Remote Manipulation Residual Stress Measurement System for Extreme Environments

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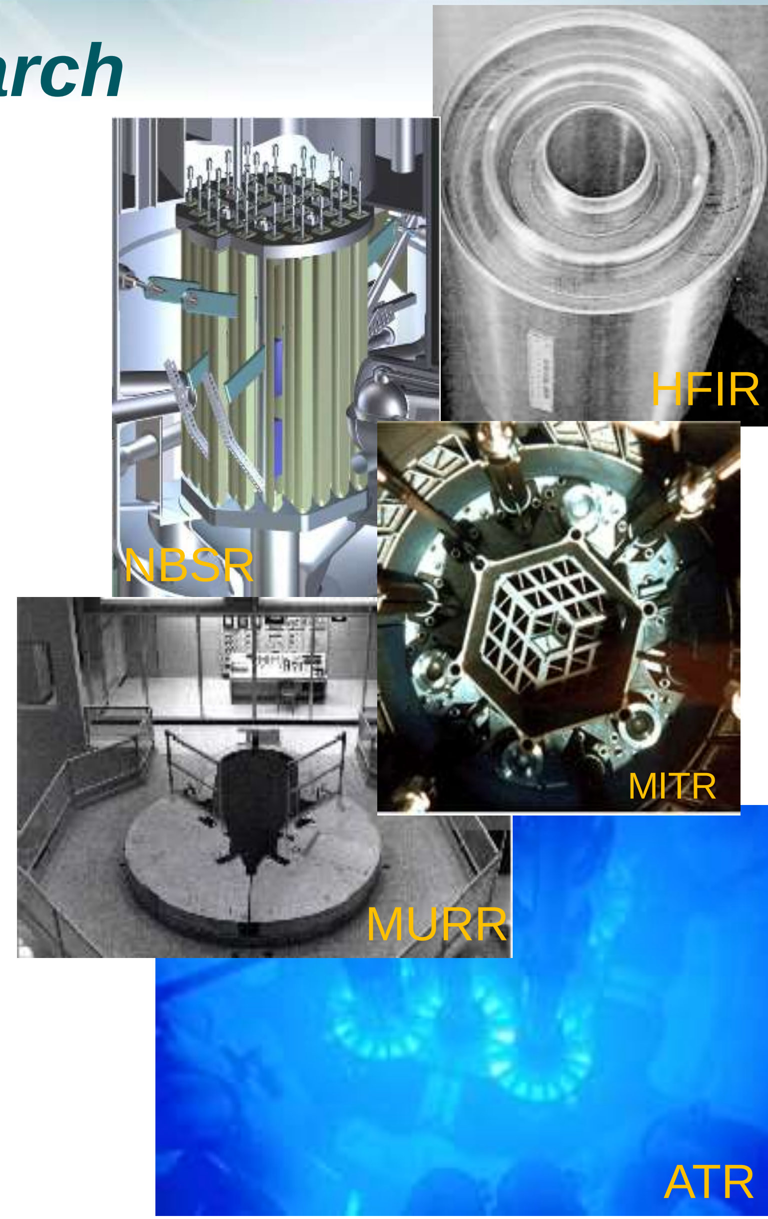
INL Idaho National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

NNSA National Nuclear Security Administration

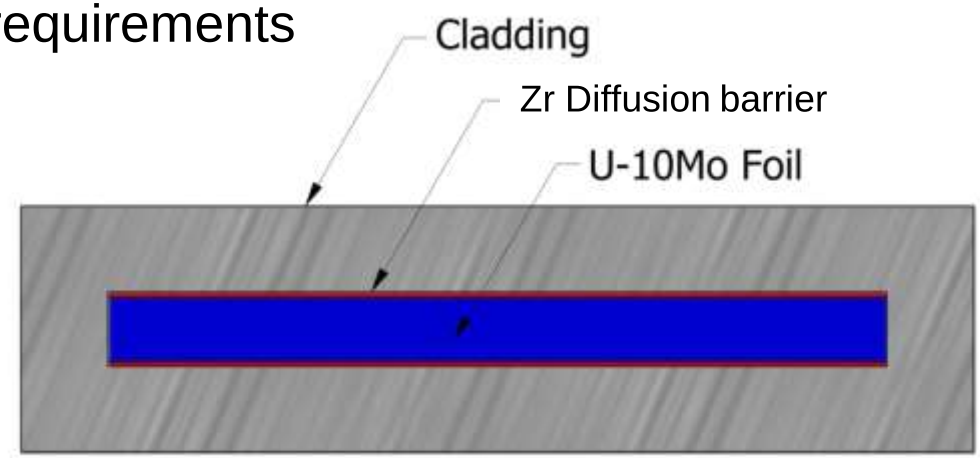
U.S. High Performance Research Reactor Fuel Qualification Program

- Objective: Development and qualification of a new plate-type low-enriched uranium-molybdenum fuel for high power research reactors
- Single 'base' fuel type to allow conversion of four U.S. High Performance Research Reactors (MURR, NBSR, MITR, ATR) and one critical facility (ATR-C)
- Application to HFIR likely requires additional fabrication development



Monolithic Low-enriched Uranium Fuel

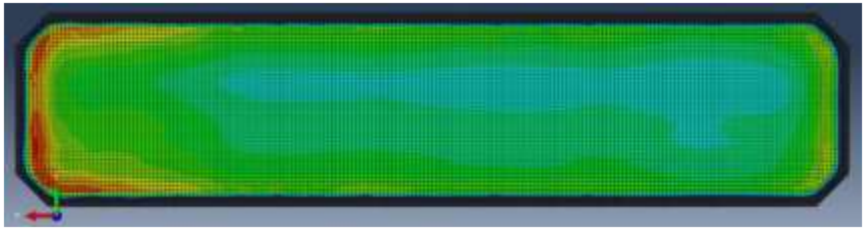
- Monolithic design selected for qualification in 2009
- Current fabrication method
  - Zr diffusion barrier hot co-rolled to U-10Mo ingot
  - Ingot rolled to final foil thickness
  - Foil trimmed to size and clad in AA 6061 by Hot Isostatic Pressing (HIP)
- Fuel system has already been demonstrated to meet basic irradiation performance requirements



U-Mo Monolithic Base Fuel Design

Fuel Qualification – Residual Stress

- Fuel qualification requirements related to residual stress:
  - Mechanical integrity
  - Geometric stability
  - Stable and predictable behavior
- As-fabricated (pre-irradiation) residual stress provides information about fabrication process
- Post irradiation residual stress provides insight into possible fuel failure modes



Prediction of End of Life shutdown stress as potential mechanism for RERTR-12 failures at high burnup

- Finite element modeling used to predicts residual stress throughout fuel cycle; data from testing can be used to validate model results.
- Residual stress is expected to relax during irradiation, then occur again during cool-down, so both as-fabricated and post-irradiation measurements desired

Residual Stress System Down-selection

- Neutron x-ray diffraction previously used for pre-irradiation not easily applied post-irradiation
- Final selection considered hole drilling and slitting methods
- Hot cell requirements key in down-selection decision and in system design
  - Remote manipulation
  - Argon atmosphere so no wire EDM
  - Strain gauges difficult to apply
  - Vision limited to binoculars/scope
  - High radiation limits electronics life in hot cell

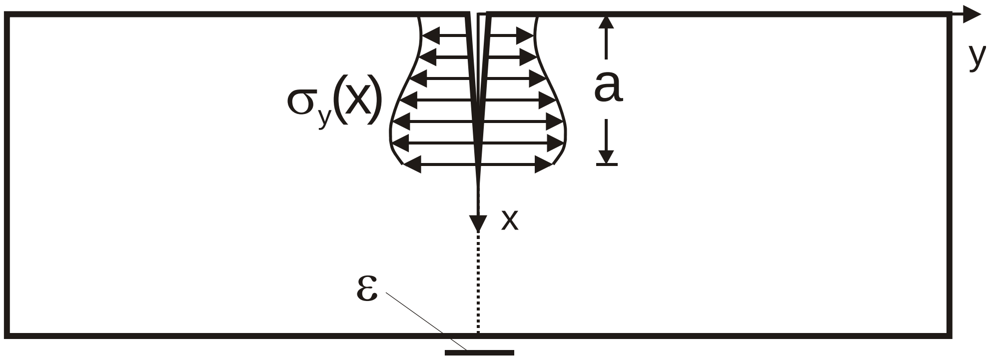
Down-selection Tradeoffs

- Tradeoffs between two approaches
  - Hole drilling offers greater mapping capability
  - But more expensive and more risky
  - Slitting more easily adapted for hot cell

	Slitting	Hole Drilling
Spatial Mapping	$\sigma_x(z)$ at different x locations	$\sigma_x(z)$, $\sigma_y(z)$, $\tau_{xy}(z)$ at different (x,y) locations
Through Thickness	Good resolution through most of specimen thickness	Ability to resolve stresses degrades ≈ halfway through plate thickness
Machining	A small mill with two translation axes (plunge depth and lateral translation)	A small mill (dental drill is often used) with one translation axis (plunge depth)
Deformation Measurement	Displacement transducer	Electronic Speckle Pattern Interferometry (ESPI), laser-based.
Calibration Coefficients	A 2-D elastic, finite element model provides coefficients for data reduction. Easily scripted.	A 3-D elastic, finite element model is required and must be customized for different hole locations.
Cost and Risk	Modest	More significant because of laser-based ESPI technique.

Slitting Method

- Incrementally introduce a slit into a part containing residual stress
- At each increment of slit depth, a_i, measure relaxed strains
- Calculate stress by solving elastic inverse problem



$$\varepsilon(a_i) = \varepsilon_i$$

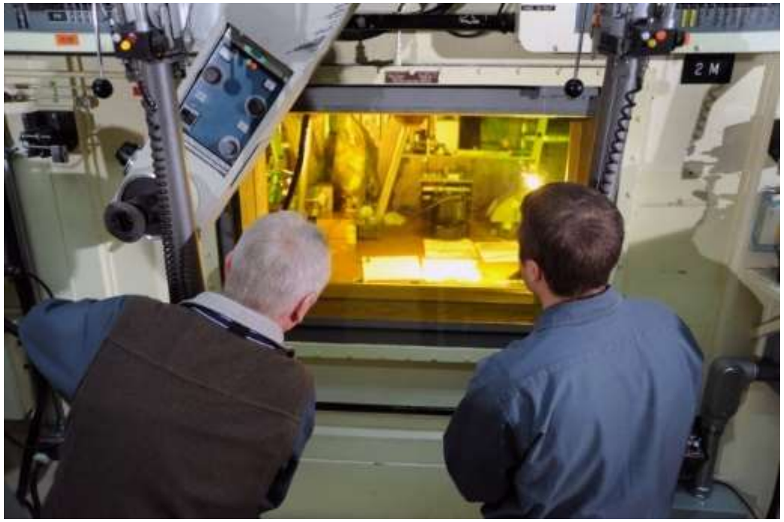
W. Cheng, I. Finnie, M. Gremaud, and M.B. Prime, "Measurement of Near Surface Residual Stresses Using Electrical Discharge Wire Machining," *J. Engineering Materials and Technology,* **116**, 1-7, 1994.

Hot Fuel Examination Facility (HFEF) Main Cell – Extreme Environment

- Inert argon atmosphere
- Cell dimensions
  - 22 m (70 ft.) long
  - 9 m (30 ft.) wide
  - 8 m (25 ft.) high
- <60 ppm oxygen and moisture
- 1.2 m (4 ft.) thick windows and walls
- 15 work stations with remote manipulators (2/window) – 20-50 lbs.
- Currently accommodates many fuels programs, fuel recycle and fabrication line, waste disposition development, and materials tests

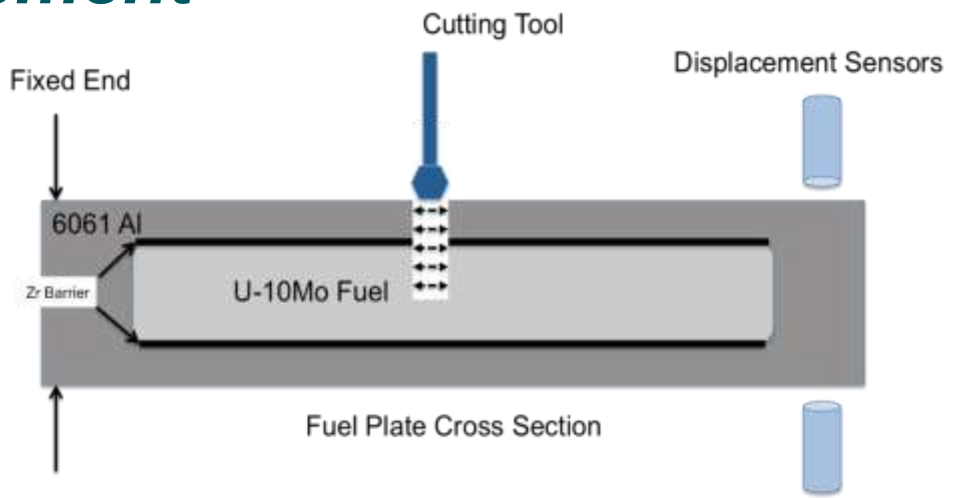
Containment Box

- Specific hot cell location used for fuel cutting, grinding, polishing
- Future location of residual stress measurement system

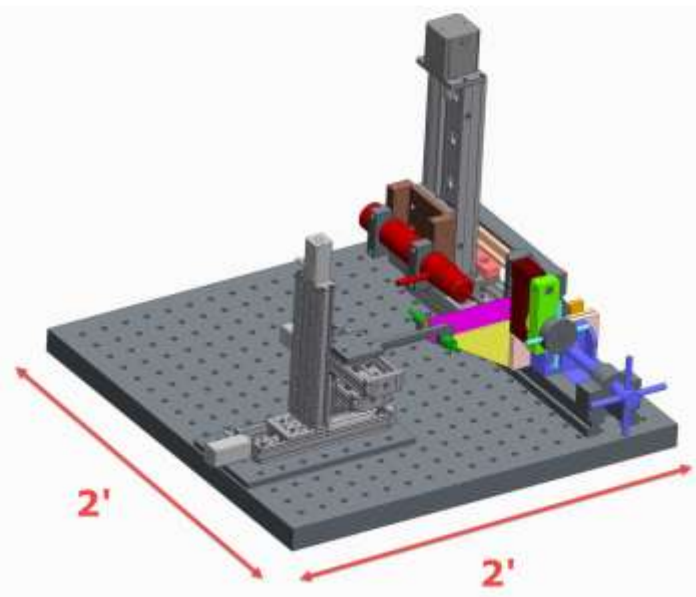


Residual Stress Measurement

- Fuel plates are effectively a layered composite system composed of materials with differing mechanical and thermal properties and constrained interfaces
- Fuel plate thermo-mechanical processing (rolling, HIP'ing etc.) will develop residual stresses



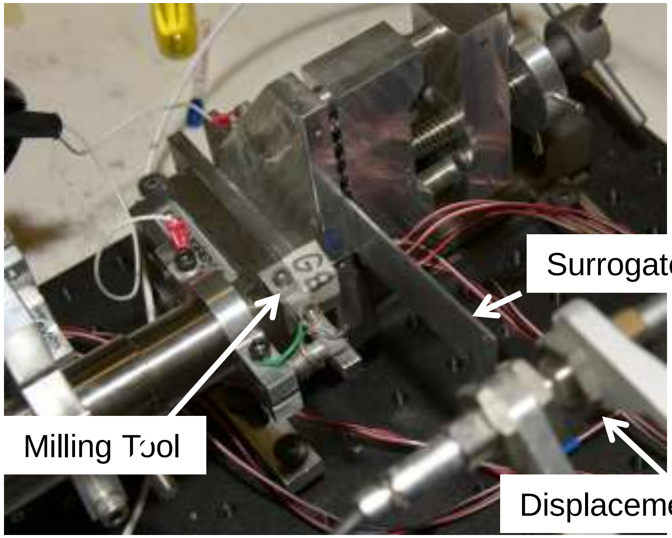
Schematic of Incremental Slitting System Design Elements



In-Cell Residual Stress System

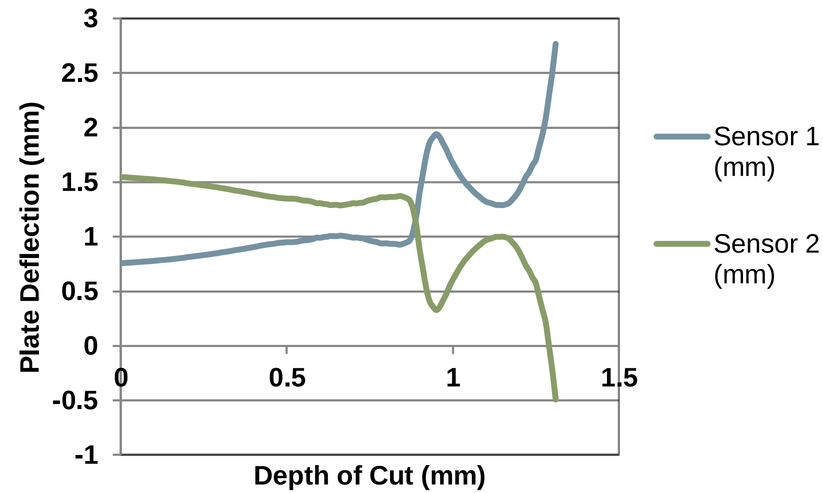
- Post-irradiation residual stresses (developed during reactor shutdown) are believed to play an important role in causing fuel failures at high burn-up levels
- Measuring (and modeling) of these stresses will be important for developing a complete understanding of fuel performance limits

Initial Qualification and Testing



- Initial results for a surrogate fuel sample that consists of an aluminum clad stainless steel foil bonded using friction stir welding
- Deflections as a function of slit depth illustrate a change in the sign of the stress at the internal interfaces
- FEM Model used to back out residual stresses from plate geometry and measured deflections

- In non nuclear applications, the slits are made with electric discharge machining and deflections are measured using strain gauges
- For hot-cell implementation, the EDM slitting has been replaced by a small milling tool, and the strain gauges have been replaced by non-contacting displacement transducers

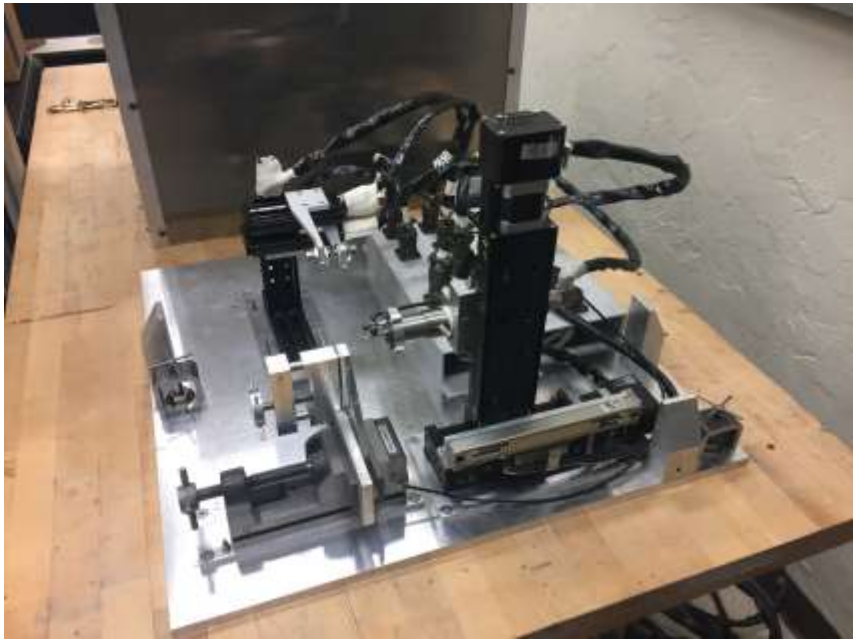


Two Residual Stress Measurement Systems

- Two nearly identical systems
  - Pre-irradiation system to understand baseline, as-fabricated stress state
  - Post-irradiation to measure effect of irradiation and cooling on stress state; aids in understanding potential failure modes such as blistering that may occur at high fuel burn-up
  - Both provide input to overall fuel cycle modeling
- Shared control system for cost savings

Post-irradiation (dry) Residual Stress System

- Contamination control provided by hot cell
- Modular parts for replacement with remote manipulation
- Radiation hardened wiring



Fresh Fuel System Development

- Fresh fuel residual stress measurement system developed for as-fabricated mini-plates
- Test plans established to define procedures for documenting and controlling residual stress measurement data to meet programmatic quality requirements
- Due to production of cutting fines, drip system and enclosure were incorporated into design
- Evaluation of radiological concerns completed and determined water drip and enclosure provide adequate level of control

Initial calculations indicate 12 samples can be run before decontamination needs to be performed (based on enrichment level)

Water slowly drips on cutting tool during machining and captures fines while minimizing splashing

Fresh Fuel/Pre-irradiation (wet) Residual Stress System

- Water drip to contain fines
- Enclosure for contamination control
- Water drip gravity feed, move trays rather than pump

System Description

- Design features
  - Horizontally mounted drill for incremental slitting
  - Eddy current sensors for displacement measurement
  - Tested on aluminum, stainless steel, and stainless clad in Hot Isostatic Pressed aluminum
  - Cut 80% of way through plate; all the way through fuel section
  - Automated operation

Dry versus Wet Comparison Test

- Comparison test conducted on Al 6061 clad SS foils and HIP bonded Al sheet material
- Two foil thicknesses, 0.008 and 0.025 inch
- Strain gauge used as secondary confirmation of measurements
- Data currently being analyzed

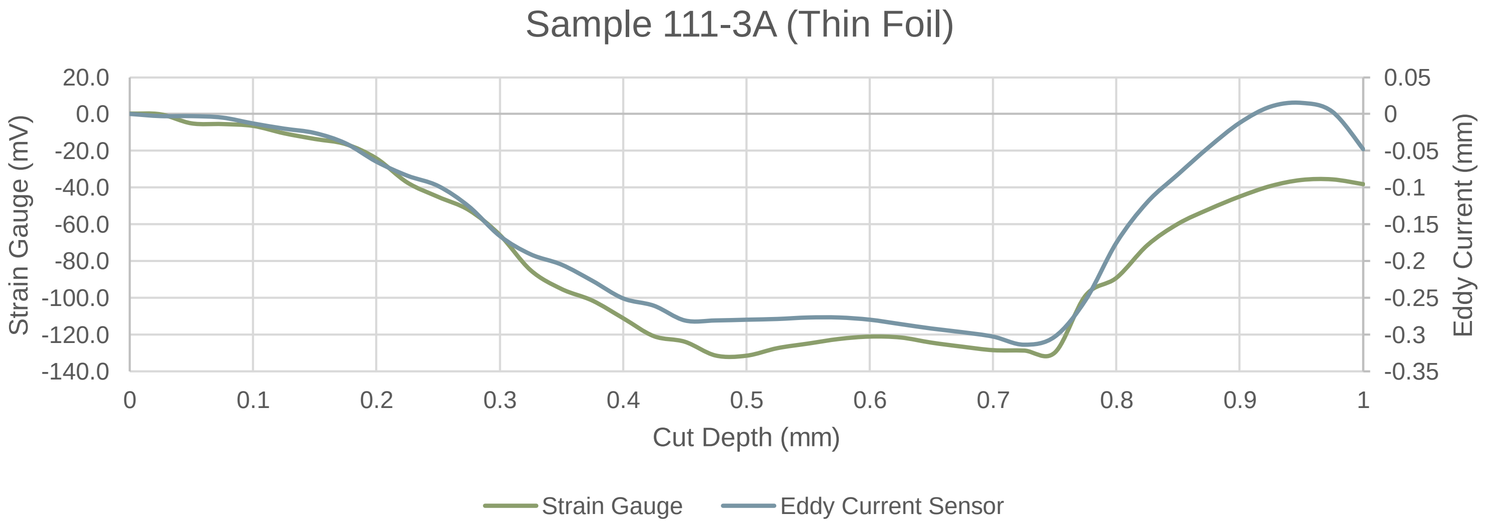
High speed fluted cutting tool for producing slit in fuel plate

Video showing surrogate fuel plate slitting on wet system during comparison test

Eddy current sensors for displacement measurement

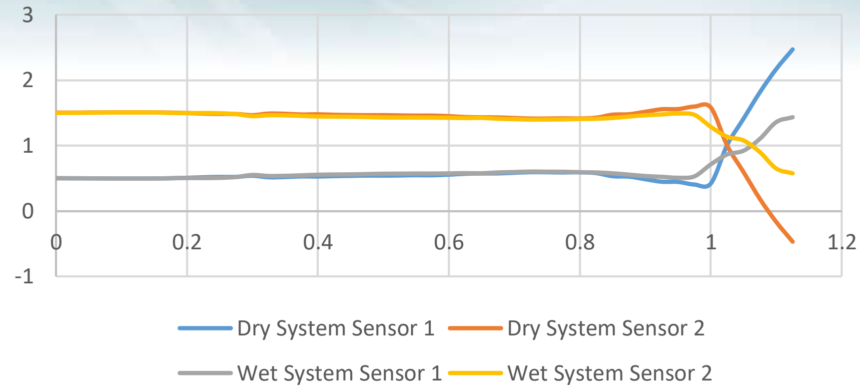
Raw Comparison Test Data

- SS Surrogate foil
- Al 6061 HIP Clad
- Thick foils
- Thin foils
- Comparison between wet and dry systems
- Comparison between eddy current and strain gauge measurement methods

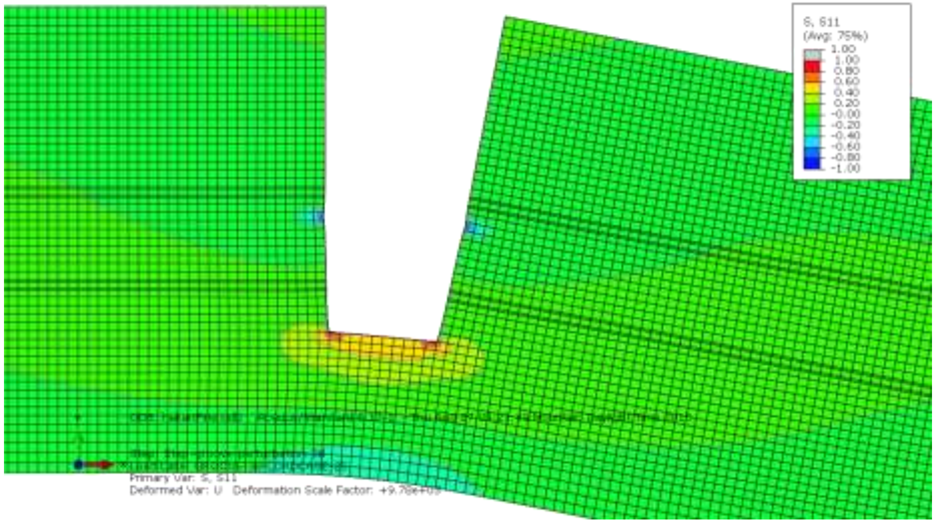


Data Analysis

- Earlier in the year, work was done to optimize machining parameters for representative materials (HIP fabricated Al 6061)
- Possible hardening of soft Al by tool during cutting was deemed inconsequential compared to measured stress levels
- Comparison test data analysis ongoing
- Finite element analysis employed to back out residual stress from deflection versus slit depth measurements
- Goal: Demonstrate comparable stress profiles from both systems.
- Move fresh fuel system to Fuels and Applied Sciences Building in FY-18 for depleted uranium, low-enriched uranium, and high-enriched uranium



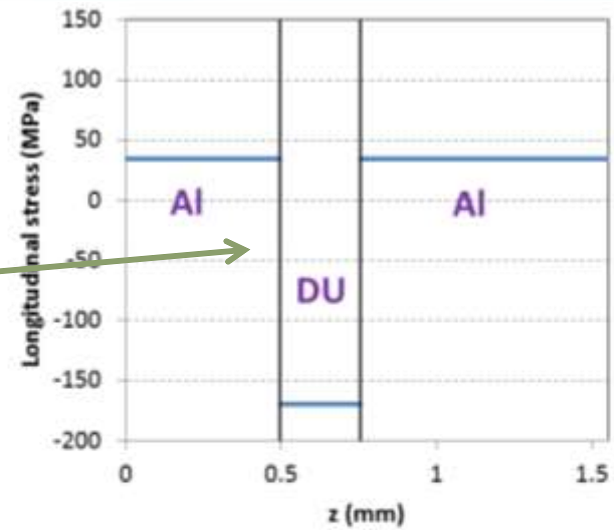
Raw deflection vs slit depth data for surrogate fuel plate with 0.025” SS foil.

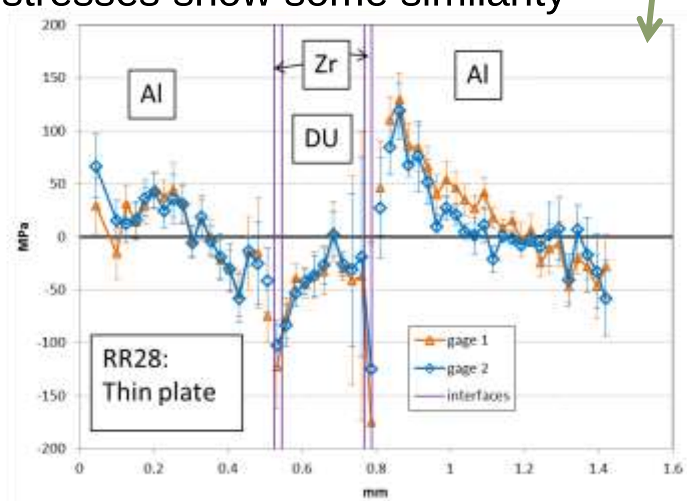


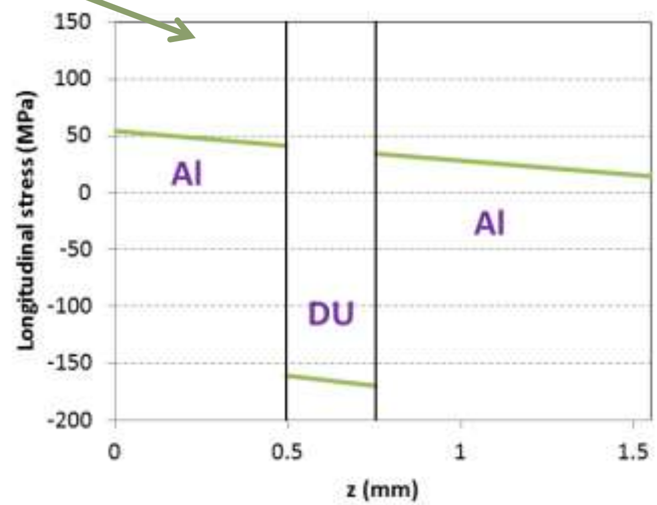
Example of FEM model used to extract stress profile. Grid size is 25 µm.

Early Example of Possible Results – Thermal Mismatch

- We can gain some insight even with a simple elastic calculation of thermal mismatch stresses from early testing
  – Use DT only 200ºC to get low enough magnitude
- Al contracts more than DU on cooling
  – Mutual restraint puts DU in compression and Al in tension (force equilibrium)
- Asymmetric Al thicknesses means part will curve to achieve moment equilibrium
- Measured stresses show some similarity







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