.





SEM of cross-sectioned specimen.

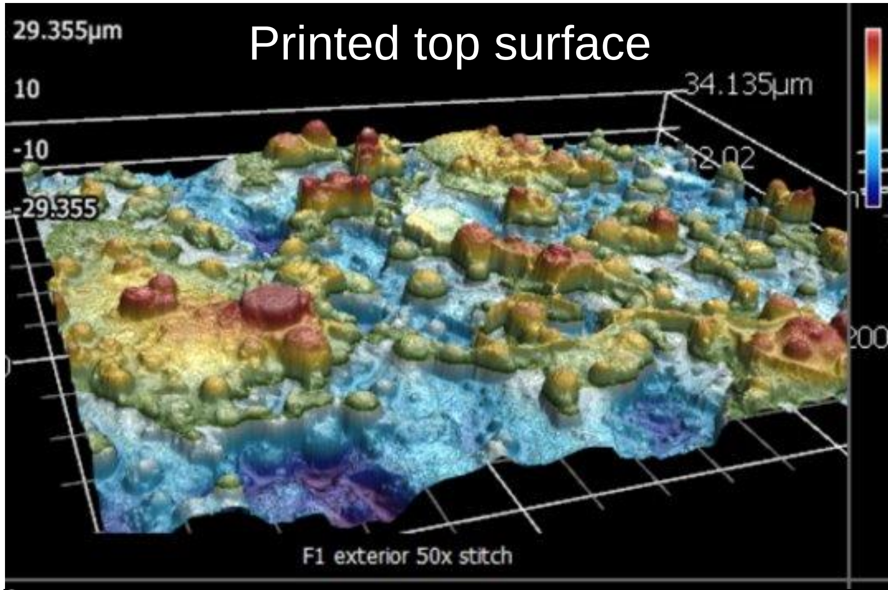
Findings and Work in Progress

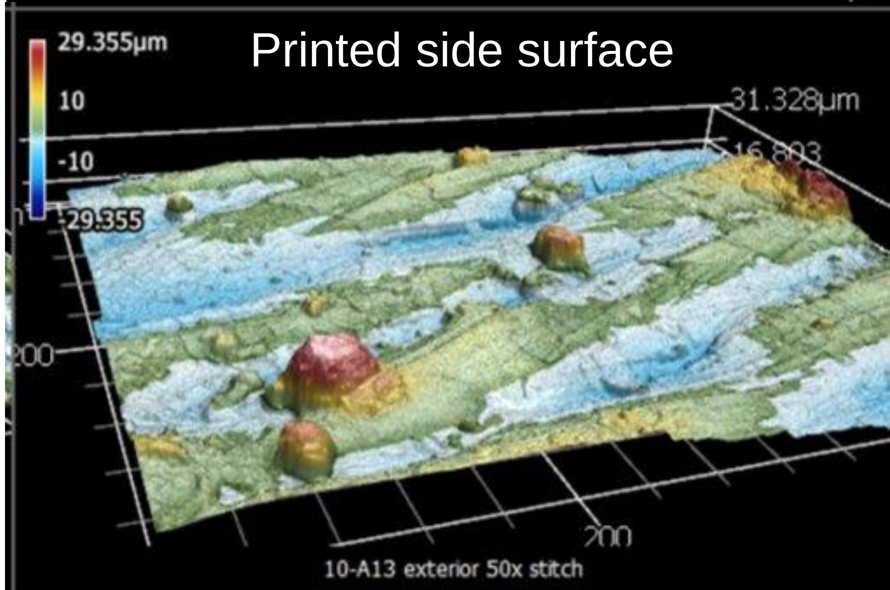
Results

- **Developed a workflow to prepare, expose, and characterize AM 316H specimens to:**
  - Study all build directions and connect performance to build axes.
  - Evaluate each surface of the build and performance in molten NaCl-$MgCl_2$.
  - Test matrix includes thermal witness specimens and wrought specimens.
- **Characterized as-printed surfaces and effect of pickling, interior microstructures**
  - Printed surface variability is significant and AM specimens may contain heterogeneous porosity and oxides that will affect oxide film stability.

Work in Progress

- **Finish post-exposure characterization to determine:**
  - Effect of pickling on LPBF 316H surface corrosion behavior
  - Corrosion with respect to build direction and microstructure changes due to thermal effects
- **Perform comparison study of LPBF 316H specimens in TerraPower-supplied NaCl-$MgCl_2$**
  - Repeatability of and comparison of results in differently supplied salts.

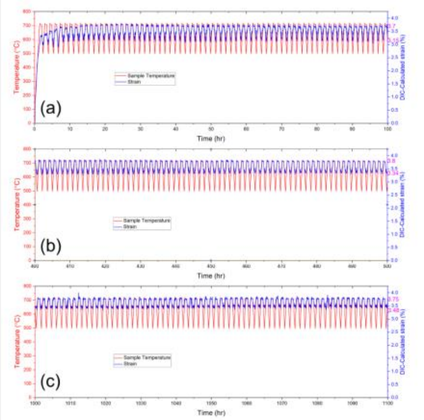




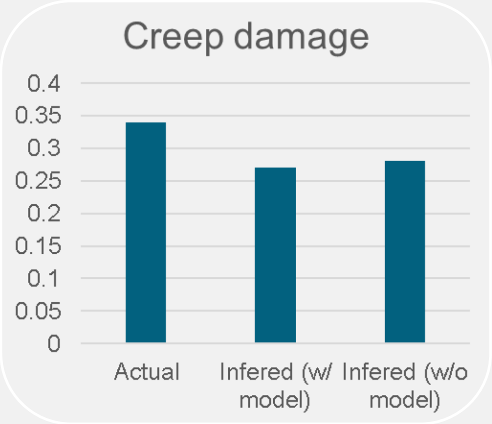
Material Surveillance Technology Development

- A material surveillance program is to monitor material degradation in service to mitigate the risk posed by the limited up-front test data.
- Develop surveillance test articles aimed at assessing material damage 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.

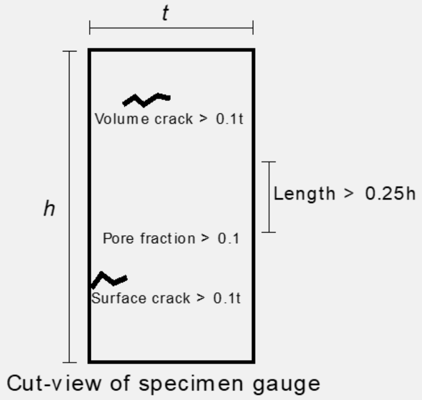
Test article design



Sample temperature and strain responses



Damage inference



Acceptance criteria: component remaining life

Summary

- **AMMT program aims to**
  - Develop advanced materials and manufacturing technologies that have cross-reactor applications,
  - Establish and demonstrate a rapid qualification framework that supports diverse materials and manufacturing technology needs,
  - Evaluate materials performance in a range of nuclear environments,
  - Accelerate commercialization of new technologies through technology maturation.
- **Materials Interaction with Molten Salts within the AMMT program currently focuses on**
  - Evaluate behavior of various Fe- and Ni-based alloys, including 316H and Alloy 709 stainless steels and Alloys 617, 625, and 244 Ni alloys, in fluoride and chloride salts
  - Compatibility of advanced alloys with molten salts
  - Effects of molten salt environments on the creep behavior
  - Corrosion kinetics and interfacial interactions
  - Processing-structure-performance relationships

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

- **AMMT-ART Program Review Meeting, July 15-17, 2025, Washington DC.**

- **AMMT Industry Workshop, September 25, 2025,** co-located with the EPRI Supply Chain Workshop, September 23-24, 2025, Discovery Hall, PNNL.