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U-Mo Mechanical Properties Degradation with Irradiation

Jason L Schulthess

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Degradation of Mechanical Properties of U-Mo Alloy from the Un-irradiated to Irradiated State

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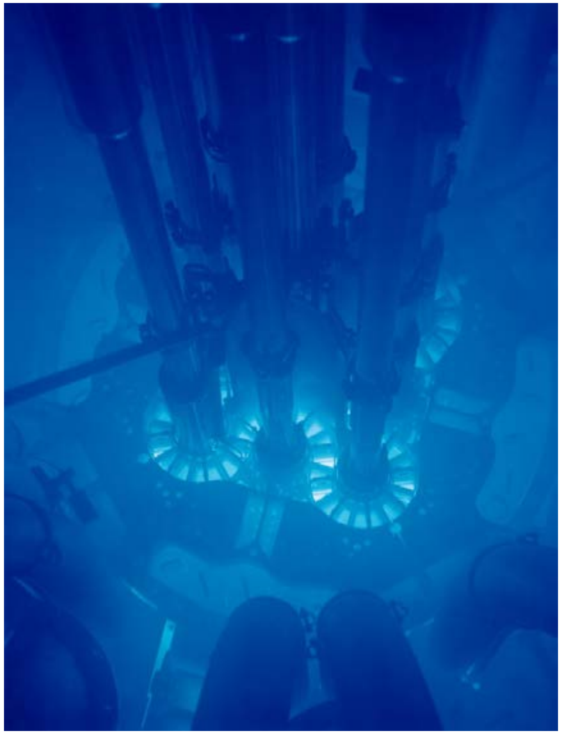
Outline

- Background
- Fuel Qualification Requirements
- Fuel Form
- Motivation
- Part 1 – Un-irradiated Properties
  - Existing Data
  - Source Material
  - Experimental Results
- Part 2 – Irradiated Properties
  - Existing Data
  - Source Material
  - Analysis Methodology
  - Experimental Results
  - Porosity Discussion
- Summary

Materials Management and Minimization (M3)

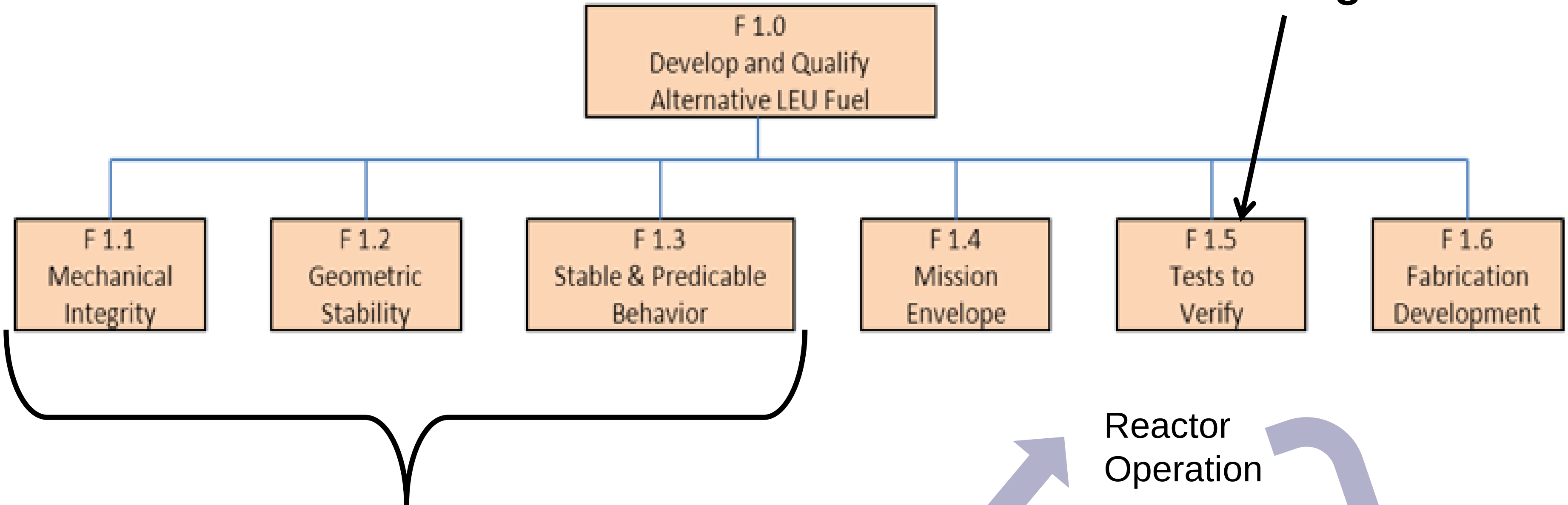
- Mission:
  - Eliminate the use of high enriched uranium (HEU) for use in research and test reactors by developing and qualifying a low enriched uranium (LEU) fuel to replace the current HEU fuel.
  - Six domestic High Performance Research Reactors (HPRRs) require a new high density LEU fuel form.
    - Massachusetts Institute of Technology (MITR),
    - University of Missouri (MURR),
    - National Institute of Standards and Technology (NIST),
    - High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory and
    - Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) and its associated critical assembly (ATRC).



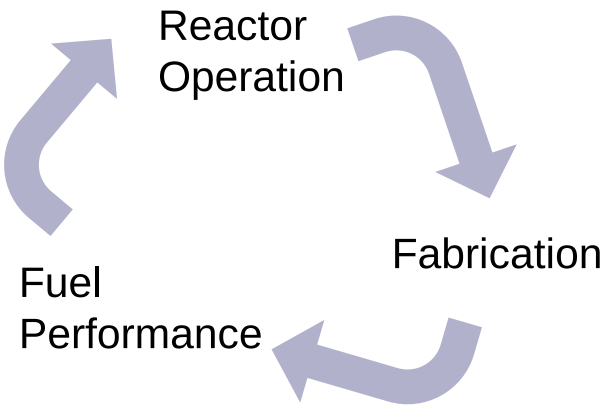
ATR Core (INL)

Fuel Requirements

Focus of Fuel Development irradiation testing



Focus of Fuel Development data generation and analyses



Summary of Fuel Performance Requirements

Mechanical Integrity

- Ensure no delamination during normal operation and anticipated transients
- Mechanical response of the fuel meat, cladding, and interlayers is established

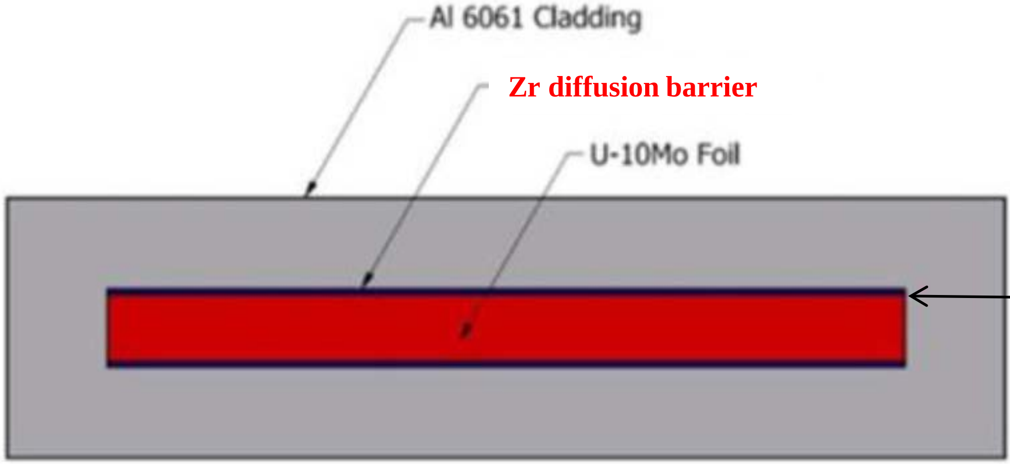
Geometric Stability

- Plate movement caused by pressure differential does not compromise ability to cool the fuel
- Geometry is maintained during normal operation and anticipated transients
- Irradiation–induced degradation of properties does not lead to conditions that result in loss of coolability

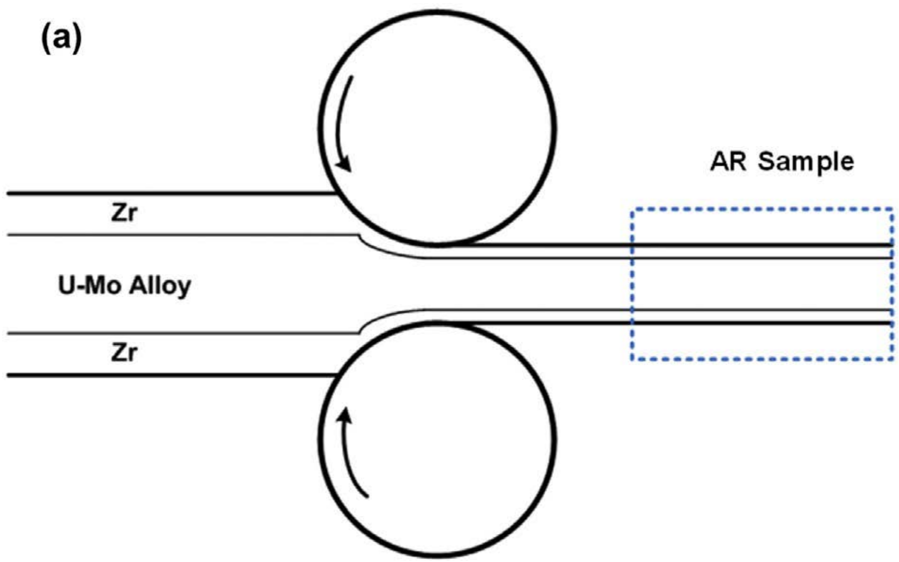
Stable and Predictable Behavior

- Fuel performance shall be known and predictable
- Fuel swelling is within a stable regime
- U-Mo corrosion behavior after breach is known
- Irradiation behavior on scale up is predictable

Fuel Sandwich



Zr/U-10Mo Interface



Fabrication Baseline

- U-10Mo fabricated by wrought thermomechanical processing (hot and cold rolling)

Image from Park, et al. 2015

Motivation:

- What are the U-Mo mechanical properties, and can the degradation of mechanical properties from irradiation be correlated with porosity?
  - Part 1: What are the un-irradiated mechanical properties, and what is the influence of temperature and variations of wrought processing on the mechanical properties
  - Part 2: What are the irradiated mechanical properties and can the degradation be correlated with increasing porosity from irradiation

PART 1 – Un-irradiated Properties

Existing Data:

Note: nothing that was cold rolled!

Reference Source	Form Tested	Prior Heat Treatment Temp (°C)	Prior Heat Treatment Time (Days)	Temp of Testing (°C)	Yield Stress (MPa)[a]	UTS (MPa)[a, b]	Youngs Modulus (GPa)[a]	Elongation (%)	Carbon Content (ppm)
Waldron	As-cast	900	7	20	NA	617.8	86.87	0.1	~700
Waldron	As-cast	450	14	20	NA	293.7	119.3	0.8	~700
Ozaltun	Hot Rolled with 90% reduction at 650 °C; annealed at either 650 °C or 675 °C for durations of 0.5, 1 or 2 h	NA	NA	21	780	790	65	NA	~54-410
Ozaltun	Cast and machined	NA	NA	94	760	760	NA	NA	NA
Waldron	As-cast	900	7	200	NA	510.2	73.77	0.5	~700
Waldron	As-cast	450	14	200	NA	303.4	91.7	Nil	~700
Kalashnikov	Hot Rolled between 900-1200°C followed by water quenching from 900°C. Held at 900°C for 7 days	NA	NA	200	NA	578.6	NA	0.5	NA
Ozaltun	Cast and machined	NA	NA	205	655	655	NA	NA	NA
Waldron	As-cast	450	14	300	NA	183.4	103.4	0.5	~700
Ozaltun	Cast and machined	NA	NA	316	527	536	NA	NA	NA
Waldron	As-cast	900	7	400	NA	358.5	51.71	1	~700
Waldron	As-cast	450	14	400	NA	256.5	108.9	0.5	~700
Waldron	As-cast	575	28	400	NA	148.9	84.12	2	~700
Kalashnikov	Hot Rolled between 900-1200°C followed by water quenching from 900°C. Held at 900°C for 7 days	NA	NA	400	NA	397.2	NA	1	NA
Ozaltun	Cast and machined	NA	NA	427	474	511	NA	NA	NA
Ozaltun	Cast and machined	NA	NA	538	427	440	NA	NA	NA
Waldron	As-cast	900	7	600	NA	179.3	33.09	0	~700
Waldron	As-cast	575	28	600	NA	124.1	59.29	0.5	~700
Kalashnikov	Hot Rolled between 900-1200°C followed by water quenching from 900°C. Held at 900°C for 7 days	NA	NA	600	NA	194.2	NA	NA	NA
Waldron	As-cast	900	7	800	NA	55.16	41.37	3	~700
Waldron	As-cast	575	28	800	NA	86.9	59.29	11	~700
Kalashnikov	Hot Rolled between 900-1200°C followed by water quenching from 900°C. Held at 900°C for 7 days	NA	NA	800	NA	62.8	NA	30	NA

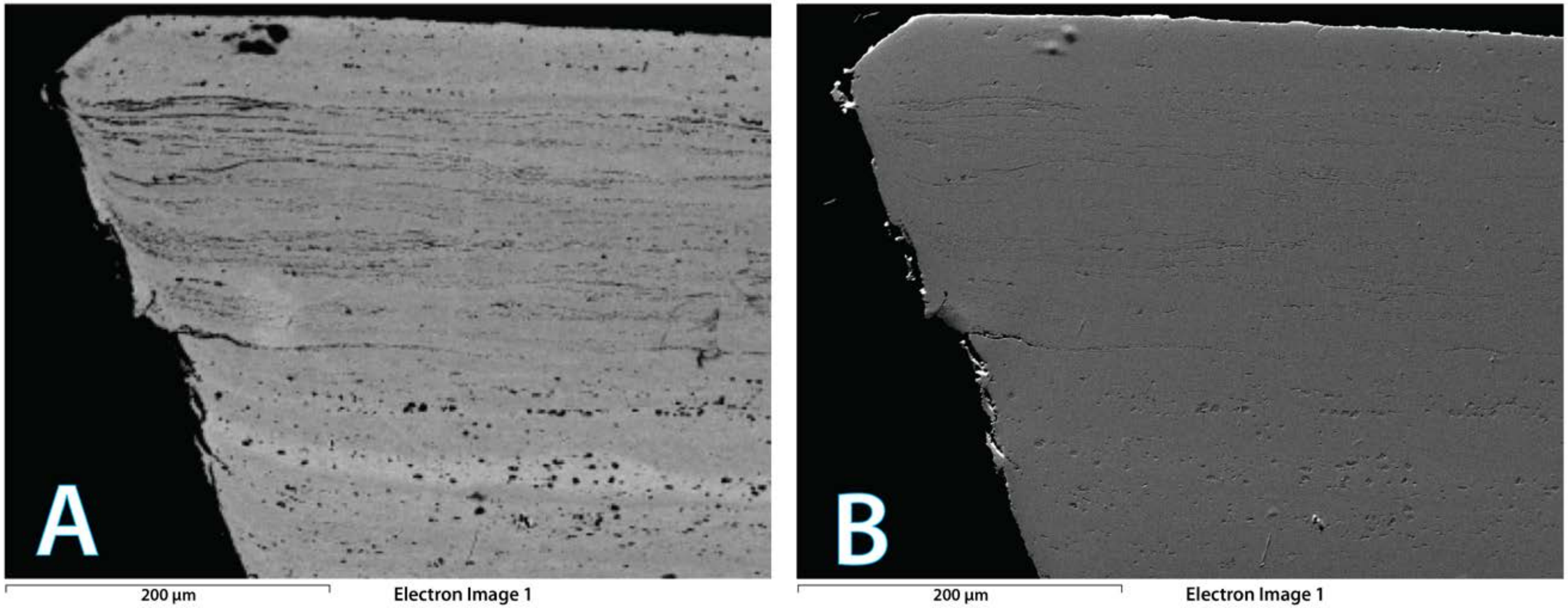
a. These values are calculated conversion from the published data for the purpose of comparison.
b. Kalashnikov does not specifically identify these values as ultimate tensile strength (UTS), but context of the paper infers these values as UTS values.
c. Where value is noted as NA, information was not provided in the source reference.

Un-irradiated material used in this study

- DU-10Mo cast at Y-12 (carbon ~710 ppm)
- Homogenized at 1000°C for 2 hours under vacuum of $5x10^{-6}$ Torr
- Hot rolled at 650°C
- 4 thermomechanical conditions
  - Foil 551-2, hot rolled from ~3.66 mm to ~0.762 mm (79% reduction), followed by additional 50% cold-rolling reduction to ~0.38 mm; 551-2 50%CW
  - Foil 551-3, hot rolled from ~3.66 mm to ~0.762 mm (79% reduction), followed by additional 50% cold-rolling reduction to ~0.38 mm, followed by stress-relief annealing at 650°C for one hour; 551-3 50% CW+A
  - Foil 551-4, hot rolled from ~3.66 mm to ~0.483 mm (87% reduction), followed by additional 20% cold-rolling reduction to ~0.38 mm; 551-4 20% CW
  - Foil 551-5, hot rolled from ~3.66 mm to ~0.540 mm (85% reduction) no further processing, i.e. hot-rolled only; 551-5 HR Only

Metallography of the as-rolled material

551-2-2-L11 50%CW

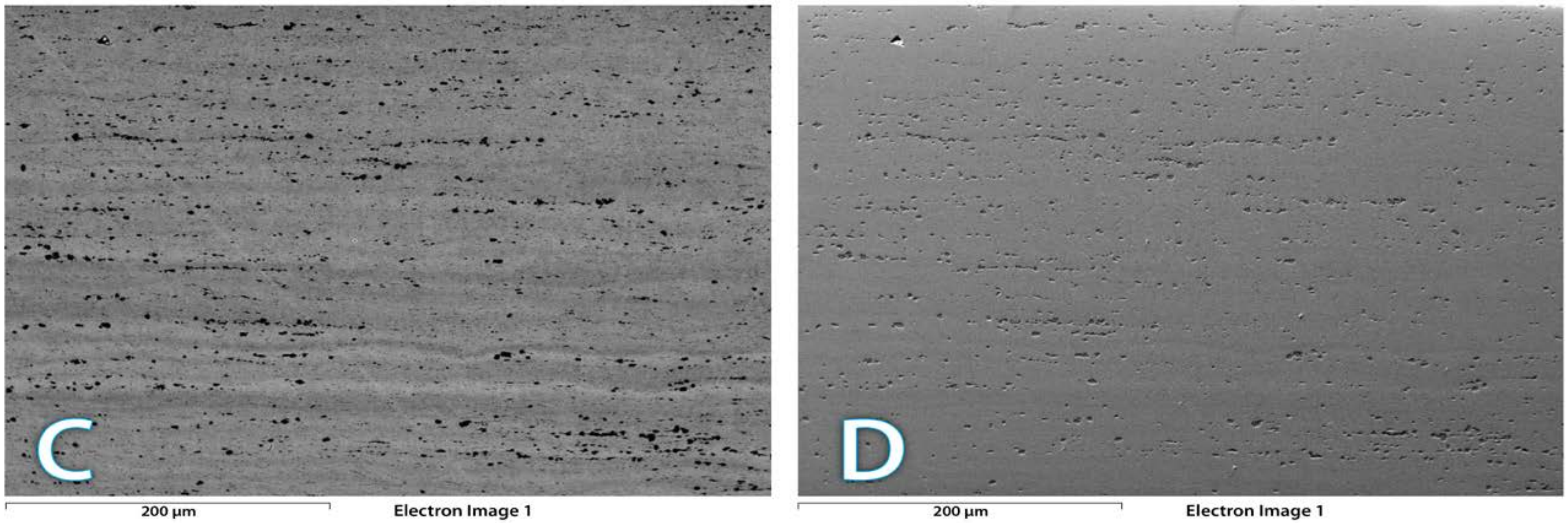


Mo banding varies between 8.35 wt% and 10.45 wt%

Grain sizes for the longitudinal and transvers cross-sections ranged from 2 to 22 µm with the greatest concentration between 15 and 18 µm for the longitudinal direction and between 7 and 8 µm for the transverse direction.

Metallography of the as-rolled material

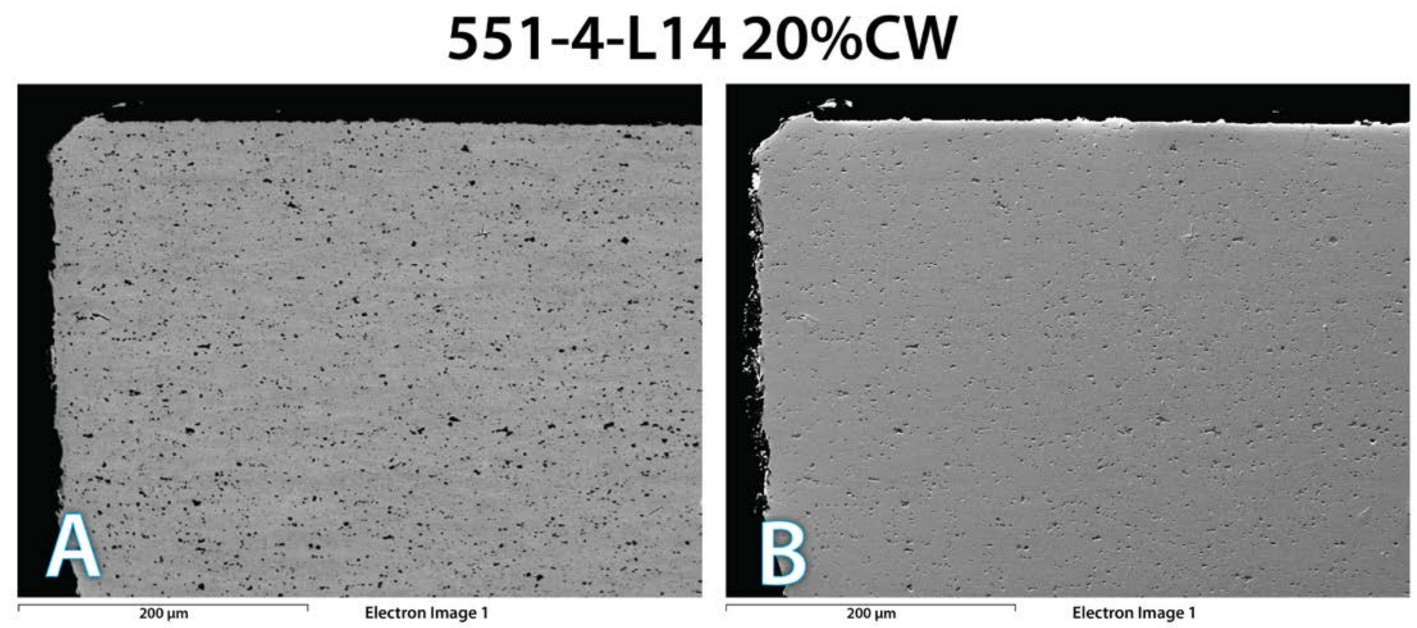
551-3-L30 50%CW+A



Mo banding ranges from 8.96 wt% to 10.81 wt%.

Grains in the range between 2 to 12 µm with the greatest concentration of grain sizes between 5 to 9 µm for both the longitudinal and transvers directions). The grains in this microstructure do not appear to show significant grain elongation. The grains in this microstructure appear more equiaxed.

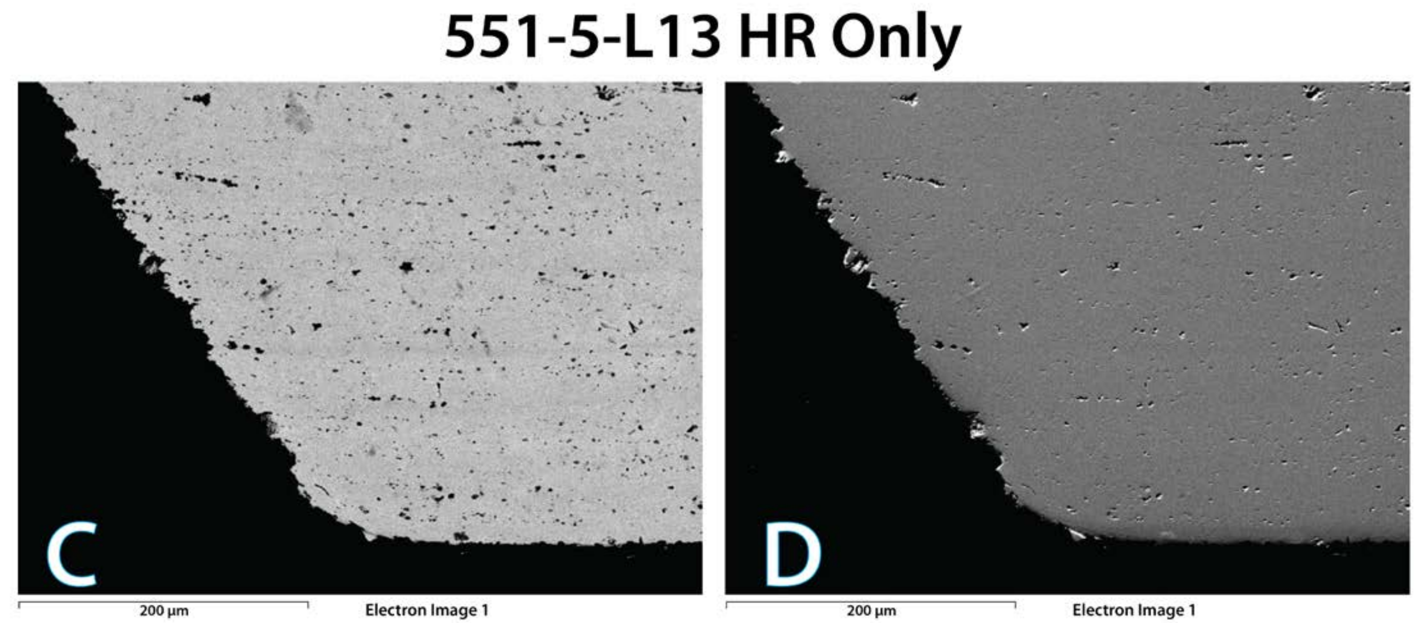
Metallography of the as-rolled material



Mo banding ranges from 9.81 wt% to 10.45 wt%

Grains between 2 to 25 µm with the greatest concentration of grains between 7 to 17 µm for both the longitudinal and transvers directions). The grains in this microstructure do appear to show elongation.

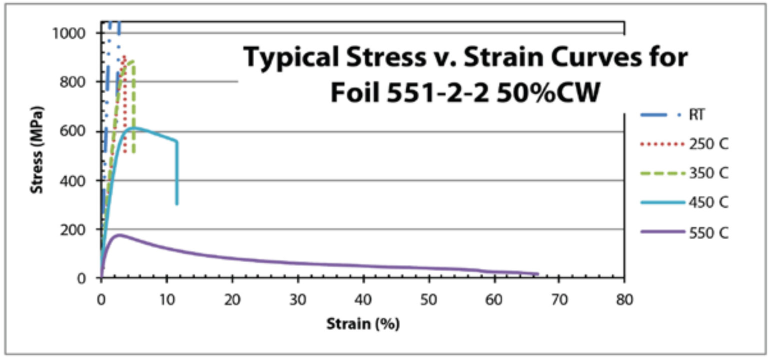
Metallography of the as-rolled material

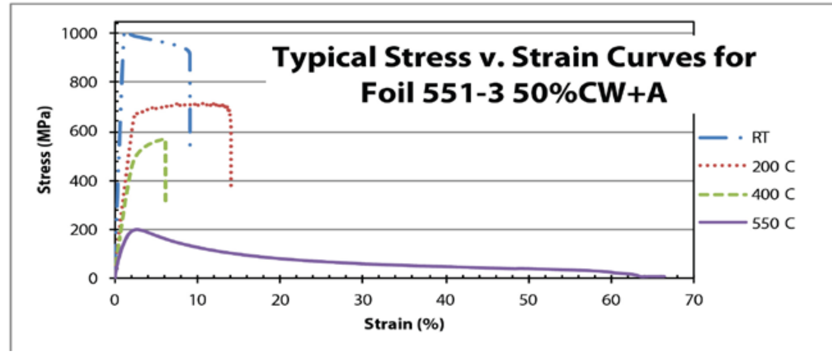


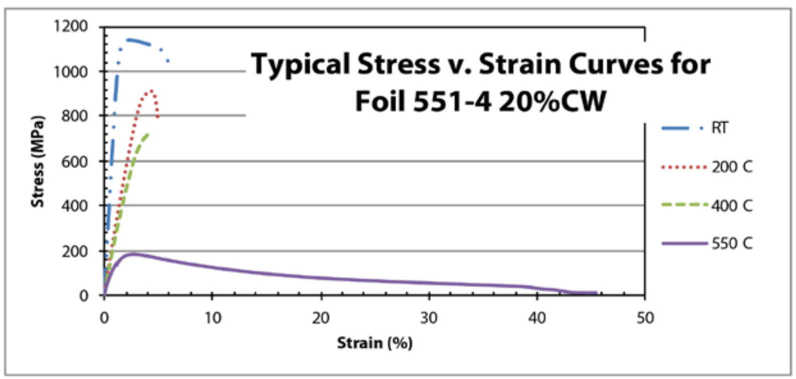
Mo ranges from 8.46 wt% to 10.41 wt%.

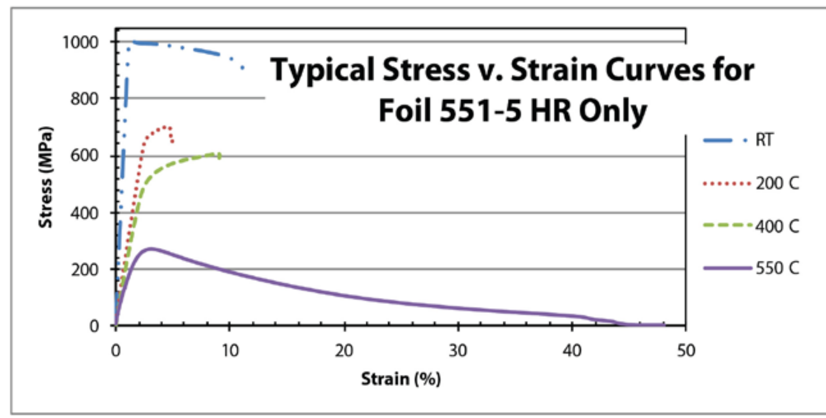
Grains between 2 and 22 µm with the greatest concentration in the longitudinal sample being 20 µm and the greatest concentration in the transvers sample being between 7 and 10 µm. The grains in this microstructure appear to show some grain elongation.

Mechanical Properties Results

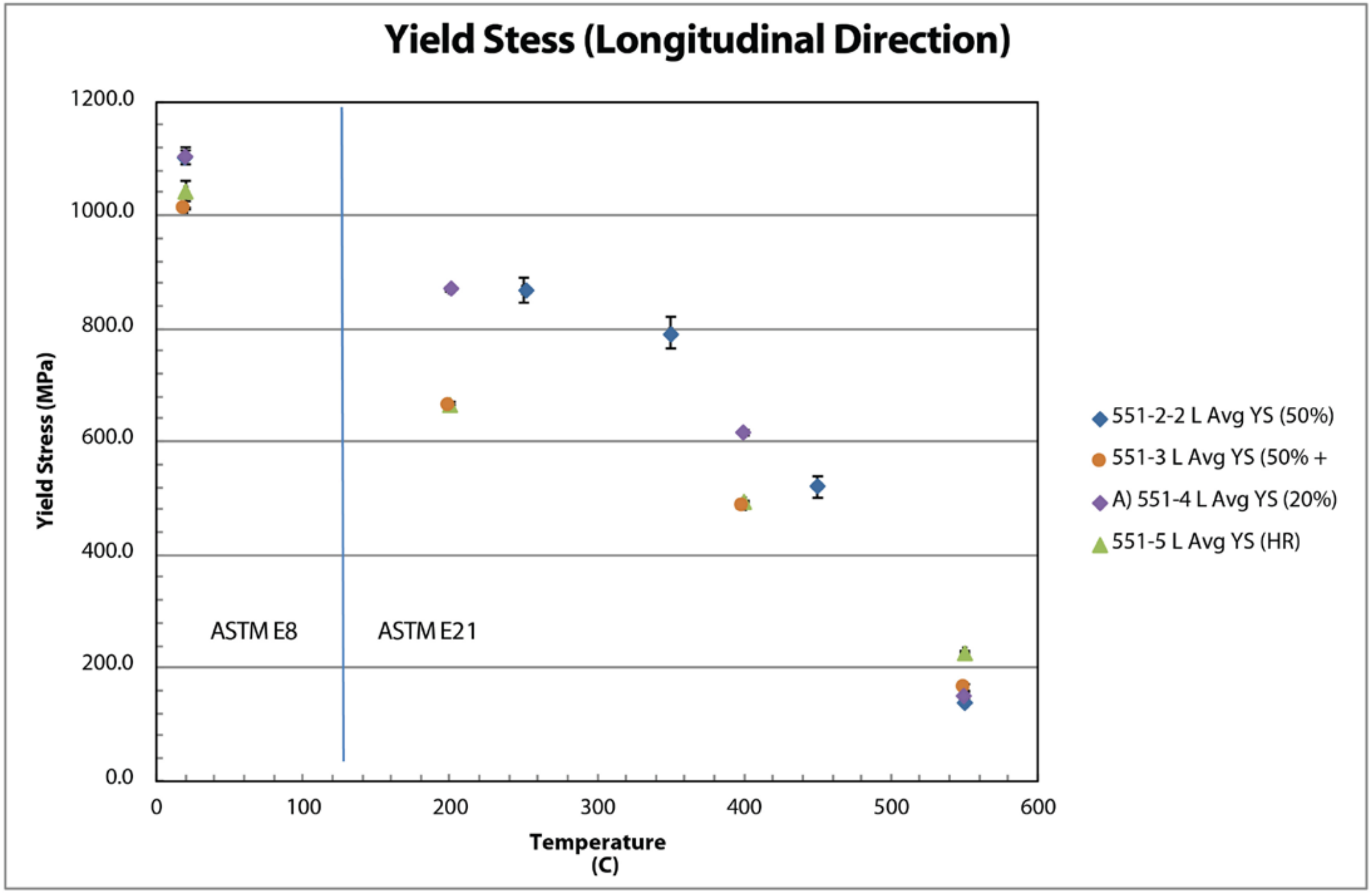






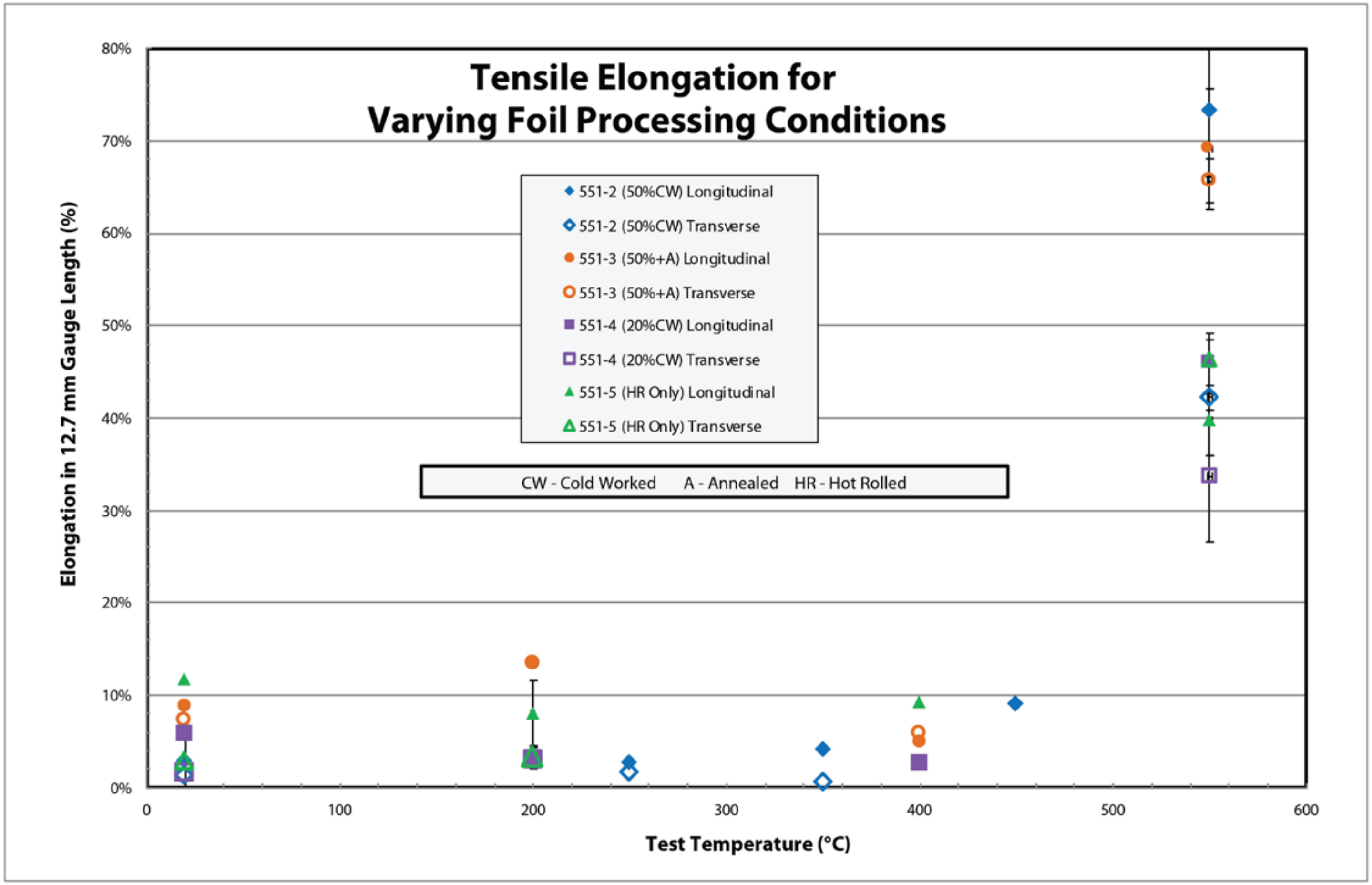


Yield Stress



Results for Ultimate stress are similar.

Elongation



Tensile Elongation for
Varying Foil Processing Conditions
551-2 (50%CW) Longitudinal
551-2 (50%CW) Transverse
551-3 (50%+A) Longitudinal
551-3 (50%+A) Transverse
551-4 (20%CW) Longitudinal
551-4 (20%CW) Transverse
551-5 (HR Only) Longitudinal
551-5 (HR Only) Transverse
CW - Cold Worked A - Annealed HR - Hot Rolled
Elongation in 12.7 mm Gauge Length (%)
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
100
200
300
400
500
600
Test Temperature (°C)

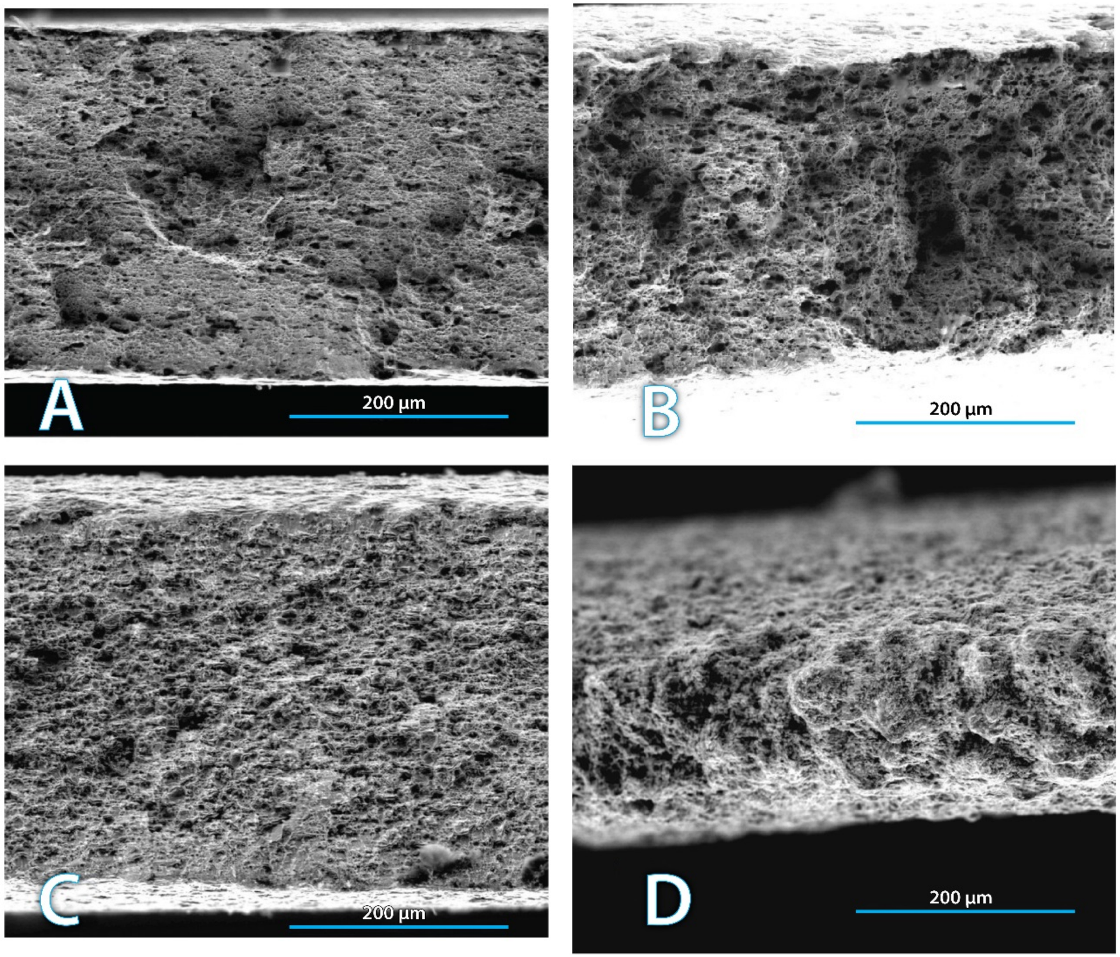
Elastic Modulus

- Testing per ASTM E8 and ASTM E21…NOT ASTM E111
- Nevertheless, the slope of the elastic portion of the stress strain curve is at each temperature:
  - 20°C - ~884 MPa/%
  - 200-250°C - ~417 MPa/%
  - 350°C - ~422 MPa/%
  - 400-450°C - ~320 MPa/%
  - 550°C - ~199 MPa/%

  - 1000 MPa/% = 100 GPa (884 MPa/% = 88.4 GPa)

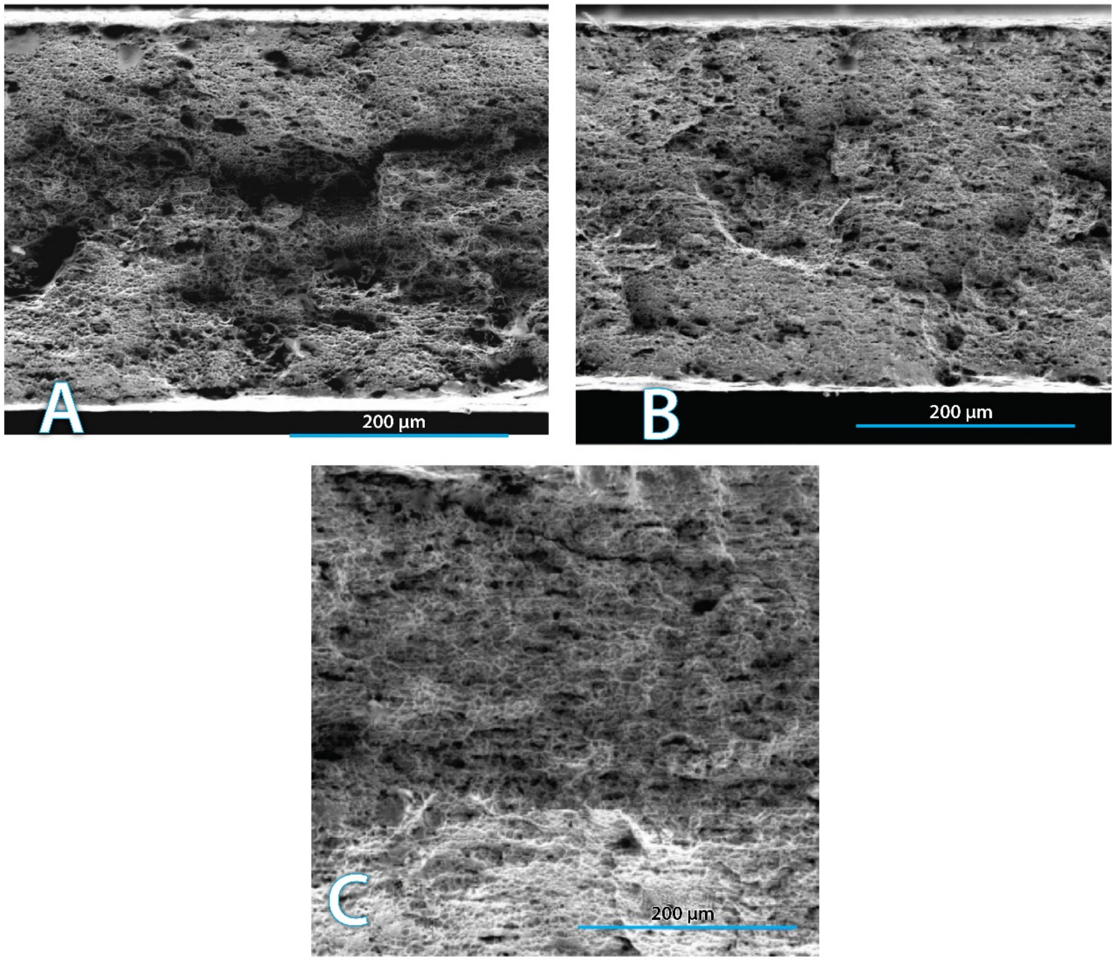
Unclear what caused this unexpected result

Fractography-1



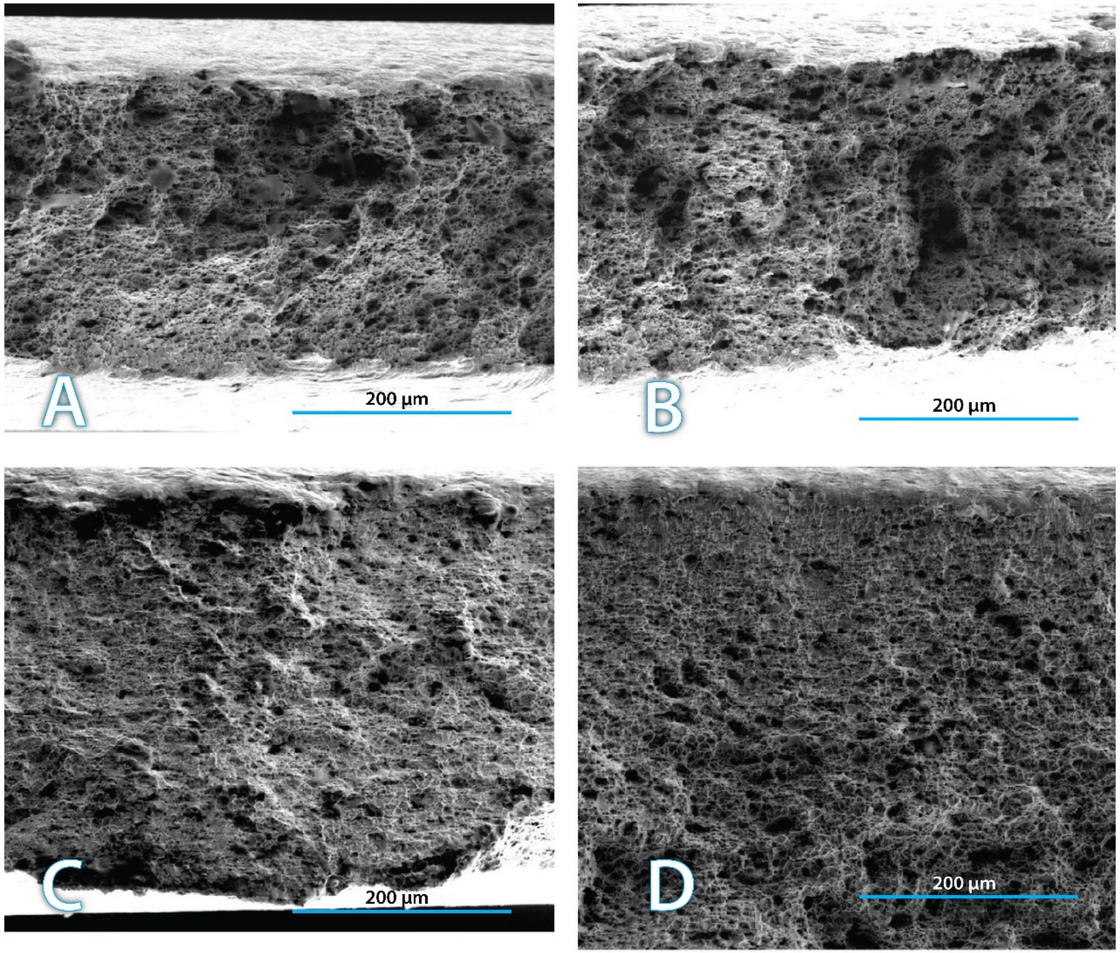
Fractography images set one. One foil condition (551-3 50%CW+A) at all test temperatures.
A) 551-3-L1, tested at room temperature, **B)** 551-3-L4, tested at 200 °C,
C) 551-3-L7, tested at 400 °C, **D)** 551-3 L10, tested at 550 °C.

Fractography-2



Fractography images set two. Different foil conditions, all tested at room temperature.
A) 551-2-2-L16-RT (50%CW), **B)** 551-3-L1-RT (50%CW+A), **C)** 551-5-T13-RT.(HR only).

Fractography-3

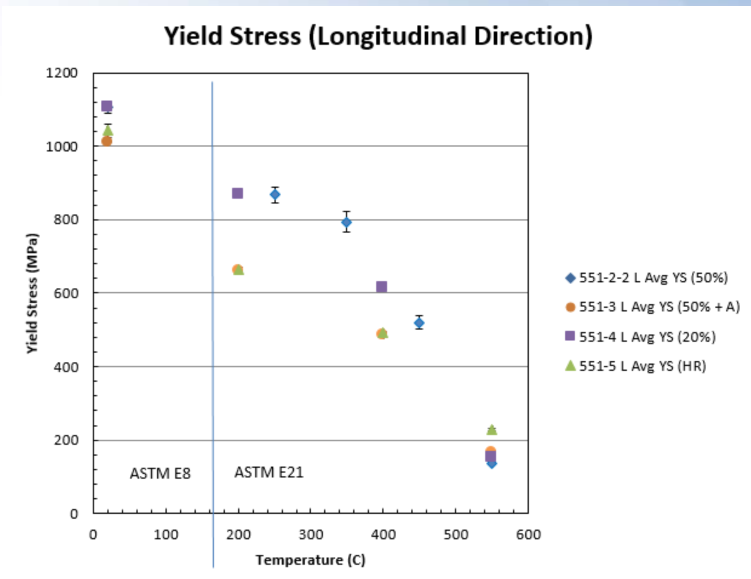


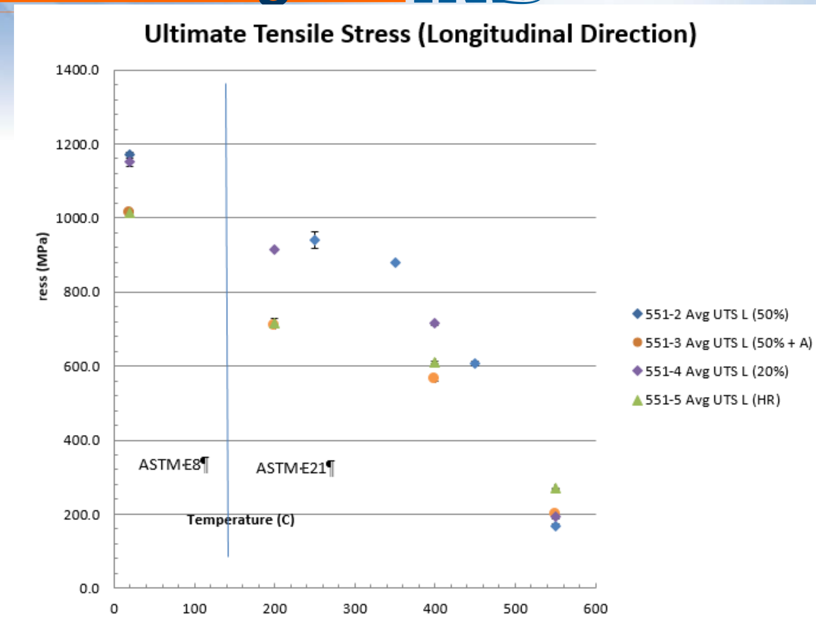
Fractography images set three, all foil conditions tested at elevated temperature (200 °C).
A) 551-2-2-L20-200 (50%CW), **B)** 551-3-L4-200 (50%CW+A), **C)** 551-4-L5-200 (20%CW), **D)** 551-5-L4-200 (HR only).

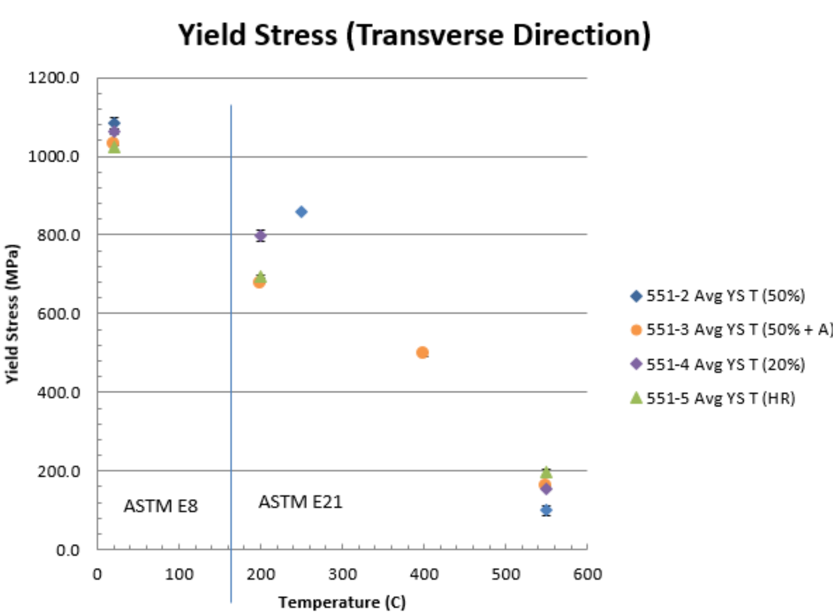
Comparison

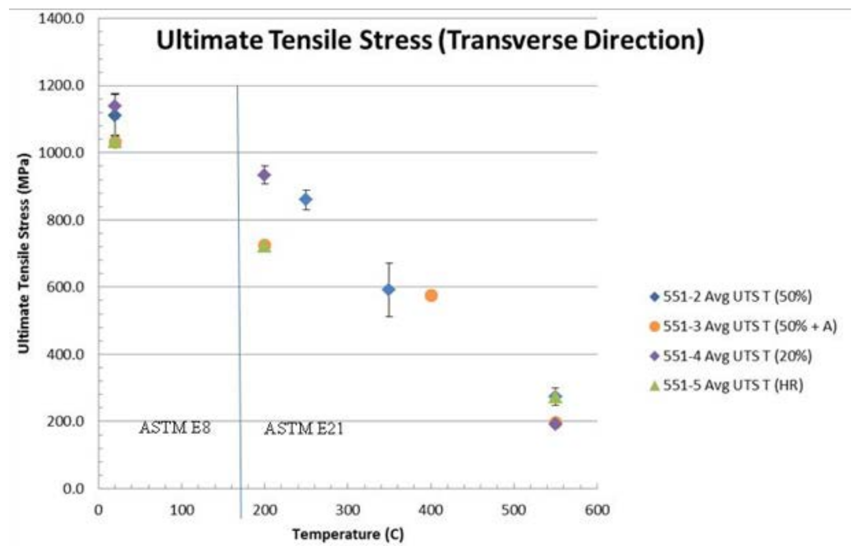
- This work:
  - RT yield stress: ~1100 MPa
  - RT ultimate stress: ~1175 MPa
  - RT elongation:~1-2%
  - Carbon: 710 ppm (1.86% Vf)
  - Grain sizes: ~2-25 µm
  - Hot rolled and cold rolled
- Waldron:
  - RT ultimate stress: ~617 MPa
  - RT elongation:~0.1%
  - Carbon: ~700 ppm
  - As-cast
  - Grain sizes: not reported
- Ozaltun:
  - RT ultimate stress: ~790 MPa
  - Carbon: ~54-410 ppm
  - As-cast and machined
  - Hot rolled
  - Grain sizes: not reported
- Causes:
  - Thermomechanical processing history
  - Grain sizes
  - Impurity content
- NOT ENOUGH INFORMATION AVAILABLE TO CONCLUSIVELY COMPARE RESULTS

Effect of thermomechanical processing









PART 2 – Irradiated Properties

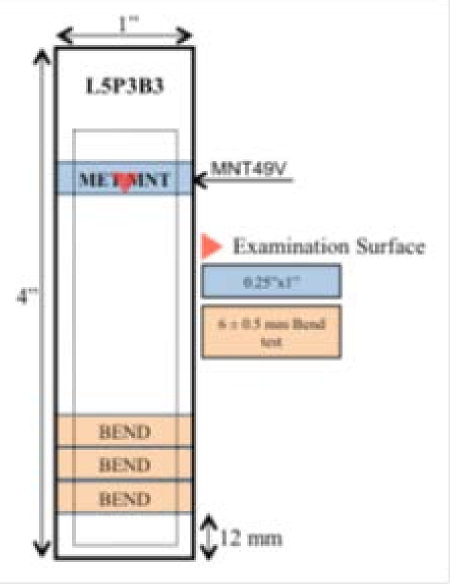
Existing Data vs. This Work

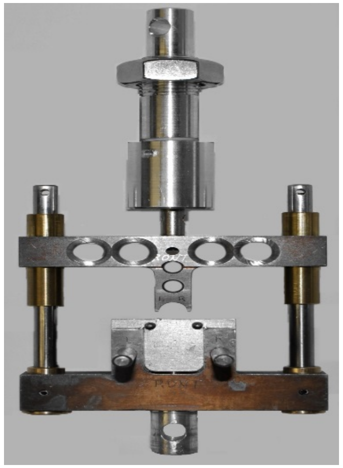
- Gates (1958)
  - Hot rolled, cold swaged, machined
  - Extruded, cold swaged, machined
  - Irradiation Temp: 130 – 600 °C
  - Burnup: 0.06 to 2.1 at.%
  - Test temp: RT - 500 °C
- Beghi (1968) / Leeser (1958)
  - Cast
  - Irradiation Temp: ~130 - 600 °C
  - Burnup: 0 – 2.1 at.%
  - Test temp: RT - 500 °C
- This Work:
  - Hot rolled, cold rolled (50% reduction), annealed, HIP
  - Fission density: 0.4 $\times 10^{21}$ – 6.3 $\times 10^{21}$ f/cm^3
  - Burnup: 11.10 - 26.76%U_{235} Depletion
  - Irradiation Temp: ~70 ~ 230 °C
  - Test temp: RT

- Previous work concluded that irradiation temp and burnup were most significant factors in mechanical properties degradation
- Differences in thermomechanial processing history, irradiation temp, and burnup make any comparison very difficult.
- Only 2 relevant data points from prior work:
  - Burnup 0.4 at%, Irradiation temp 130 °C, Test temp: RT; E~84 GPa,
  - Burnup 1.0 at%, Irradiation temp 200 °C, Test temp: RT; E~69 GPa

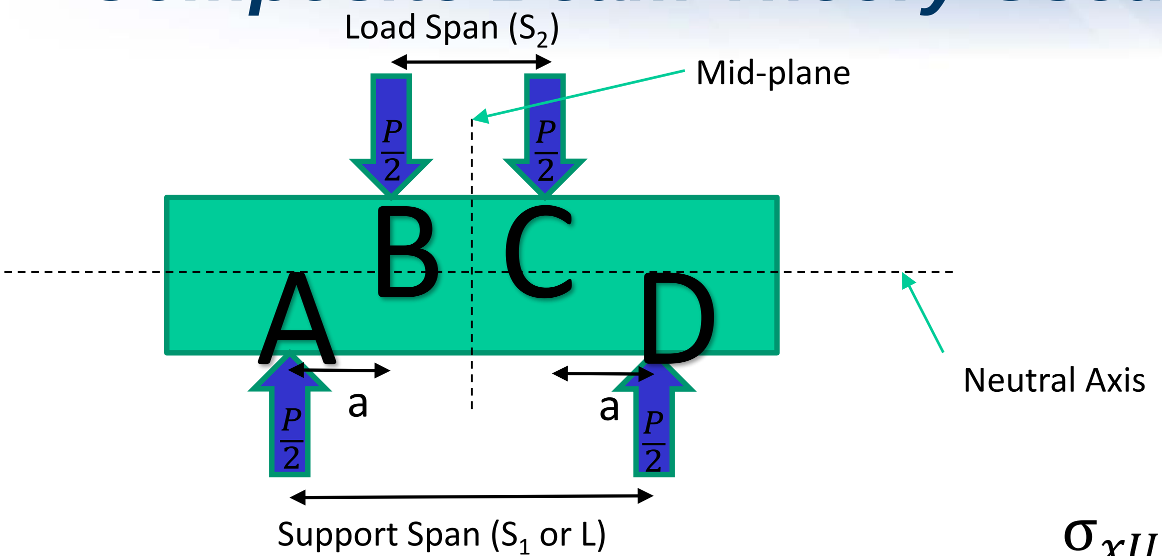
Source Material, Specimen and Test Prep

- Material from flat plate type fuel from RERTR-12 and AFIP-6 Mk2 Irradiation experiments
- Limited specimen machining capability drove decision to perform 4-point bend tests with rectangular specimens sectioned from plate fuel
- Customized Instron 5869 loadframe with custom 4-point bend fixture used for tests (2:1 support to load span ratio)
- Aluminum clad chemically dissolved from specimen leaving U-Mo core coated with Zr





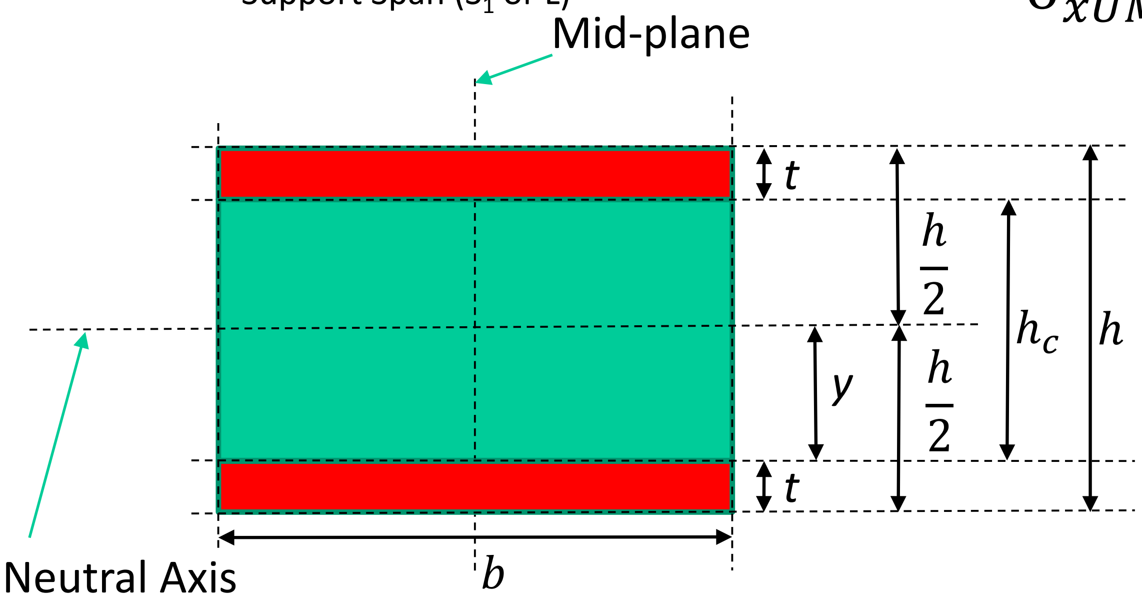
Composite Beam Theory Used for Analysis



$$\varepsilon_x = \frac{-12yv_{ll}}{L^2}$$

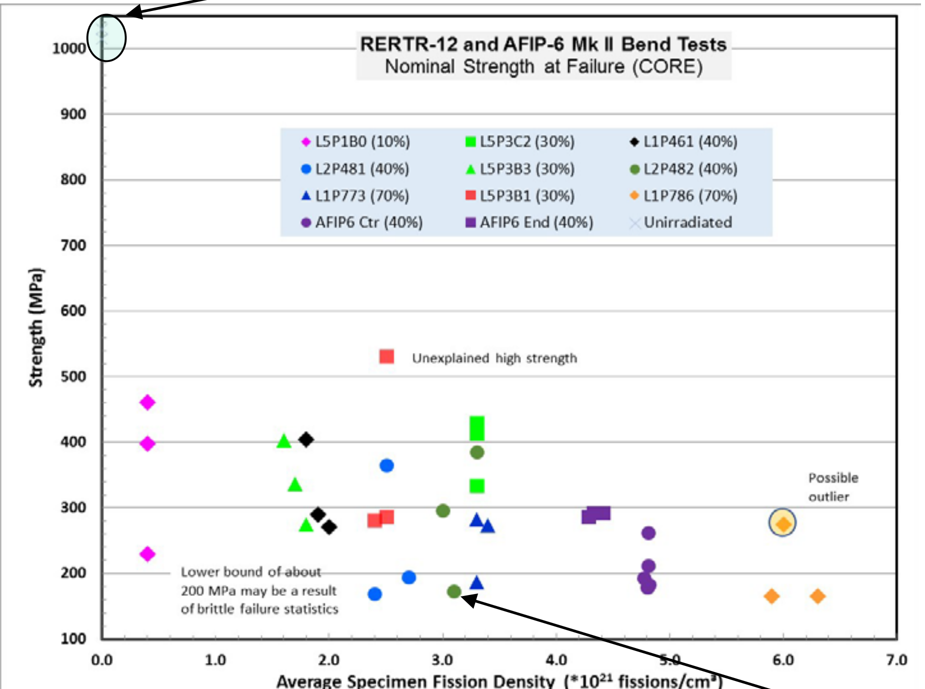
$$E_{UMo} = \frac{M - kE_{Zr}I_{Zr}}{kI_{UMo}}$$

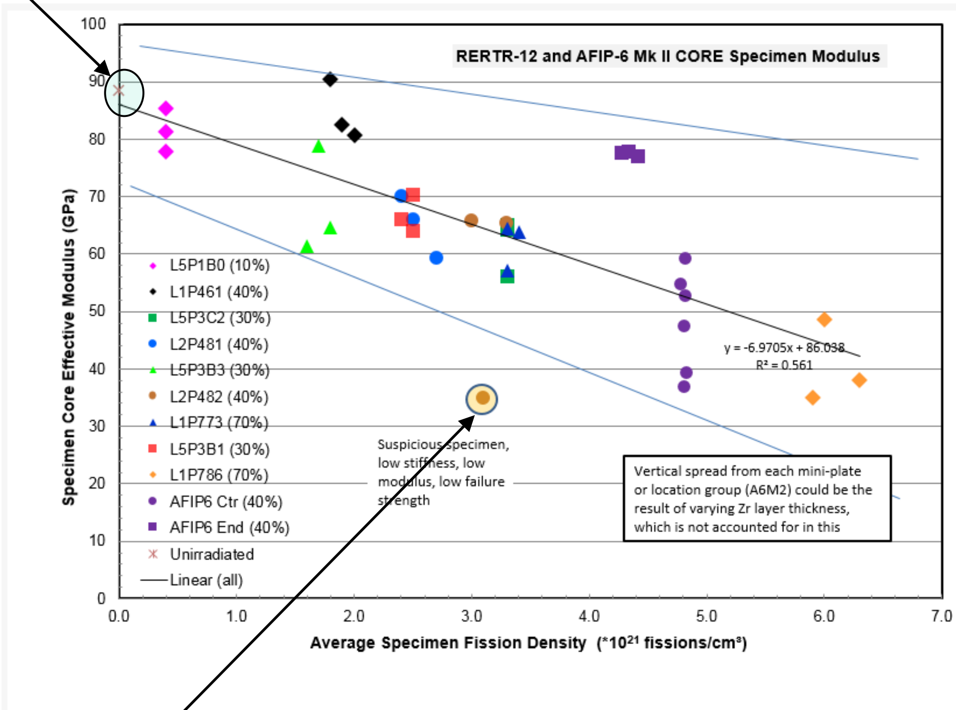
$$\sigma_{xUMo} = \frac{-MyE_{UMo}}{E_{Zr}I_{Zr} + E_{UMo}I_{UMo}}$$



Effect of irradiation

Unirradiated value





- Significant decrease in strength at low fission density
- No measureable ductility compared to unirradiated which had 1-2% elongation (brittle failure)

Same specimen

What about porosity?

- Previous work concluded that mechanical properties degradation was due primarily to irradiation temp and burnup.
- We also know that porosity increases with burnup/fission density and is also related to irradiation temp
- Can the mechanical properties degradation be related to the porosity?

Table 7. Summary of average phase fraction in percent for each sample.

Sample ID	Fission Density	Carbide precipitates [%]	Un-recrystallized regions [%]		Porosity [%]
				Region growing sub-routine excluded	
AFIP–6 MkII Top	4.53E+21	1.0	22.3	13.8	11.8
AFIP–6 MkII Middle	4.85E+21	0.9	11.4	6.9	16.5
AFIP–6 MkII Bottom	4.90E+21	0.8	2.8	1.6	27.2
L1P755	4.67E+21	0.0	10.6	4.7	13.3
L1P773	3.35E+21	0.0	25.1	15.2	13.7

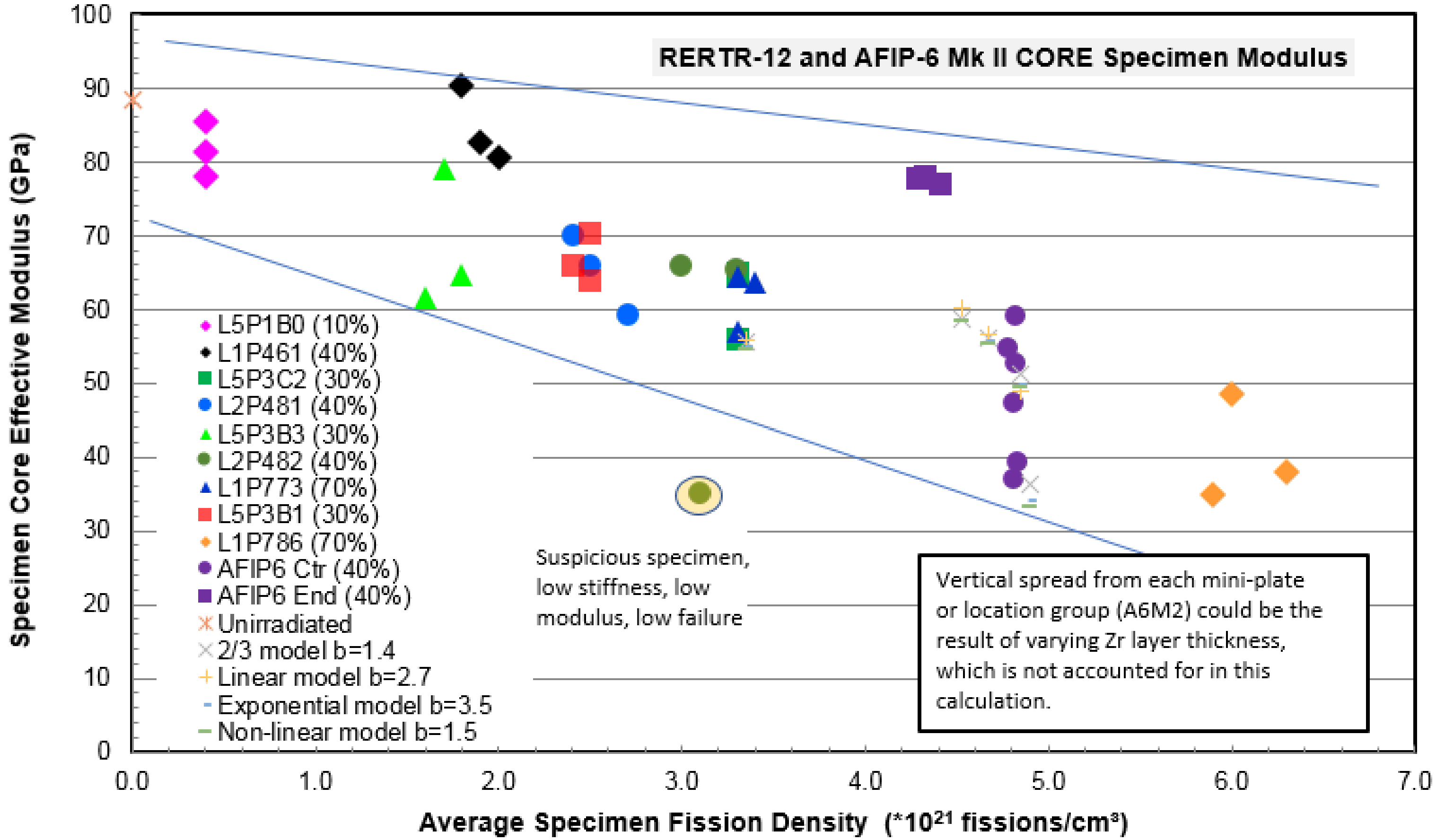
Table from Robinson et al (INL/LTD-18-50149)

Note: the samples in this analysis were taken adjacent to the samples used in the bend testing. Therefore, differences in the irradiation temperature and burnup/fission density between these samples and the bend test samples is considered negligible.

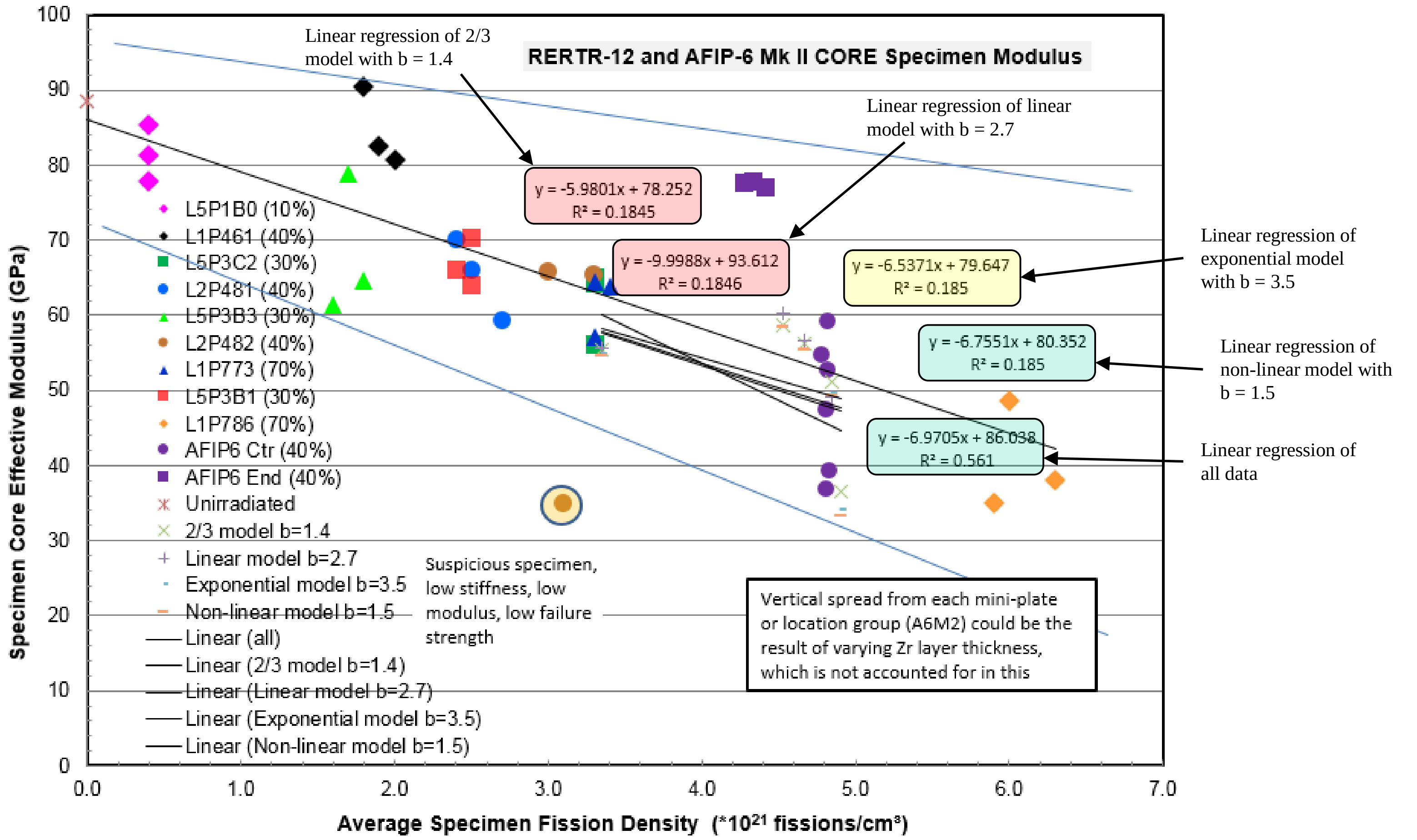
What we know

- *E = E(FD) (from experimental data)*
- *p = p(FD) (from experimental data)*
- Prior work from powder metallurgy field suggesting the following models:
  - $E = E_0(1 - bp^{2/3})$ Hyun (2001) (2/3 model)
  - $E = E_0(1 - bp)$ Fryxell (1964) (linear model)
  - $E = E_0 e^{-bp}$ Rice (1993) (exponential model)
  - $E = E_0 \frac{(1-p)^2}{(1+pb_\theta)}$ Ramakrishnan and Arunachalam (1990) (non-linear model)

Compare experimental modulus with modulus predicted by porosity models



Is there a best fit?



Summary

- PART 1 Un-irradiated Properties of U-10Mo –
  - 4 fabrication variants tested from room temp to 550 °C
  - Variants produced different yield and ultimate strengths at intermediate temps
  - Higher strengths that previously reported, but comparison is difficult due to differences in material history, and missing information on historical material
- PART 2 Irradiated Properties of U-10Mo –
  - Flat plate source material required use of bend testing through custom load frame and 4-point bend fixture
  - Limited previous data exists, comparison is difficult
  - Significant reduction in strength with low fission density, decreasing trend in modulus observed
  - Large scatter in data, small number of samples available, brittle failure mechanisms based on no ductility observed
  - Limited porosity data available
  - Compared predicted modulus from porosity model to experimental modulus, reasonable agreement given limitations in available data
- Recommendations –
  - More work is needed to understand outliers (microscopy), and improve statistics (more samples)
  - Fracture modeling to evaluate sensitivity to pore size and volume fraction may be helpful

Acknowledgements

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- Katelyn Wheeler
- Thomas Walters
- Michael Heighes

QUESTIONS?