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Development of surveillance test articles for materials degradation management in MSR environments

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FY24 Work Packages

- **Work funded by the US DOE Office of Nuclear Energy, Molten Salt Reactor Campaign, under two work packages**
- **RD-24IN060403 Materials Surveillance Development – INL**
  - Development Team
    - Heramb Mahajan, Michael McMurtrey, Tate Patterson, Ting-Leung Sham
  - Experimental Support
    - Xinchang Zhang, Austin Matthews, Dave Cottle, Joel Simpson
  - Milestone: Design, Fabrication and Testing of Surveillance Test Articles to Support MSR Materials Degradation Management (9/24/24)
- **RD-24AN060402, Materials Surveillance Development – ANL**
  - Mark C. Messner, Bipul Barua, and Guosheng Ye
  - Milestone: Acceptance criteria for in situ surveillance of MSR materials based on thermally-loaded mechanical test articles (9/20/24)

Overview of MSR materials surveillance

- **MSR materials experience both mechanical and environmental degradation**
  - Thermal cycling and pressure (creep-fatigue)
  - Salt corrosion
  - Irradiation
- **We have very limited combined effects data to quantify/bound this degradation for component design**
- **A material surveillance program would monitor material degradation in service to mitigate the risk posed by the limited up-front test data**
- **This work seeks to develop the technology required to implement a surveillance program in an operating plant**

Size test articles
- Sizing procedures to mimic component loading
- Passively actuated test articles

Insert into reactor
- Decide on locations/quantity
- Design test articles to minimize impact on component operation

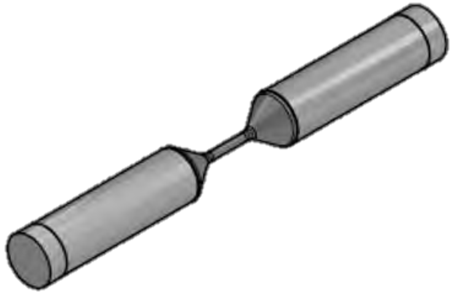
Periodically remove and test ex-situ
- How often to remove and how many?
- Robust article design
- Instrumented out of reactor testing – strain measurement

Acceptance criteria
- Damage inference based on out of reactor testing
- Acceptance criteria: what is the component remaining life?

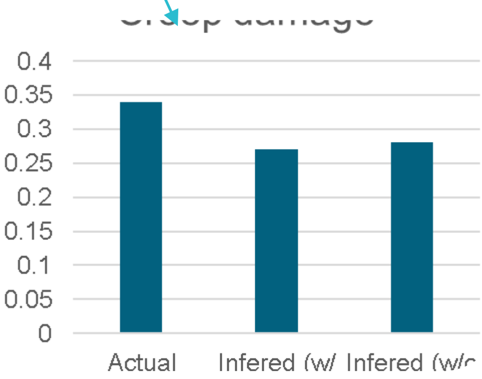
Four pillars of an MSR surveillance program

Smaller effort to simplify methods developed in the past

Robust test articles



Sizing procedures



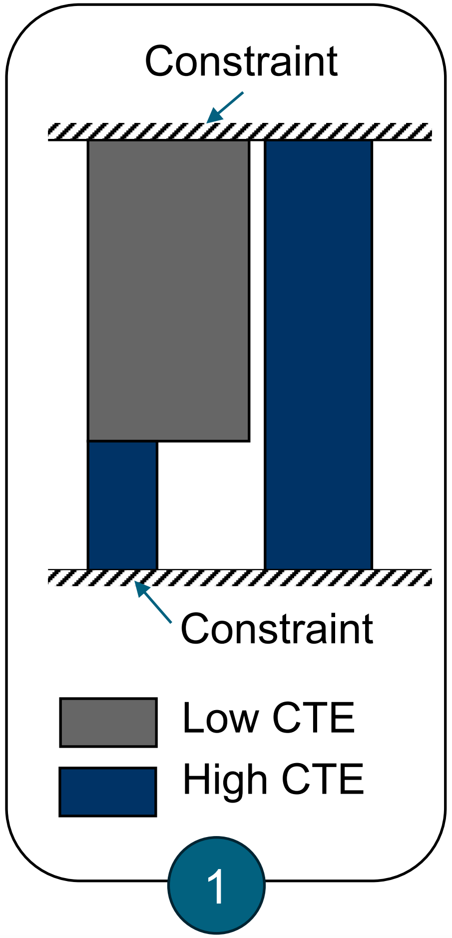
Damage inference

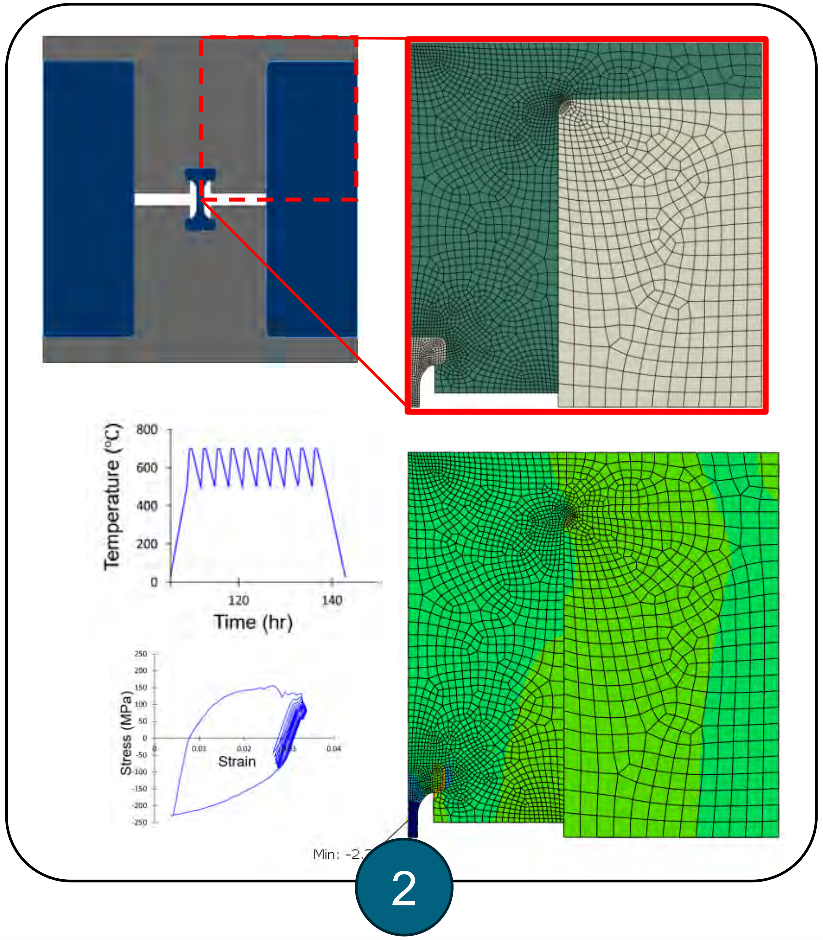
Acceptance procedures

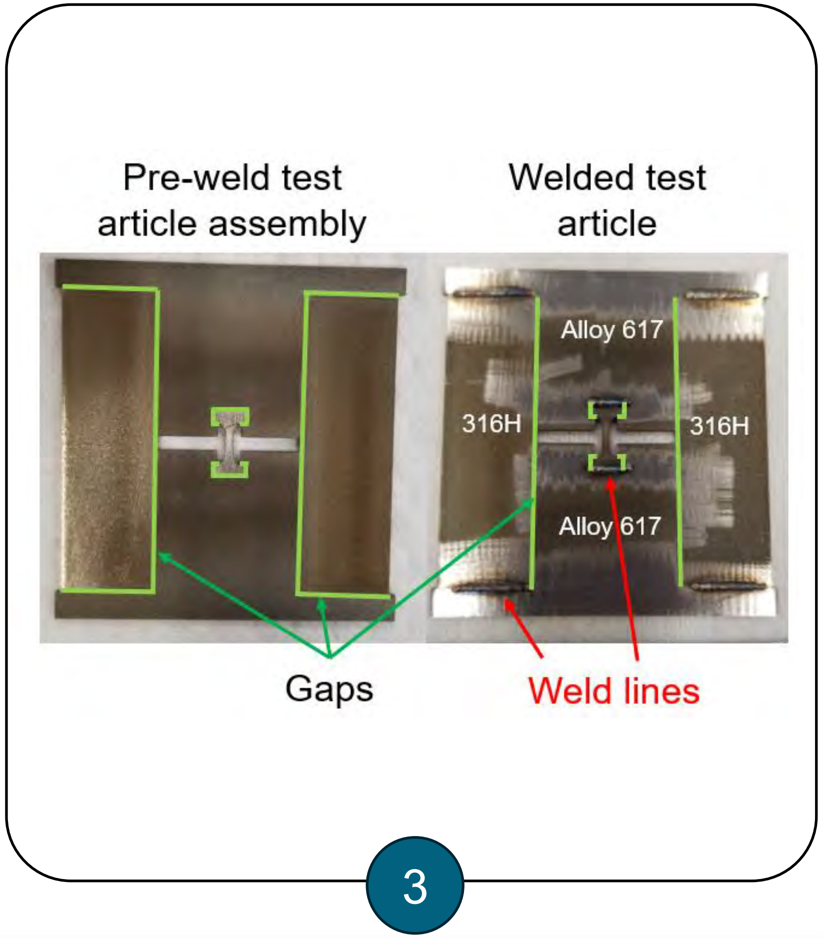
Main focus for this FY

Surveillance Article Development

Overview – Test Article Design







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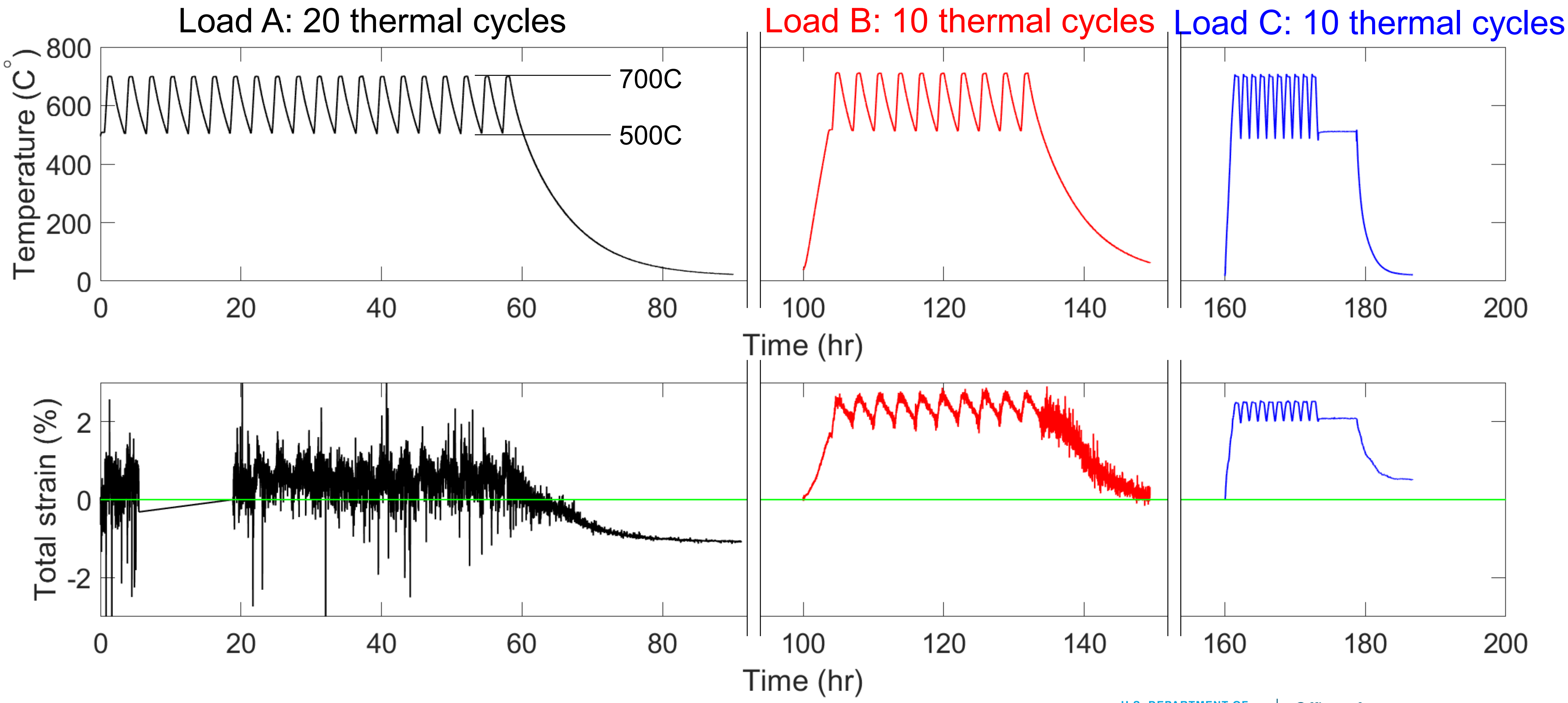
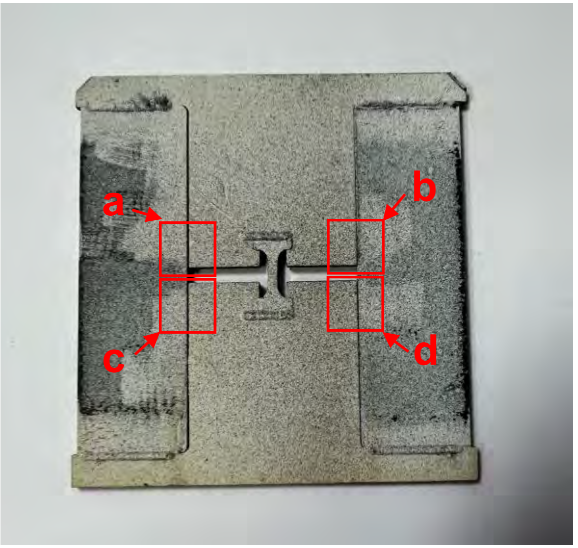
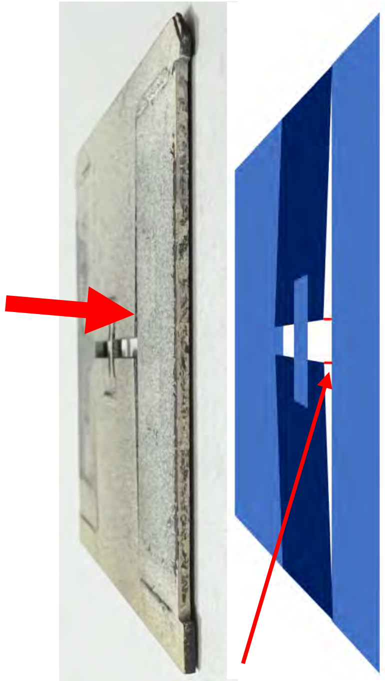
Thermal Cycling of Test Article



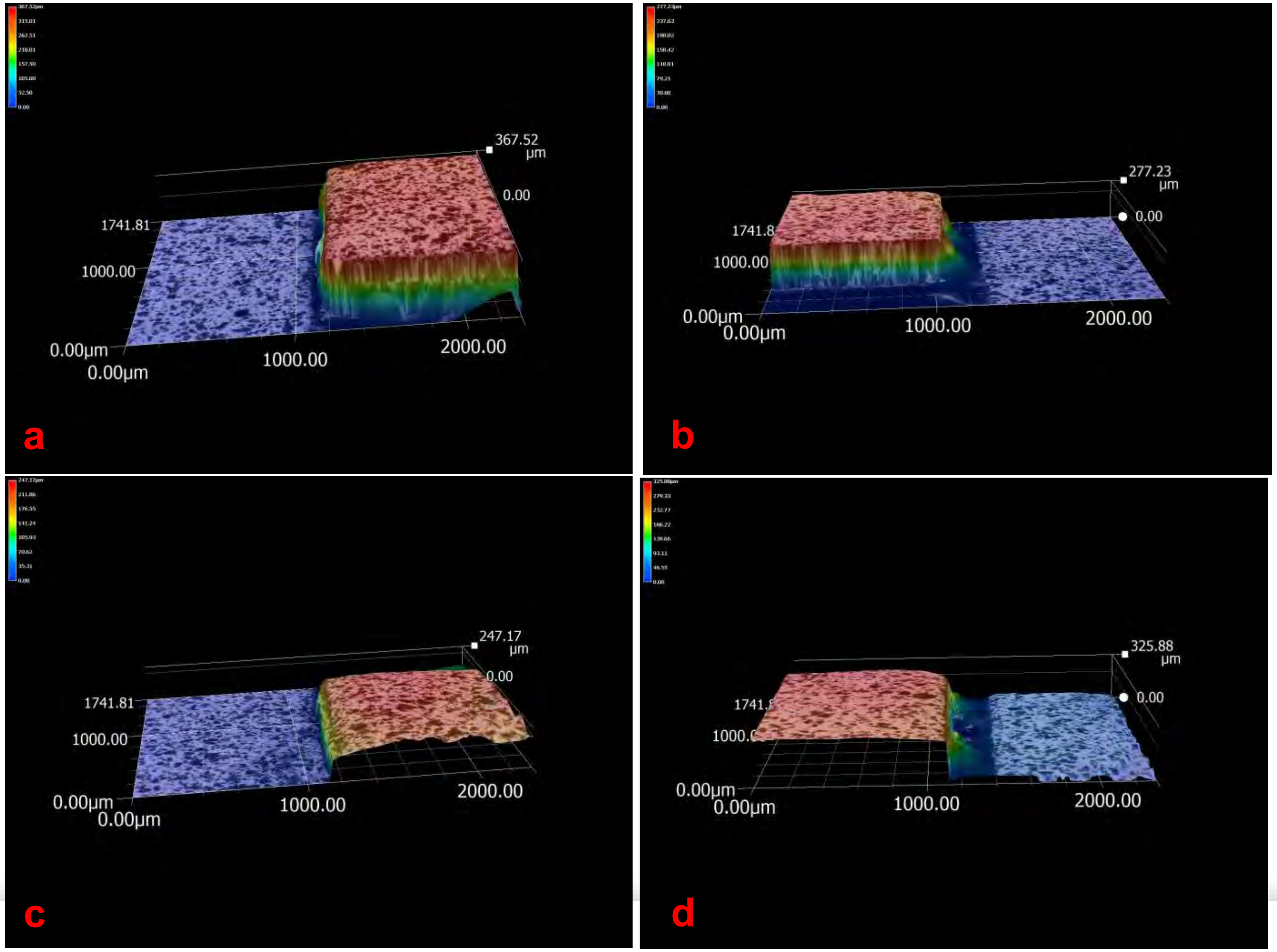
Bending Of Sample After Load A

Out-of-plane bending





Schematic figure highlighting bending



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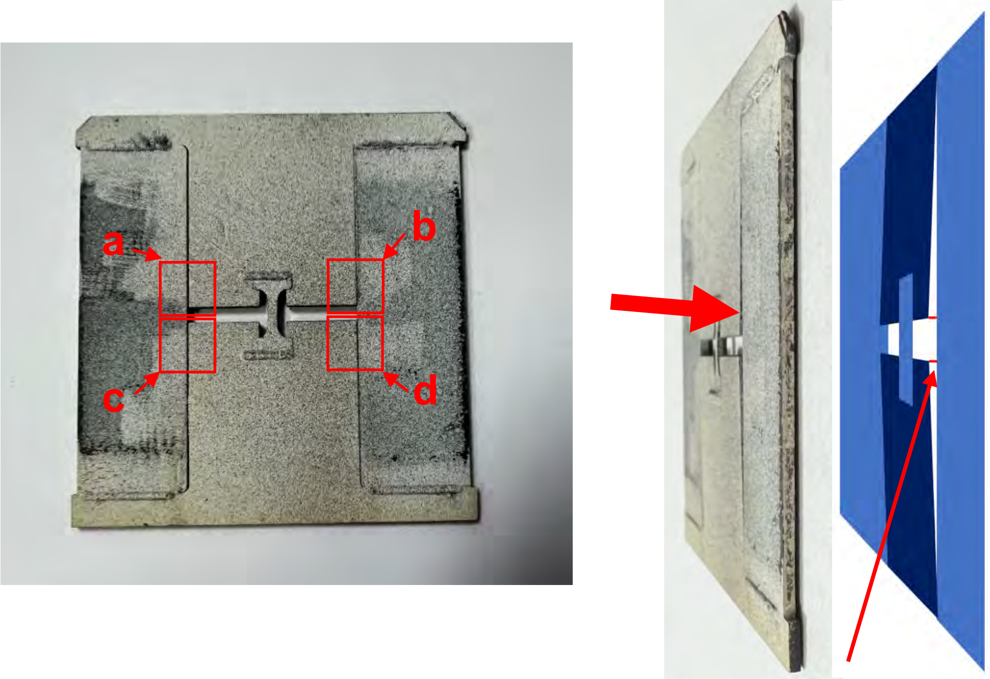
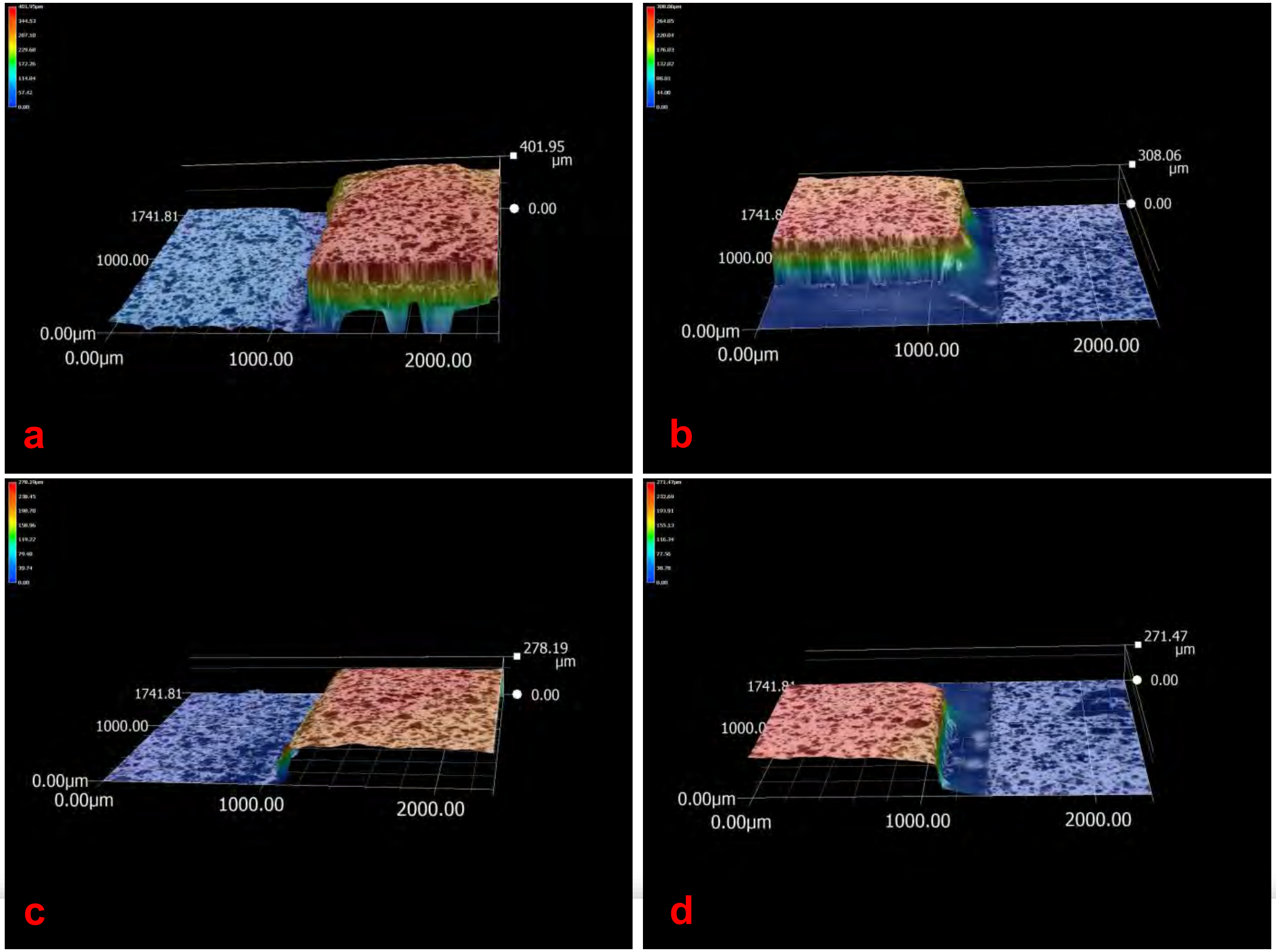
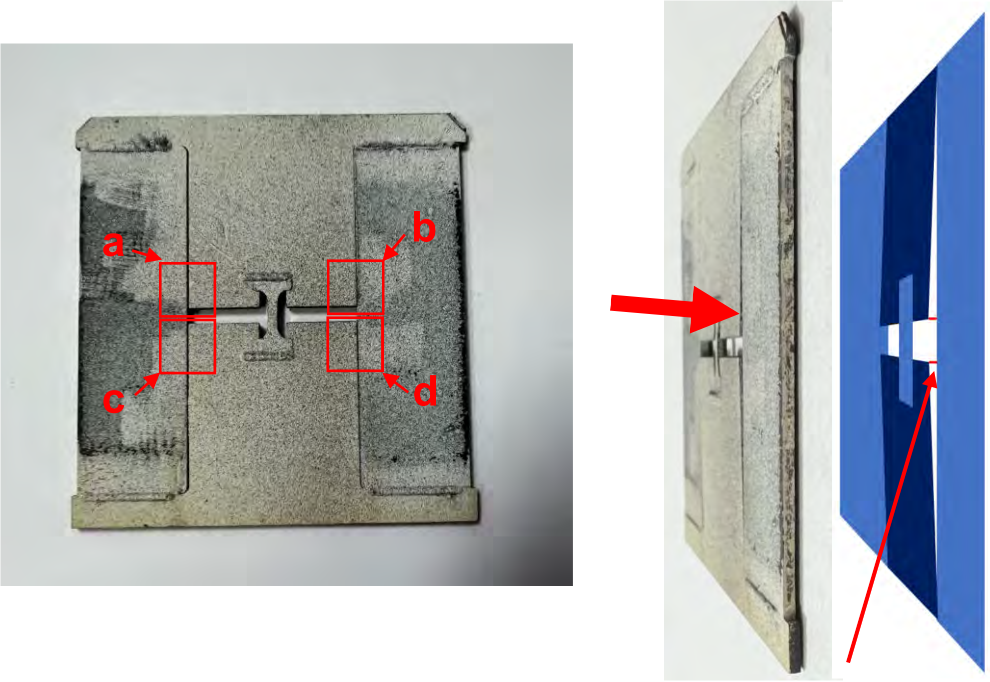
Bending Of Sample After Load B



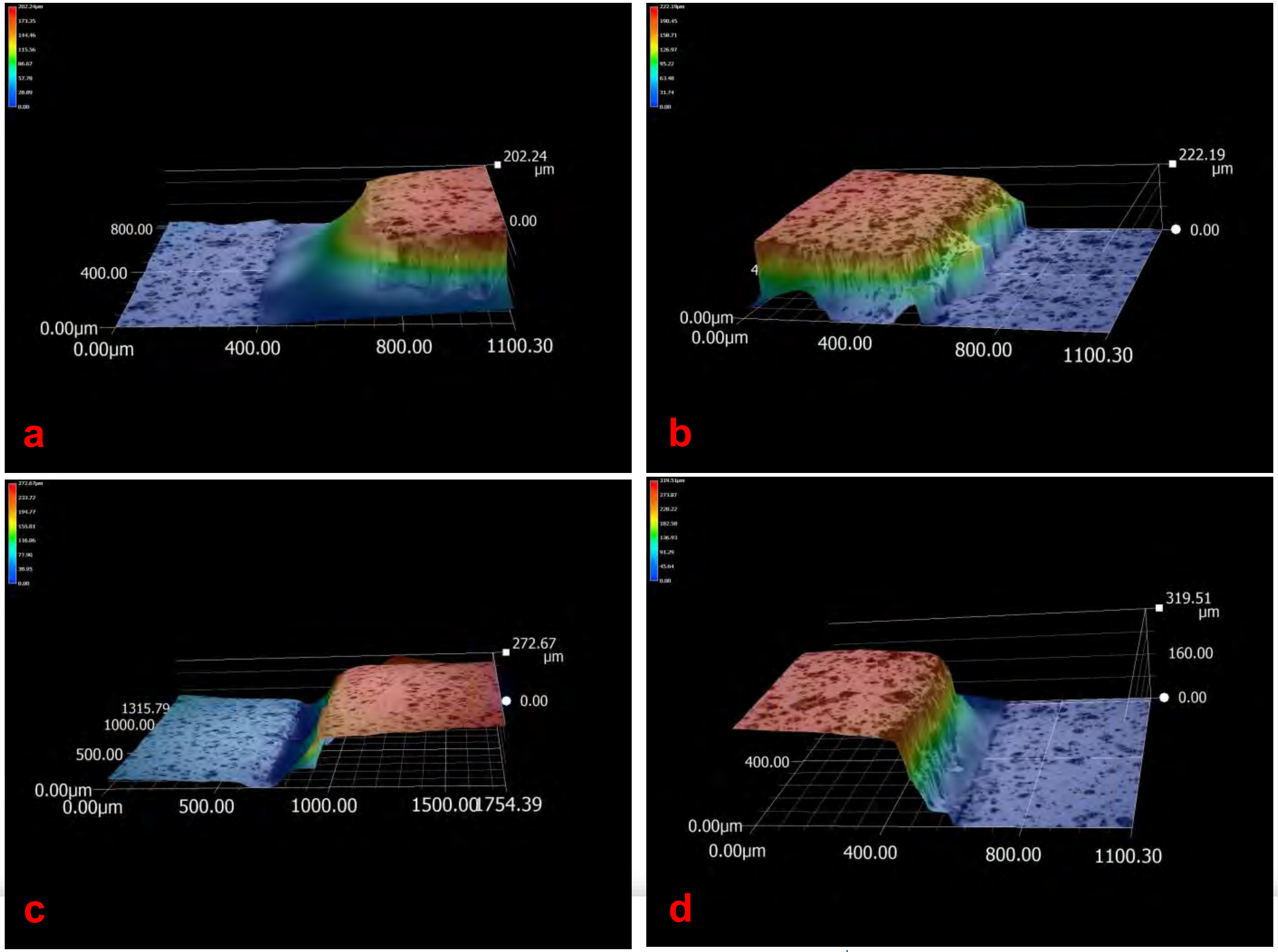
Schematic figure highlighting bending



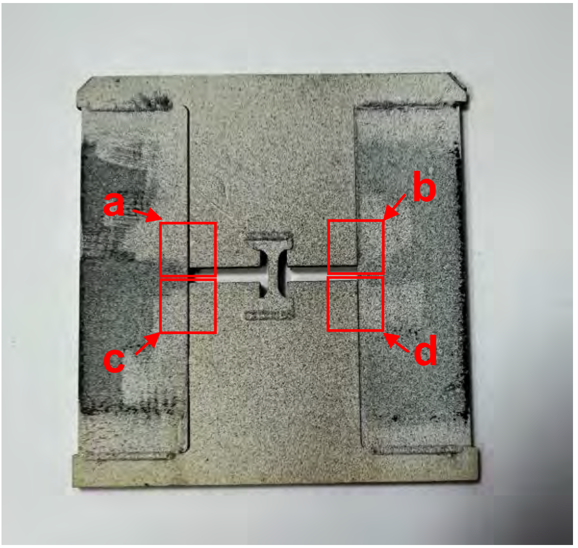
Bending Of Sample After Load C

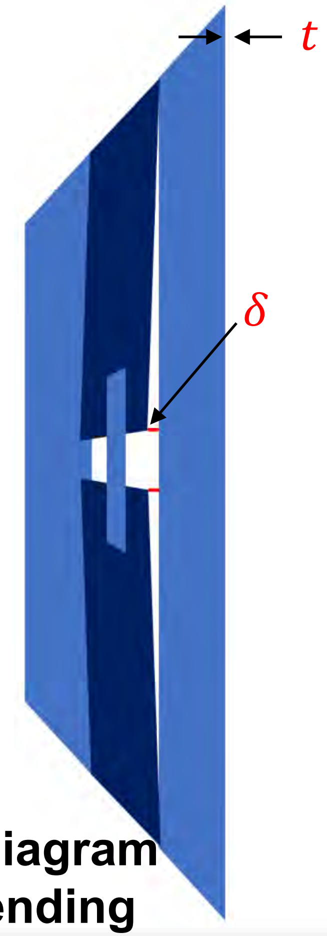


Schematic figure highlighting bending



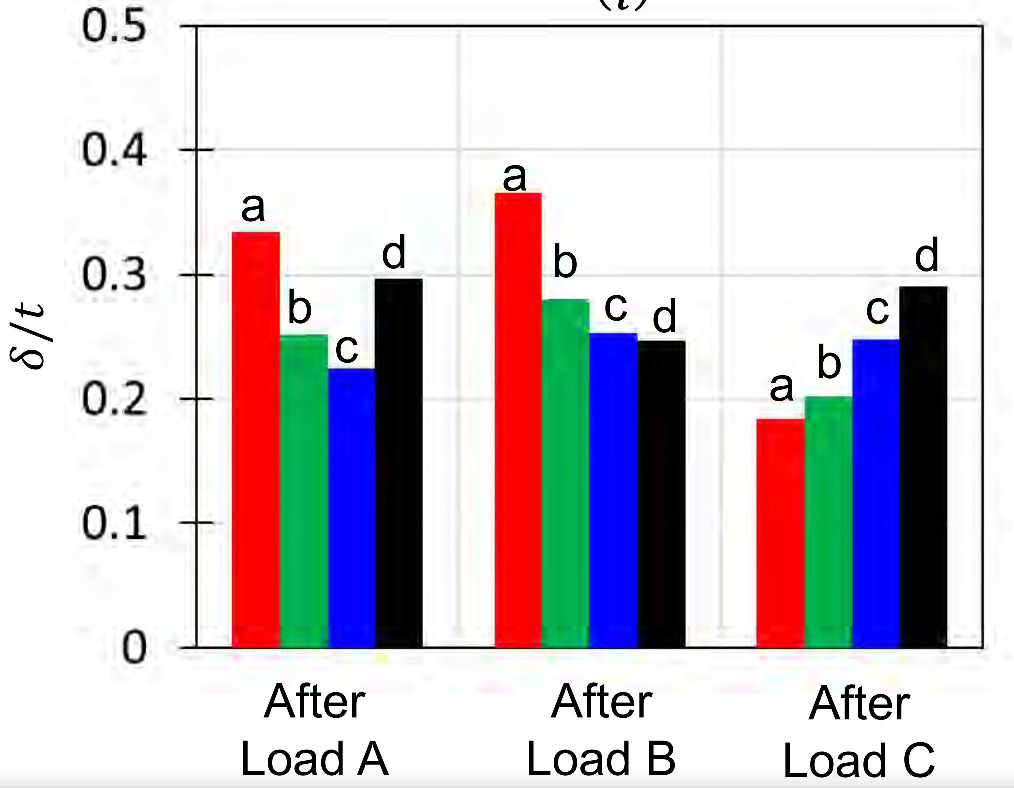
Out-of-plane Bending of Sample



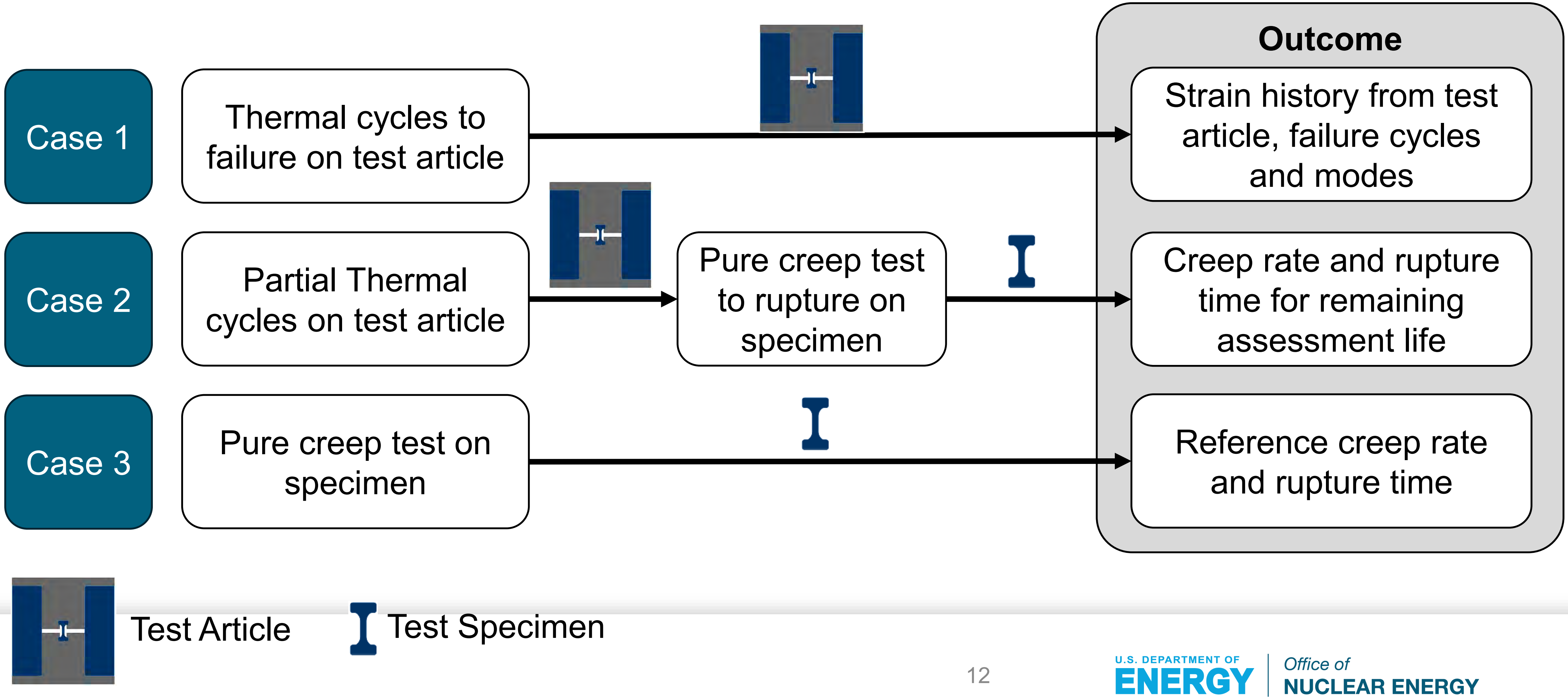


Schematic diagram showing bending

Normalized out-of-plane deformation at the end of each load $\left(\frac{\delta}{t}\right)$ at four points

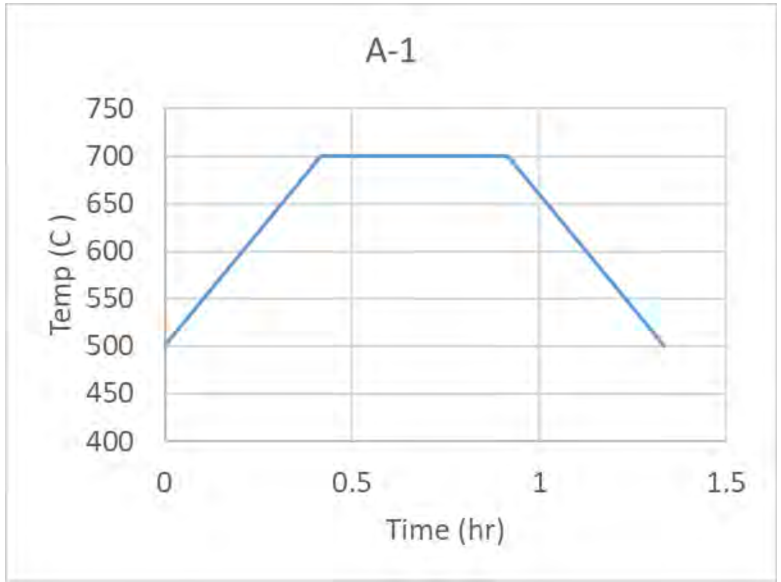


How To Use Surveillance Test Article? – Experimental Support



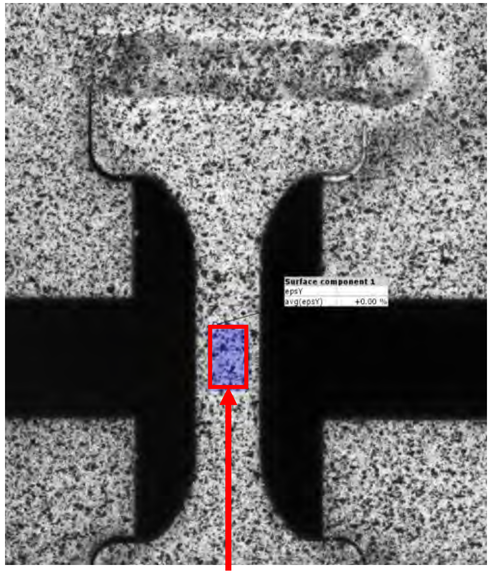
Thermal Cycling On Test Article

- **Temperature cycle: A-1**
- **Peak T: 700C, Valley T: 500C**
- **~8C/min ramps and 30 min dwell at peak temperature of 700C**
- **Cycle time ~1.4 hours**
- **Continues cycles till failure**

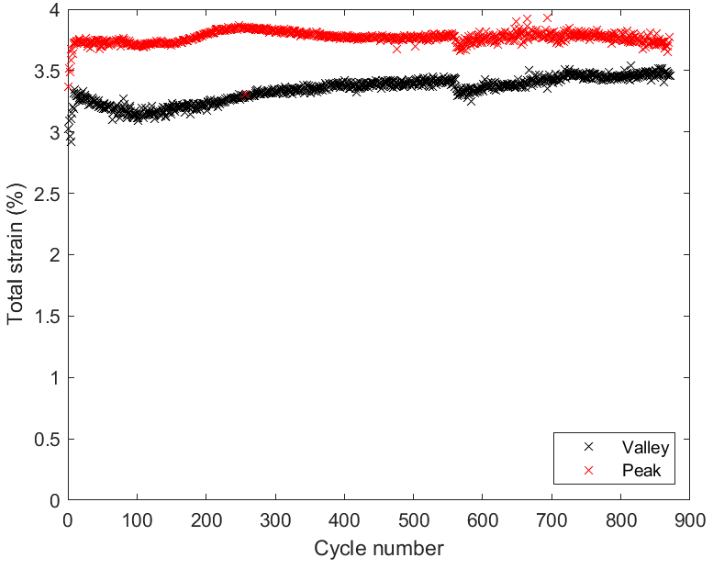


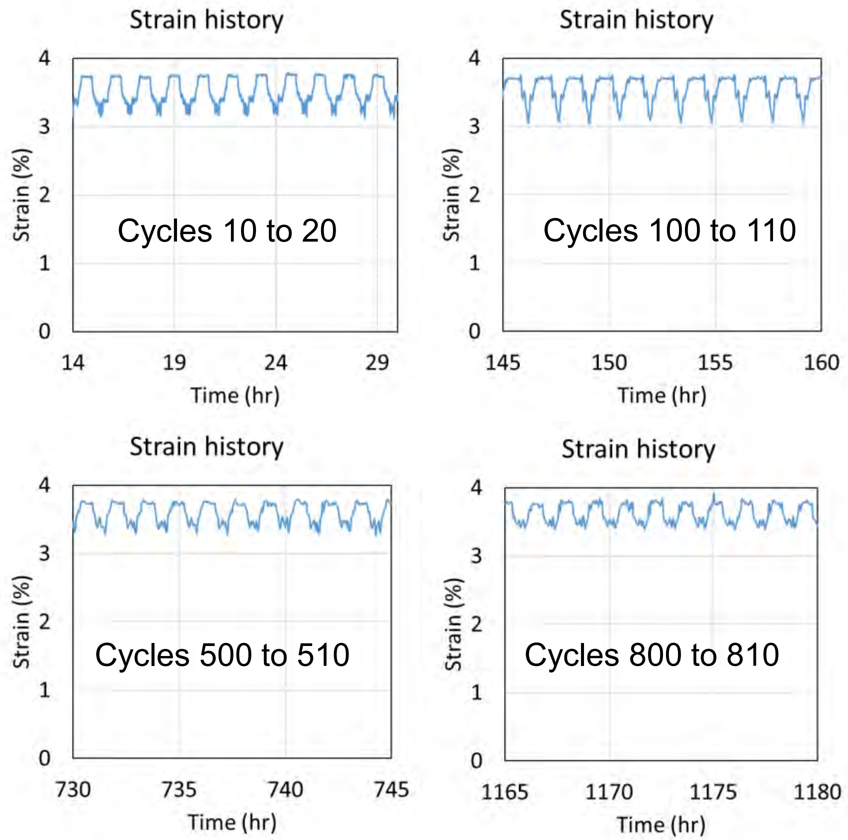
Data From Test Article

- **Strain measurement through Digital Image Correlation**



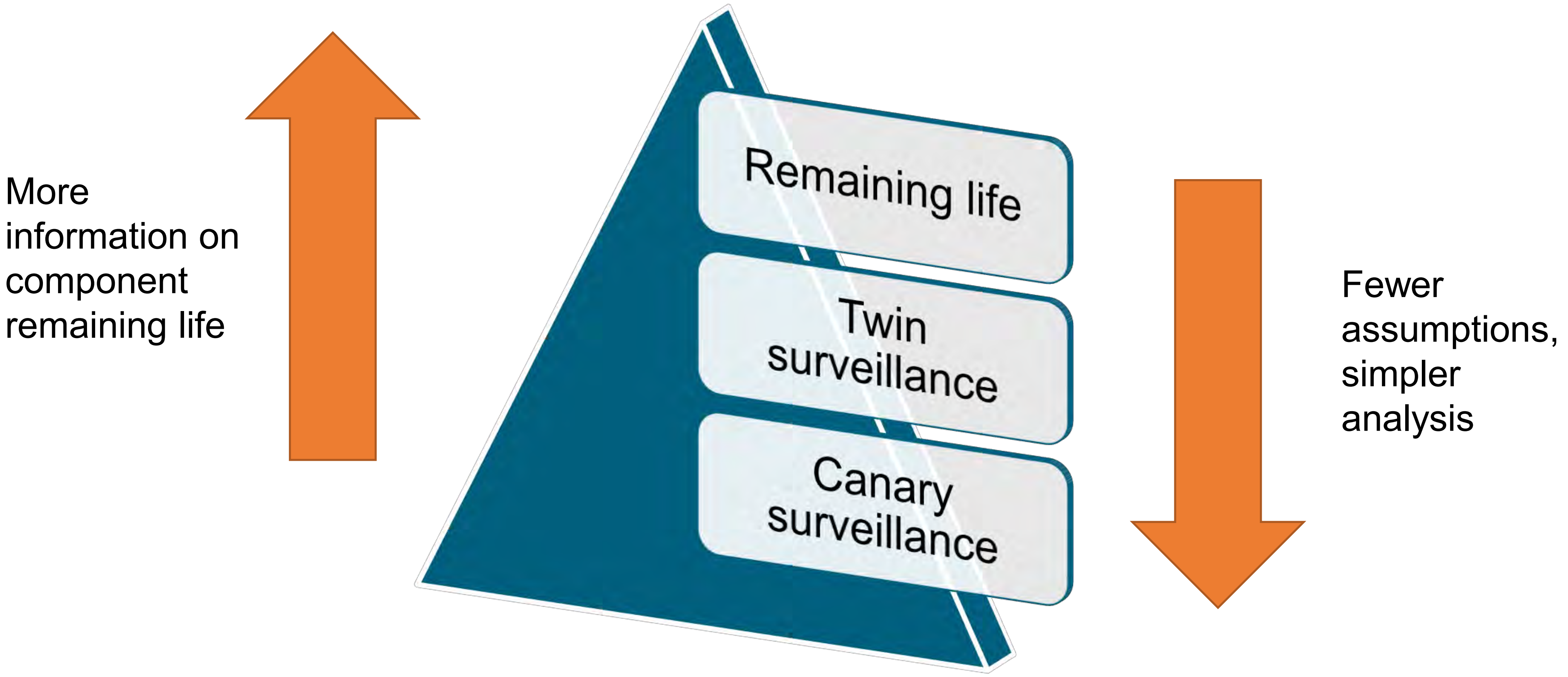
Measurement window





Acceptance Criteria

Outline of three surveillance program types:

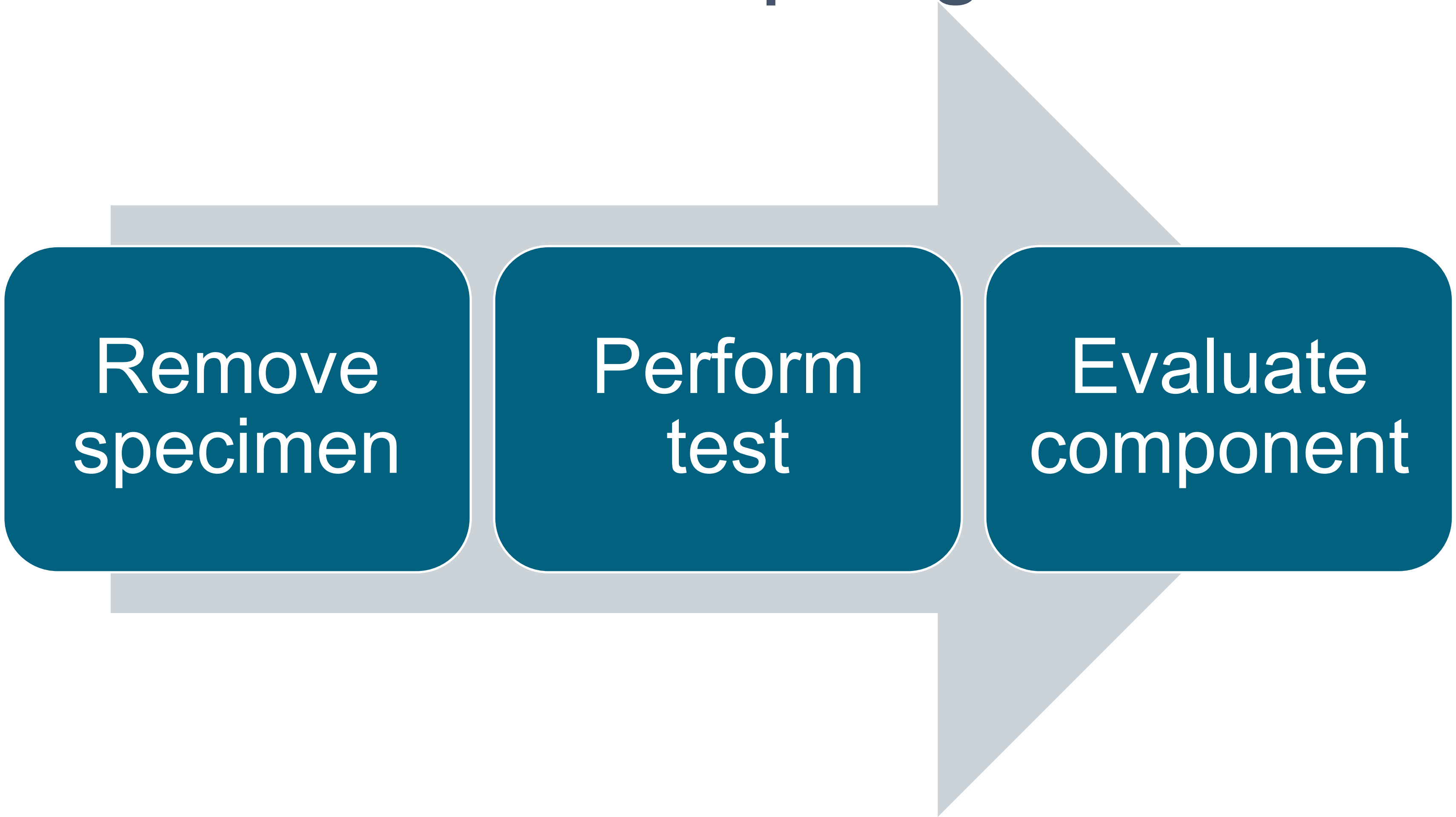


Constraints

Common constraints assumed for all three programs:

1. No in reactor measurements, except for temperature
2. Out of reactor measurements limited to strain in test section for known thermal cycle
3. Periodic access to samples (for example, during maintenance or refueling outages)
4. Creep-controlled damage
5. Test articles will fail in the test specimen; no significant damage in other parts of the test article or at the connections

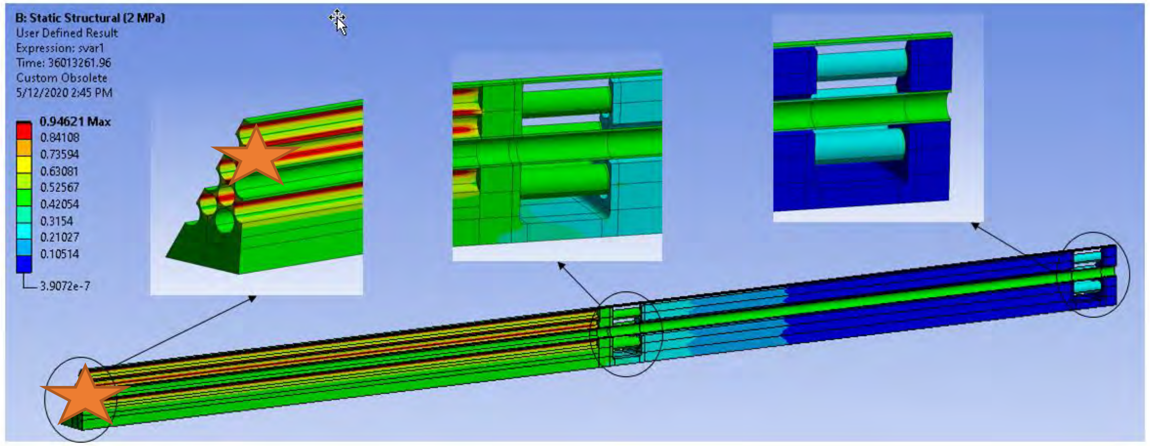
Basic idea of a materials surveillance program



Will the component survive until the next inspection?

Common procedures: sizing specimens

- **Given a target hysteresis loop and a representative temperature history we can size a test article to match**
- **Extract target hysteresis loop from ASME design analysis of component at critical location**
- **Critical location: highest creep damage over typical component loading**



ASME creep damage analysis of a heat-pipe-cooled reactor core block from past work, showing critical damage location

Common procedures: general practices

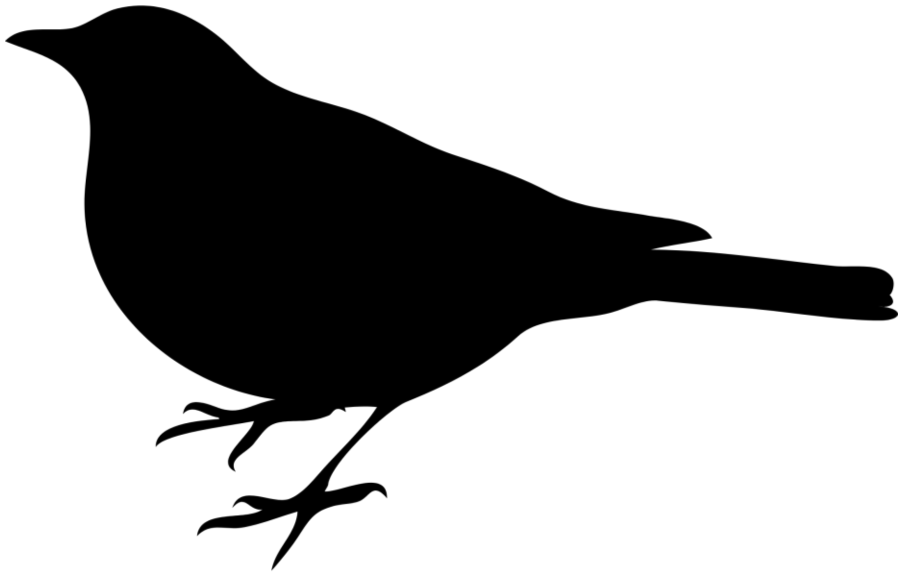
- **Insert samples into component**
  - "The surveillance specimens must be located near the inside surface of the component, in contact with the primary reactor coolant, in a region so that the specimen irradiation history duplicates, to the extent practicable within the physical constraints of the system, the neutron spectrum, temperature history, and maximum neutron fluence experienced by the component inner surface. For components with flowing coolant, the test articles must be placed in the coolant stream, at a location where they will experience as near to the maximum flow rate as practical within the physical constraints of the system."
  - Adapted language from 10 CFR 50, Appendix H
  - Need a fairly large number of test articles – samples will need to be small
- **Define an inspection interval and a representative loading**
  - Inspection interval should be significantly shorter than component design life
  - Representative loading: ASME Service Level A between inspections
- **Each inspection interval remove three samples**
  - One for archiving
  - Two for testing

Common procedures: out of reactor testing

- **Two of the concepts require out of reactor testing**
- **General procedure:**
  - Remove samples
  - Potential cool down period
  - Place samples in furnace
  - Cycle through short (24 hours?) test thermal cycle *while recording strain in the test section*

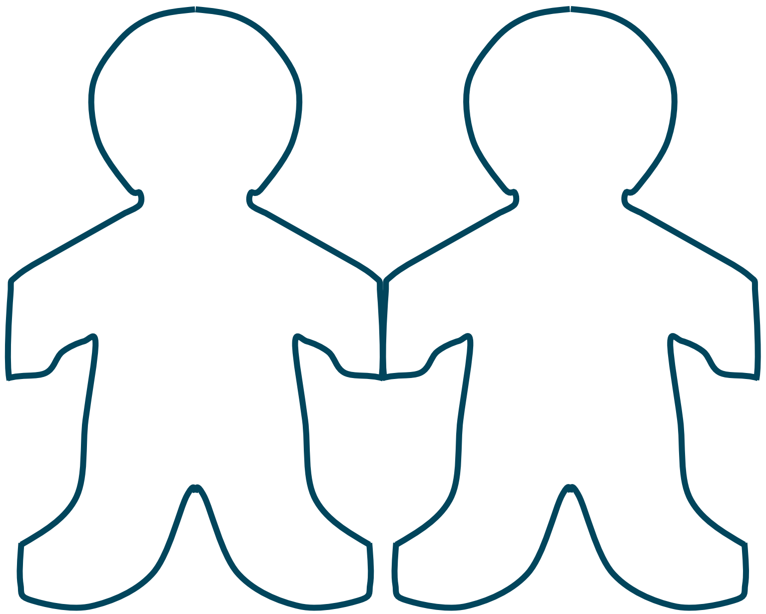
Program 1: canaries

- **Design specimens to experience *greater* creep damage per inspection period than critical location**
- **Simple test and acceptance criteria: if both samples are intact the component passes, if either is broken it fails**



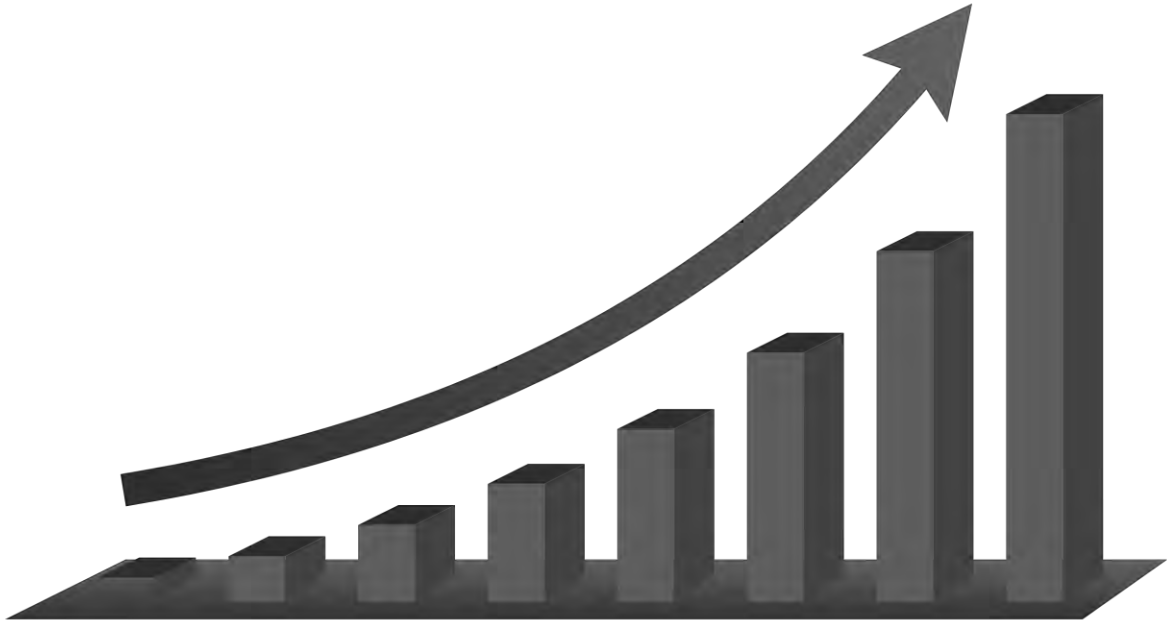
Program 2: twins

- **Mimic the in reactor sample temperature history on a battery of twin samples outside the reactor**
- **Remove two samples from the reactor**
- **Run test cycle on both removed samples and twin samples**
- **Assess the rate of creep damage accumulation by comparing the strain histories**
- **Assume the in reactor samples have been accumulating damage at this rate *for the entire component life***
- **Extrapolate over next inspection cycle: pass if creep damage at next inspection less than 1.0**



Program 3: remaining life

- **Determine/assume expected material performance without reactor environment**
  - ASME constitutive models?
  - ASME damage model?
- **Remove two samples**
- **Run test cycle on removed samples**
- **Assess current creep damage with damage inference procedure**
- **Add expected damage from next inspection cycle**
- **Pass if expected creep damage at next inspection less than 1.0**



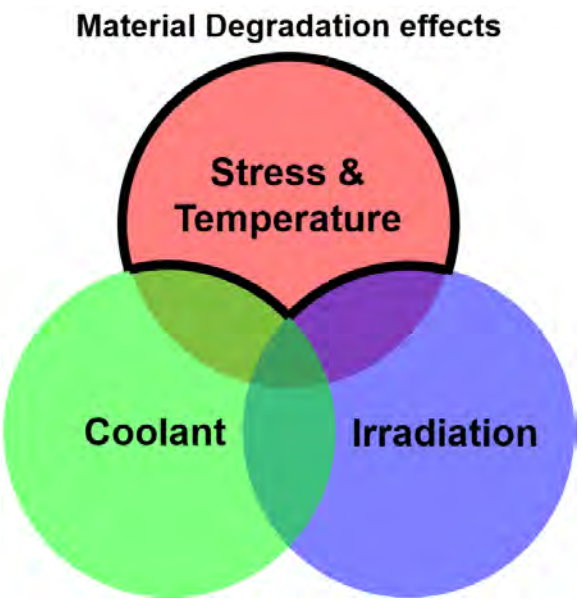
Conclusions

Conclusions/next steps

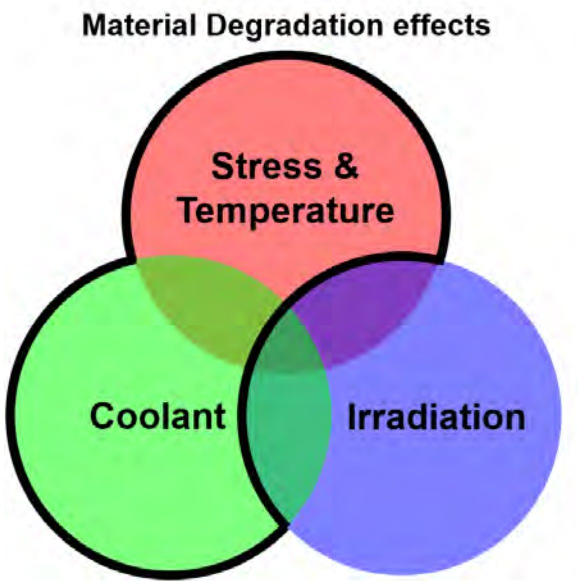
- **By the end of FY24 we will have the outline for a complete MSR surveillance program**
- **Next steps:**
  - Validate the approach with in-salt tests
  - Continue work to miniaturize the test articles
  - Promote wider adoption of the methodology – simplifications, user-friendly tools, work towards codification

- **Questions? michael.mcmurtrey@inl.gov**

In-progress material degradation due to mechanical loads



Future work: Mechanical loads in presence of salt environments



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