



MRS: Surveillance Test Article Development

June 2023

Changing the World's Energy Future

Michael D McMurtrey, Ting-Leung Sham, Mark Messner



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**Idaho National Laboratory
Idaho Falls, Idaho 83415**

<http://www.inl.gov>

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MSR: Surveillance Test Articles Development

Joint ART Materials/AMMT Program Review

DOE Headquarters, Germantown, MD

June 5-8, 2023

Michael McMurtrey

Idaho National Laboratory

Mark Messner

Argonne National Laboratory

FY23 Work Packages

- **RD-23IN060302, Materials Surveillance Development – INL**
 - Development Team
 - Michael McMurtrey, Heramb Mahajan, Mahmut N. Cinbiz, Tate Patterson, Xinchang Zhang, 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

What is Materials Surveillance?

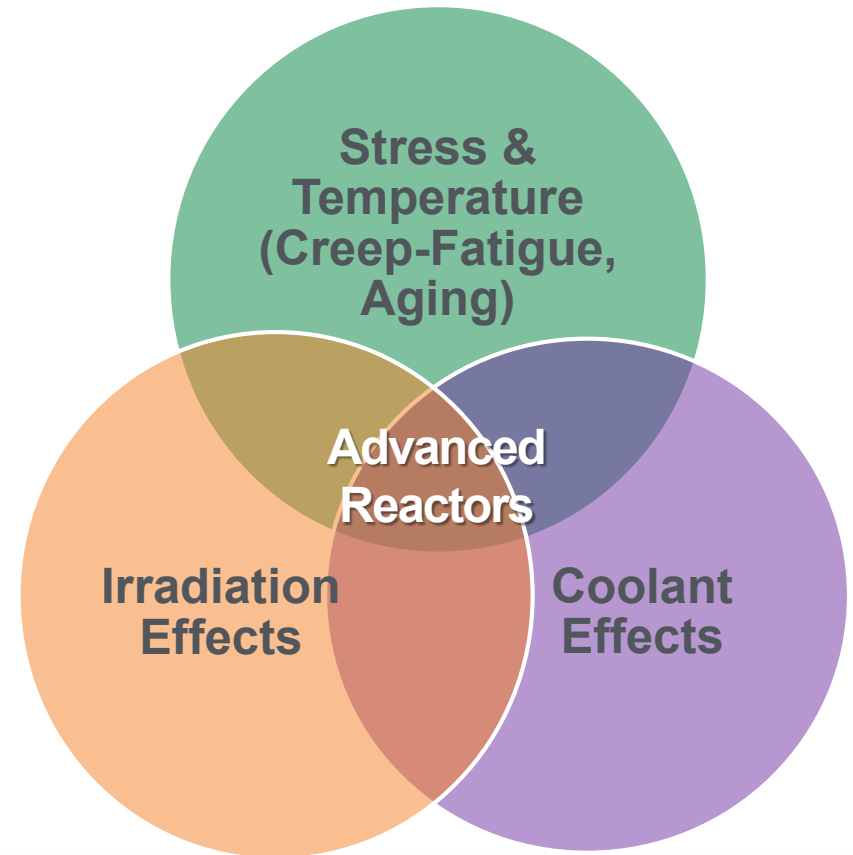
- For Light Water Reactors (LWRs), integrity assessment of reactor vessel (RV) requires their materials properties
- ASME Section III has provisions for properties in the unirradiated condition
- Changes in properties due to irradiation are monitored using the surveillance program
- Primary material property of interest for RV integrity of LWRs is the fracture toughness of the RV material

Reactor Vessel Material Surveillance Program for LWRs

- **Charpy-V notch impact specimens for the base and weld metals are irradiated in surveillance capsules**
 - Surveillance capsules are exposed to the same operating conditions as the RV
 - Capsules are located closer to the reactor core than the RV inner diameter
 - Surveillance specimens are generally exposed to higher neutron irradiation dose than the RV, hence experience degradation in fracture toughness due to neutron embrittlement in advance of the RV
 - Charpy specimens are periodically withdrawn, impact tested, and evaluated to determine the effect of radiation effect on the RV material
 - Adjustments to the pressure-temperature curves or operating procedures might be required
- **Surveillance programs for LWRs are designed to**
 - Examine the current status of RV material properties, and
 - Predict the changes in these properties resulting from the cumulative effects of radiation

Materials Degradations During Operations of High Temperature Reactors

- Mechanical damages due to creep, fatigue and creep-fatigue
- Damages due to radiation
- Damages due to exposure to reactor coolant environment, including mass transfer in the coolant circuit
- These damages are synergistic



ASME Section III, Division 5, Metallic Components Scope

- Division 5 specifies the mechanical properties and allowable stresses to be used for design of metallic components in high-temperature reactors
- HAA-1130 and HBB-1110(g) state that Division 5 rules do not provide methods to evaluate deterioration that may occur in service as a result of corrosion, mass transfer phenomena, radiation effects, or other material instabilities
 - These effects shall be taken into account with a view to realizing the design or the specified life of the components and supports
 - The changes in properties of materials subjected to neutron radiation may be checked periodically by means of material surveillance programs

Materials Surveillance Necessary for Division 5 Design Properties

- The need for performance monitoring and surveillance programs, particularly for very long design lifetimes, e.g., 500,000 hour, has been reinforced in Division 5 recently
- A General Note has been added to Table HBB-I-14.10E-1 on the stress rupture factors for 9Cr-1Mo-V weldment (2023 Edition):

The values in this table are extrapolated from shorter term test data using an engineering model. For longer design lives, the designer should consider further strength reductions to account for potential in-service material degradation, per HBB-2160(a). In addition, enhanced material surveillance programs and/or heightened in-service inspection per the rules of ASME Section XI may be warranted.

NRC Draft Interim Staff Guidance on Material Compatibility

- **NRC issued a Draft Interim Staff Guidance (ISG) on Material Compatibility for non-LWRs in February 2023**
 - DANU-ISG-2023-01, Accession Number ML22203A175
- **The ISG identifies information the NRC staff should consider in its review related to materials qualification**
- **It also indicates where monitoring and surveillance may be appropriate to be relied upon to ensure component integrity**

Materials Surveillance Technology Is an Important Technology to Ensuring HTR Component Integrity

| LWRs | HTRs |
|---|--|
| Fracture Toughness | Allowable stresses, ductility, cyclic properties |
| Surrogate surveillance materials only accumulate radiation damage | Surrogate surveillance materials need to accumulate damages due to stress/strain histories (monotonic and cyclic), irradiation and corrosion (including mass transfer effects) |
| Charpy specimens are used to capture radiation damage | Challenging in developing surveillance test articles to capture these synergistic damages |
| Impact tests of irradiated Charpy specimens are not long-term tests | Types of testing on surveillance test articles removed from HTRs are to be developed; testing could be time dependent |
| Acceptance criteria based on shift in transition temperature are well established | Acceptance criteria are to be developed |

Technology Gaps for High Temperature Materials Surveillance

Gaps

- Lack of suitable surveillance test articles that can induce mechanical damage passively during reactor operation and interact synergistically with materials degradation due to corrosion and irradiation
- Lack of appropriate acceptance testing methods and acceptance criteria
 - ASTM E531 - Standard Practice for Surveillance Testing of High-Temperature Nuclear Component Materials
 - Originally approved in 1975, based on LWR surveillance technology
 - E531 is currently being updated so that it would be more applicable to the new HTR designs

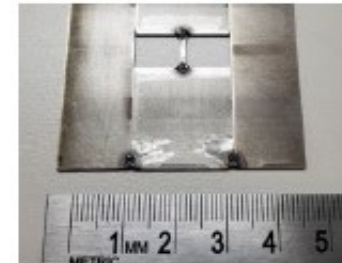
R&D Goals For the Surveillance Test Article Development and FY23 Plans

- 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

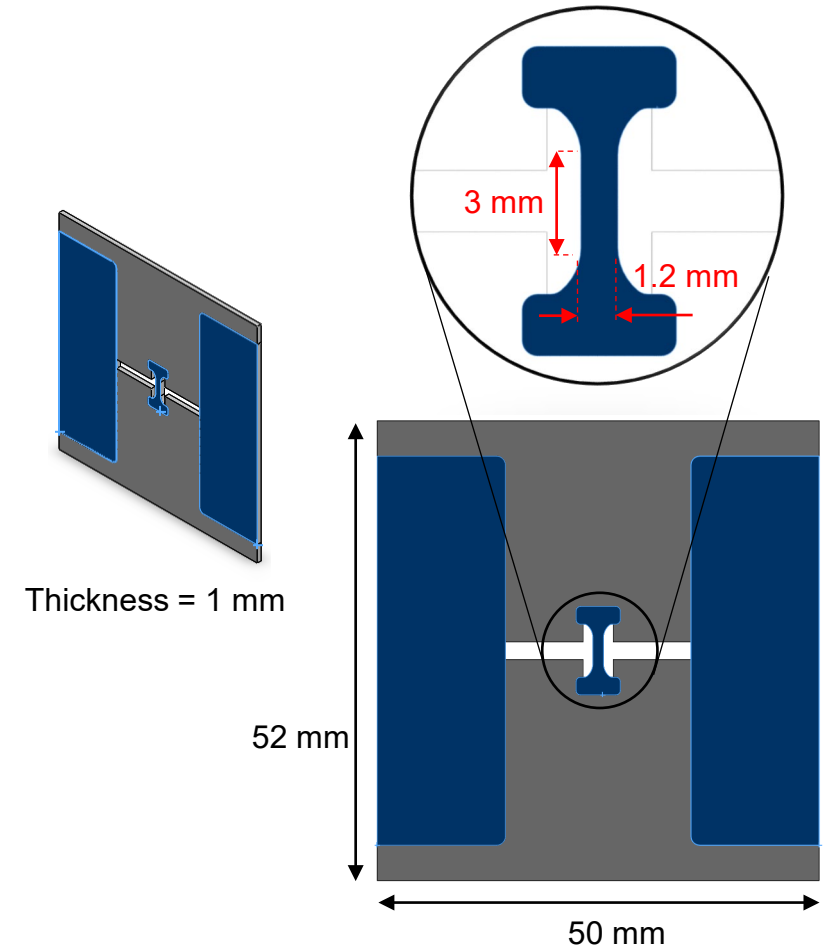
25-mm diameter,
75-mm long



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



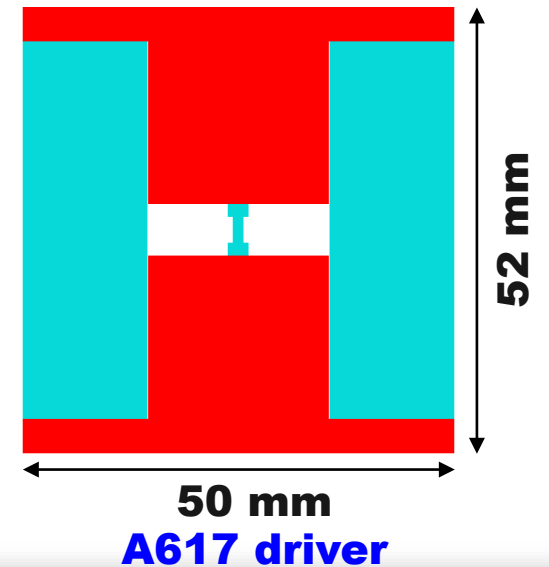
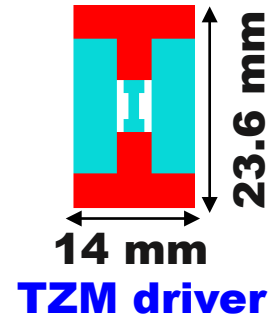
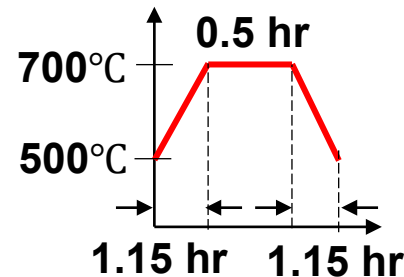
Comparison of Different Driver Materials in the New Test Article

- **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

Temperature cycle



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

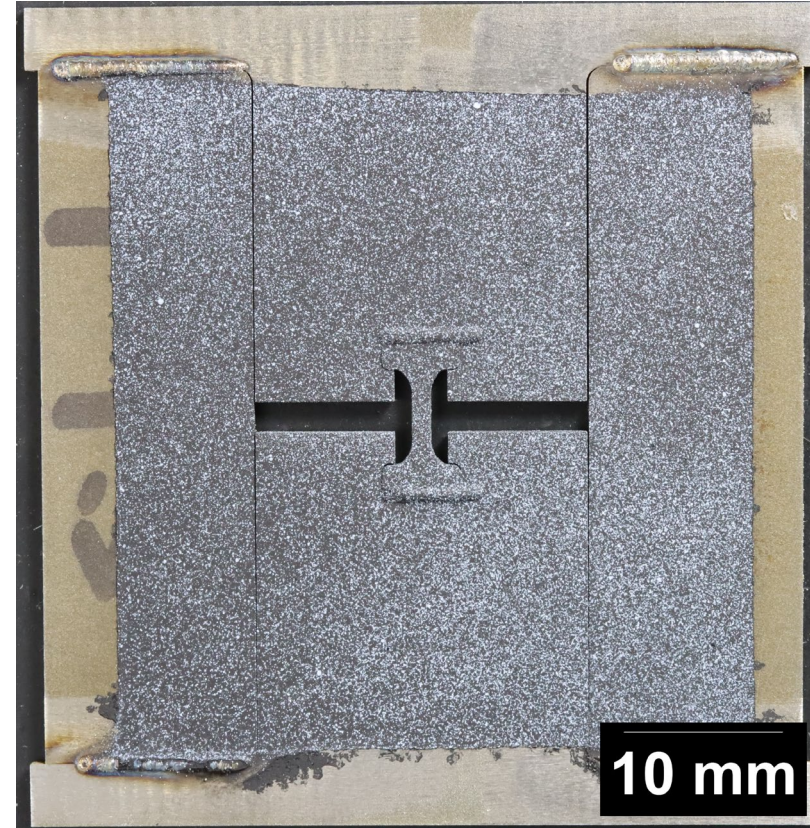


Arrangement of parts with cover plates



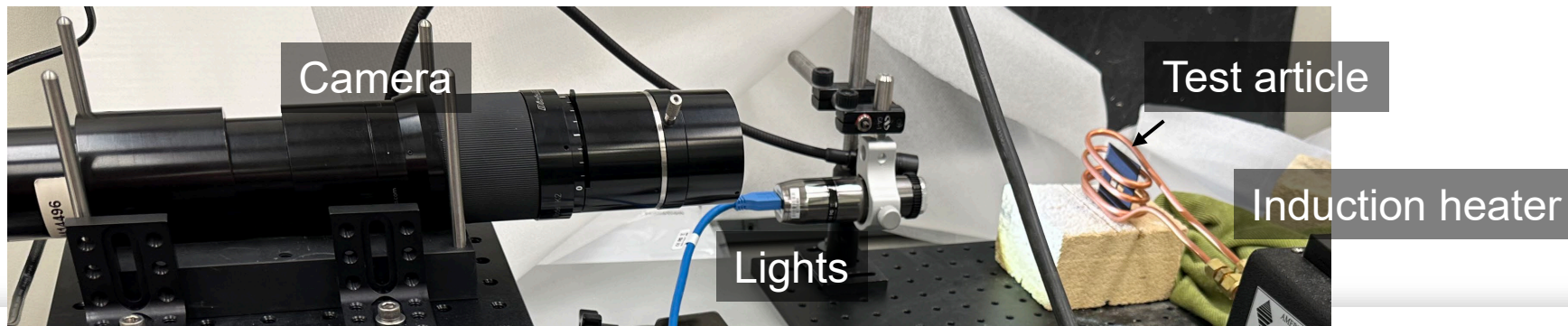
Local Strain Measurements Through Digital Image Correlation

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



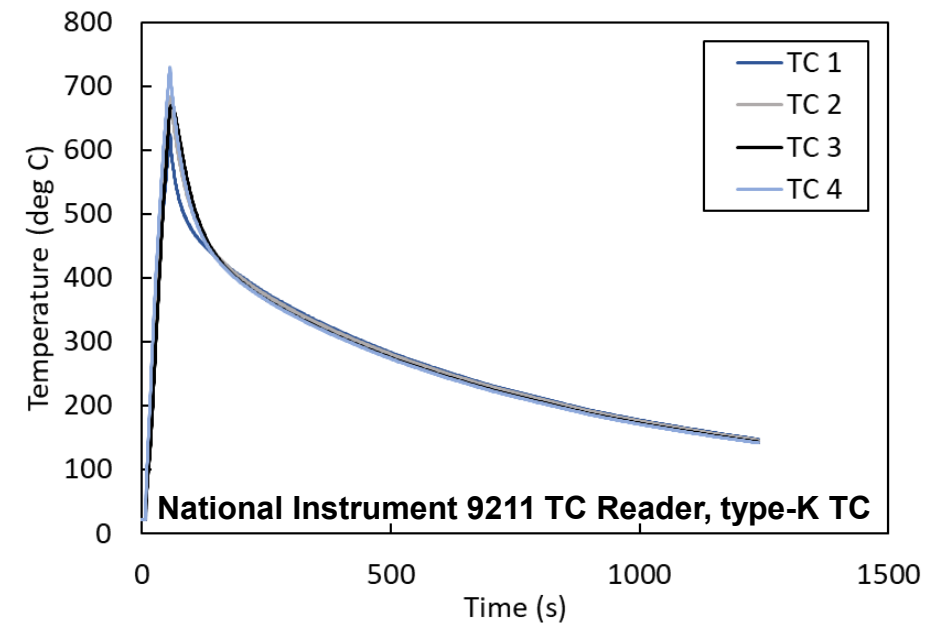
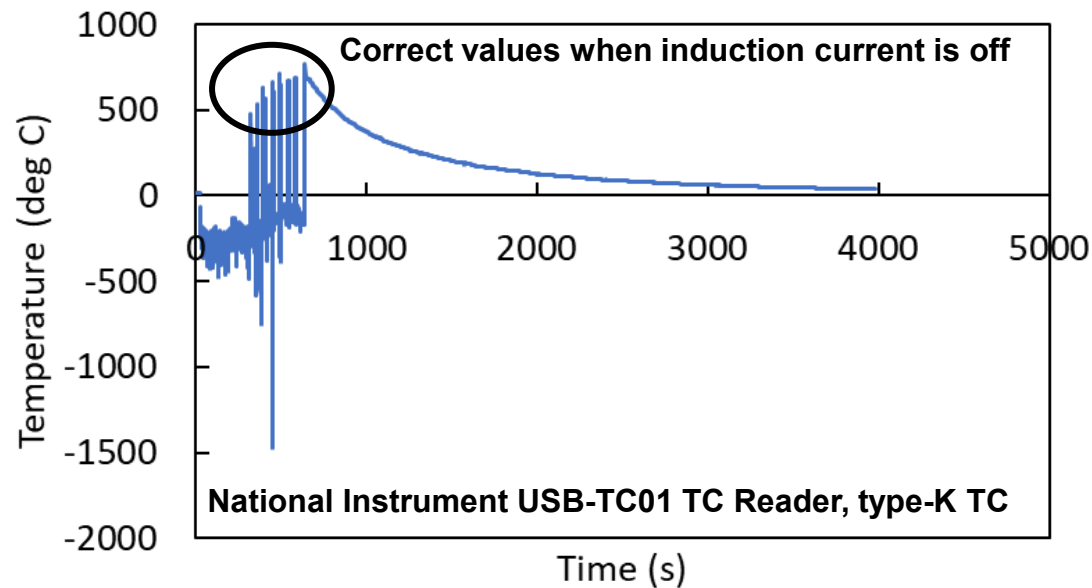
Induction Heating Tests

- **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.



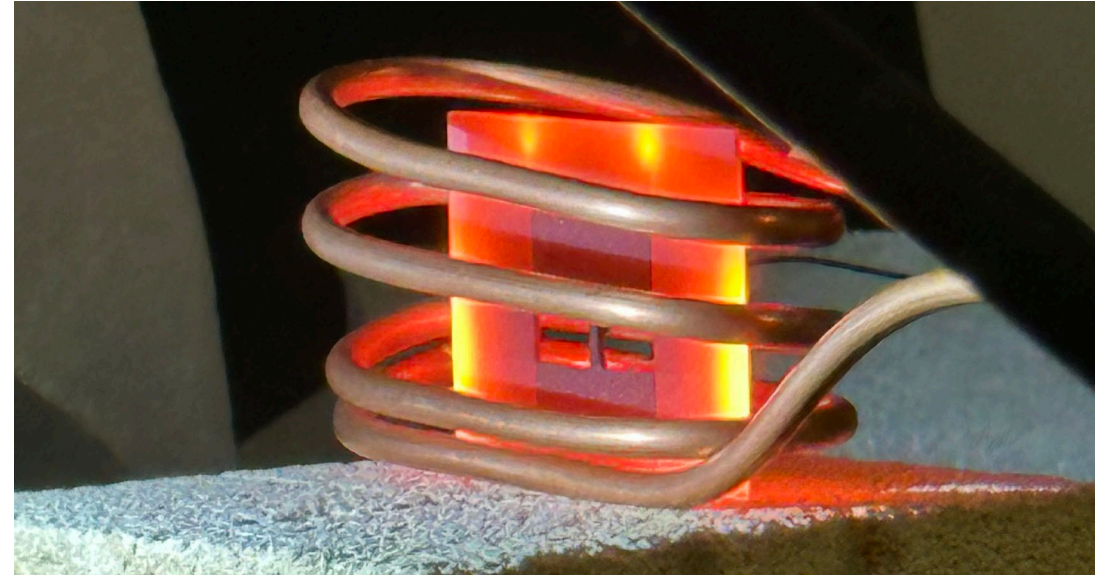
Induction Heating Temperatures

- Concern with temperature readings and induction heating interference mitigated through correct hardware



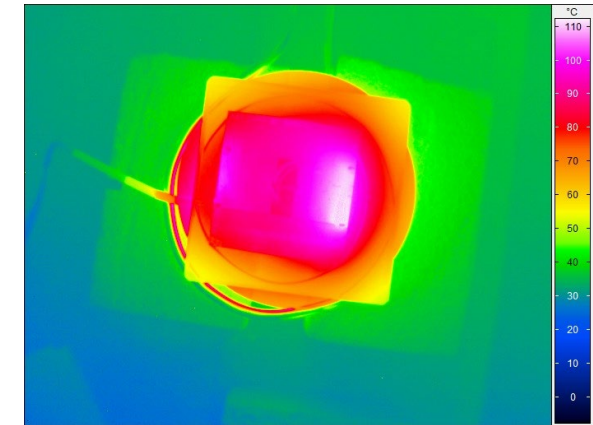
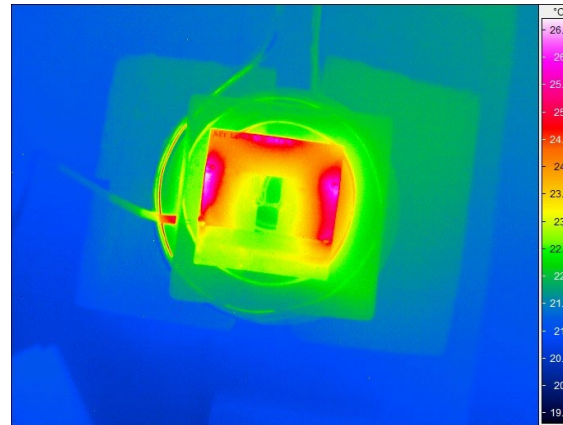
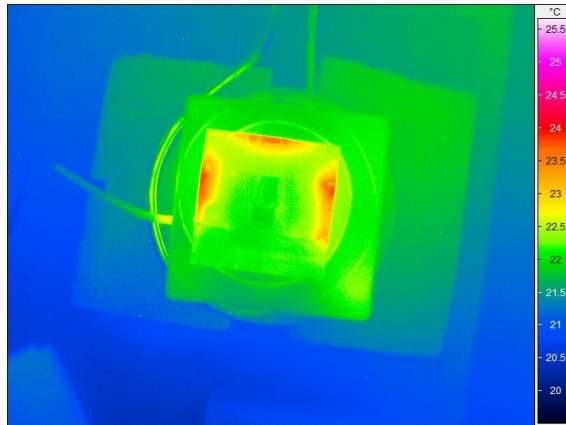
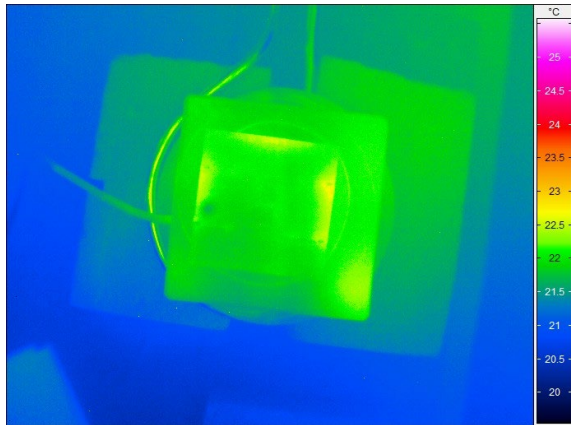
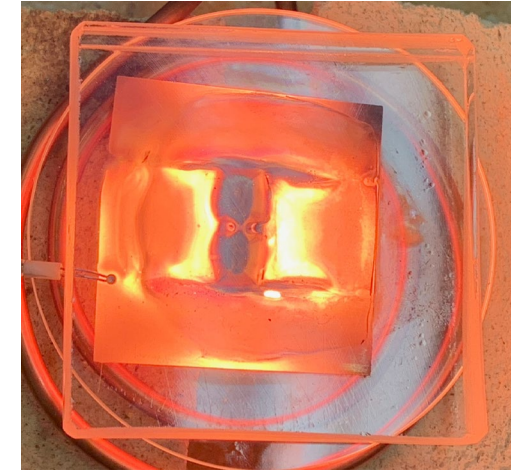
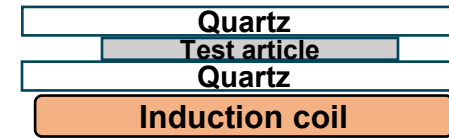
Induction Heating Coil

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



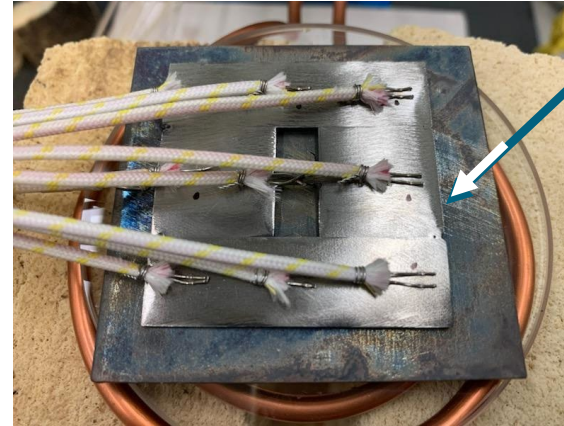
Pancake Coil Induction Heating

- Uneven heating when specimen heated directly from the pancake coil

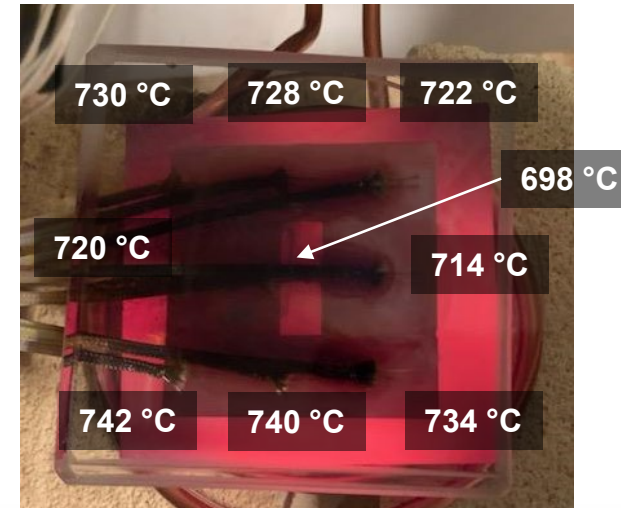
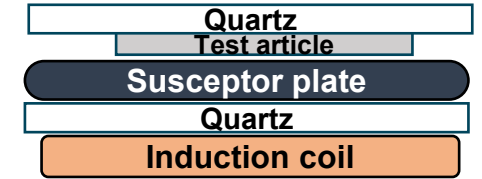


Induction Heating Pancake

- 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



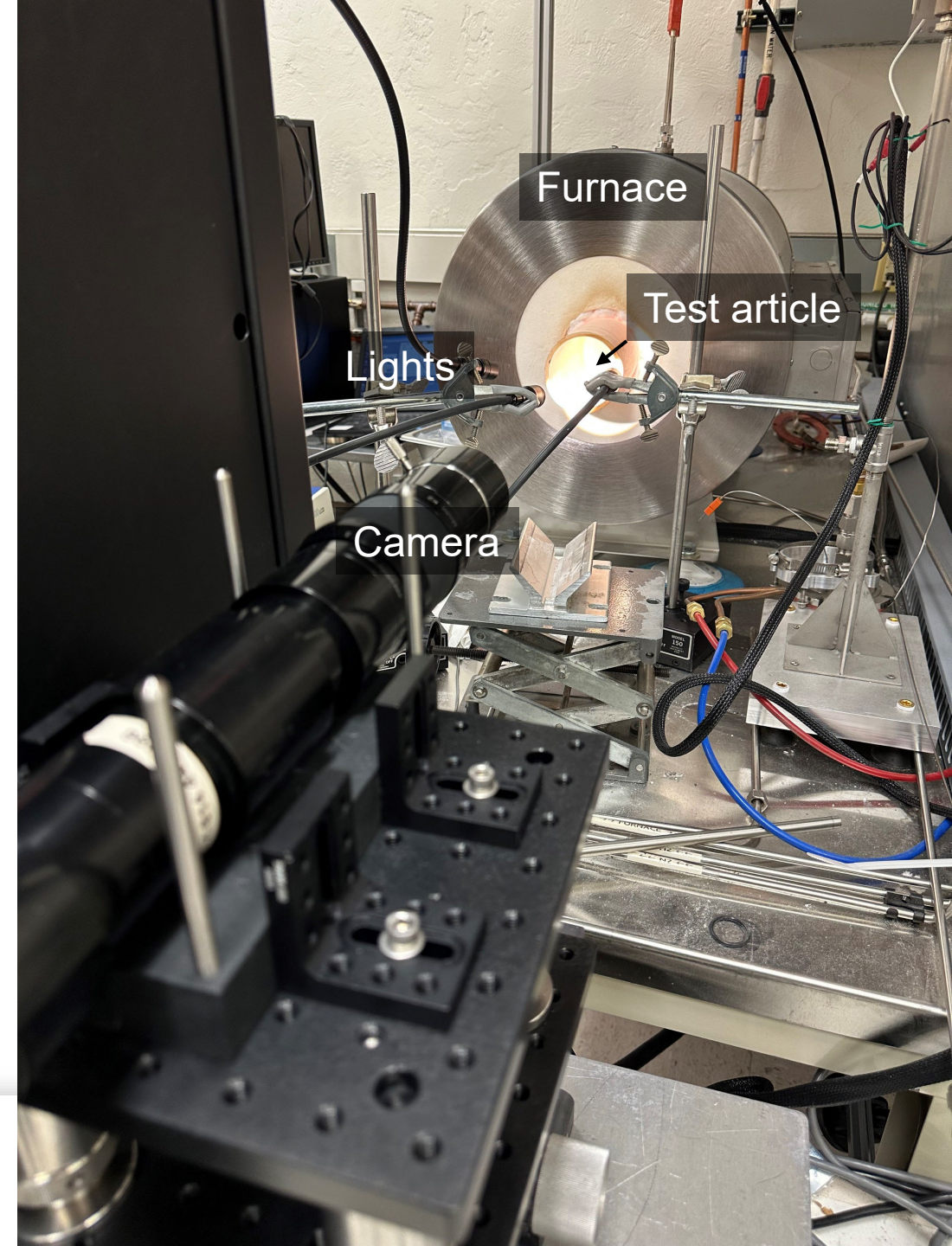
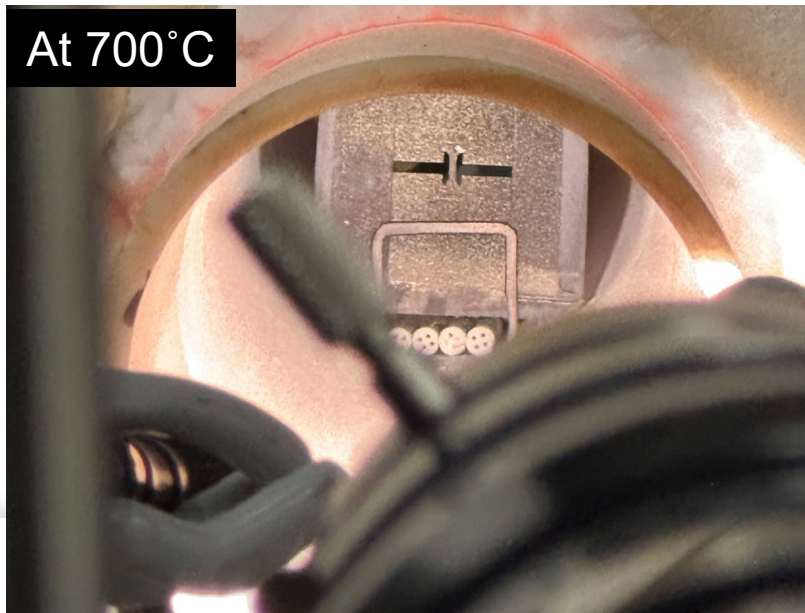
Susceptor Plate



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

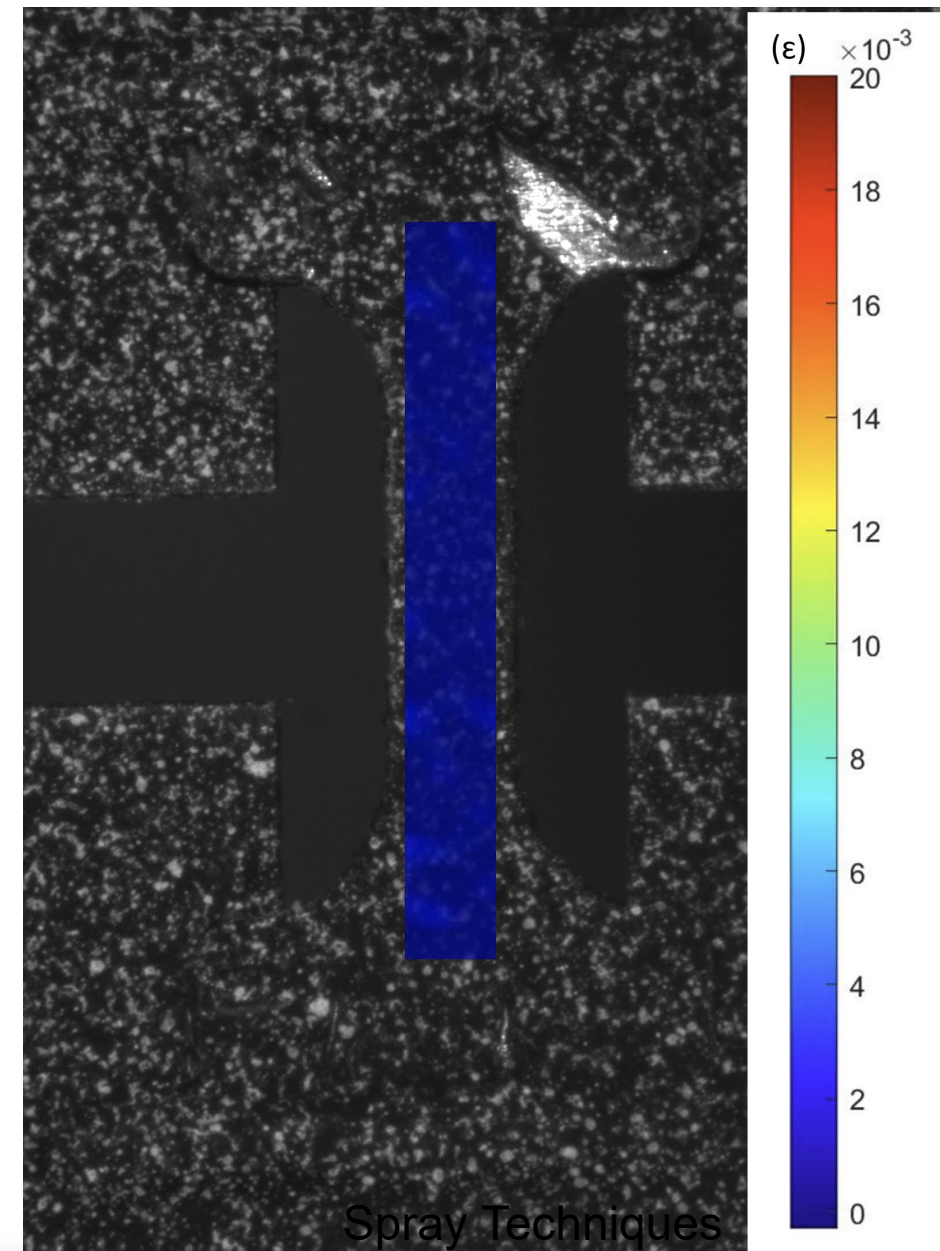
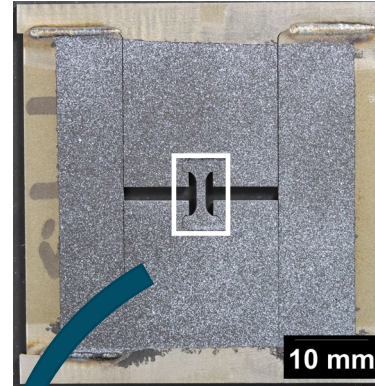
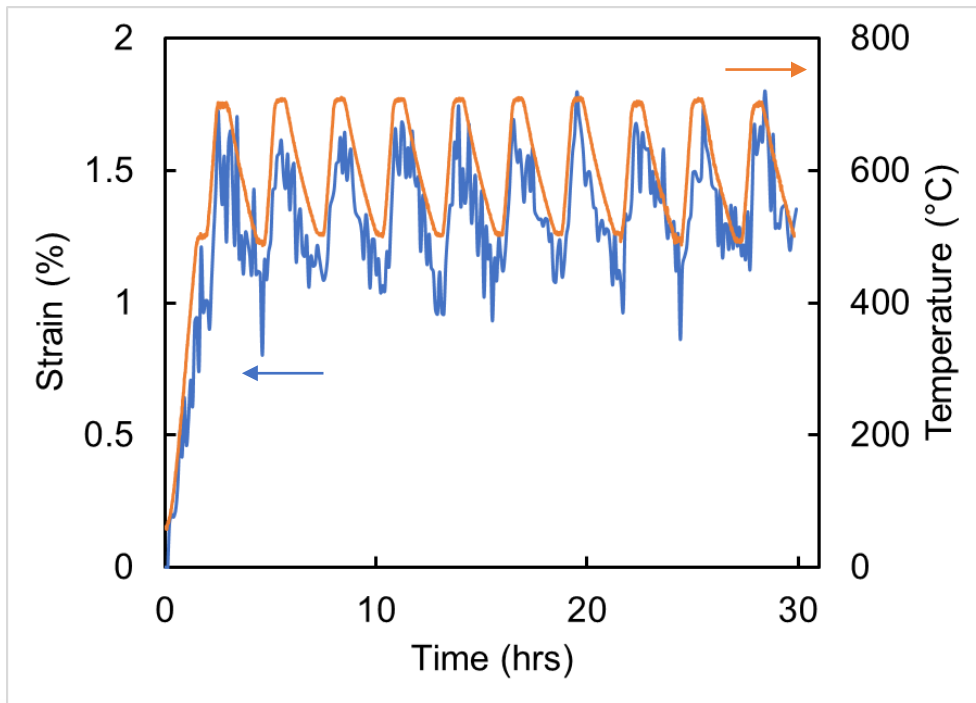
Furnace Testing

- 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



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



Next Steps for Surveillance Test Articles Development

- **Continue the effort to reduce the surveillance test article dimensions**
 - Conduct thermal cycling tests
 - Welded flat test article using tube furnace and induction heating “pancake” with susceptor plate, in air
 - Interlocking flat test article (Moly-TZM driver), in argon environment
 - Three-inch cylindrical test article in tube furnace, in air
 - All with DIC setup to collect strain histories
- **Develop test protocol for thermal cycling of flat test articles in molten salt static capsule**
- **Exchange technical information with international collaborators**

“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

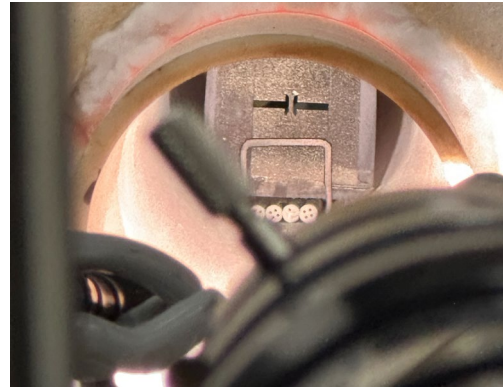
Creep-Fatigue Remaining Life Assessment

- **Knowns:**

1. Original sample response before damage – for example furnace test an instrumented specimen
2. Mechanical response after reactor service – furnace test an instrumented sample for a few cycles

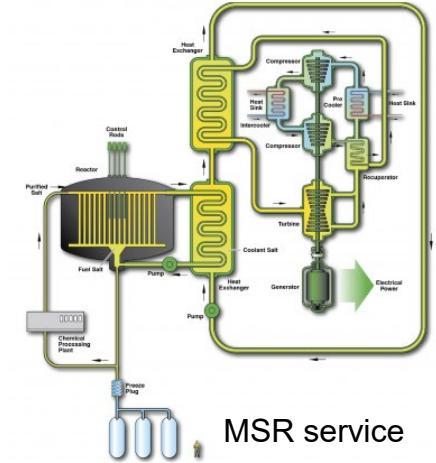
- **Unknowns:**

1. Mechanical response while in service
2. Amount of material property degradation/damage

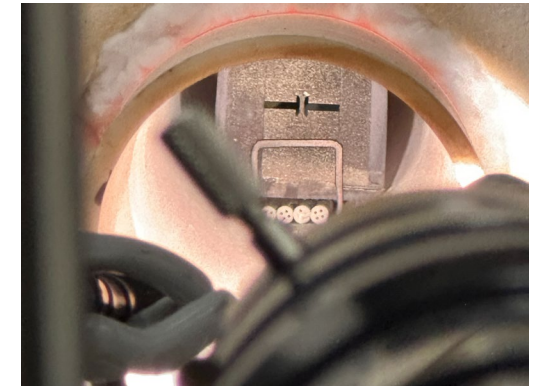


Furnace test samples **before** MSR service – establish baseline mechanical properties

Can we infer how much damage the sample accumulated?



MSR service

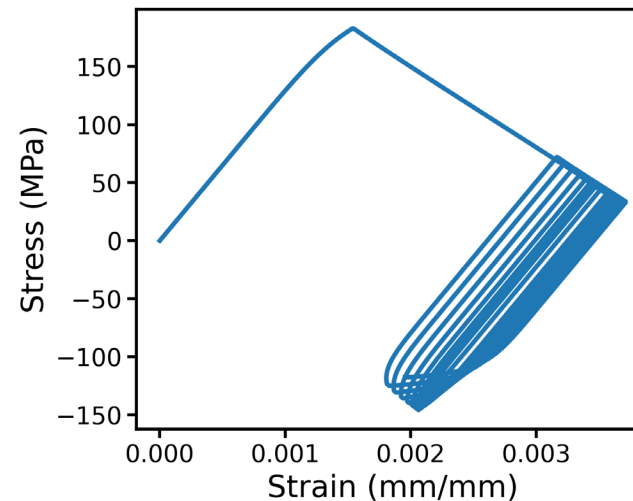


Furnace test samples **after** MSR service – establish damaged mechanical properties

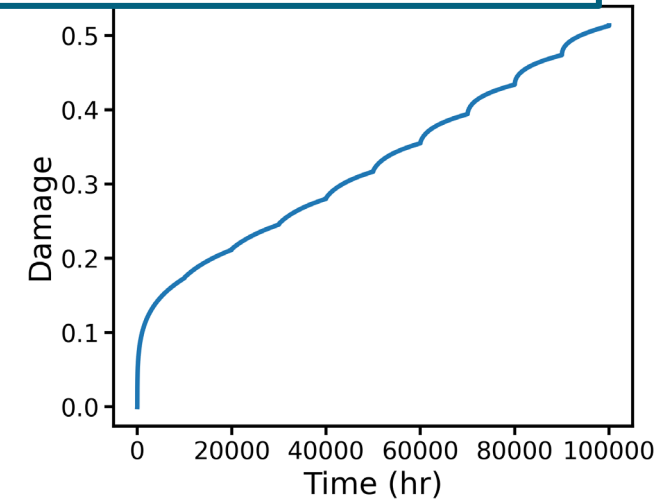
Example on Synthetic Data

- **Simulate material degradation in service**
 - Simulation of creep-fatigue damage accumulation the sample sees under representative, long-term cyclic loading
 - “Remove” sample (save material model state)
 - Do not save simulated response— we couldn’t measure this in an actual monitoring program
- **Simulate short-term creep-fatigue testing “out of service”**
 - Single repetition of a short term (2 hour) loading cycle
 - Record strain-versus-time data – DIC, extensometer, ...
- **Try to use this strain data to infer how much damage the sample accumulated**

Test load cycle: $\Delta T = 100^\circ\text{C}$ increase over 1 hour, hold for 10,000 hours, reverse and repeat



Specimen mechanical response

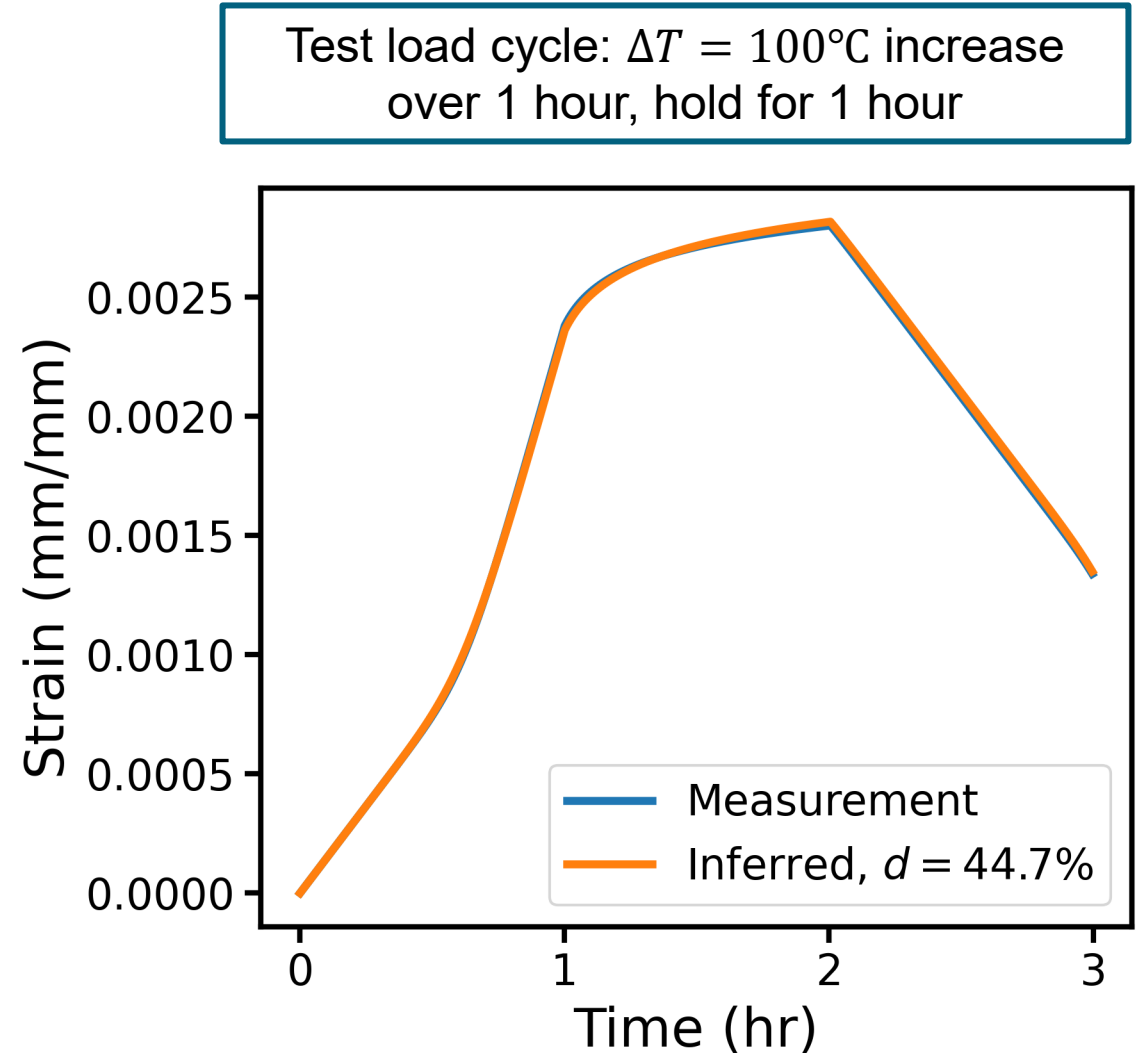


Ground truth – specimen accumulated 51.3% damage over 100,000 hours

Neither could be measured in actual surveillance program

Results

- Damage inference – *pyoptmat* (Bayesian inference)
- Results
 - Ground truth – accumulated 51% damage
 - Inference result – 45% damage
 - So remaining life is about 100,000 additional hours
- Demonstration of a feasible approach for inferring damage in actual specimens!



Surveillance Program Outlines

| | Creep/steady load | Cyclic load (traditional) | Cyclic load (no damage) |
|--|---|---|--|
| Mechanical properties required | Creep to failure (including strain measurement) | Creep-fatigue to failure | Short term creep-fatigue deformation |
| In-reactor surveillance test article type | Steady mechanical, thermal, and environmental | Cyclic mechanical, thermal, and environmental | Cyclic mechanical, thermal, and environmental |
| “Out-of-pile” testing on surveillance specimens | 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 criteria | Remaining life (time to expected failure) | Remaining life (cycles to expected failure) | Remaining life (cycles to failure) assuming linear damage accumulation |

Next Steps For Remaining Life Determination

- **Try this with real data!**
 - Sample specimen in furnace many times (with or without strain measurements)
 - Sample specimen once with strain measurement
 - Return to furnace and cycle to failure
 - Validate approach by predicting remaining life from measured data
- **Which “mode” of remaining life modeling works best**
 - Choose a damage model: more likely to extrapolate accurately
 - No damage model: no out of reactor failure data needed, likely to be less accurate, would need to assume linear damage accumulation



Thank you

michael.mcmurtrey@inl.gov
messner@anl.gov

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