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Results of Irradiated TRIGA Fuel Furnace Tests

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Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

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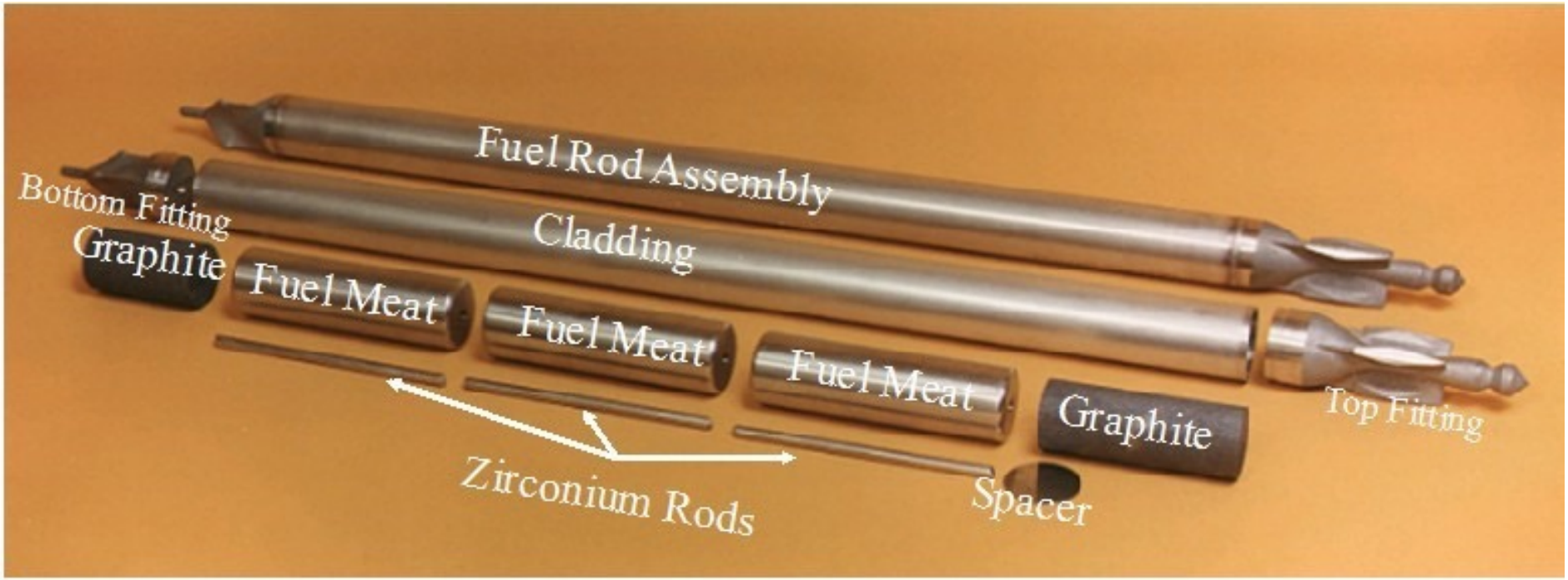
Outline

- Introduction
- Characterization of Irradiated TRIGA Fuel Rod Used for Annealing Tests
- Description of Furnace Testing
- Results of Post-Test Visual Examinations
- Result of Post-Test Microstructural Characterization using Optical Metallography
- Summary

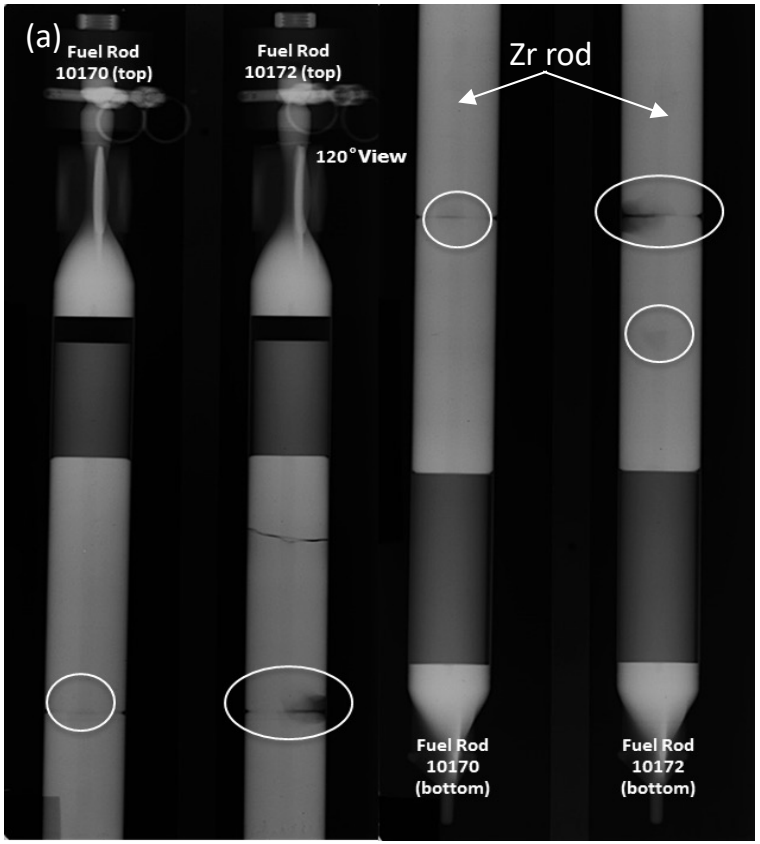
Introduction

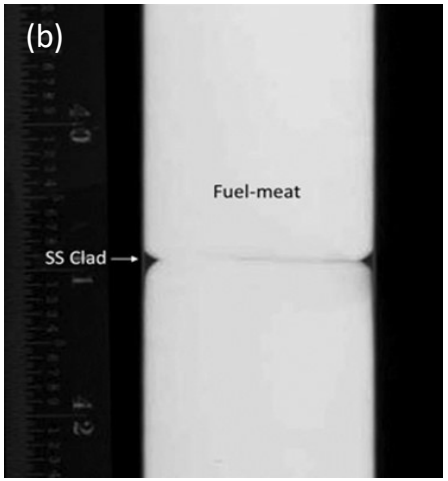
- The high-temperature behavior of irradiated Training, Research, Isotopes, General Atomics (TRIGA) fuel (U-ZrH/Type 304 stainless steel) has been investigated.
  - Information important for improving understanding of fuel behavior during a reactor transient (e.g., LOCA).
  - Of interest, if there are signs of liquefaction at the fuel/cladding interface due to presence of low-melting phases that formed due to fuel/cladding chemical interaction during irradiation.
- Annealing experiments performed using sections from a (30 wt.% U, ^{235}U <20%) TRIGA fuel rod with Type 304 stainless steel irradiated to a calculated depletion of 20% ^{235}U.
  - Starting irradiated fuel rod non-destructively and destructively examined
  - Tests run for 6 hours at 730, 800, 900, 950, and 1,000˚C, and one test was run at 950˚C for 12 hours.
- Annealed sections were visually examined and then mounted, polished and examined using optical metallography (OM).
- Results of starting irradiated fuel rod characterization and visual examination and OM characterization of the annealed samples will be presented.

As-Fabricated TRIGA Fuel Element



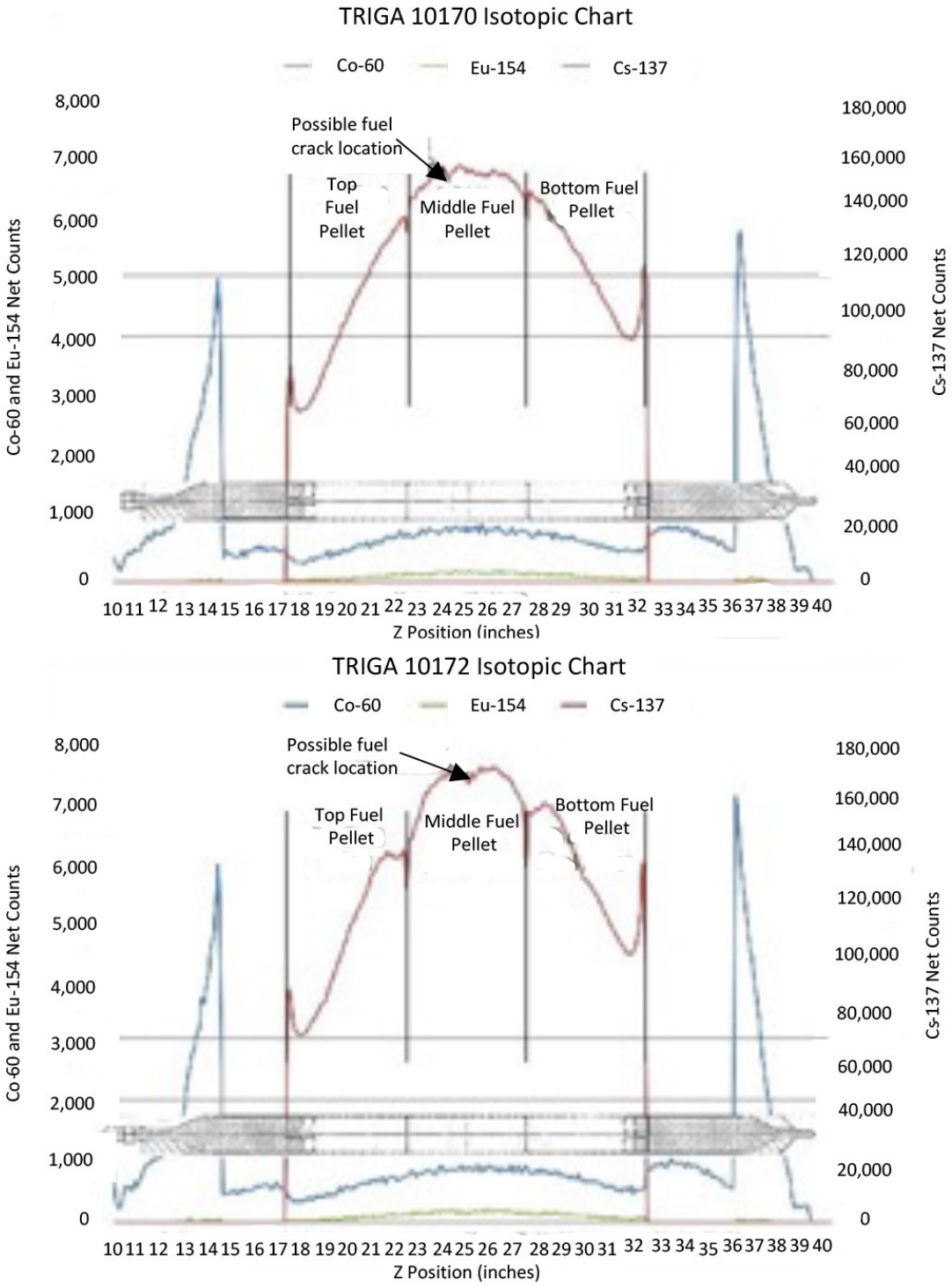
Neutron Radiography



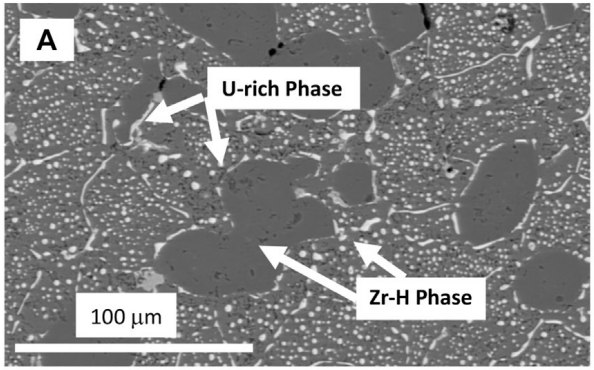


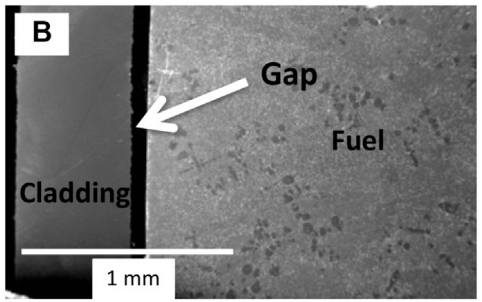
Precision Gamma Scanning

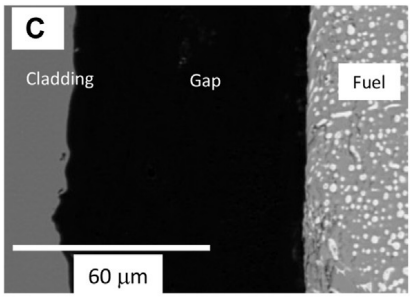
Fuel rod 10172 selected for annealing experiments



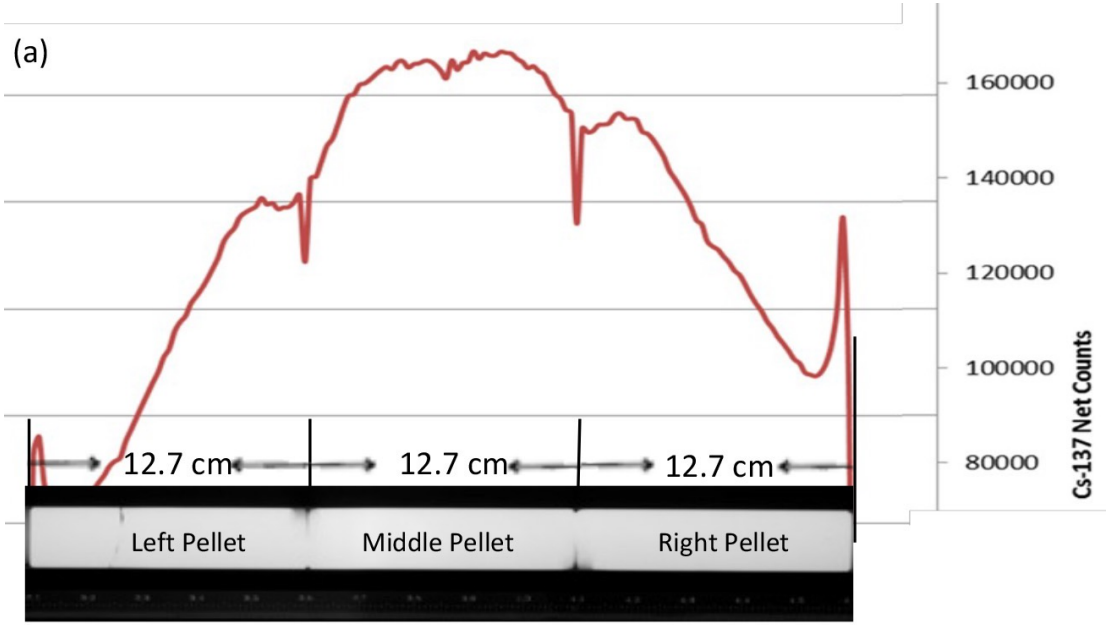
Sample Production

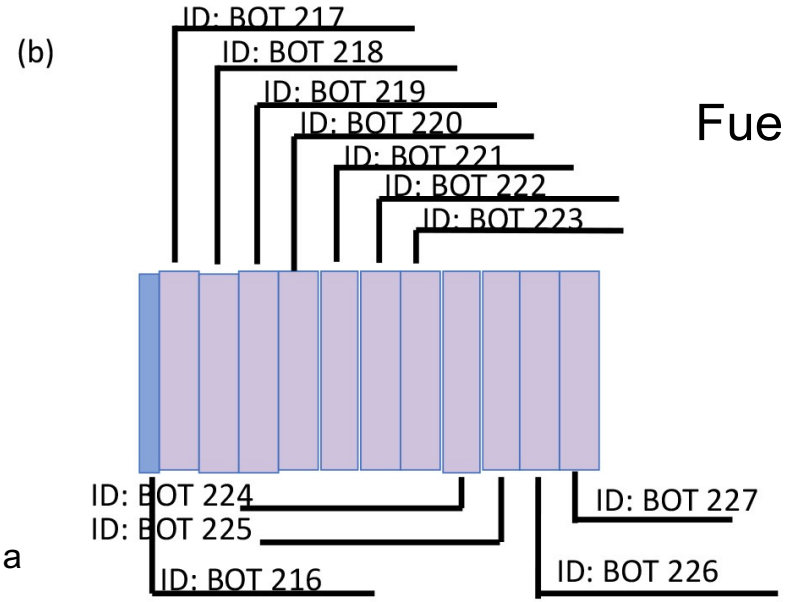






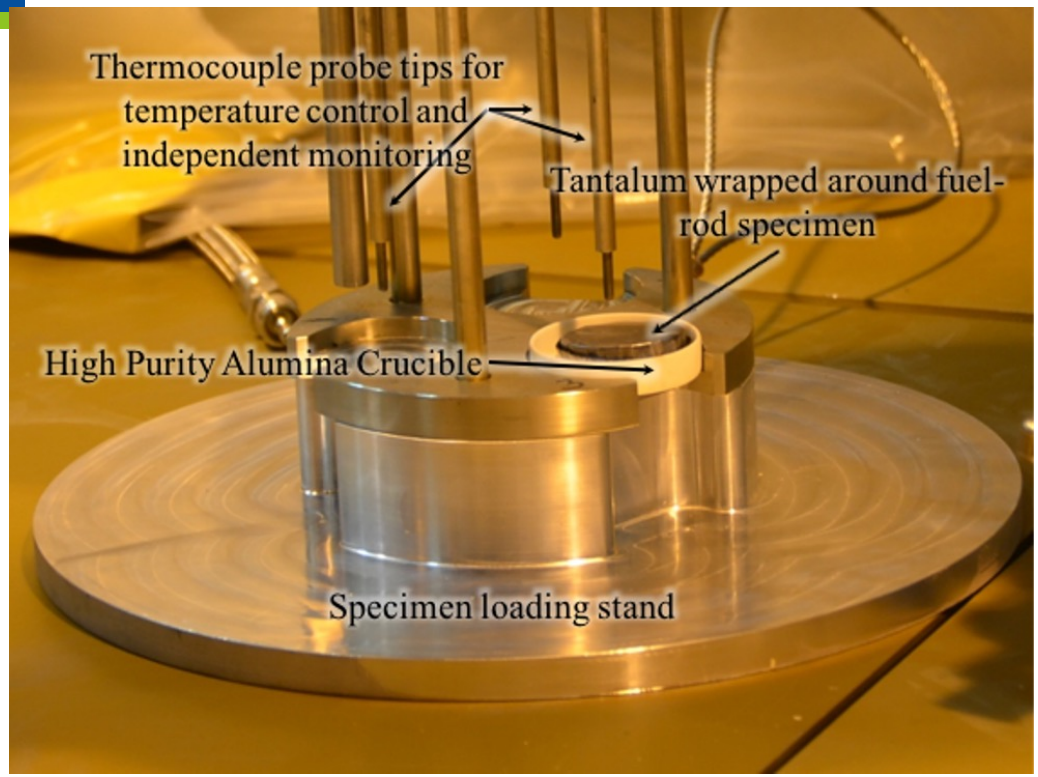
[Dennis Keiser, Jr., et al. "Post Irradiation Examination of a Uranium-Zirconium Hydride TRIGA Fuel Element," Front. Energy Res. 11:1106601. doi. 10.3389/fenrg.2023.1106601]

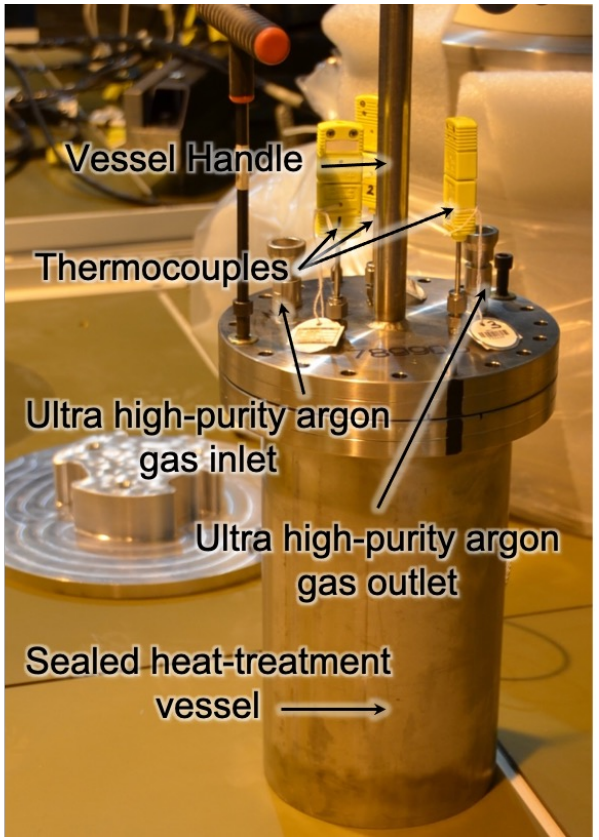




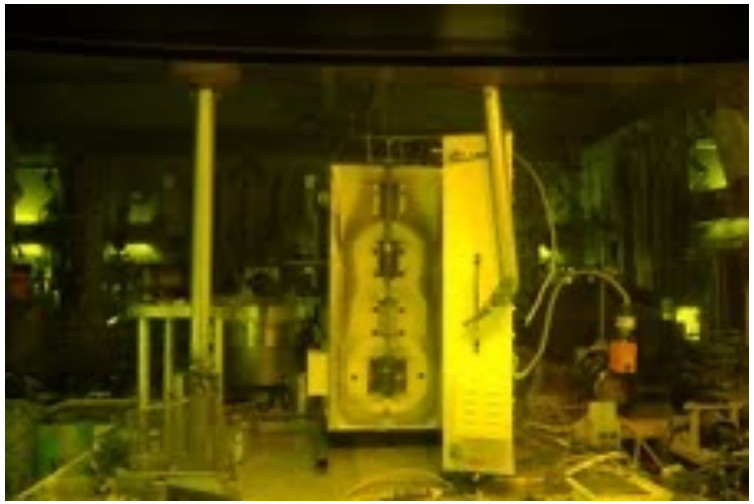
Fuel Rod 10172

Experiment Furnace





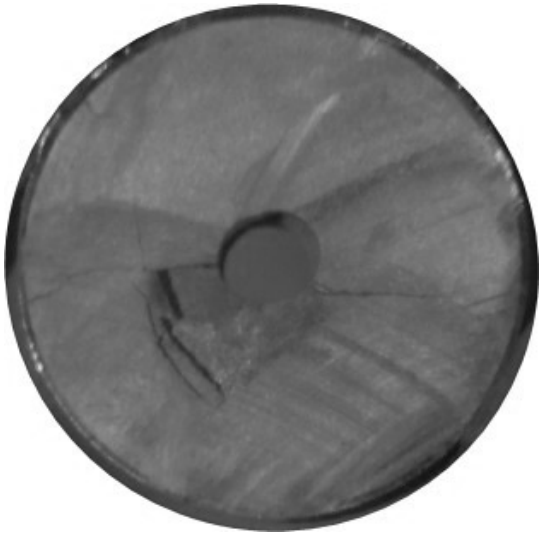
Resistance Furnace



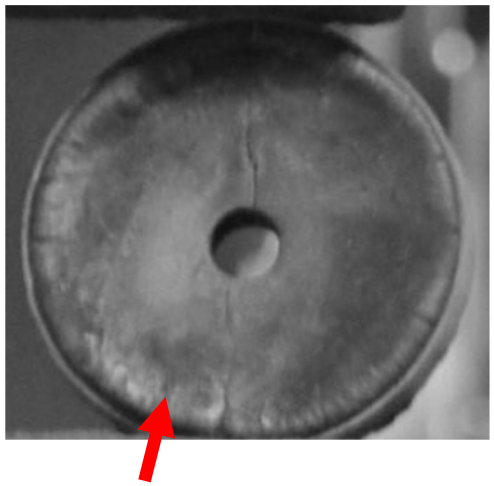
Furnace Testing

- Tests run for 6 hours at 730, 800, 900, 950, and 1,000˚C, and one test was run at 950˚C for 12 hours.
  - Ultra-high purity argon environment
  - Three Ta foils put on top of crucible to absorb any trace oxygen or impurities
- Bulging observed for sample tested at 950˚C for 6 hours.
  - Immersion density performed on an additional sample before and after annealing at 950˚C for 6 hours
    - Dimensional increase of 23% and a mass loss of ~5% (assumed to be due to hydrogen loss)
- Each tested section was visually examined, and no melting was observed.

As-received

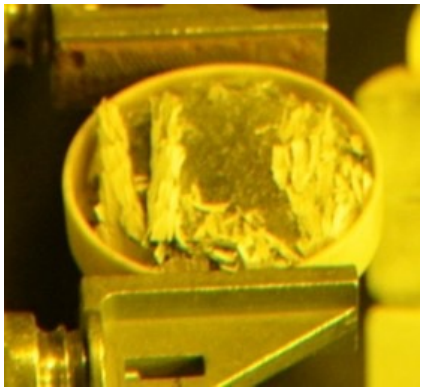


(950˚C, 6 hours)

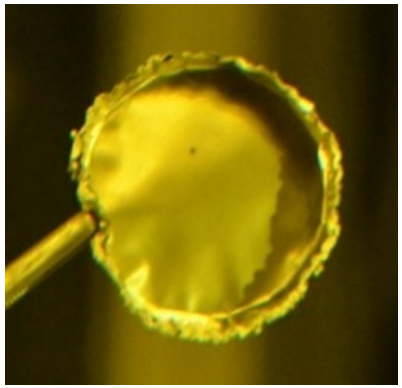


Bulging

(800˚C, 6 hours)

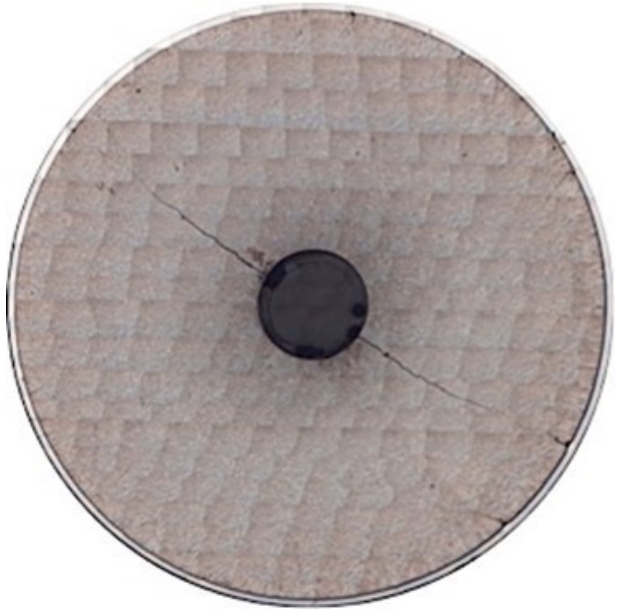


Top Ta layer reacted

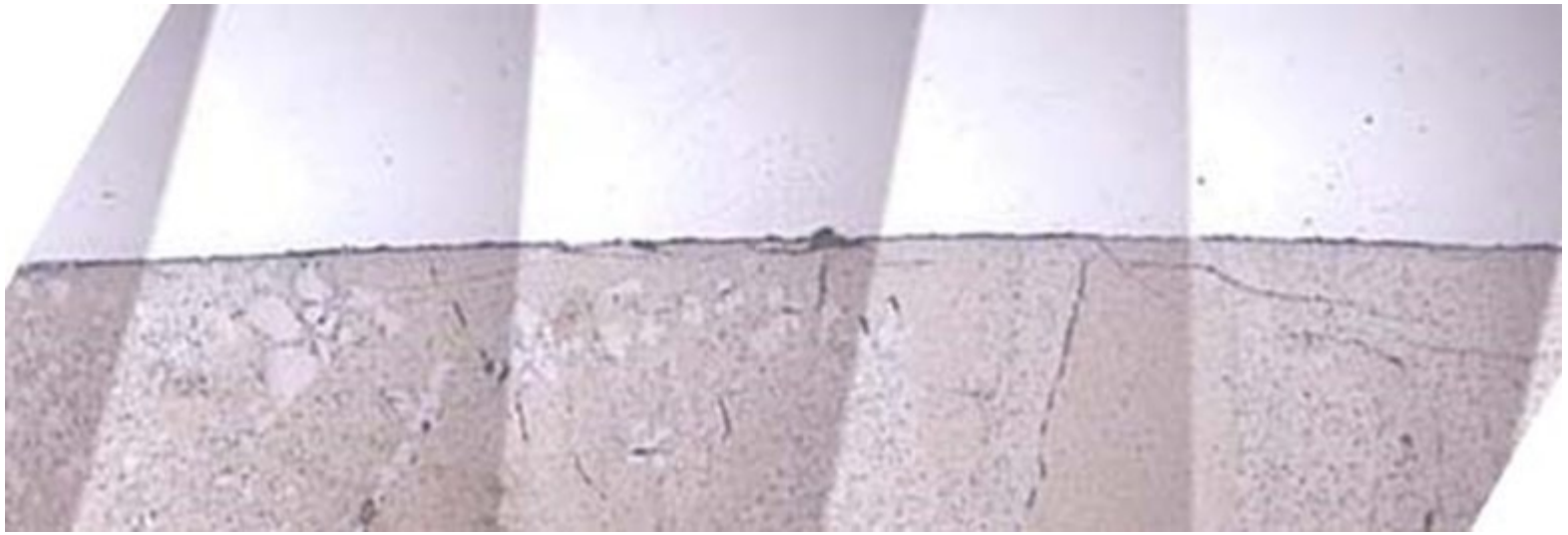


Bottom Layer of Ta

Microstructural Characterization (OM)



As-irradiated, non-heat-treated (montage of 31.x images)



Montage of 200x images

No obvious contact at the fuel/cladding interface

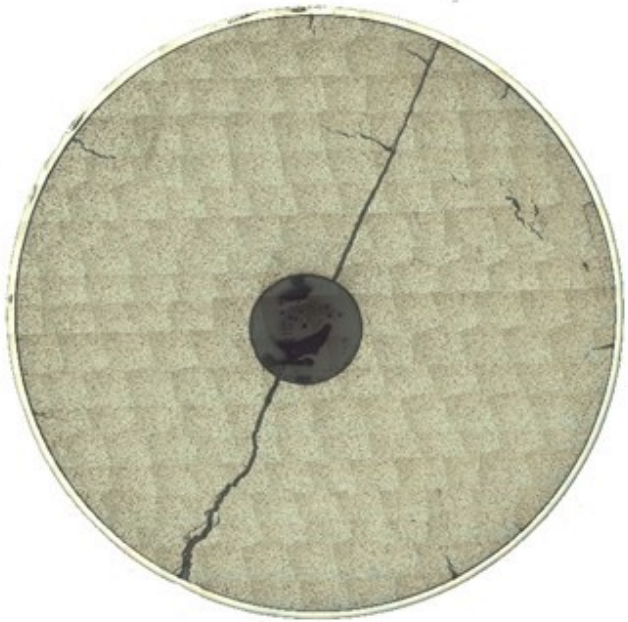
Microstructural Characterization (OM)

Annealed at 730˚C for 6 hours

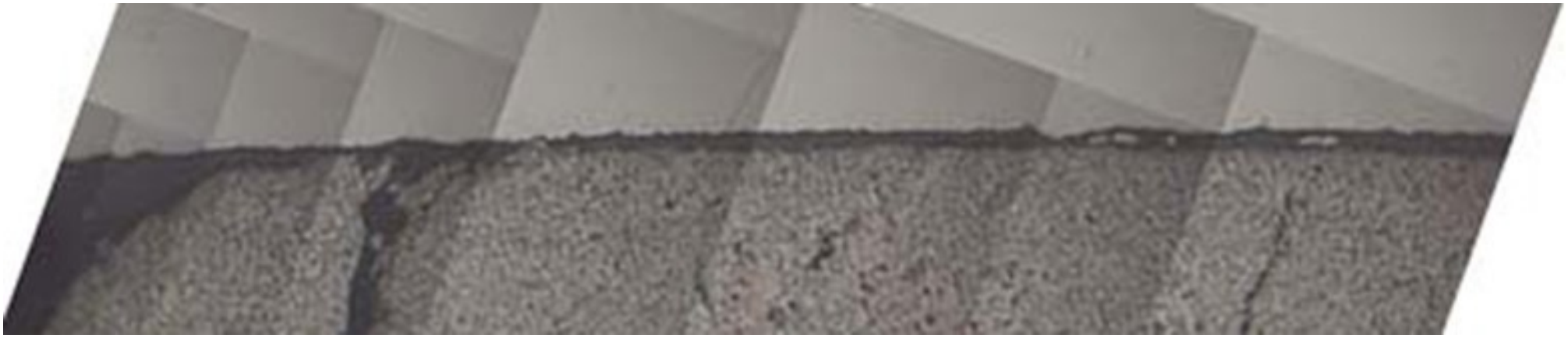
Montage of 100x images

Some limited fuel/cladding contact possible

Microstructural Characterization (OM)



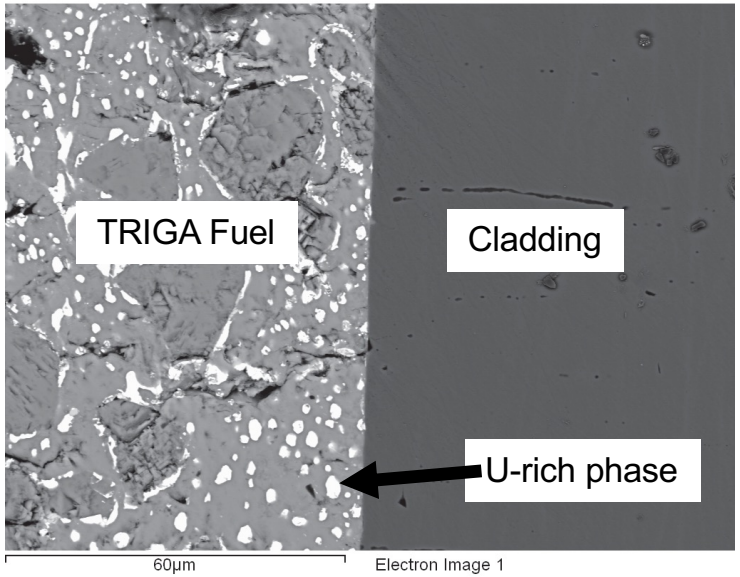
Annealed at 800˚C for 6 hours



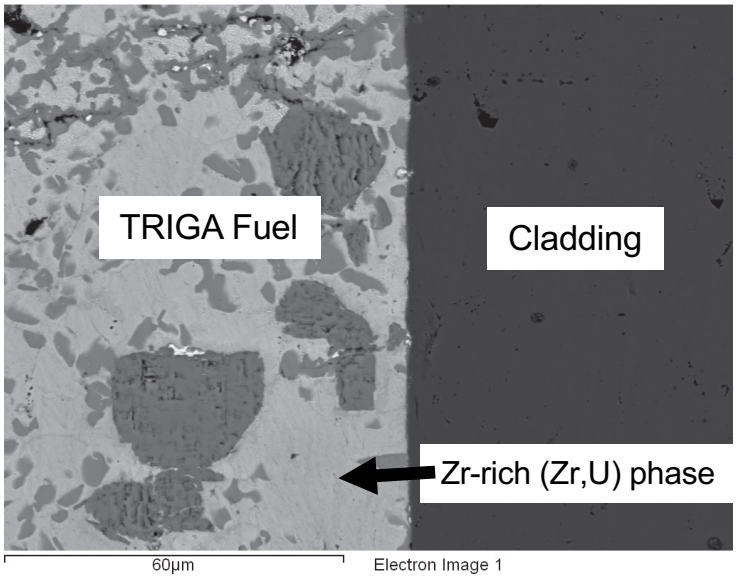
Montage of 200x images

Some limited fuel/cladding contact possible

Microstructural Differences for TRIGA Fuel Heated at 730 and 800˚C

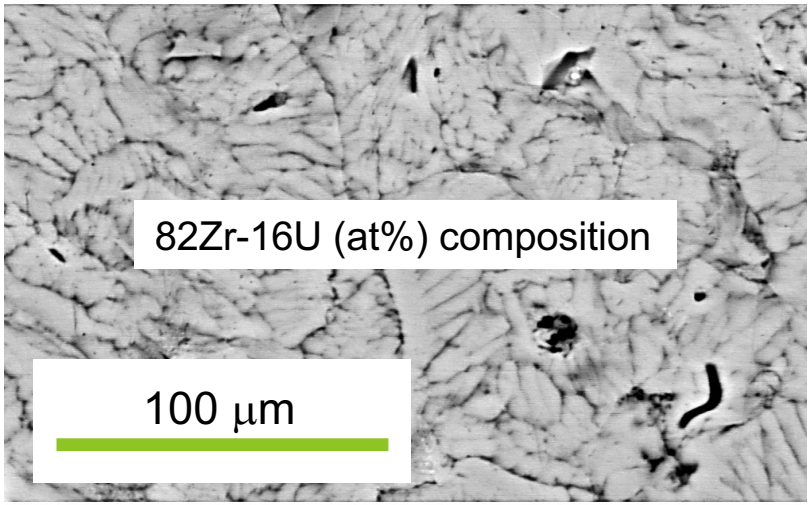


730˚C, 1 Hour (similar to as-fabricated microstructure)



800˚C, 1 Hour (microstructure not similar to as-fabricated microstructure)

Diffusion couple tests employed as-fabricated TRIGA fuel and Type 304SS

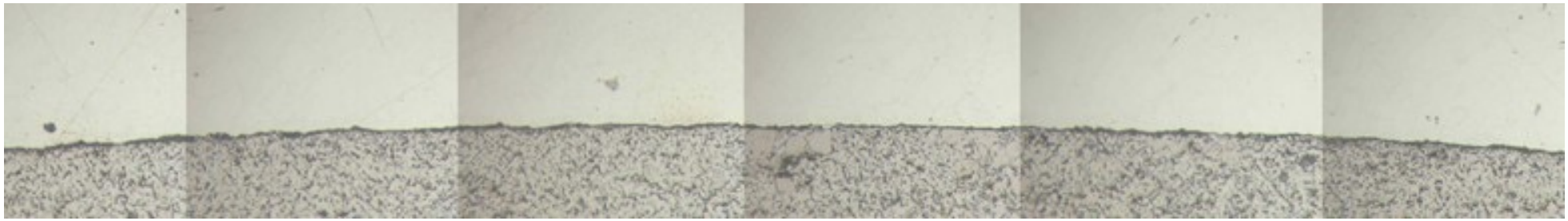


As-fabricated TRIGA fuel heated at 950˚C for 6 hours

X-ray diffraction indicated presence of UZr_2

Microstructural Characterization (OM)

Annealed at 900˚C for 6 hours



Montage of 200x images

Appears to be narrow gap at fuel/cladding interface

Microstructural Characterization (OM)

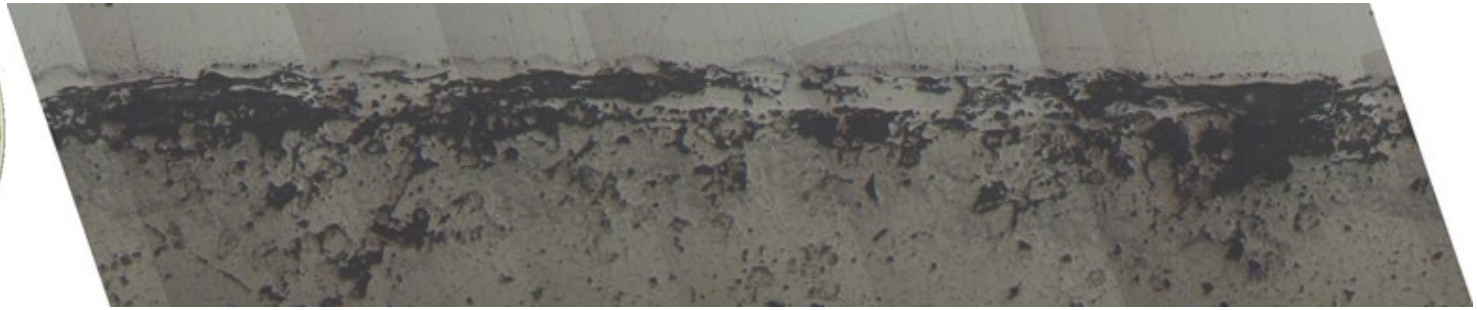
First section annealed at 950˚C for 6 hours

Montage of 200x images

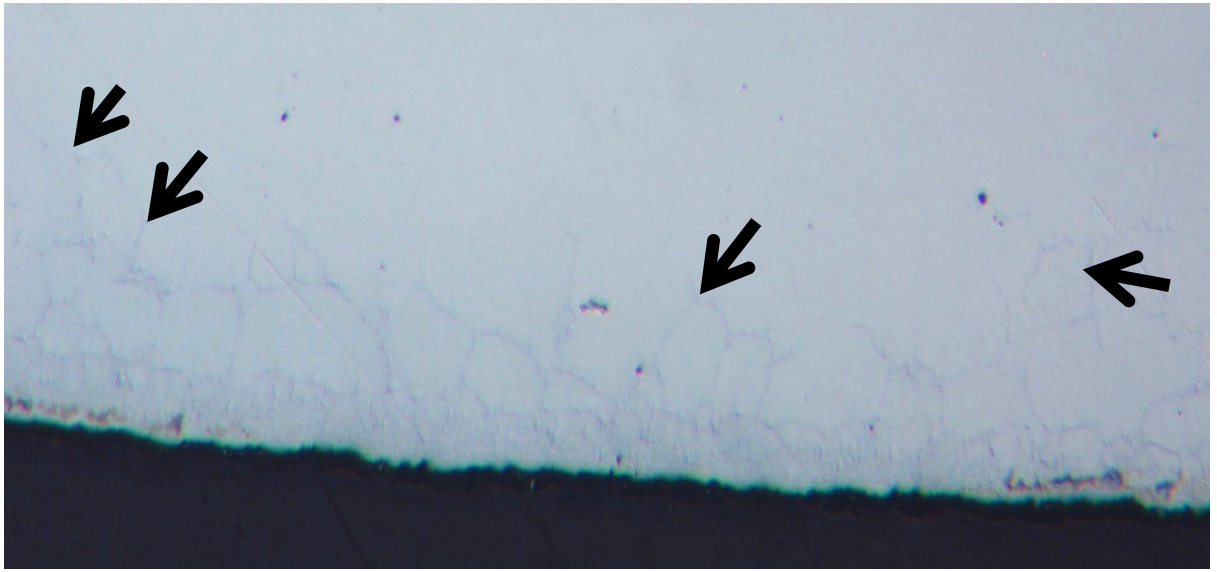
Layer due to fuel/cladding chemical interaction (FCCI) seems to be present.

Microstructural Characterization (OM)

Second section annealed at 950˚C for 6 hours



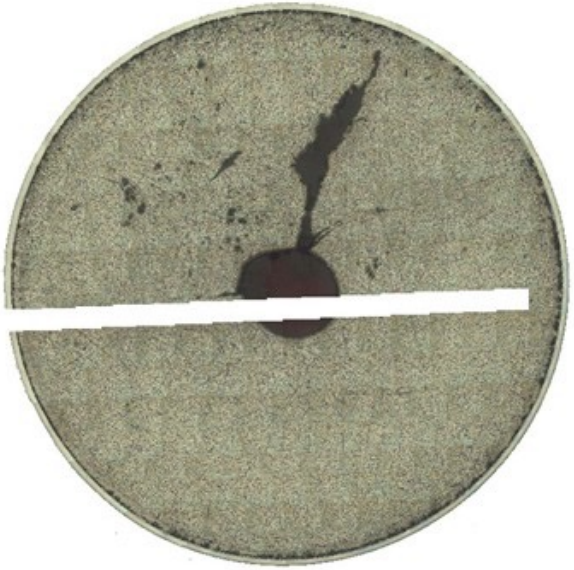
Montage of 200x images



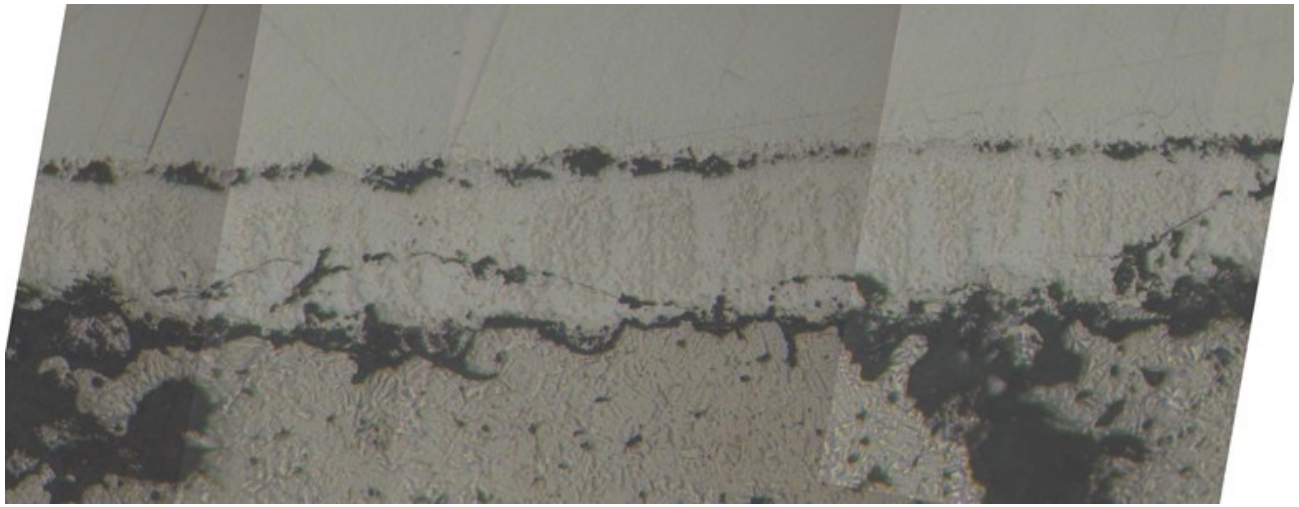
OM image (100x magnification) showing possible grain boundary phases

Layer due to fuel/cladding chemical interaction (FCCI) and possible cladding grain boundary phases seem to be present.

Microstructural Characterization (OM)



Annealed at 950˚C for 12 hours

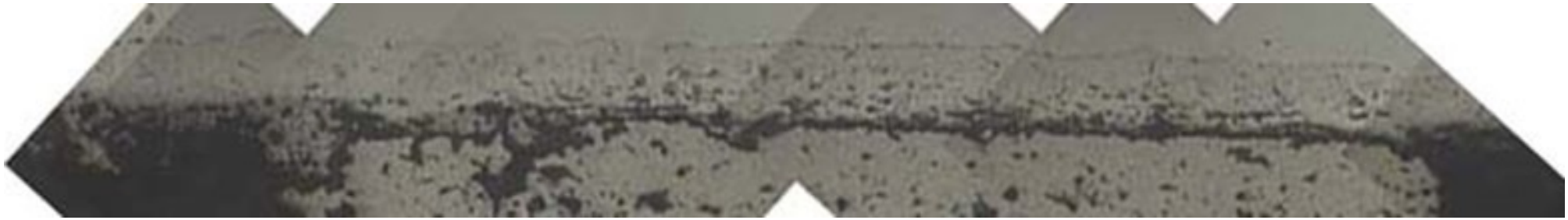


Montage of 200x images

Layer due to fuel/cladding chemical interaction (FCCI) seems to be present.

Microstructural Characterization (OM)

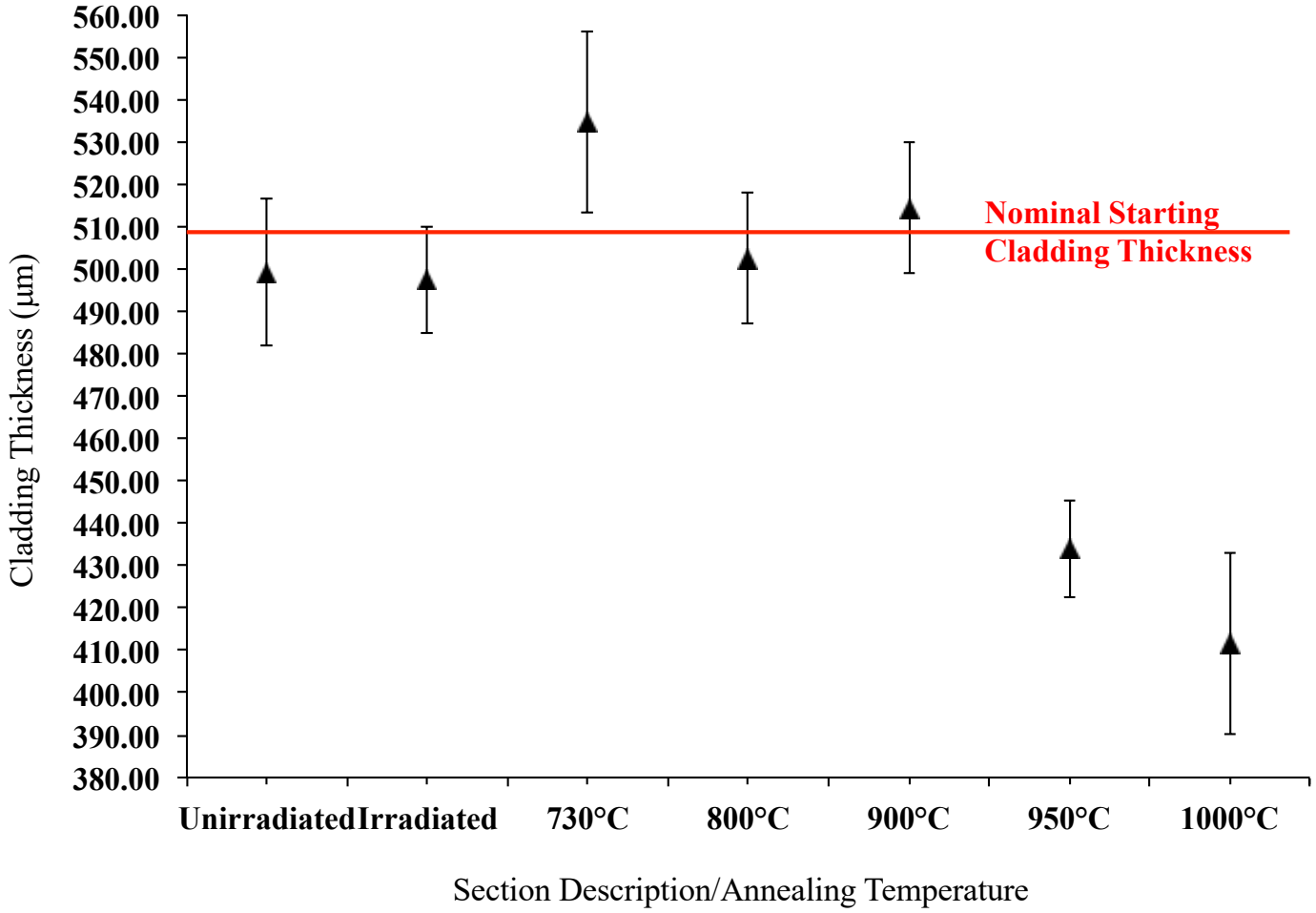
Annealed at 1,000˚C for 6 hours



Montage of 200x images

Layer due to fuel/cladding chemical interaction (FCCI) seems to be present.

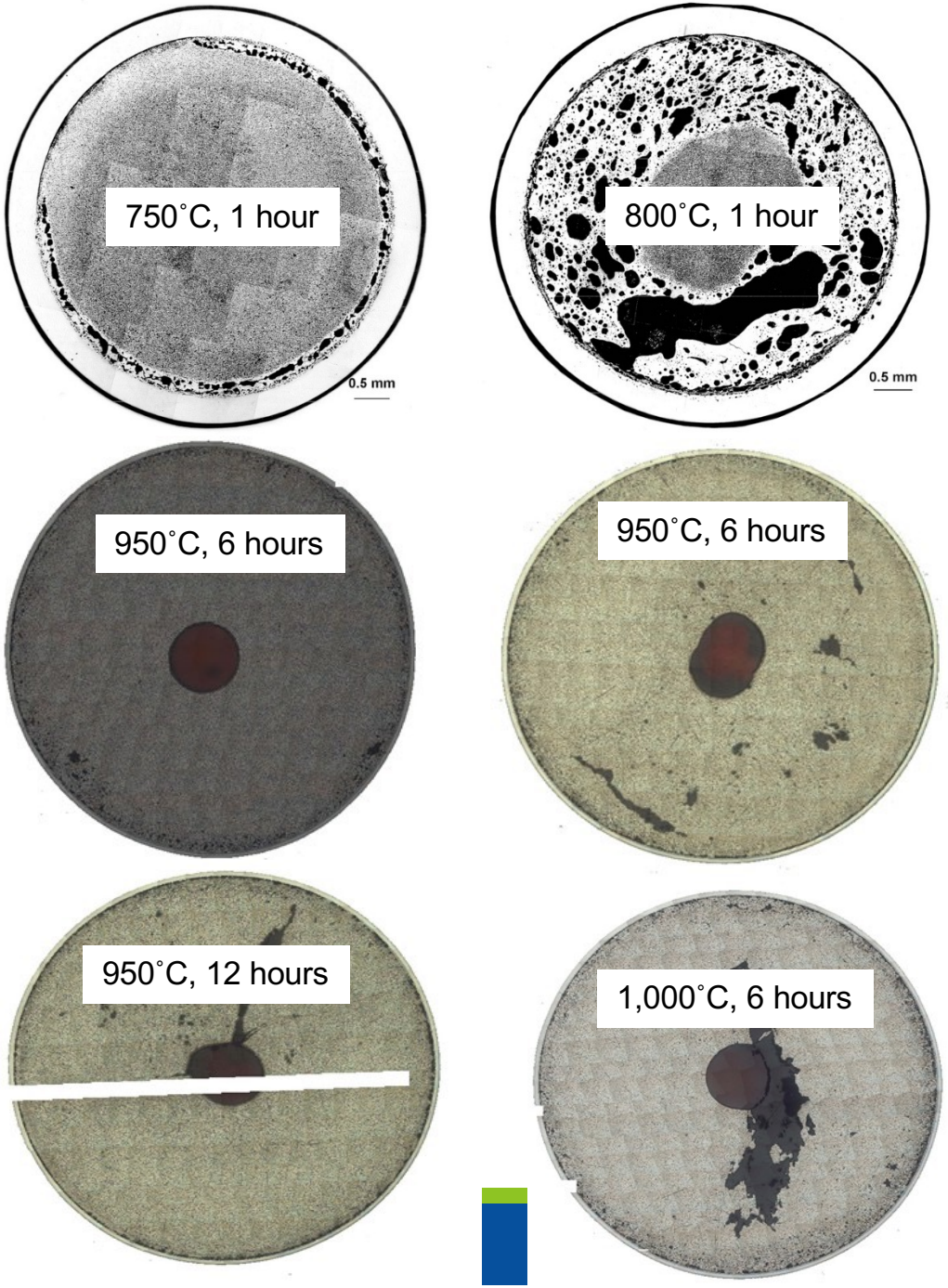
Cladding Thickness not Impacted by FCCI



Even after annealing at 1,000˚C for 6 hours, over 75% of the cladding thickness is devoid of observable FCCI

Comparison to Reported Annealing Experiments Using U-10Zr/HT9 Fuel Irradiated in the Experimental Breeder Reactor to 3 At.% Burnup

H. Tsai, F. E. Savoie, L. R. Kelman, and W. D. Jackson, "Compatibility of Low-Burnup U-10Zr Fuel with HT9 Cladding at Elevated Temperatures," Argonne National Laboratory Report. ANL-IFR-104 (February 1989).



Summary

- Annealing experiments performed using sections from (30 wt.% U, ^{235}U <20%) TRIGA fuel rod with Type 304 stainless steel irradiated to a calculated depletion of 20% ^{235}U.
  - Tests run for 6 hours at 730, 800, 900, 950, and 1,000˚C, and one test was run at 950˚C for 12 hours.
- No evidence of liquefaction after visual examinations were performed.
- Microstructural characterization using optical microscopy (OM) was performed, and no evidence of gross liquefaction was observed in any of the tested sections.
- Using OM, a FCCI zone was identified for the sections tested at 950 and 1,000˚C.
  - Gap at fuel/cladding interface seemed prevalent for lower temperature annealing tests.
- Even for the section tested at 1,000˚C, over 75% of the cladding thickness was devoid of observable FCCI.

Acknowledgments

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Idaho National Laboratory

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