U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Molten Salt Reactor PROGRAM

Materials Surveillance Development

Ting-Leung (Sam) Sham
Idaho National Laboratory

Annual MSR Campaign Review Meeting 2-4 May 2023

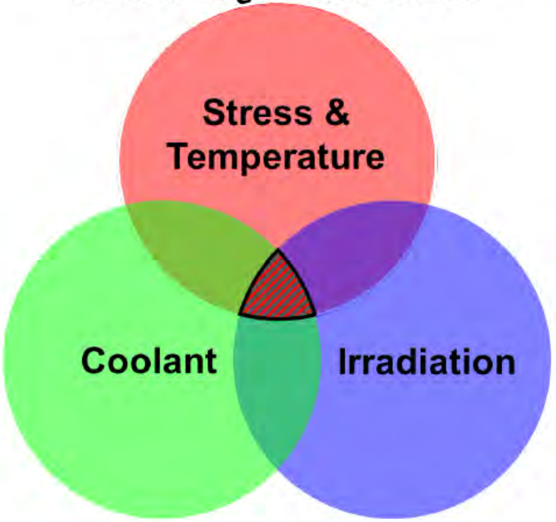
FY23 Work Packages

- **RD-23IN060302, Materials Surveillance Development – INL**
  - Development Team
    - Michael McMurtrey, Heramb Mahajan, Mahmut N. Cinbiz, Tate Patterson, Ting-Leung Sham
    - Kaelee A. Novich (INL Intern, Boise State University PhD student)
  - Experimental Support
    - Austin Matthews, Dave Cottle, Joel Simpson, Caleb Picklesimer
- **RD-23AN060301, Materials Surveillance Development – ANL**
  - Mark C. Messner

Overview – Materials Surveillance Technology

- **Synergistic material degradation effects in operating reactors**
  - Irradiation
  - Corrosion
  - Stress and temperature exposure (creep-fatigue loading)
- **Limited Information on materials degradation in molten salt reactor environment**
- **Surrogate materials surveillance technology can be used to**
  - Validate conservatism of allowable stresses based on time-extrapolation of failure data (ASME Section III, Division 5)
  - Generate key performance data on materials degradation to support the execution of the Reliability and Integrity Management (RIM) program (ASME Section XI, Division 2)
- **Technology gaps**
  - Availability of surveillance test articles that can induce mechanical damage passively during reactor operation and interact synergistically with materials degradation due to corrosion and irradiation
  - Testing of surveilled test articles, acceptance criteria, and remaining life determination
- **This work bridges these gaps by developing and maturing such materials surveillance technology**

Material Degradation effects



R&D Goals For the Surveillance Test Article and FY23 Plans

- **Reduce the size**
- **Enhance fabricability**
- **Demonstrate design robustness:**
  - Thermal cycling in air
  - Thermal cycling in molten salt
  - Thermal cycling in molten salt and under irradiation
- **Develop acceptance criteria**
- **Collaboration**
  - Bilateral with JAEA [sodium coolant] under CNWG, started in mid 2022
  - Formalize collaboration with the Canadian Nuclear Laboratories (CNL) [reactor grade helium] through INL/CNL CRADA under US-Canada Bilateral

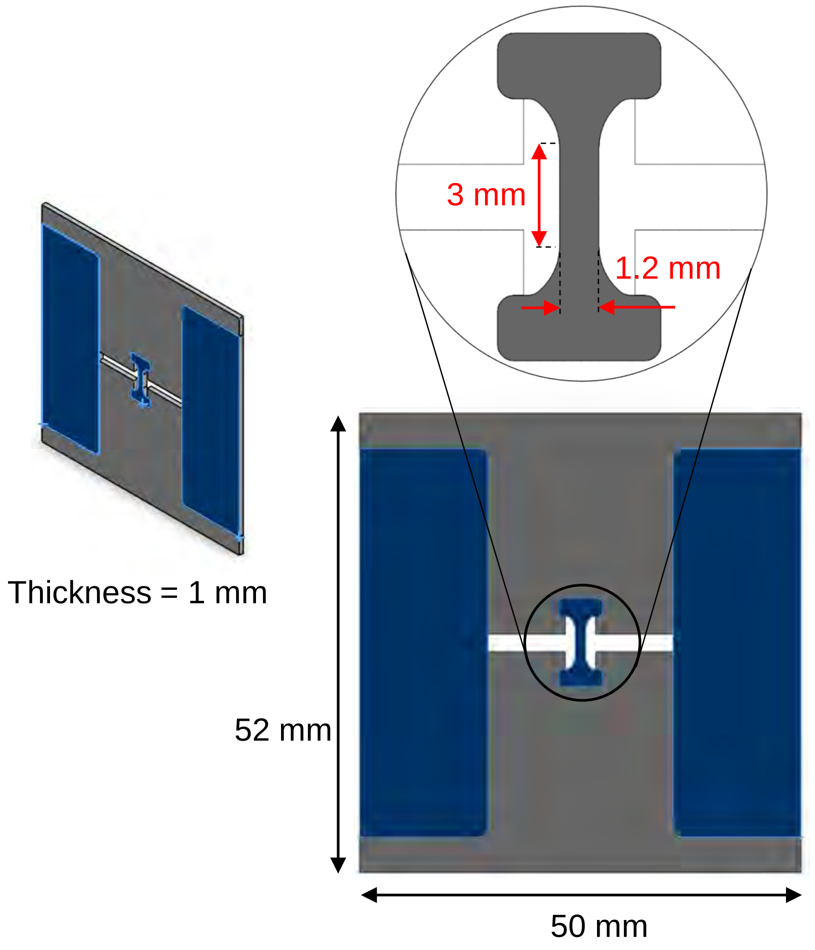
25-mm diameter, 300-mm long

25-mm diameter, 75-mm long

50x50x1 mm

New Surveillance Test Article

- **Easier to manufacture**
- **Easier to instrument and monitor during the validation of the technical basis**
- **Smaller and less disruptive to fluid flow/plant operation**
- **Design is more accessible for evaluation and mechanical testing after the test articles are removed from the reactor; also, smaller activated volume**

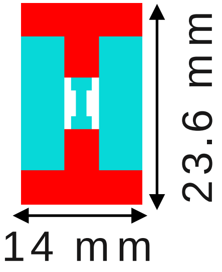


Comparison of Different Driver Materials in the New Test Article

- **Test article design with**
  - Same gauge length and different driver materials
  - Identical test article design parameters
- **Higher expansion mismatch between driver and test material results in**
  - Reduction in the test article size
  - Wider coverage of strain ranges and follow-up factors

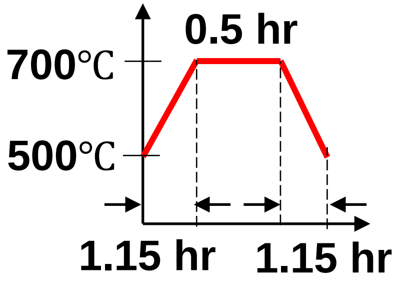
Design parameters

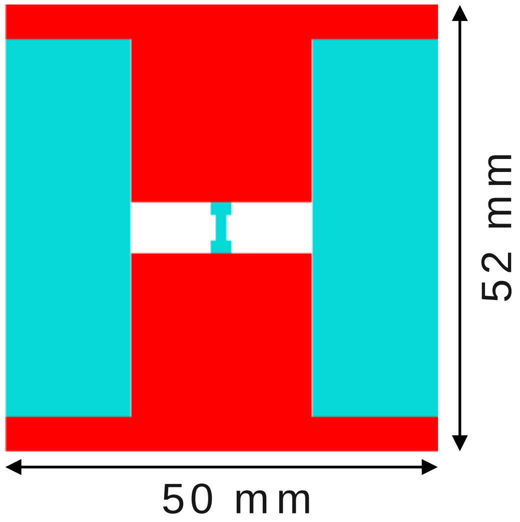
1. Strain range = 0.52%
2. Follow-up = 2.7
3. Temperature cycle
4. Dwell time = 30 min



TZM driver

Temperature cycle

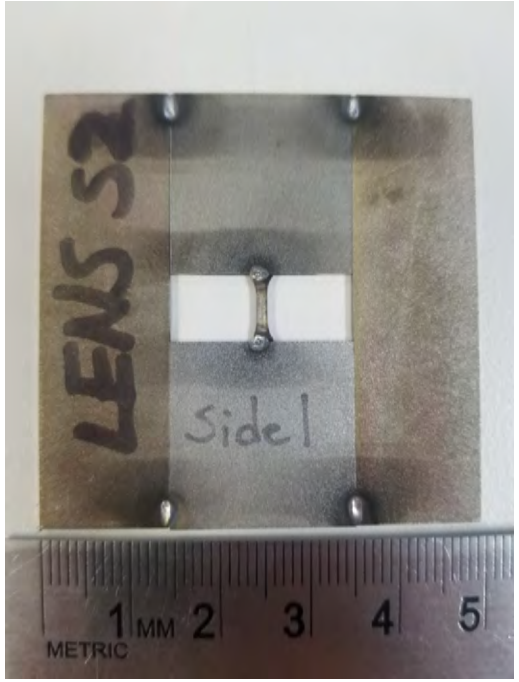




A617 driver

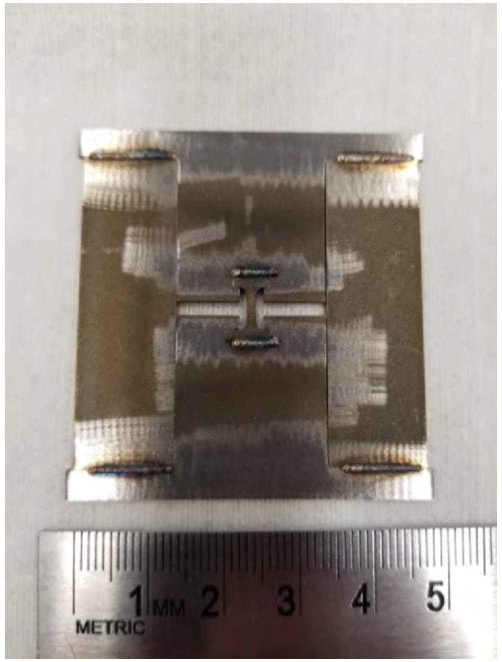
Welded Flat Test Article, Version 1 and Version 2

Version 1



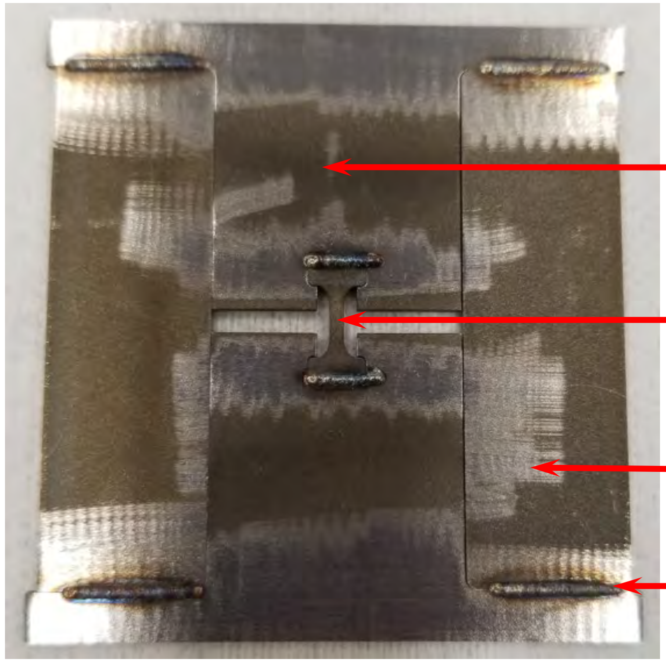
- **Two versions of welded flat test articles were examined**
- **Version 2 improved the weldment location to reduce the stress concentrators at the weldments of version 1 that led to premature failure**

Version 2



Test Article Fabrication Through Welding – Version 2

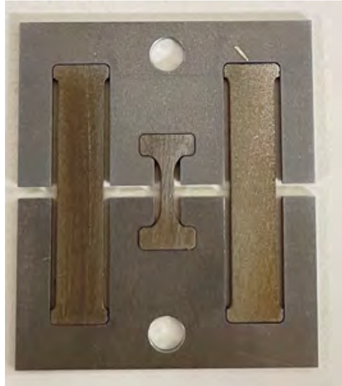
- **Welded using blown powder laser directed energy deposition (laser-DED) system**
- **Continuous wave ytterbium fiber laser**
- **300 W of power with an approximately 1 mm beam diameter**
- **316L powder composition**
- **4.2 mm/s travel speed**



Interlocking Specimen

- **Designed to be weld-free**
  - Weldments are a potential early failure point
  - Some desirably materials, like TZM, with low thermal expansion coefficients have low weldability
- **Assembled from individual components and bolted together with cover plates**

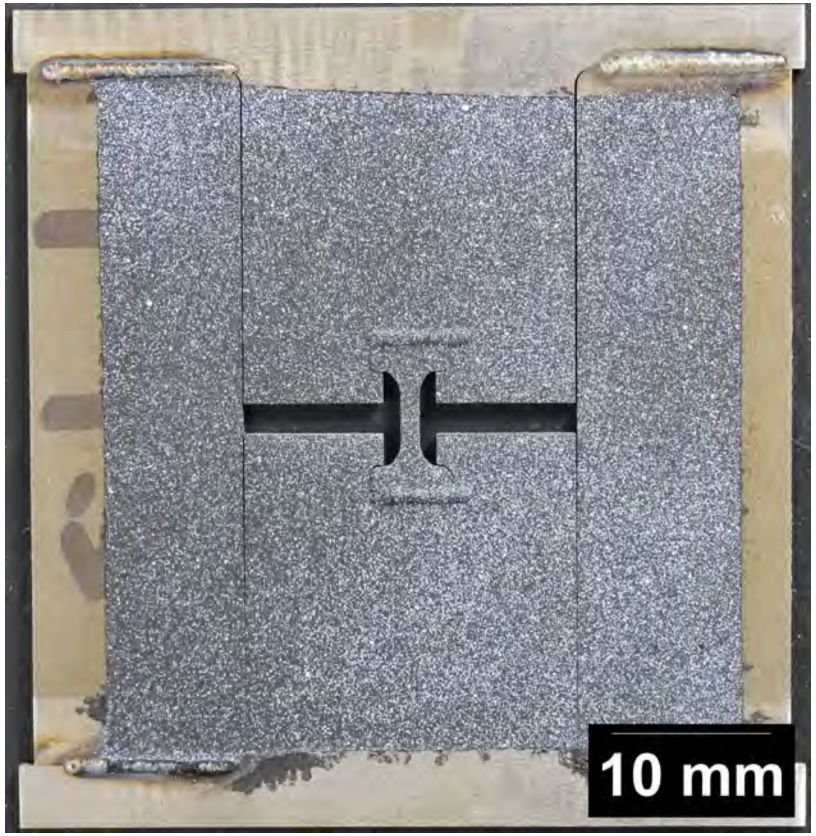
Arrangement of parts without cover plates



Arrangement of parts with cover plates

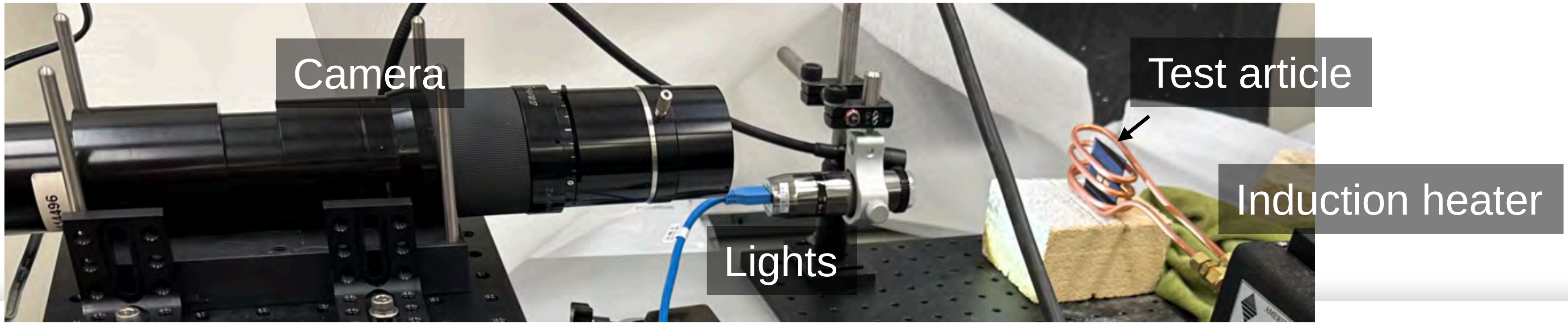
Local Strain Measurements Through Digital Image Correlation

- **Speckle pattern applied through spray techniques**
- **Requires line of sight for strain measurements**



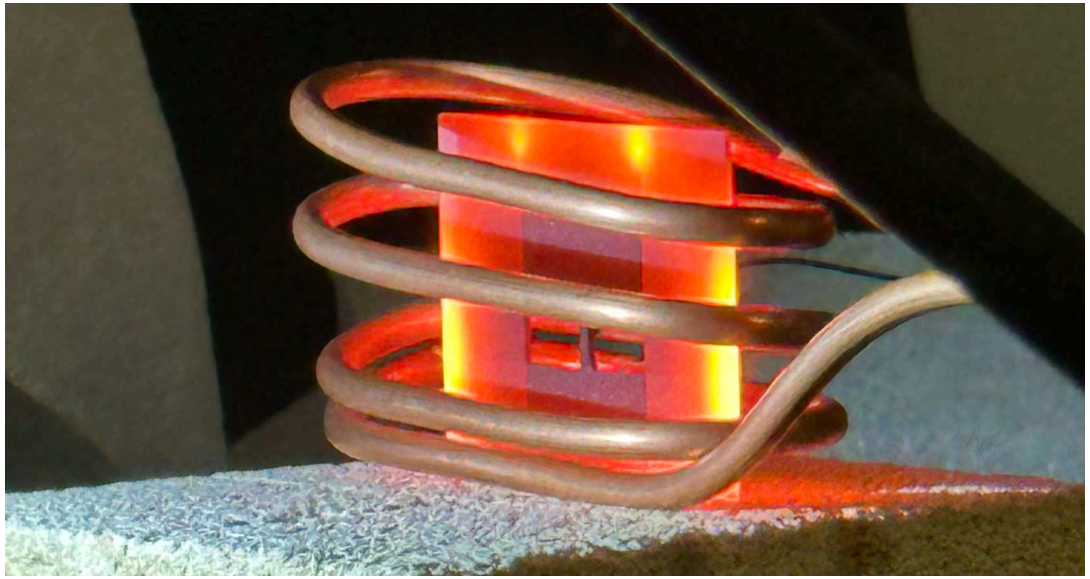
Induction Heating Tests

- **Allows for easier strain measurements on test article**
- **Drastically increases temperature ramp rate**
  - Furnace test, with a 30-minute hold time at peak temperature, resulted in approximately 10 cycles per day
  - Induction heater, with a 30-minute hold time at peak temperature, was able to perform the full cycle in 36 minutes.



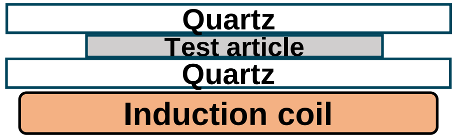
Induction Heating Coil

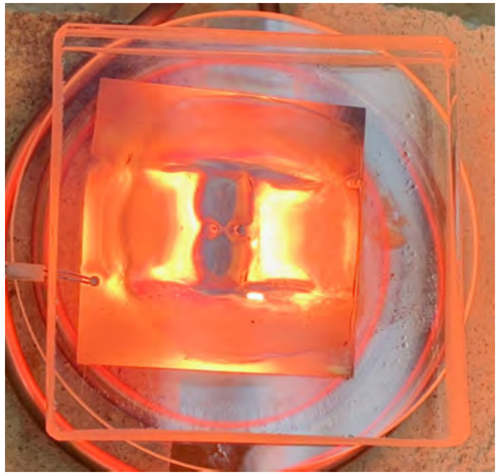
- **Largest challenge is uniformity of temperature**
- **Significant overheating on edges and at weld joints**

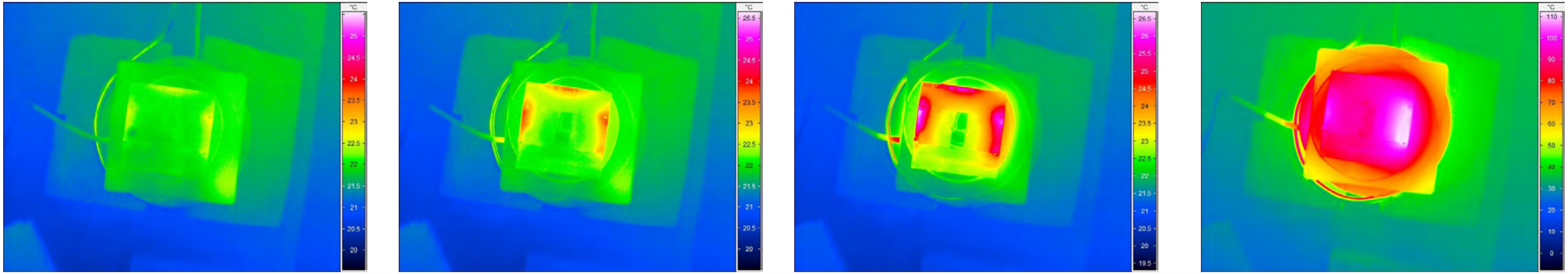


Pancake Coil Induction Heating

- **Uneven heating when specimen heated directly from the pancake coil**

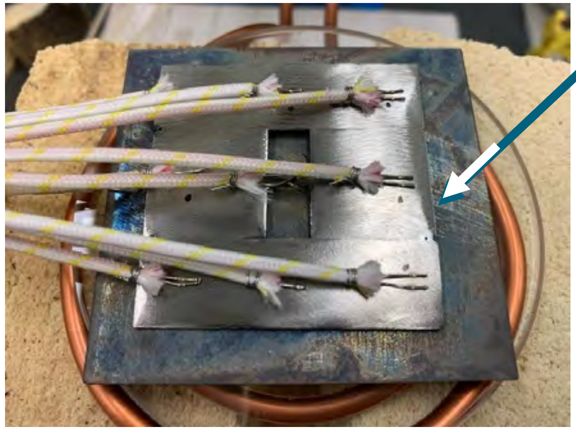




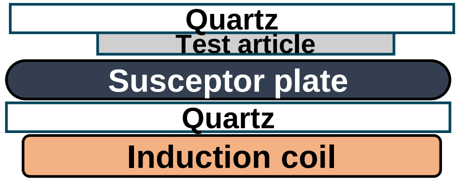


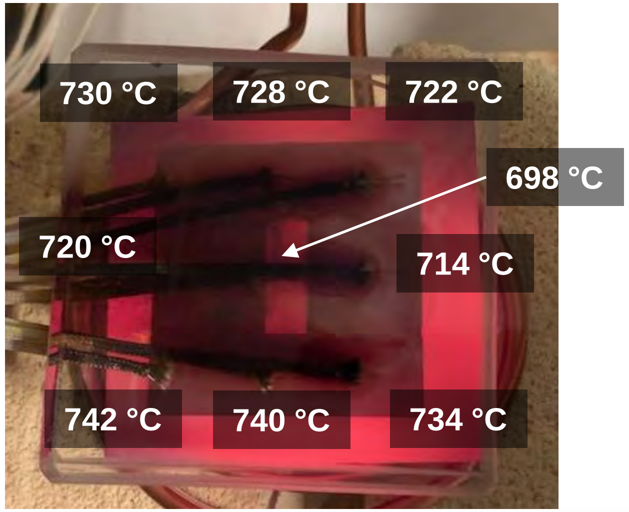
Induction Heating Pancake

- **Pancake coil design was used**
- **Still significant temperature gradients when test article was heated directly by the coil**
- **Susceptor plate was placed between the coil and the specimen, helped moderate the temperature**
- **Further modification of susceptor plate and coil geometries is expected to further reduce the temperature gradient**



Susceptor Plate

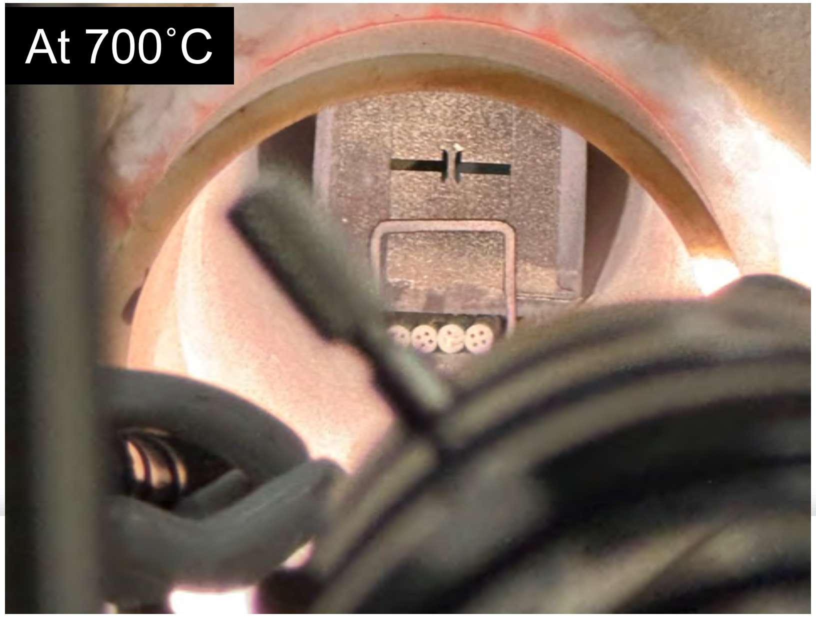


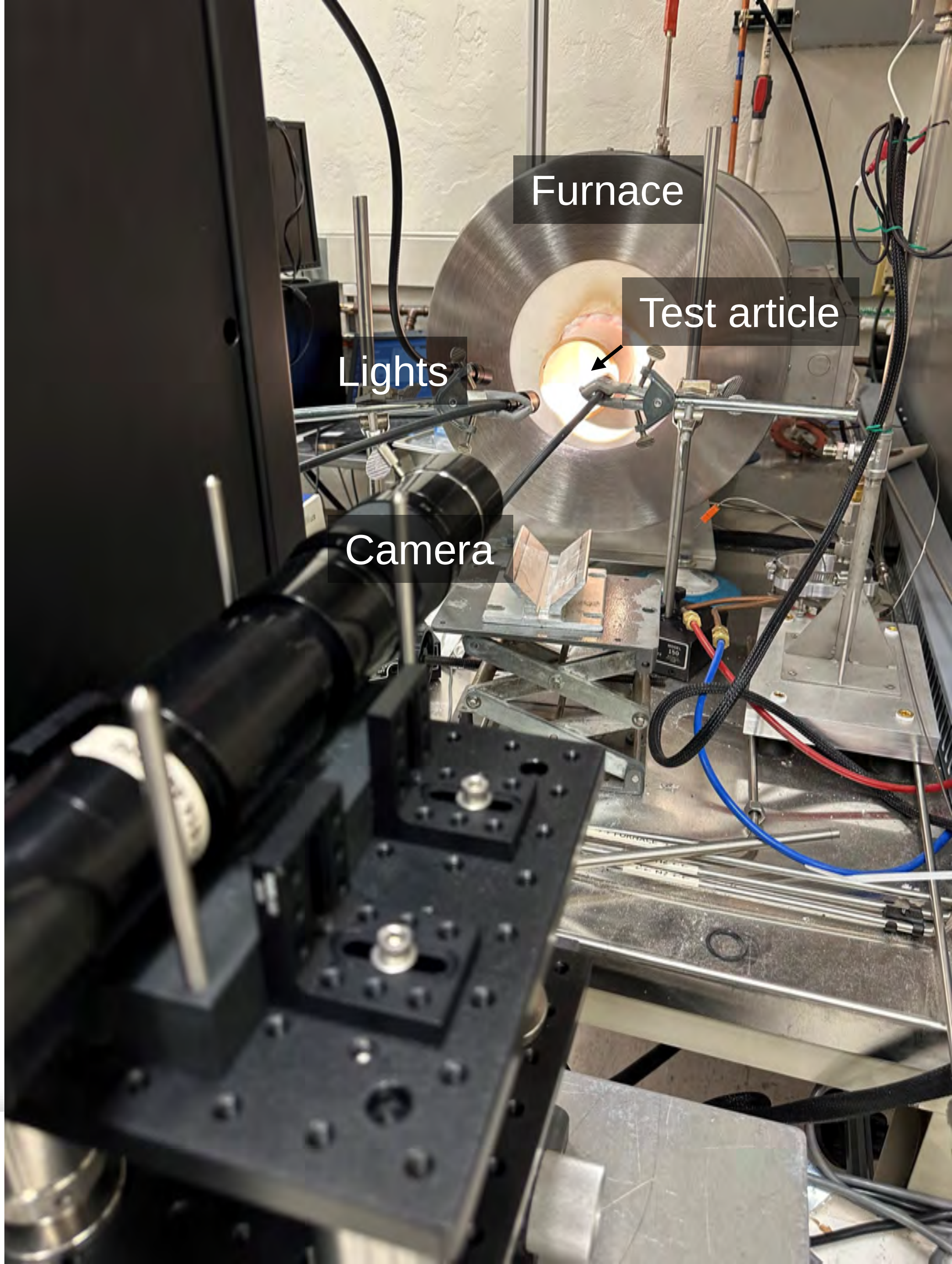


- Thermocouples readings
- Used for validation only
- Will not be welded to actual test article during test

Furnace Testing

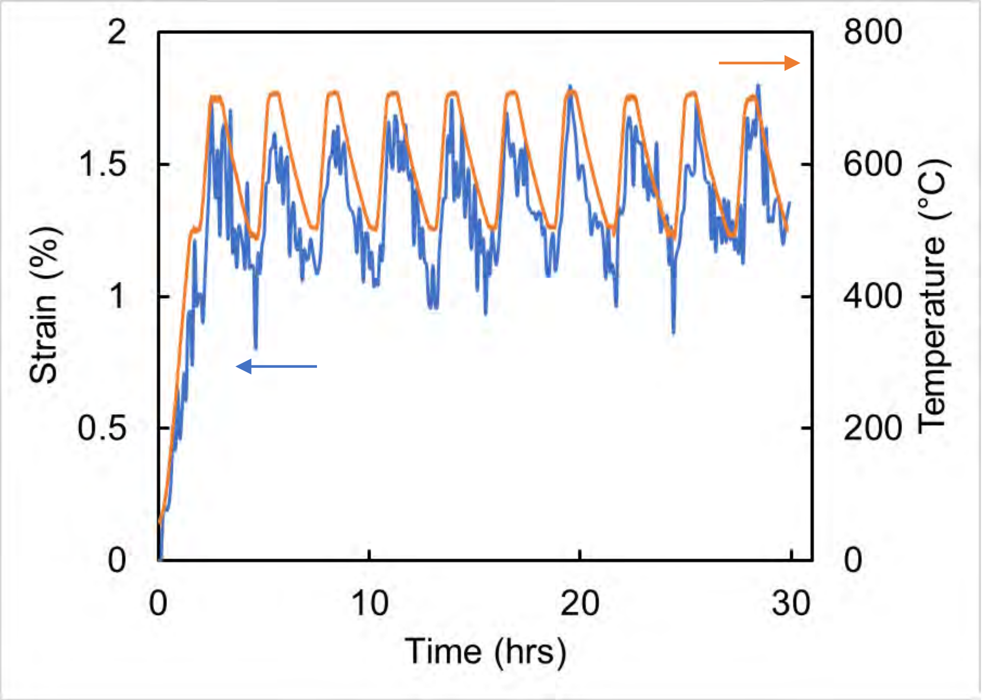
- **Temperature ramped to 700°C**
- **Temperature hold at 700°C for 30 minutes**
- **After hold, cycled to 500°C, then back to 700°C**

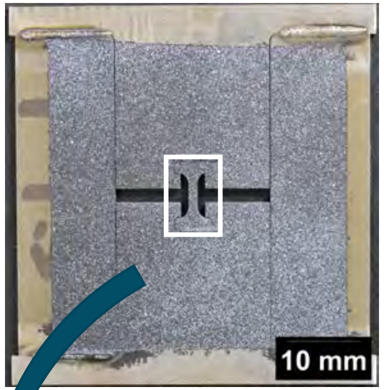


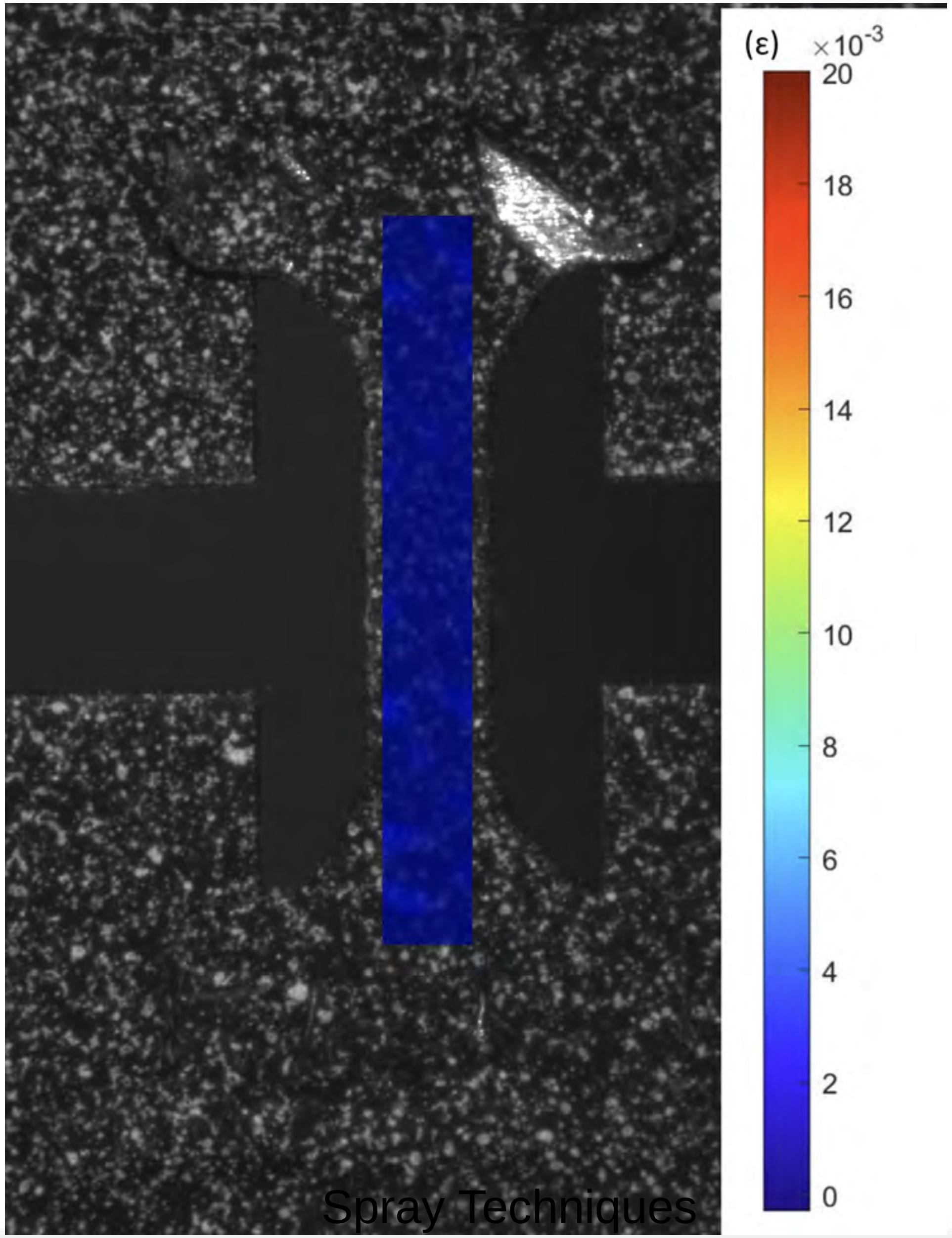


Furnace Test Results

- **Strain map from first ten cycles**







U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Induction Heating of Cylindrical Test Article

- **Uneven heating noted on the outer casing**
- **Modified coil design is capable of fixing this, however, internal specimen temperature was also noted to be significantly cooler than casing**
- **This specimen design is better suited for furnace testing**

“Measuring” Remaining Life

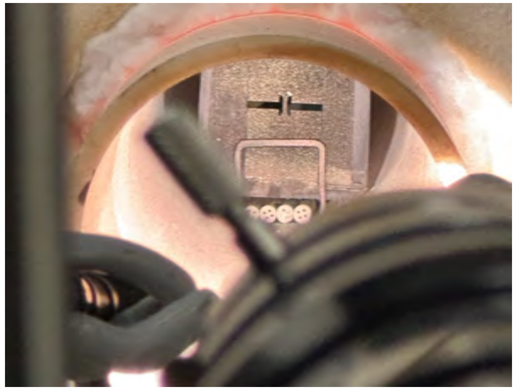
- **Samples exposed to long-term service in MSR environment**
- **Periodically removed**
- **What type of testing can we do to determine “remaining life” = how long the material would have lasted under service conditions?**
- **Limitations:**
  - In-situ monitoring of samples may be limited – can’t continuously monitor mechanical behaviour
  - Samples may be irradiated when removed from reactor
  - Test should be short – will want answer quickly/during outage to make operation decisions

Surrogate Materials Surveillance Protocols

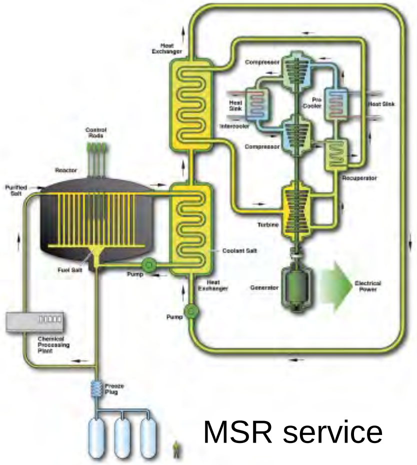
	Creep/steady load	Cyclic load (traditional)	Cyclic load (no damage)
Mechanical properties data from temperature and stress	Creep to failure (including strain measurement)	Creep-fatigue to failure	Short term creep-fatigue deformation
In-reactor surveillance test articles	Steady mechanical, thermal, and environmental	Cyclic mechanical, thermal, and environmental	Cyclic mechanical, thermal, and environmental
“Out-of-pile” testing of surveilled materials	Creep – subscale samples or indentation	Cyclic	Cyclic
Models for inferring damage in the surveilled material	MPC Omega – analytical formula to relate creep rate to damage	Damage inference using established creep-fatigue damage model	Damage inference with no assumption on damage model
Remaining life determination and acceptance assessment	Remaining life (time to expected failure)	Remaining life (cycles to expected failure)	Remaining life (cycles to failure) assuming linear damage accumulation

Creep-Fatigue Remaining Life Assessment

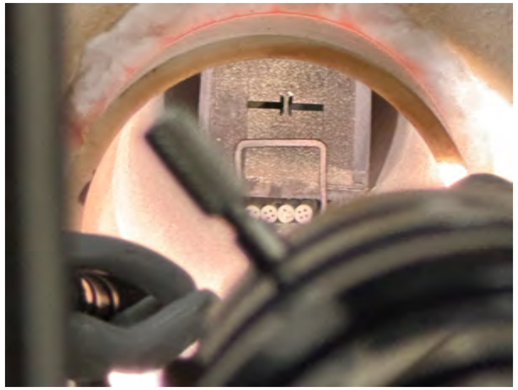
- **Knowns:**
    1. Original sample response before in-reactor service (irradiation and corrosion) – for example furnace test an instrumented specimen
    2. Mechanical response after in-reactor service – furnace test an instrumented sample for a few cycles
- **Unknowns:**
    1. Mechanical response while in service
    2. Amount of material property degradation/damage



Furnace test samples ***before*** MSR service – establish baseline mechanical properties



MSR service



Furnace test samples ***after*** MSR service – establish damaged mechanical properties

Can we infer how much damage the sample accumulated?

Thank you

tingleung.sham@inl.gov

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY