July 22, 2026

NSUF Workshop:

Foundations of Irradiation Testing: A Workshop for Researchers

INL/MIS-25-85883

INL/MIS-26-93511

Mechanical and Environmental Testing

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Motivation

- Need for structural materials and fuels for advanced reactor systems[1, 2, 3]:
  - Higher Energy Neutron Spectrum
  - Higher Temperatures
  - Corrosive Environments
- Example: research on new materials is being conducted, including on Multi-Principle-Element-Alloys (MPEA's, aka High-Entropy-Alloys, aka Complex-Concentrated-Alloys)
  - In a 2021 review paper[4], ~4000 papers published on MPEA
  - Of those, only ~100 were focused on nuclear applications and were topical on fabrication, modeling, ion irradiation, and corrosion.
  - Very limited neutron irradiation data on MPEAs
  - Nearly limitless composition space for MPEAs

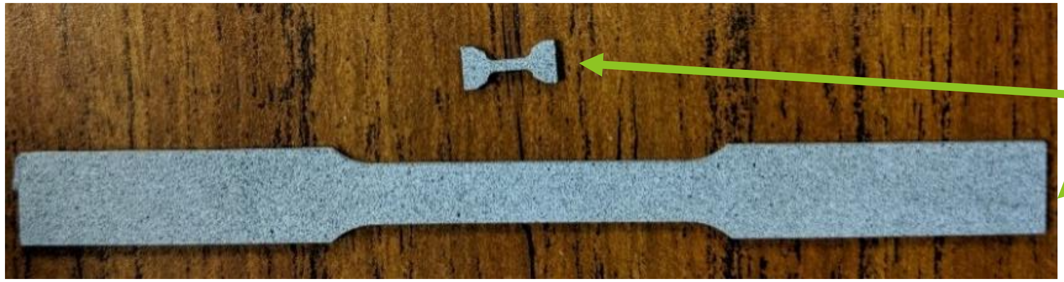
- This talk will focus on mechanical testing, but other kinds of testing such as creep, stress corrosion cracking, etc are possible.

1 – https://doi.org/10.1016/j.matre.2021.01.002
2 – https://doi.org/10.1016/j.cossms.2016.10.004
3 – https://doi.org/10.1038/ncomms13564
4 – https://doi.org/10.3390/e23010098

Challenges and Opportunities

- How to reduce time and cost to perform neutron irradiation of structural materials?
  - Develop ”Standard Capsule” with analysis basis to perform irradiations in ATR “A” positions. Reduces cost and time to get new experiments into ATR using highly available “A” positions.
  - Allows for large numbers of specimens to be irradiated.
- How to deal with large numbers of specimen materials?
  - reduce specimen size to accommodate greater number of specimens in reactor
    - Validation of smaller specimen size for mechanical testing[1]

1 – Karnati, Isanaka, Zhang, Liou, Schulthess, “A Comparative Study on Representativeness and Stochastic Efficacy of Miniature Tensile Specimen Testing”, Accepted.



Miniature “MT2” Tensile Specimen
ASTM E8 Standard ”Sub-sized Specimen”

Challenges and Opportunities

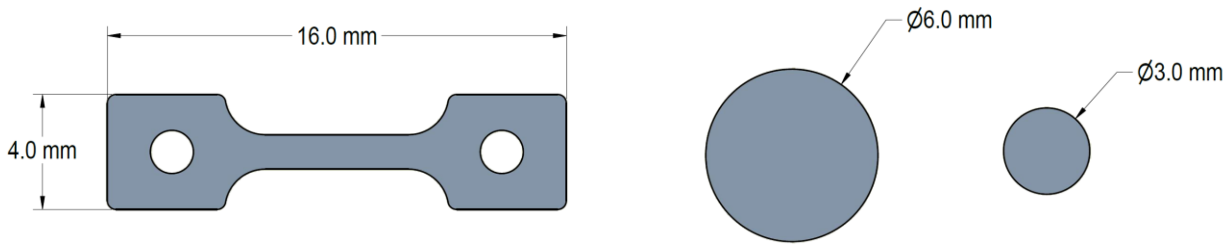
- How to increase throughput, reduce cost, and increase data extracted from each specimen?
  - As of 8 July 2022, 1,683 entries in the NSUF Material Library containing the word "Tensile" in the sample description

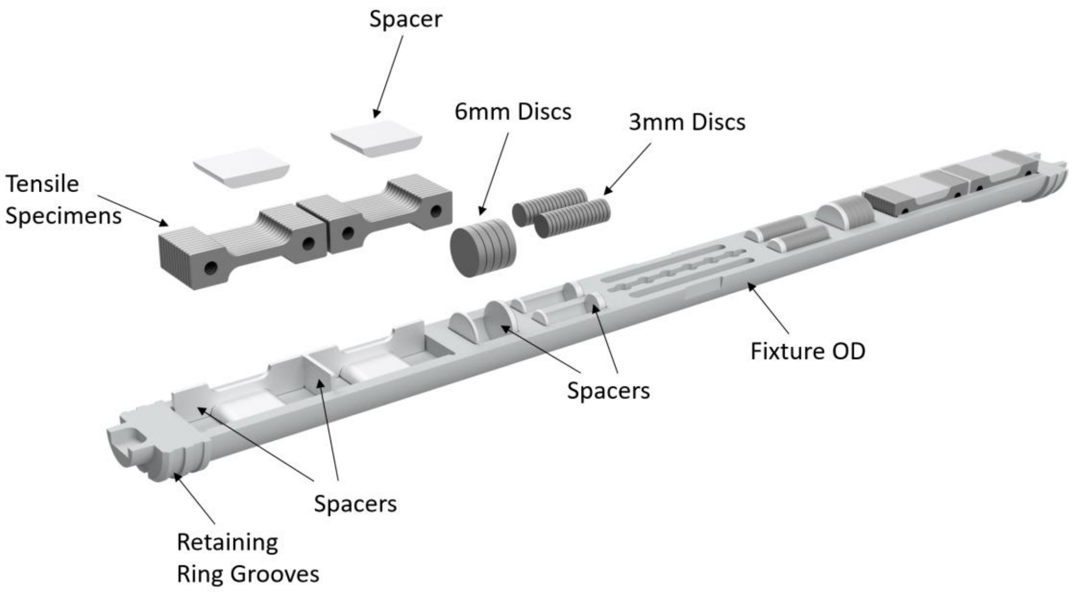
  - Automate mechanical testing,
  - Incorporate advanced Digital Image Correlation Analysis
    - Localized Strain Mapping
    - Spatial variation
    - Inhomogeneous materials
    - Etc.

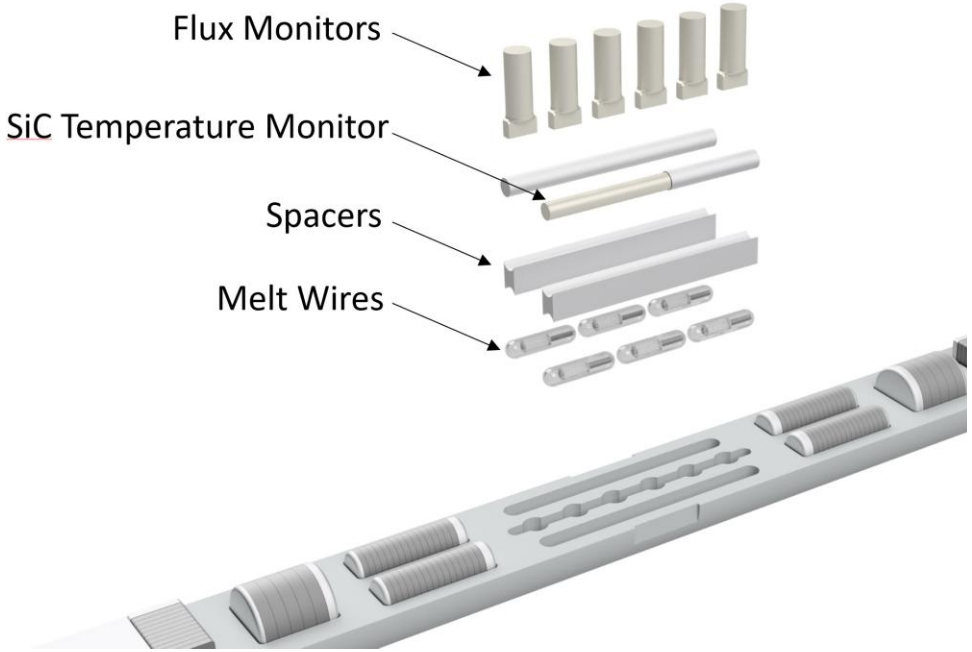
TTUSC – Tensile Test Using Standard Capsule

- Capsule design driven by three objectives:
  - Capsule should fit into a 15.9 mm diameter or larger position
    - Opens virtually every irradiation position in ATR (availability) and allows selection of test position based on flux values without limitation of the vehicle
  - Capsule should accommodate and maximize the amount of standard specimen sizes used for structural materials irradiation testing
    - Basketless design with interlocking endcaps increases inner diameter (more room for specimens) and makes reconfiguration between cycles possible.
  - Capsule analysis should be enveloping in nature so future tests can leverage the analysis to decrease deployment time
    - Parametric analysis model developed using COMSOL to allow rapid analysis for future tests.

TTUSC - Design



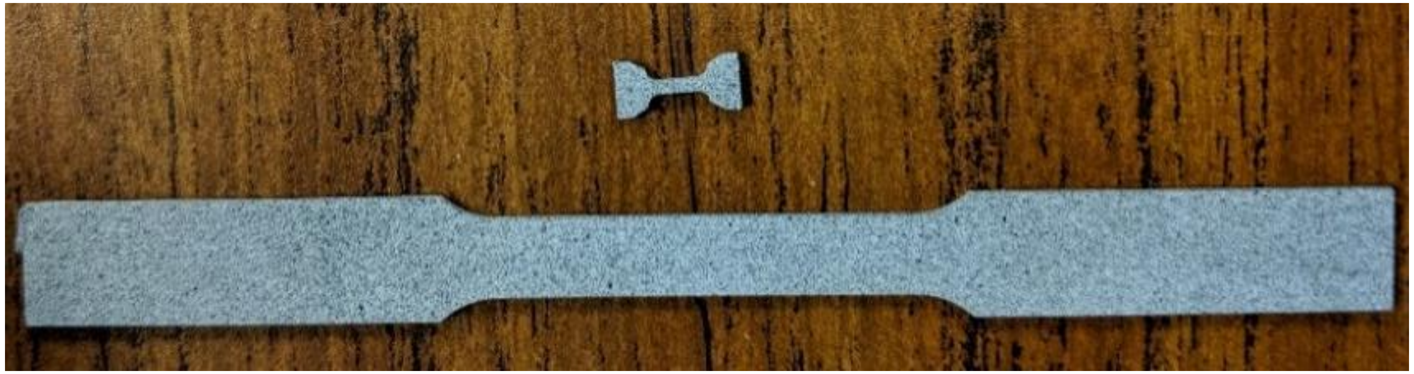




Successfully deployed for different irradiation testing campaigns:

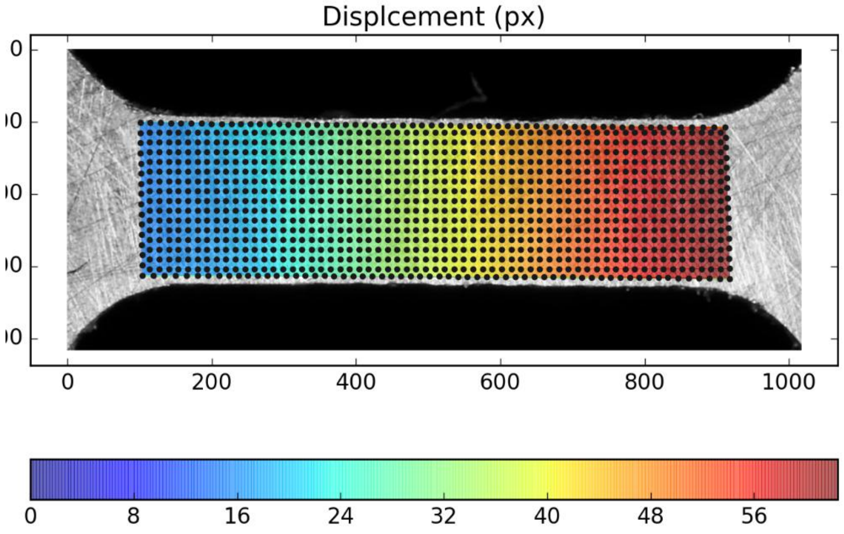
1) TTUSC
2) SAM-2
3) SAM-3
4) GENIE

Miniature tensile specimen



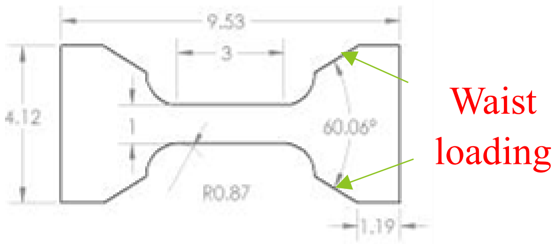
- Material characterization
- Chemistry variation
- Spatial variation
- Process variation
- Benchmarking
- DIC analysis

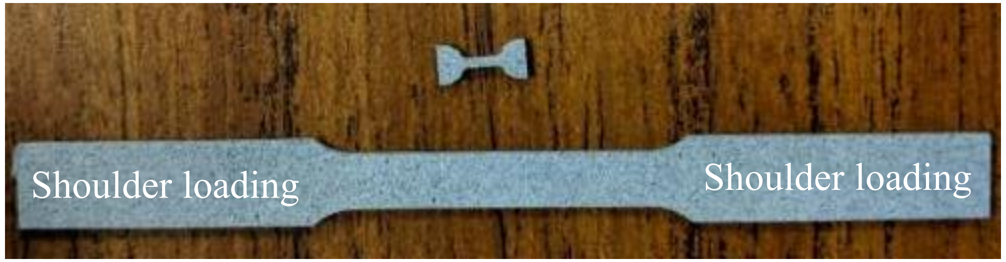
- ASTM sub-size "dog bone" specimen
  - 102 mm long with a gage length of 25.4 mm
- Miniature specimen
  - 9.65mm long with a three mm gage length

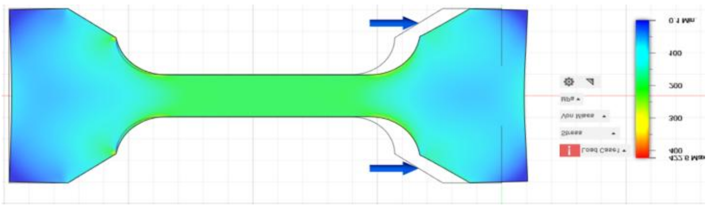


Considerations of specimen design

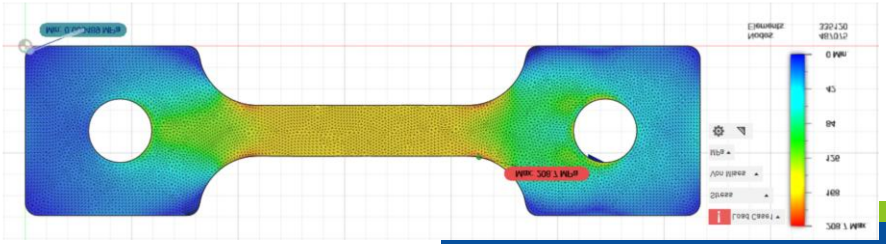
- What we call “waist loading” or “shoulder loading” to minimize complexity of miniature specimen
  - Minimizing manufacturing complexity for tough and/or brittle materials
  - Minimizing testing complexity due to the load applications without the need for clamping, pin loading and other loading mechanisms (i.e. easier for remote work in hot cell application)
  - Minimize stress concentrations





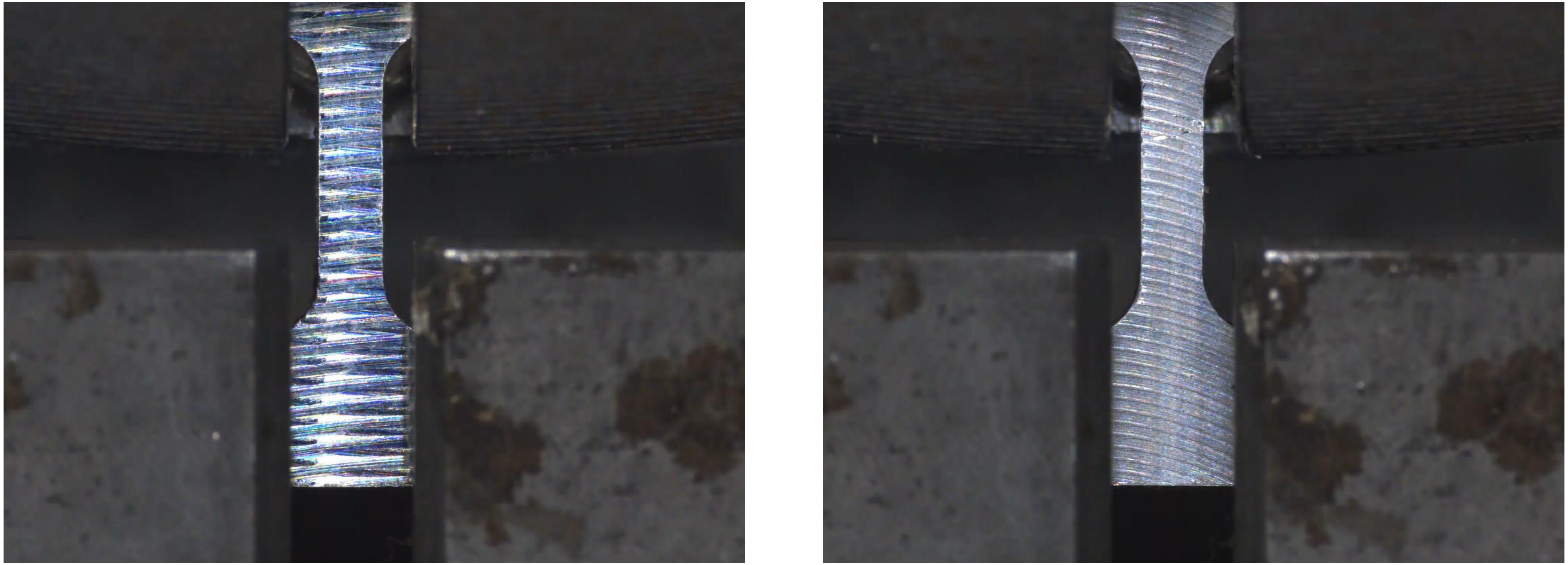


MT2



SSJ-3

Effects of manufacturing process



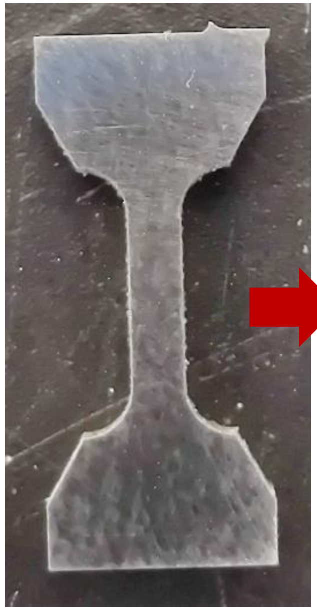
- CNC machining tends to work harden material
- Leading to zones that affect the neck formation and material elongation behavior

Specimen preparation

- Miniature specimen come with manufacturing and specimen preparation challenges
- EDM Manufacturing process chosen to minimize work hardening
- Lapping process included to remove scale, oxide layer and other artifacts like burr, formed during specimen manufacture

EDM specimen before polishing using 600 grit and 800 grit media. Average of 3 measured values for the dimensions

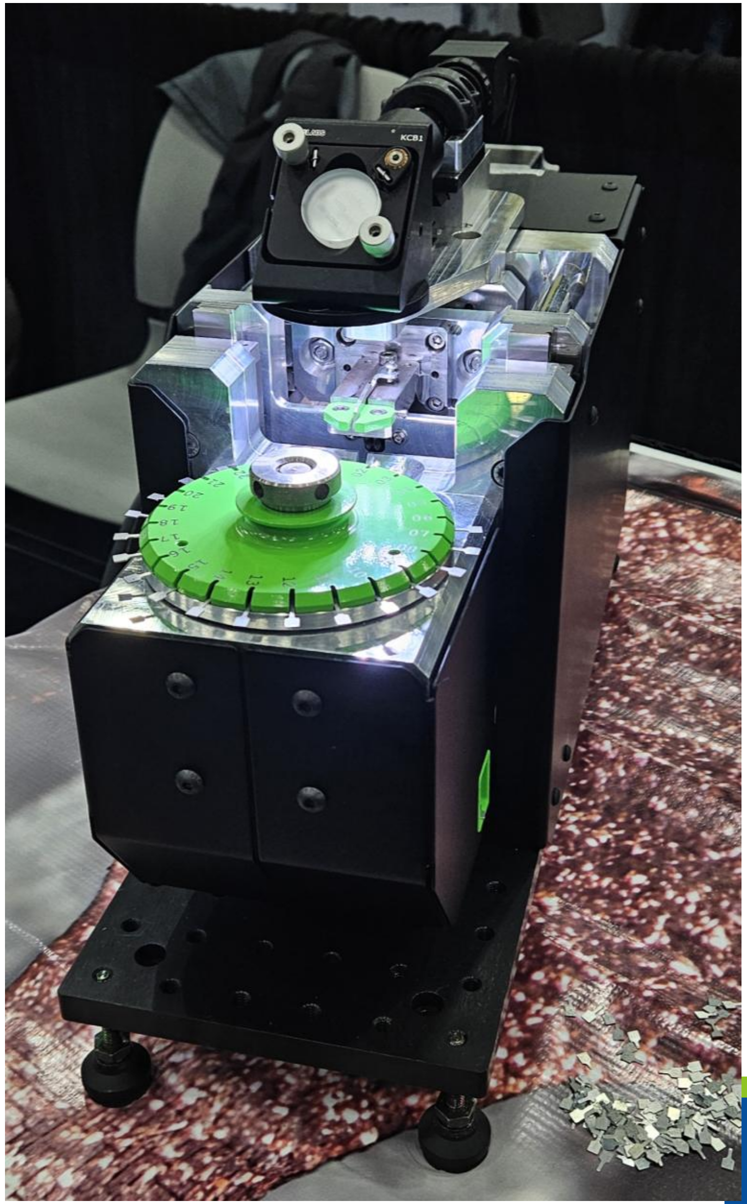
Length = 10.06 mm
Width = 0.91 mm
Thickness = 1.01 mm



EDM specimen after polishing using 600 grit and 800 grit media. Average of 3 measured values for the dimensions

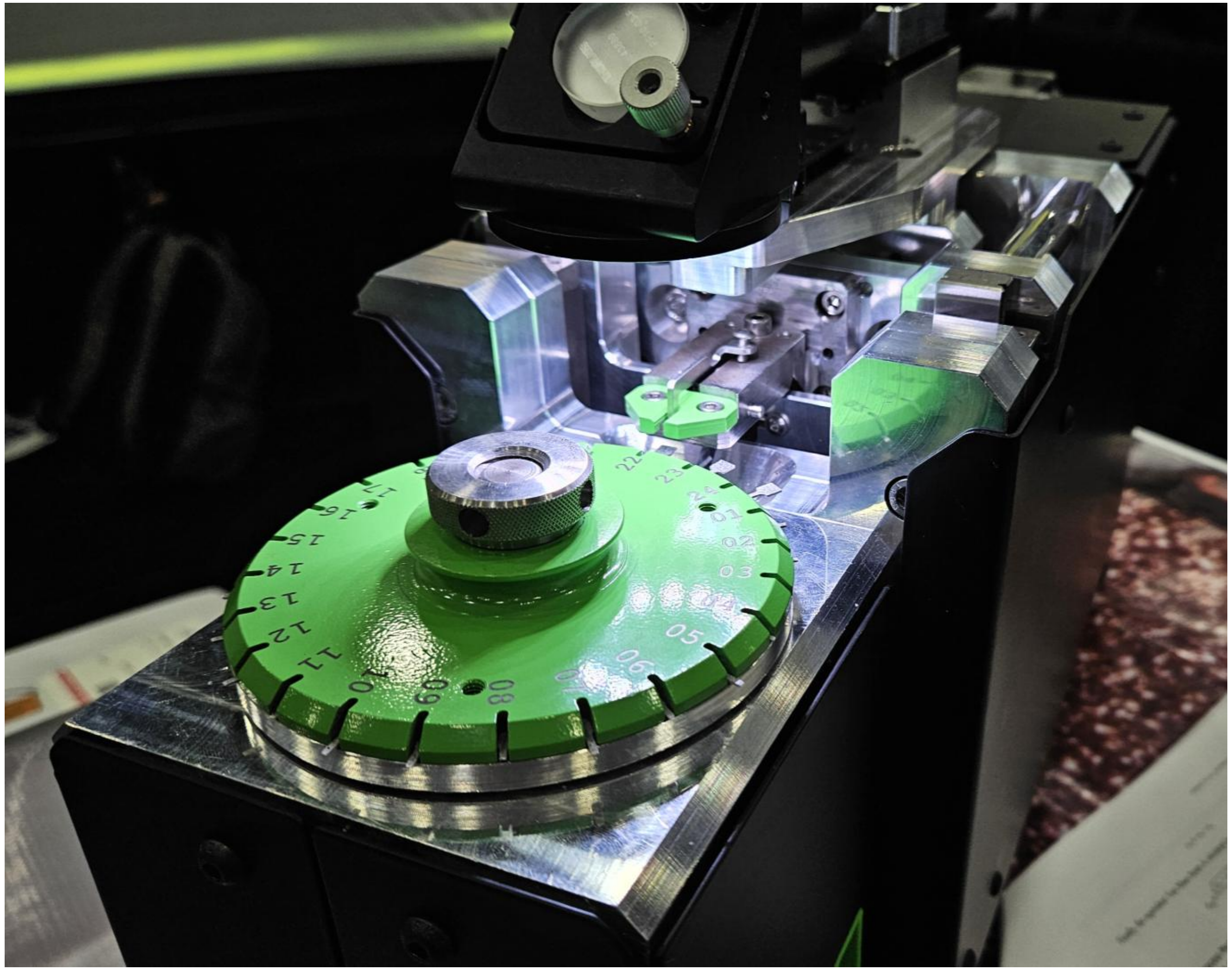
Length = 10.06 mm
Width = 0.91 mm
Thickness = 0.97 mm

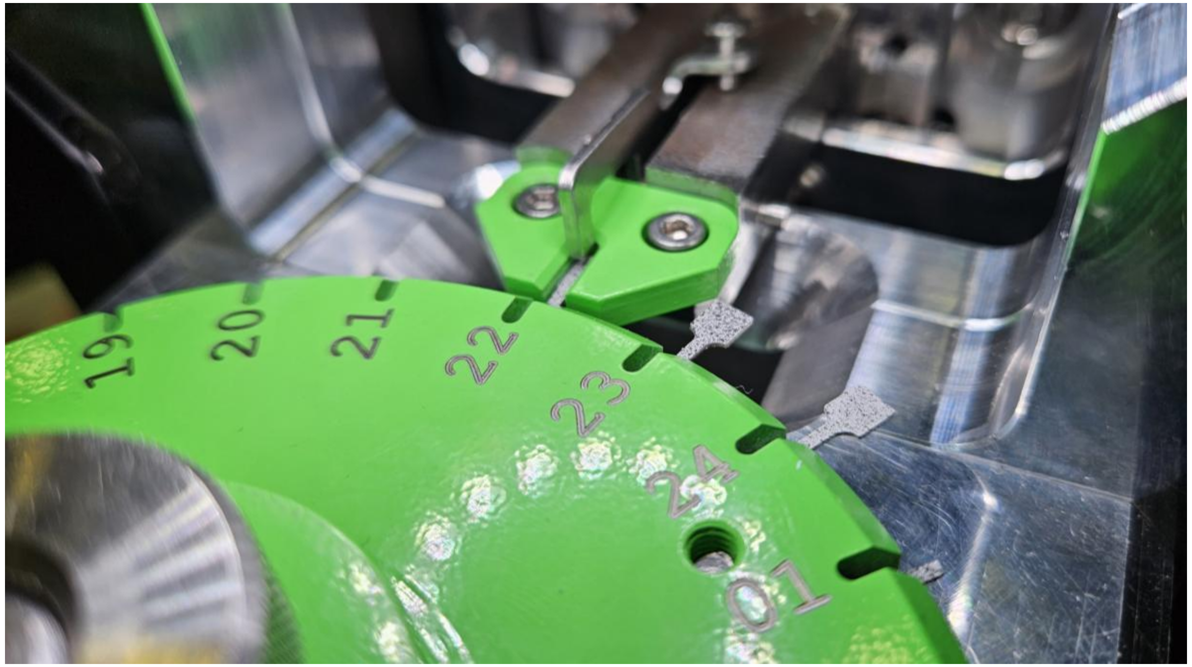
Advanced Mechanical Test System (AMTS), non-rad



- Cartridge design to house 24 specimen
- Rotational indexing to position specimen, apply preload, and test

Advanced Mechanical Test System (AMTS)





- Close ups of AMTS performing tests
- SSJ Specimen or other specimen geometry like MT2
- Speckle pattern applied

Data generated

PINE PRODUCT INNOVATION AND ENGINEERING

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Date: August 20, 2024
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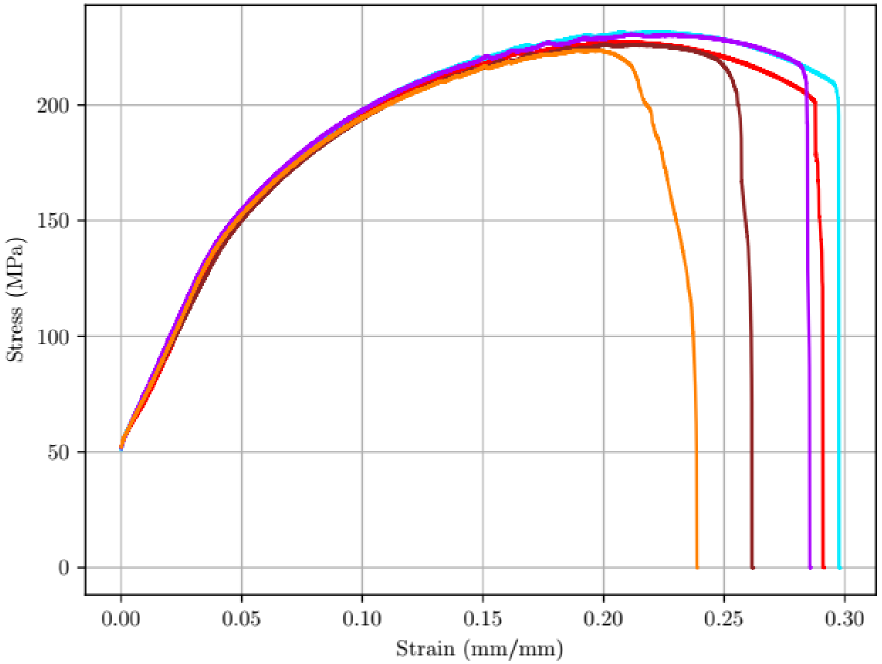
Tensile Test Report

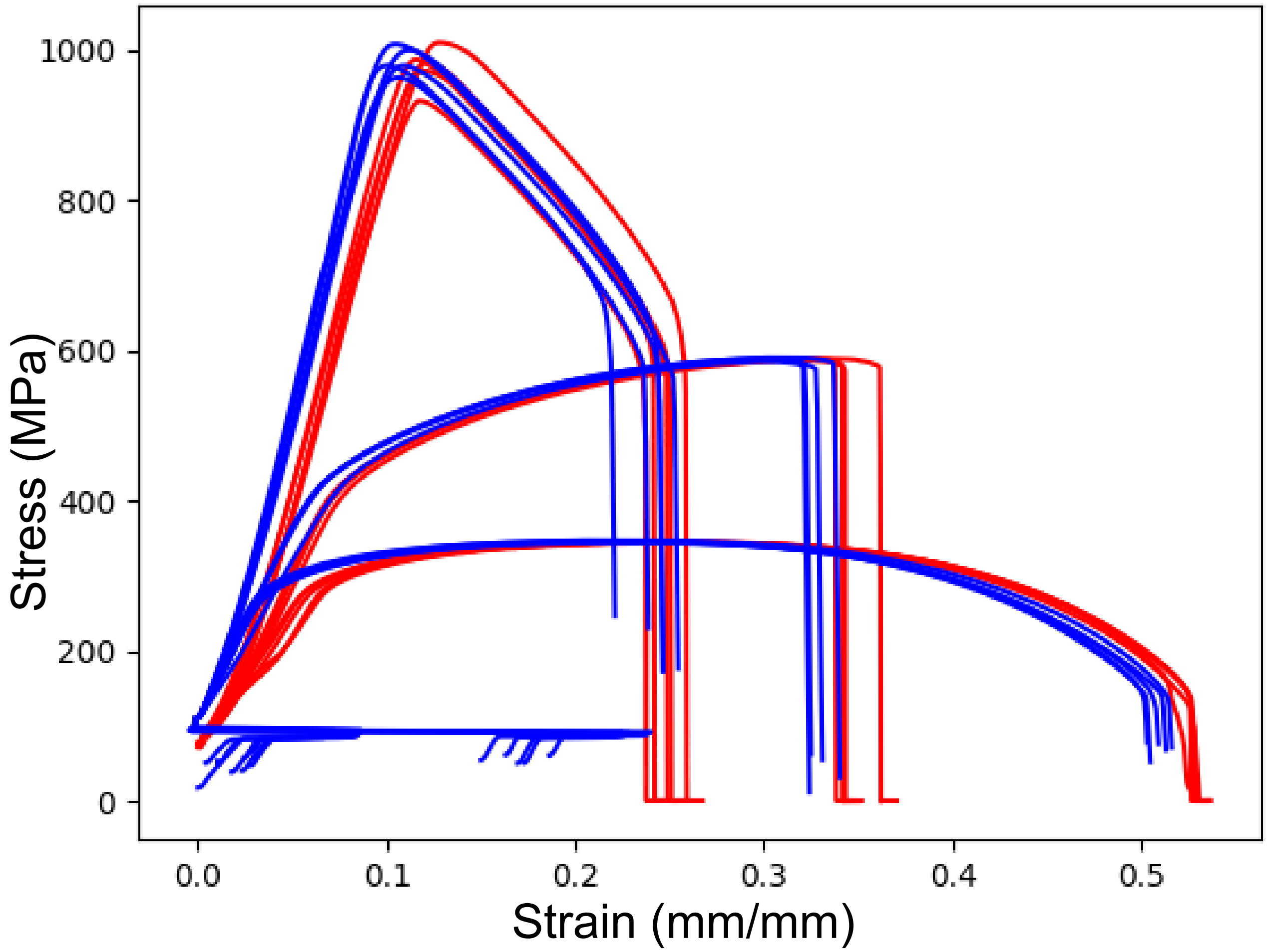


Sample Name	UTS (MPa)	0.2% YS (MPa)	Break Strain (mm/mm)
2E1	227.35	156.67	0.291
2E2	226.30	156.40	0.262
2E3	231.63	159.55	0.298
2E4	230.73	158.77	0.286
2E5	223.71	153.89	0.239

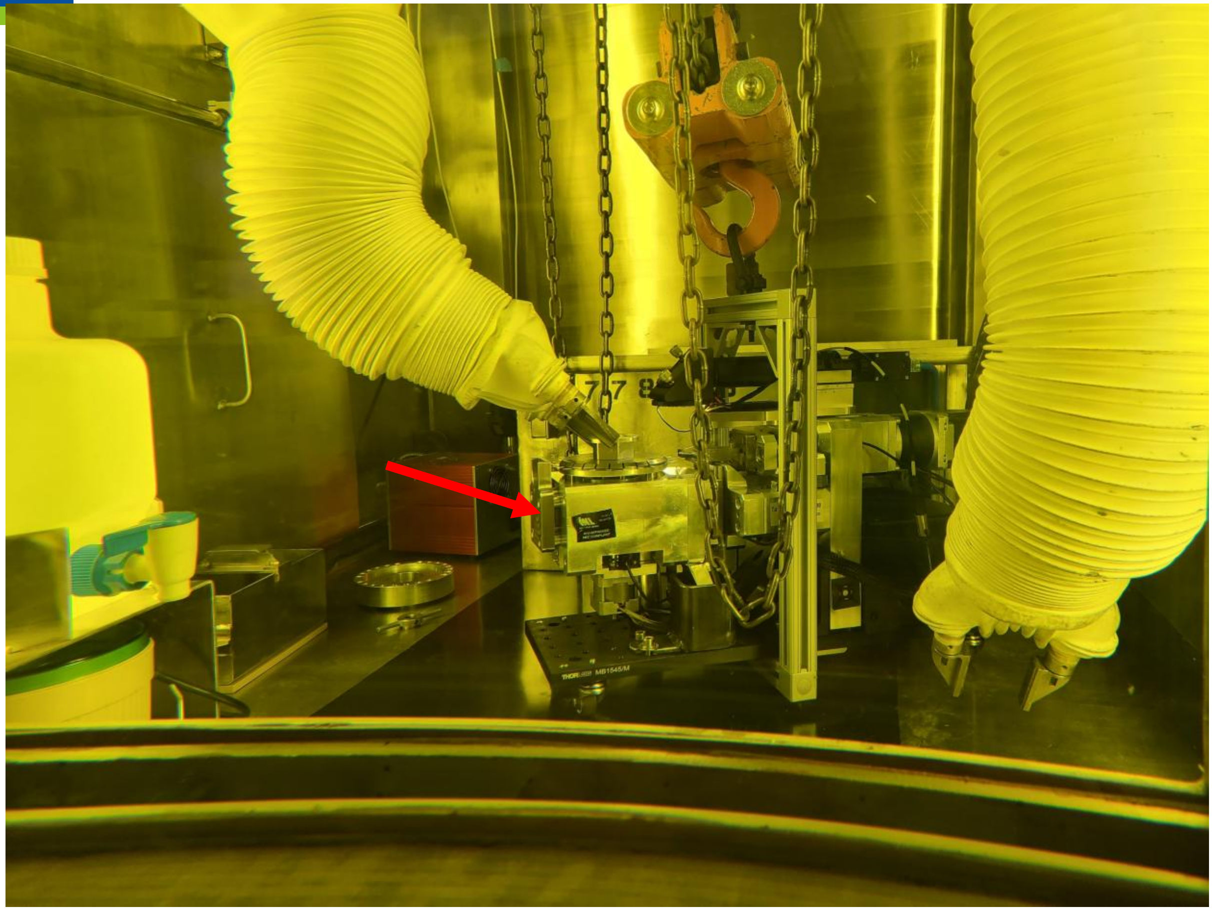
- Reports compiled for individual tests and groups with important metrics

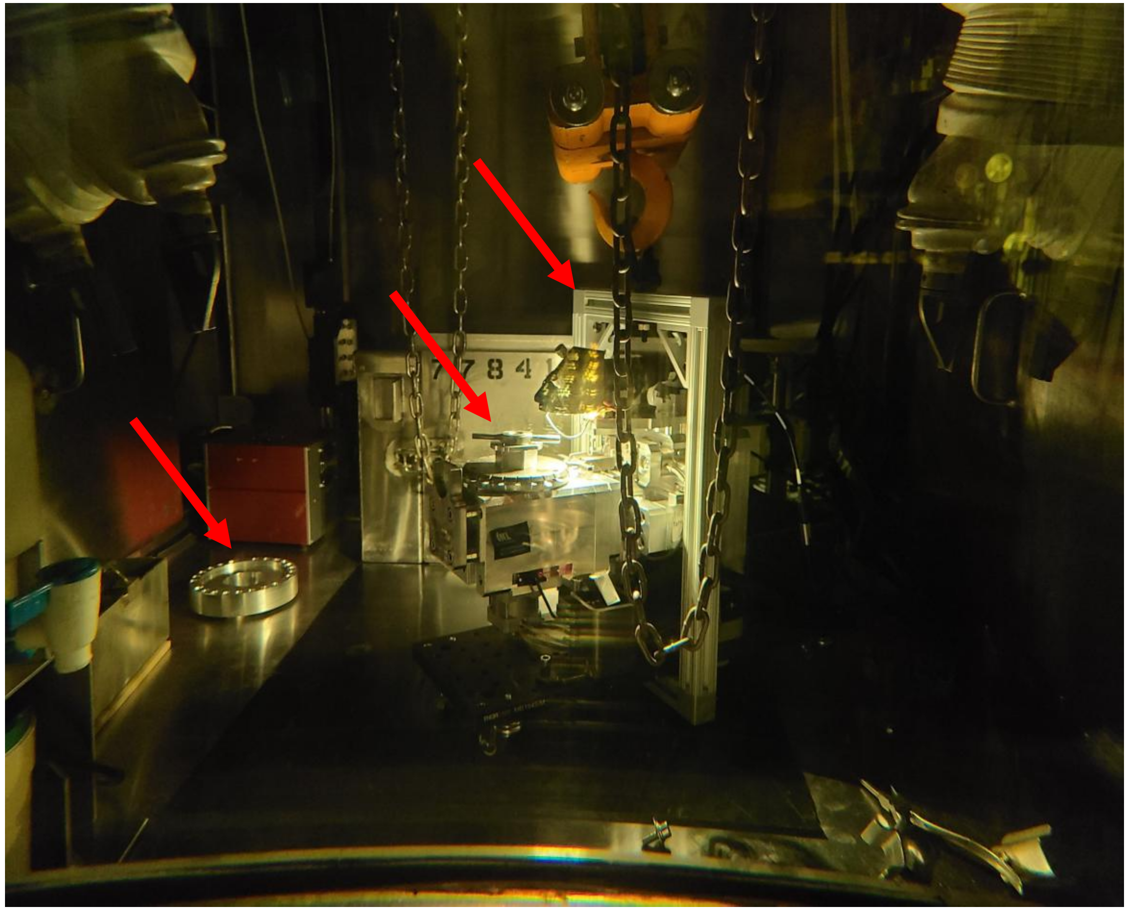
AMTS comparison with traditional test frames

- Comparative test between Tinius Olsen 25 kN frame and AMTS
- 3 materials
  - 17-4 PH steel
  - Al 7075-T6
  - C1008 steel
- 5 specimen per material each tested on the TO and the AMTS
- TO data in blue, AMTS data in red



AMTS for irradiated material, located at INL, in FASB Hot Cell

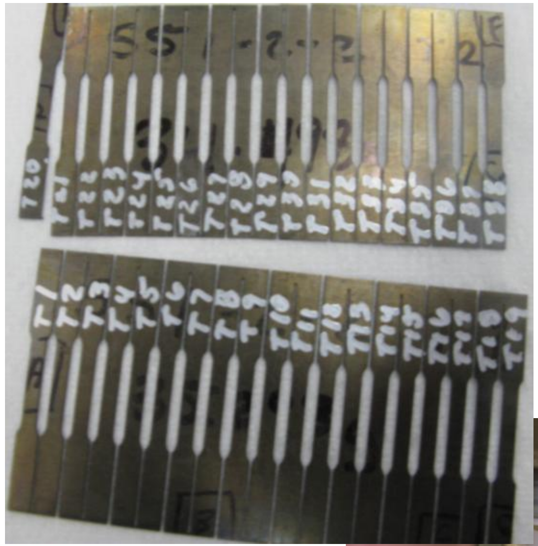


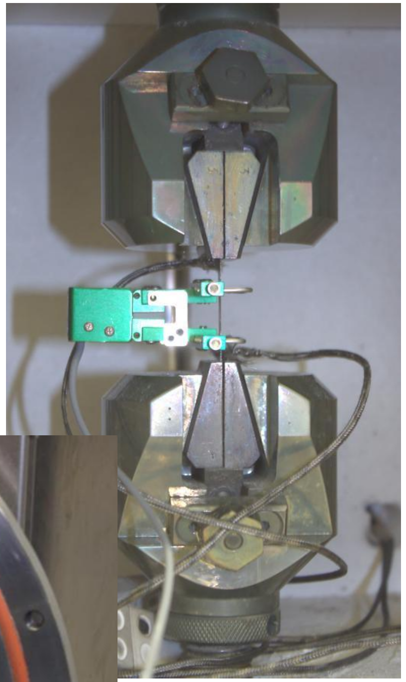


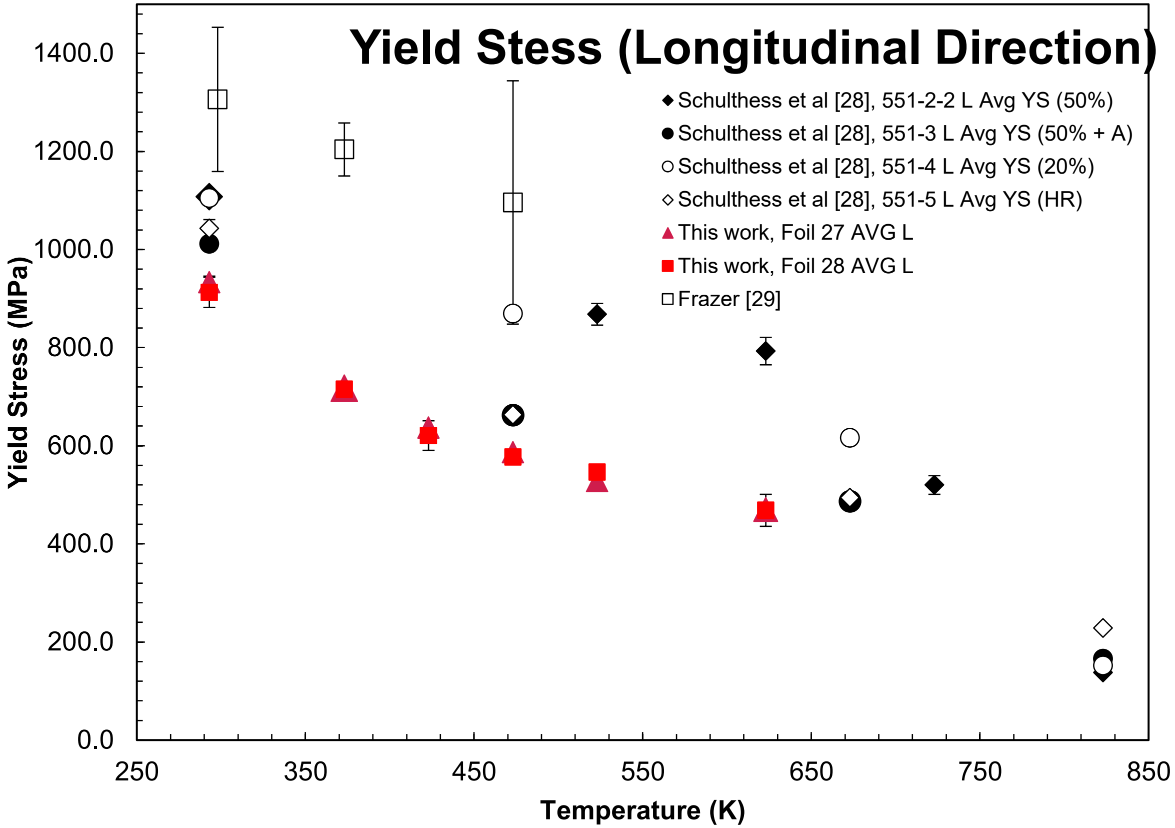
- Advanced mechanical test system installed in hot cell facility at INL, FASB
- Frame for lifting, Cartridge modifications for ease of loading
- Calibration fixture to periodically test and correct load cell

Mechanical Testing Nuclear Fuel

- Mechanical properties of nuclear fuel also important for understanding mechanical integrity, geometric integrity, and mechanical failure limits.
- Example of U-Mo alloy tensile tests on unirradiated material

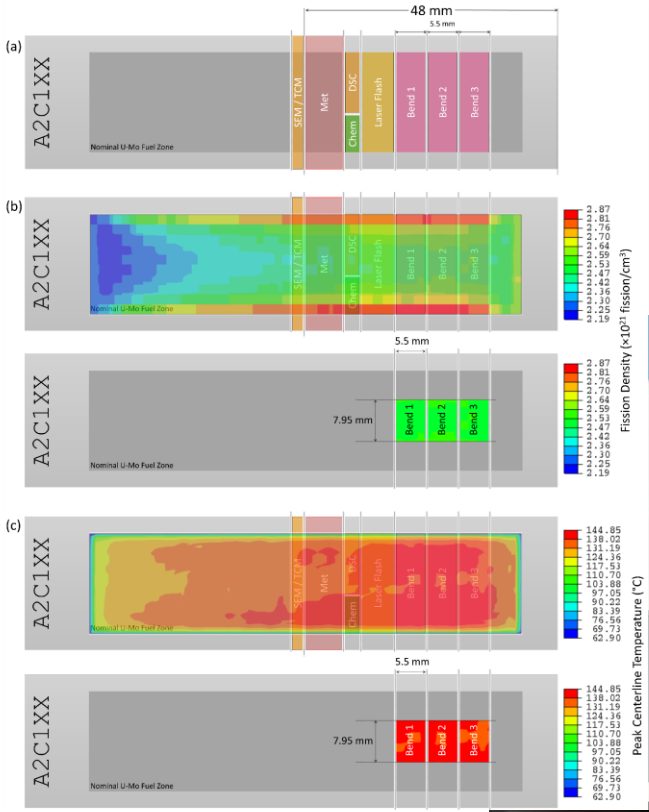


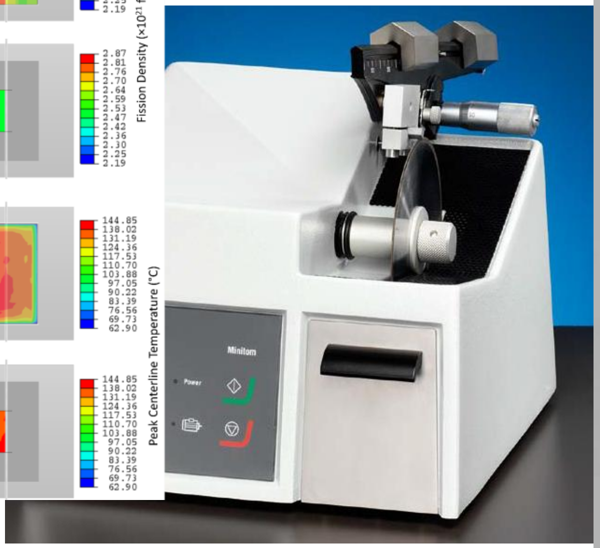


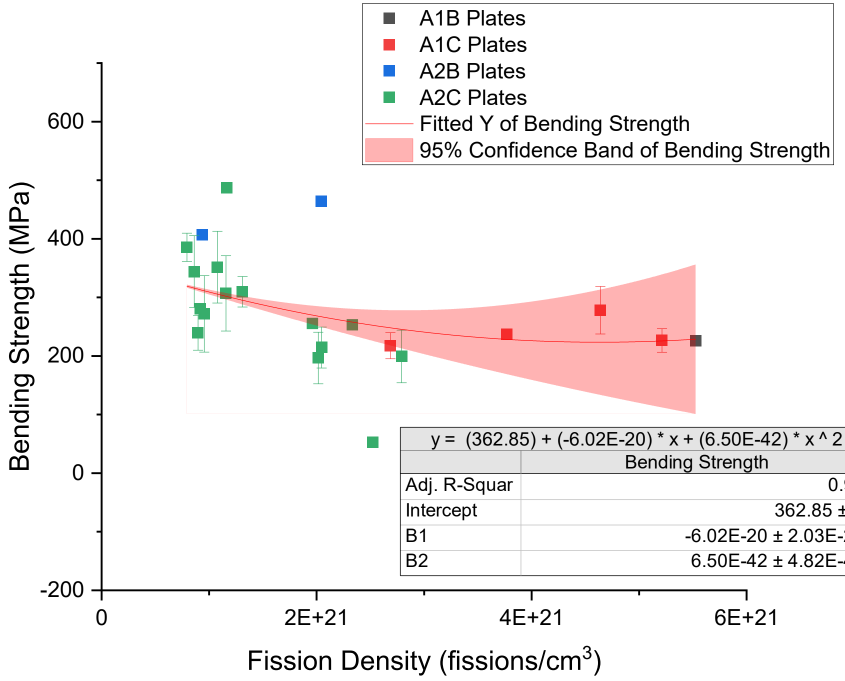


Mechanical Testing Nuclear Fuel

- 4-point bend testing irradiated U-Mo alloys
- Sample geometry (flat plates) and hot cell machining capability (no wire-EDM) means specimens are limited to rectangular geometries

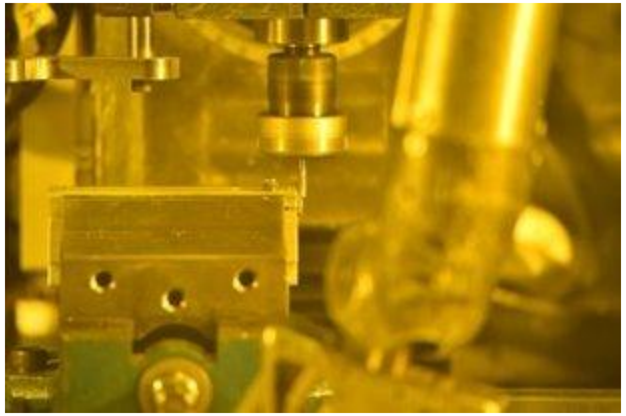


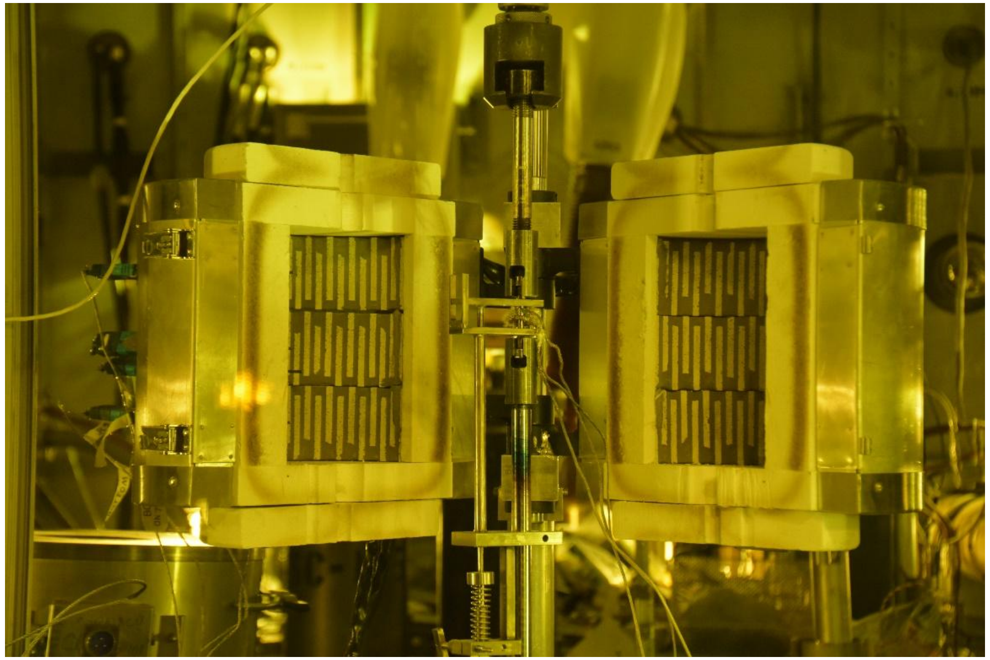




Mechanical Testing (HFEF)

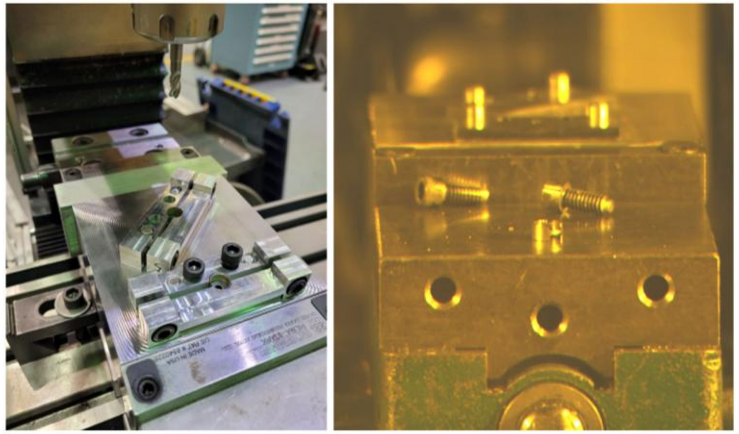
- Conventional mill used to machine test specimens
  - Customized machining jigs
- Twin column remote load frame
  - 50kN, customized for in-cell
- Clamshell furnace with pull rod feedthroughs
- Capable of many test methods and elevated temperature
  - SSJ, standard tensile, 4-pt bend, standard compression
  - Non-standard test methods possible, but require engineering effort and in-cell qualification



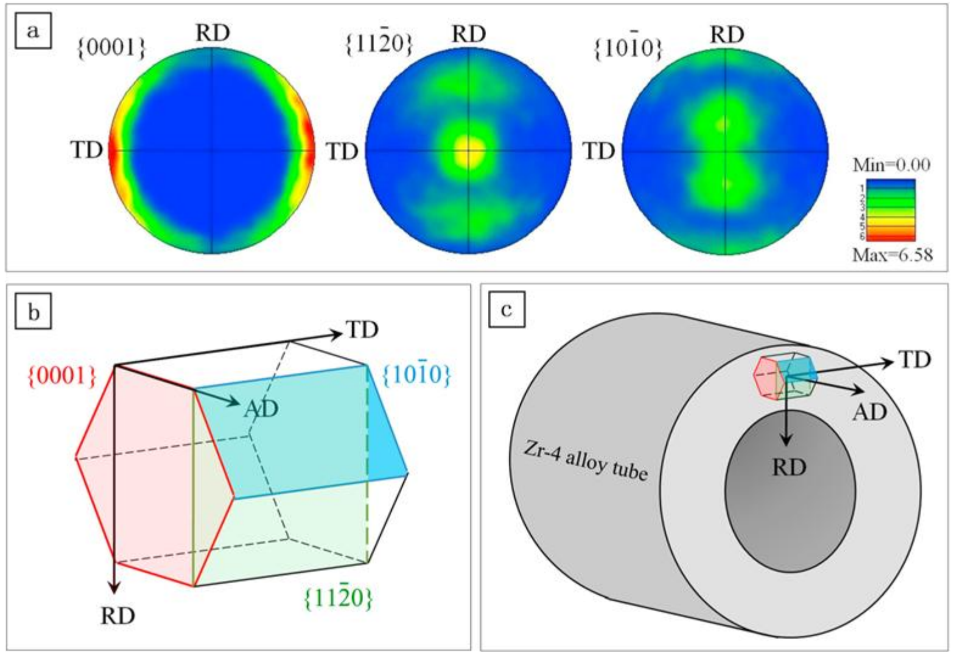


Mechanical Testing of Tube Geometries

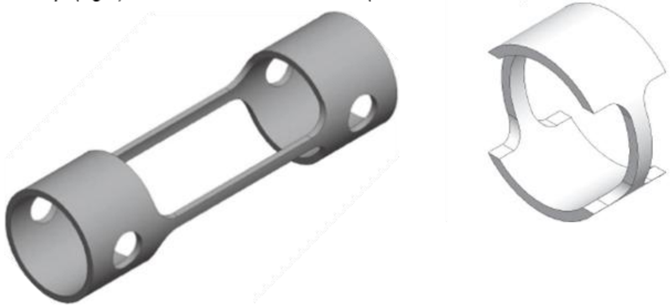
- Geometry of irradiation test samples often determines type of testing available
- Tube materials (like LWR or advanced reactor cladding) often must be irradiated in specific geometry
  - Anisotropy, coatings, oxide layers, etc.
  - No ASTM standard
  - Specimen availability limitations (maximize data)
- Ring tension, ring compression, axial tension
- Often requires machining of samples in cell
  - Can be expensive



Zircaloy-4 shows strong texture, with c {0001} axis parallel to hoop or transverse direction (Liu et al., Mat. Sci. and Eng.: A, 2018)



Axial (left) and hoop (right) mechanical tension tests (Kamerman et al., Nuc. Materials and Energy, 2022)

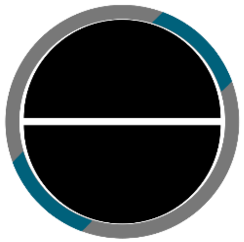


Irradiated Material testing

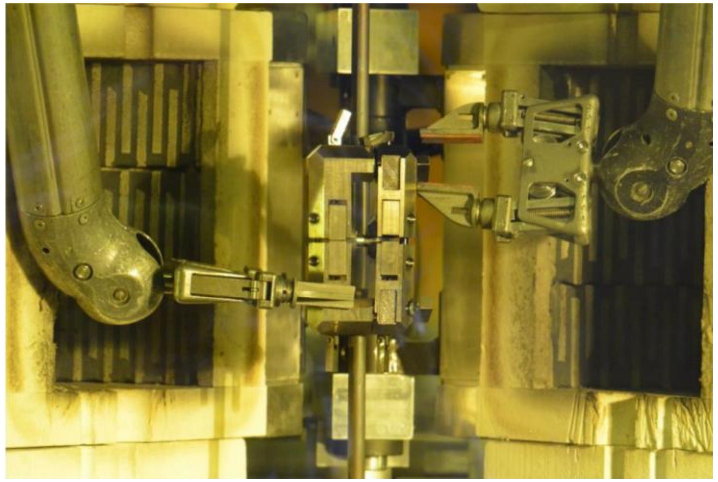
Two primary options at INL:

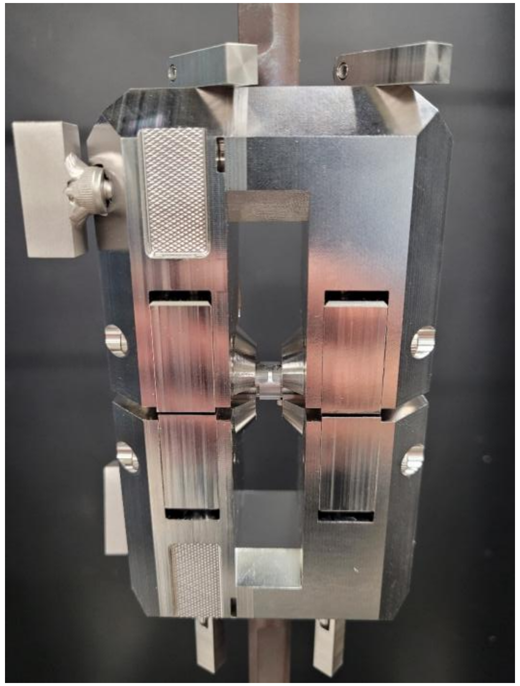
- Hot Fuels Examination Facility (HFEF)
  - 50kN electromechanical frame
  - α, β, and γ materials (irradiated fuels)
- Structural Properties Lab (SPL)
  - Hydraulic frame (100kN)
  - β and γ materials (no fuel)
- Remote operations with manipulators
- 4-foot-thick concrete walls, 4-foot-thick leaded glass windows
- Calibration verification of load cells, crosshead, and other instrumentation is challenging

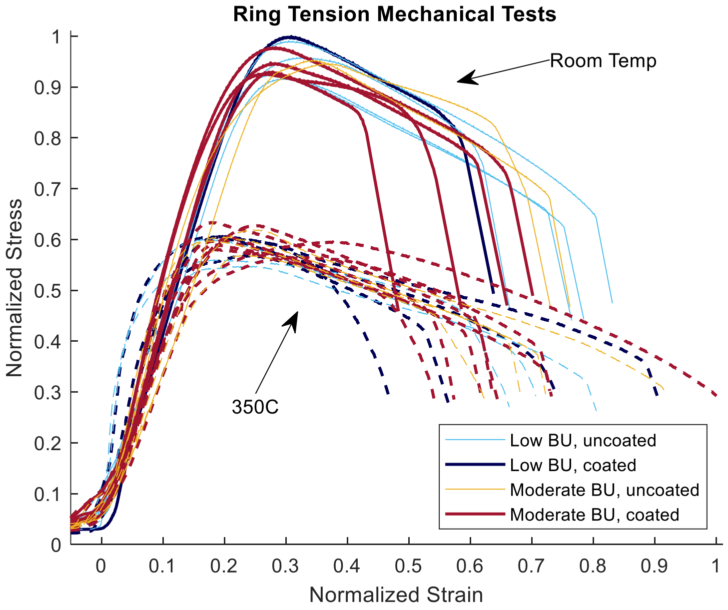
Ring Tension Test (RTT)

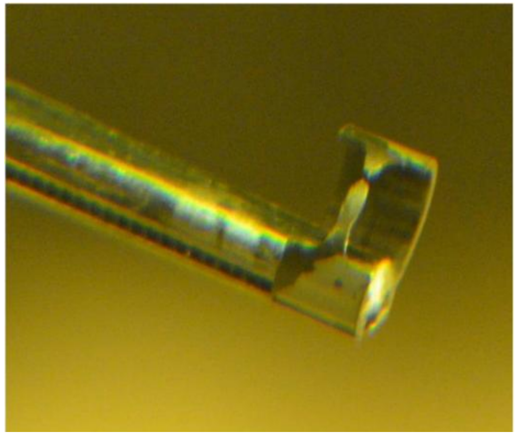


- Pull mandrels apart with universal testing machine
  - Places ring in hoop tension
- Custom grips with interchangeable mandrels[1]
- Correct for ring-mandrel friction[2]
- Can be performed up to 400ºC
- Several campaigns have been performed on irradiated commercial ATF cladding concepts in INL hot cells[3,4]







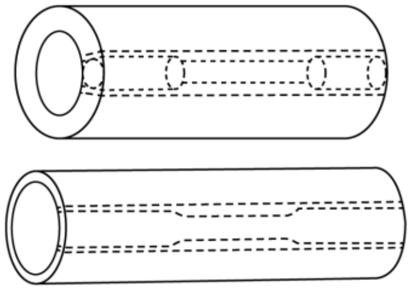


Schematic showing gauge and mandrels (upper left), custom grips in-cell (upper middle) and out of cell (upper right), tested ring in-cell (lower right), stress-strain curves from irradiated cladding at room and elevated temperature (lower left).

[1] Petersen et al., "Design and Evaluation of ring tension test grip…", *J. Testing and Evaluation*, 2024
[2] Hansen et al., "Friction Corrections to improve accuracy…", *Water Reactor Fuel Perf. Mtg.*, 2023
[3] Hansen et al., "Examinations of Cr-Coated M5Framatome Cladding…", *TopFuel*, 2024
[4] Hansen et al., "Integral Irradiations and Post-Irradiation Examinations…", *IAEA TM on ATF*, 2025

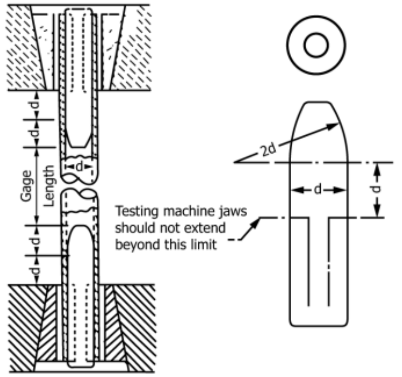
Axial Tension Test – Motivation

- Tubular materials with microstructural anisotropy
  - e.g. Zirconium alloy nuclear cladding (HCP)
  - Requires axial, hoop direction tests
- Axial Tension Test (ATT)
  - Maximize # of tests, limited material
  - Leverage existing infrastructure (load capacity)
  - Unique geometry, irradiated material constraints prevent use of ASTM E8
- Investigate ATT configurations
  - a) Aligned pin loading (original)
  - b) Offset pin loading
  - c) Collet loading
- Compliance outside gauge an issue



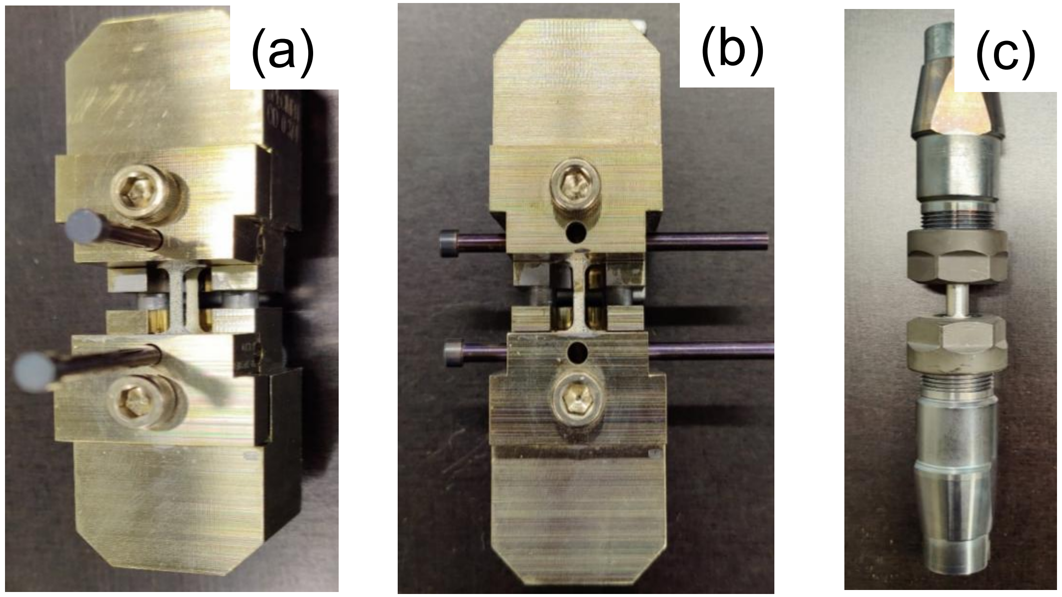
NOTE 1—The edges of the blank for the specimen shall be cut parallel to each other.

FIG. 13 Location from Which Longitudinal Tension Test Specimens Are to be Cut from Large-Diameter Tube



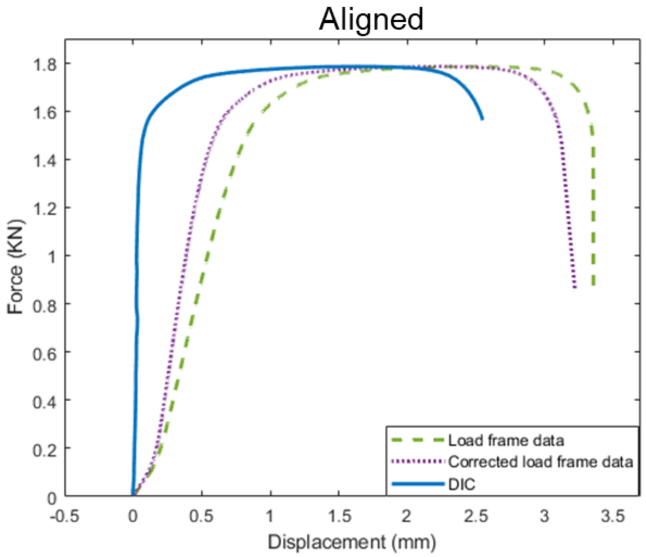
NOTE 1—The diameter of the plug shall have a slight taper from the line limiting the test machine jaws to the curved section.

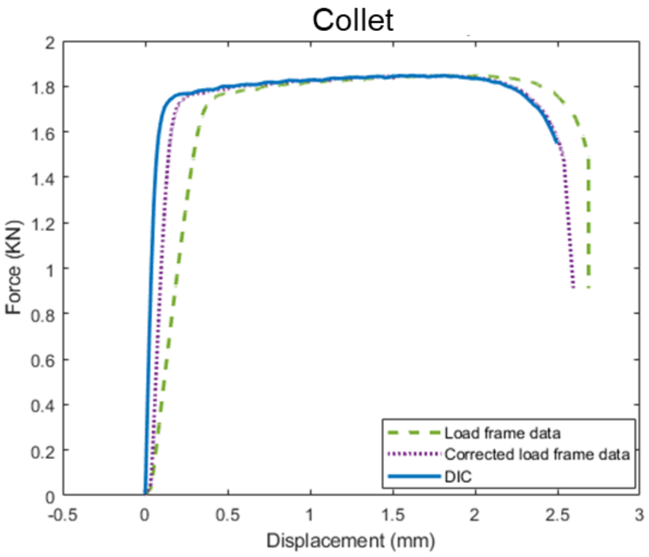
FIG. 12 Metal Plugs for Testing Tubular Specimens, Proper Location of Plugs in Specimen and of Specimen in Heads of Testing Machine



ATT – Configurations

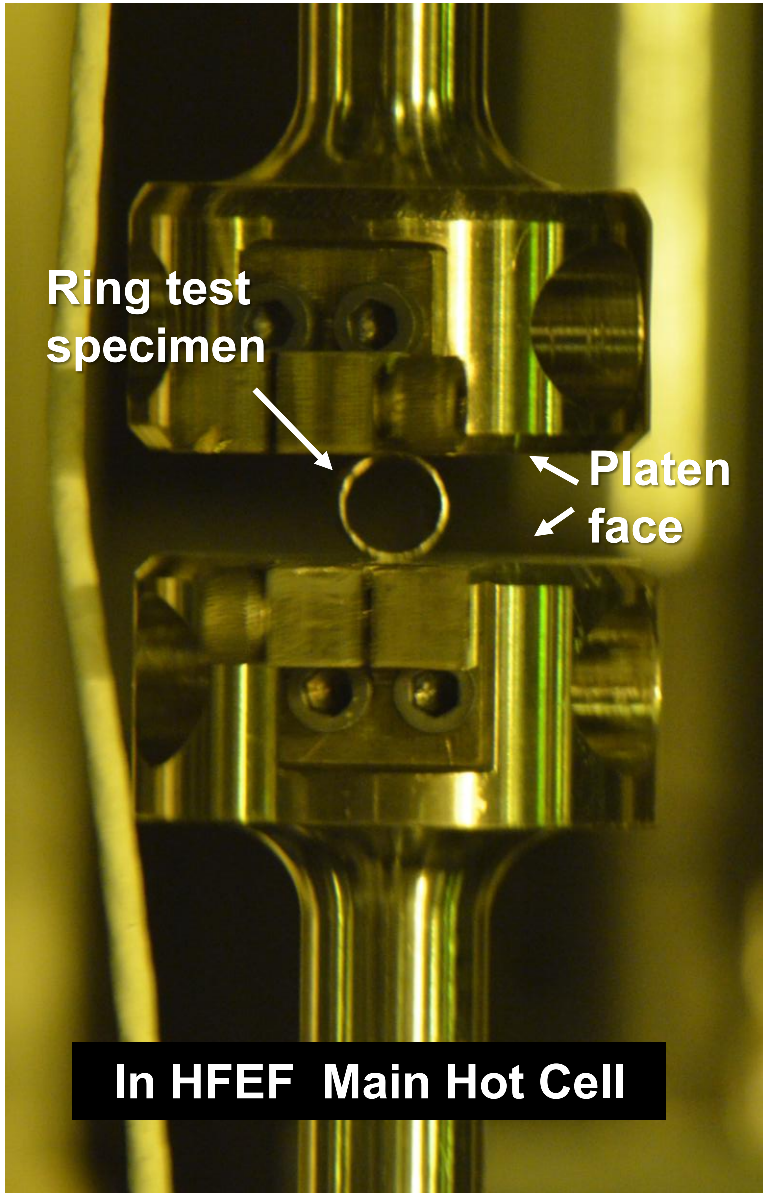
- Aligned pin loading
  - Initial design
  - Prone to elongation in hole post-test
  - Potential stress concentration with gauge?
- Offset pin loading
  - Rotated hole position 90°
  - Reduce stress concentration
  - Potential bending in shoulders
- Collet loading
  - Avoid deformation in hole
  - Potential challenge for gripping
  - Sharp teeth machined into collet ID
  - Performed the best (greatly reduced compliance)





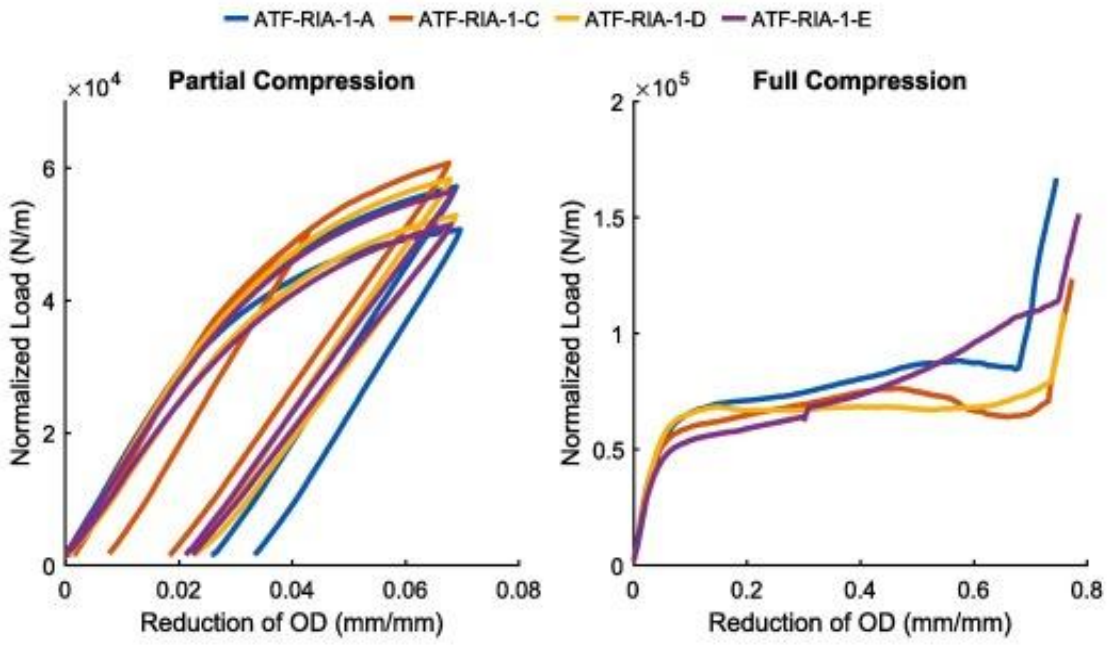
Ring Compression Testing

- Simple compression, using a ring specimen
- Often used for post-transient ductility
- Room and elevated temp
- Example: Post-TREAT testing for ductility



Partial compression for yielding, limited retained ductility

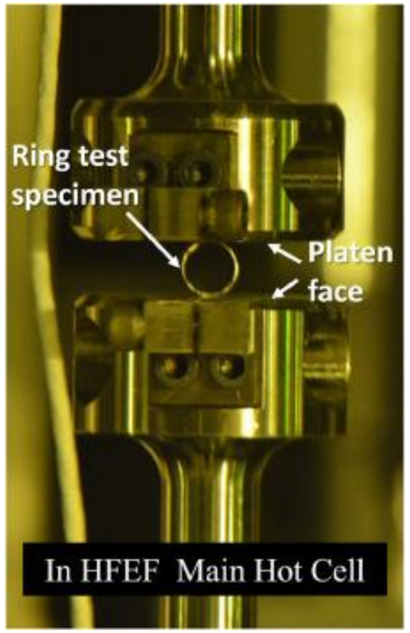
Full compression for cracking, ductility assessment



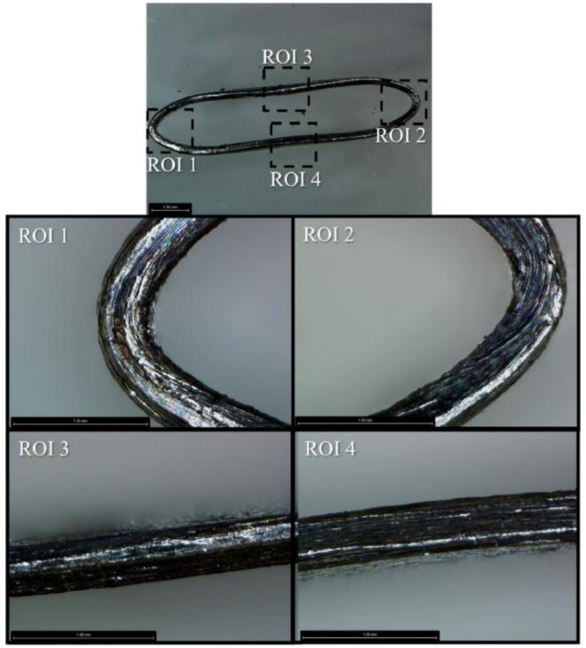
Folsom et al, *Nuc. Eng. Design*, 2023 https://doi.org/10.1016/j.nucengdes.2023.112509

Ring Compression Testing (RCT)

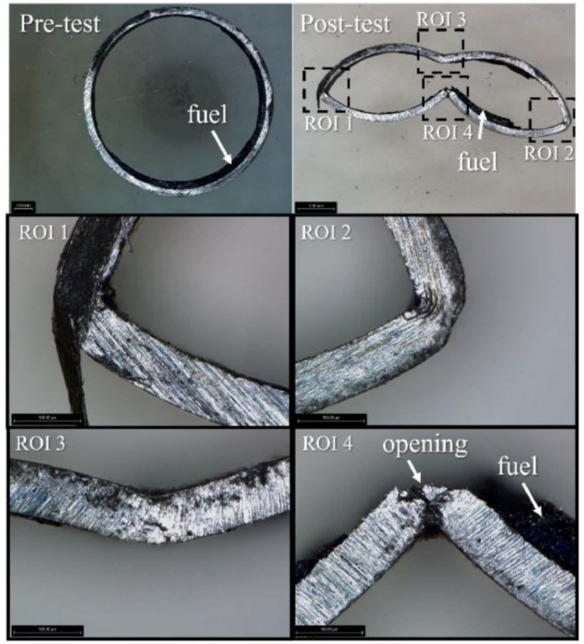
- Useful for assessing ductility, but challenging to extract traditional material properties
  - NUREG/CR-7139
- Performed in-cell at room and elevated temperatures
  - Irradiated FeCrAl cladding concept[1]
  - Assess DBTT behavior
  - Compare unirradiated with irradiated

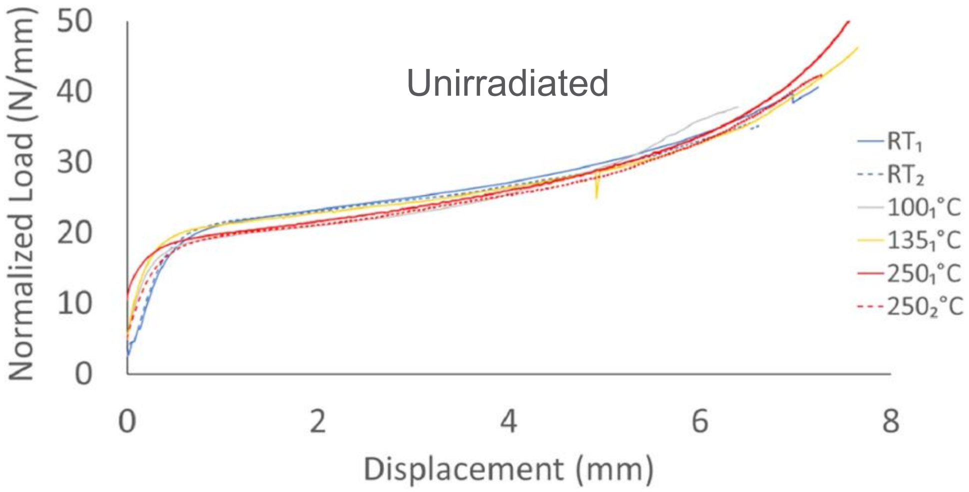


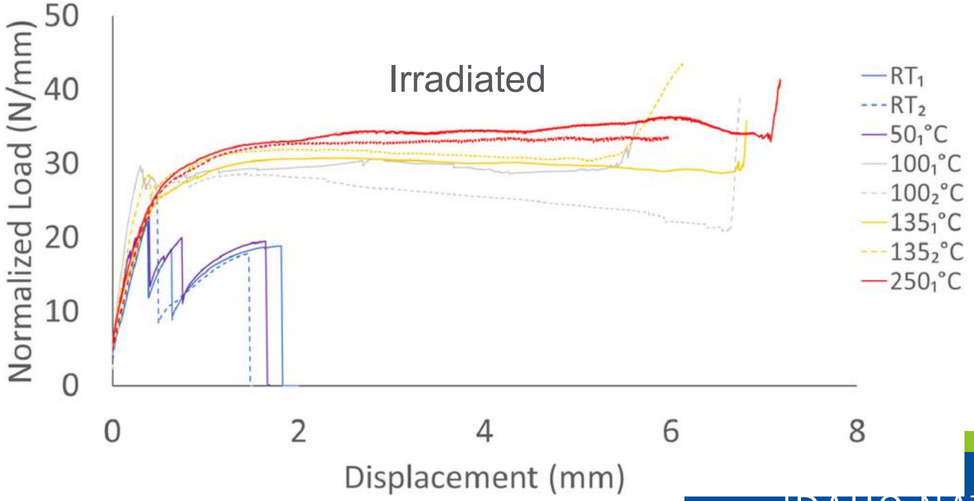
Unirradiated, Room Temp



Irradiated, 135ºC



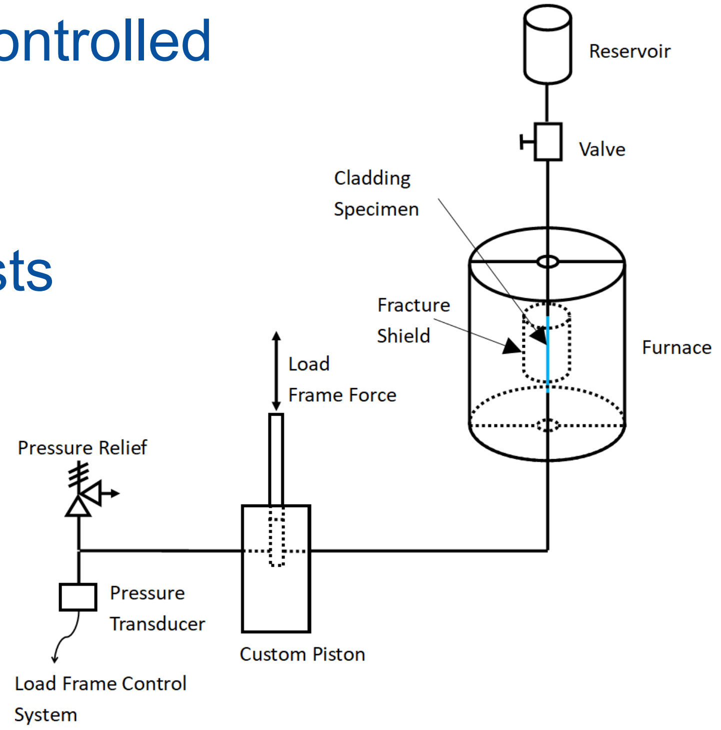




All images and plots from [1] Colldeweih et al., "Post-Irradiation Examinations of FeCrAl cladding in PWR conditions", *JNM*, 2025

Hydraulic Burst Test

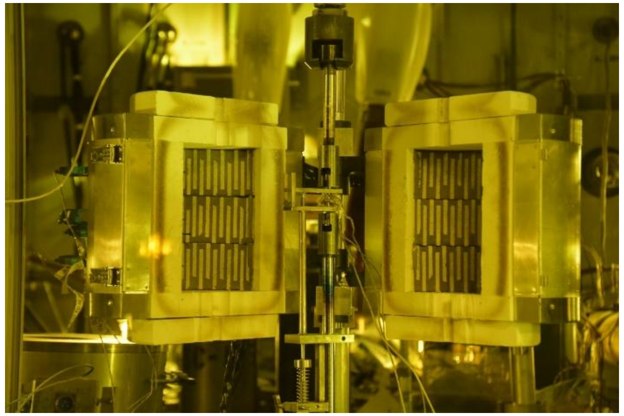
- Currently developed for out-of-cell use, intending to install in-cell within the next year
- Goal: achieve displacement- or pressure-controlled internal pressurization tests
- Offers biaxial stress states
  - Complementary to previous uniaxial tests
  - Prototypic loading conditions
  - Understand isotropic effects
- Hydraulic fluid instead of pneumatic
  - More challenging to implement
  - Improved safety
  - Integration with load frame in cell
- Need for room and elevated temperature capability



Burst Test System Description

- High pressure testing (up to 20ksi)
- Reconfigurable for different specimen types
  - Various diameters, metallic and SiC composite cladding materials
- Custom piston to convert load frame force to hydraulic pressure
- In-line pressure transducer
  - Measurement and control
- Paired with DIC (windowed fracture shield)
- Compatible with multiple working fluids
  - Room temperature: water
  - Elevated temperature: Galinstan (liquid metal)

Assembled system

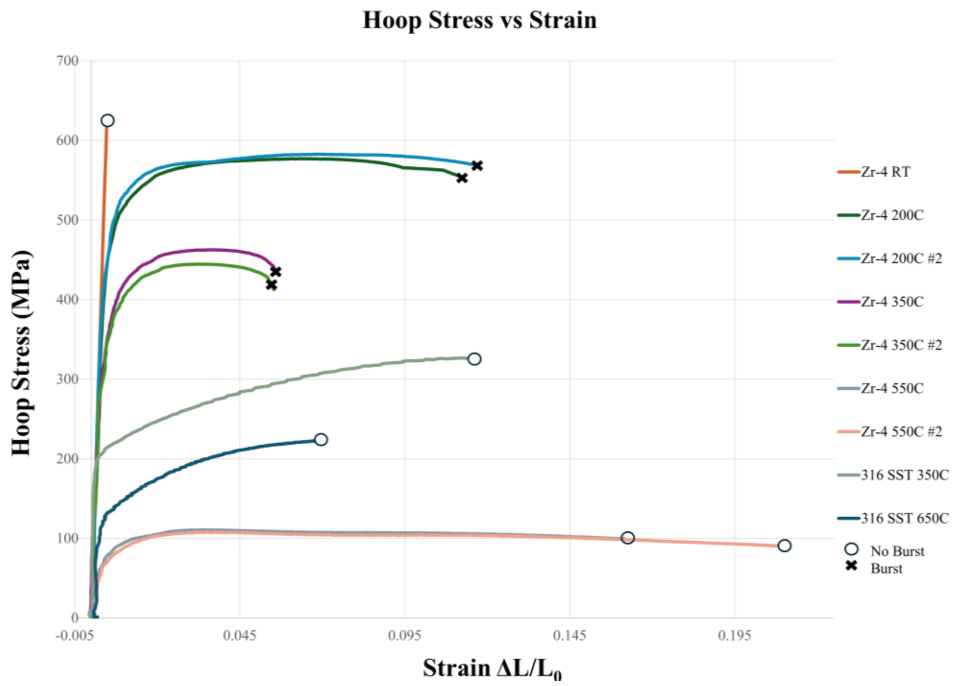


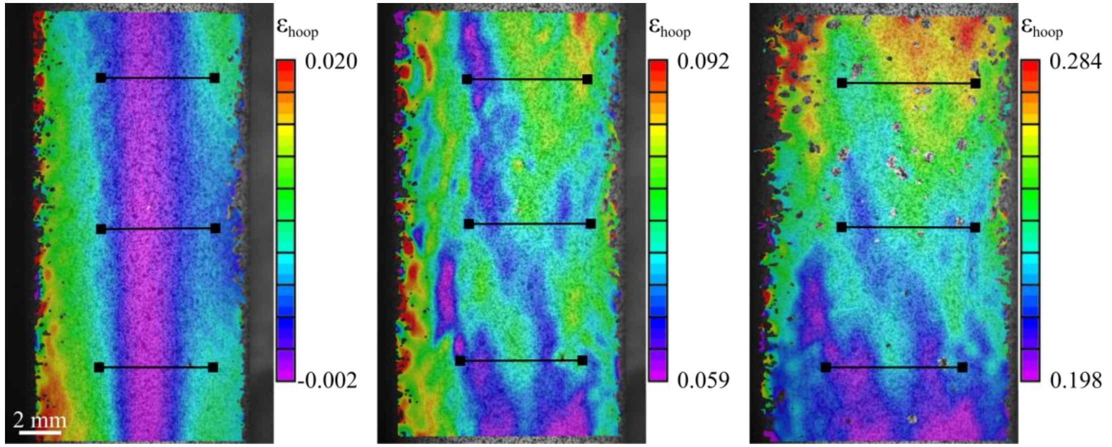
Load frame and furnace in hot cell

Tested specimens, featuring Swagelok fittings

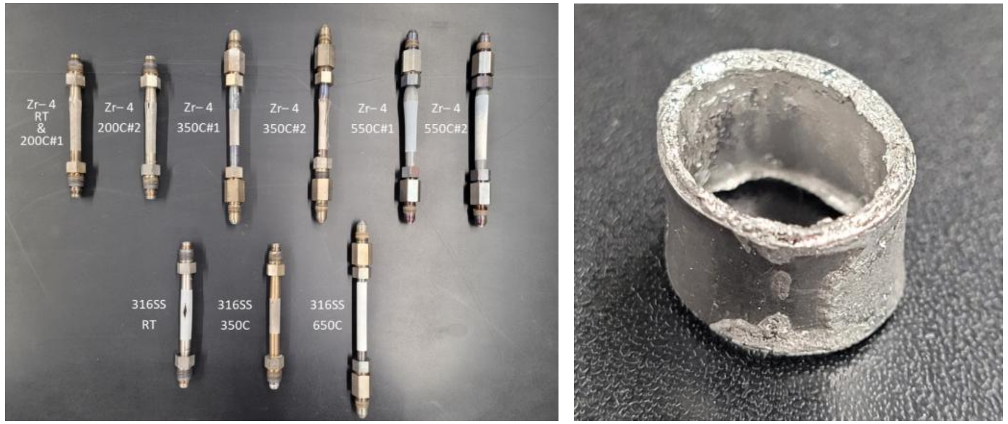
DIC tests at temperature out-of-cell

- Zircaloy-4 and 316 stainless steel burst tests
  - Range from room temperature to 650ºC
  - Galinstan working fluid (liquid at room temperature)
  - 1.5 mm/min crosshead (0.184 cc/min volume)
  - Some did not burst prior to hitting load cell limit
- DIC, virtual extensometers
  - Average of 3 axial locations
  - Cylindrical transformation
  - Will underpredict post-ballooning (balloon above ROI)
- Zircaloy-4 corrodes above 550°C





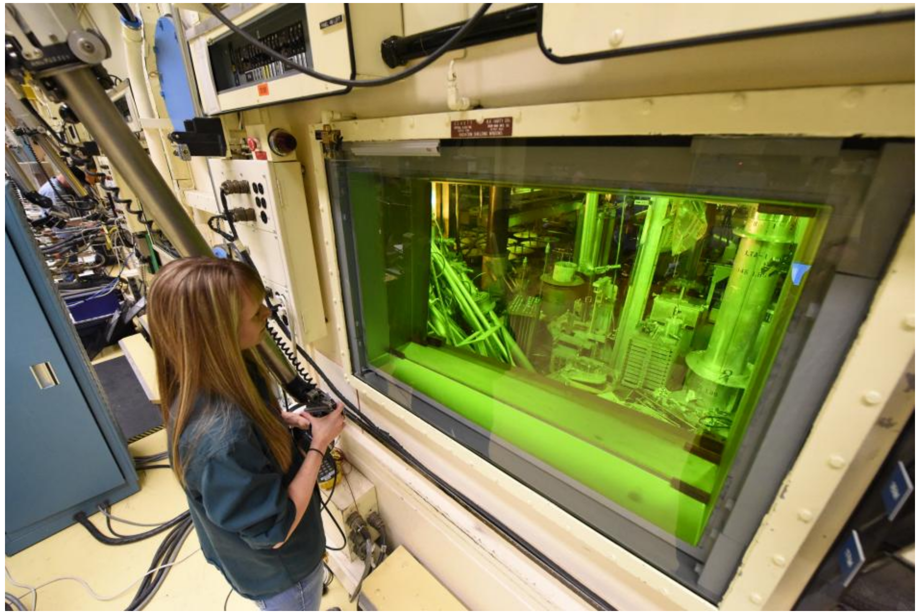
Hoop strain contour plots with virtual extensometers at beginning, middle, and end of test, Zr-4 @ 550°C

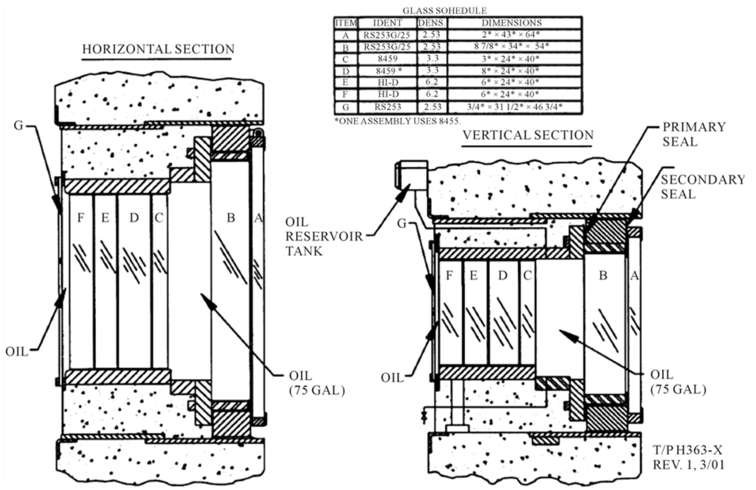


Failed specimens (left), 5mm axial section of zircaloy-4 after 2 hrs in Galinstan at 650°C (right)

Through-Window DIC for Hot Cells

- Several mechanical testing methods have been covered
  - In-cell, no DIC (room and elevated temp)
  - Out-of-cell, with DIC (room and elevated temp)
- How can we add DIC as a hot cell capability?
  - Low-dose situations allow some DIC, but not fueled
- Cameras in-cell:
  - Expensive (consumable equipment), degradation concerns, limited adjustability, data feedthroughs
- Cameras out-of-cell (through-window):
  - Refraction, dispersion, resolution/working distance
- Promising results for through-window; demonstrated at SPL and planned for implementation at HFEF





C. W. Solbrig and S. A. Warmann, “Thermal Stress in HFEF Hot Cell Windows Due to an In-Cell Metal Fire,” *World Journal of Nuclear Science and Technology*, 2016