Disc Irradiation for Separate Effects Testing (DISECT) with Control of Temperature

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The DISECT project includes the design and fabrication of a uniquely instrumented, separate effects testing vehicle; specimen fabrication and pre-characterization; irradiation; and post-irradiation examination to enable a more comprehensive understanding of in-pile phenomena.

As modern advanced reactors, such as those proposed within the Versatile Test Reactor and the Advanced Fuel Cycle programs, envision the use of metallic fuels, there is renewed interest in examining these fuel systems in order to comprehensively understand in-pile fuel behavior and maximize fuel performance while maintaining fuel integrity in a stable and predictable manner. Metallic fuels and materials require immediate and extensive testing that expands upon the historical knowledge amassed over decades [1–4] in order to provide a more fundamental and scientific understanding of metallic fuels, assess their material performance, and to validate models. Investigation into the fundamental, nano- and microscale phenomena that impact bulk fuel behavior is critical to the understanding of future fuel systems and reactor development. Historical hindrances to this effort included convoluted experimental parameters that are challenging to isolate during neutron irradiation, such as temperature, alloy composition, and power rate. These variable experimental conditions are compounded by the coexistence of various in-pile phenomena, such as constituent redistribution, swelling, and fuel/cladding chemical interaction. Separate effects testing has the ability to isolate these parameters and competing phenomena within single irradiation campaigns of relatively short duration.

Uranium-zirconium (U-Zr) and uranium-molybdenum (U-Mo) are the two most-commonly utilized and historically studied metallic fuel systems that are also under consideration for advanced reactor use. To address the aforementioned gaps that exist within the metallic fuel body of knowledge, these two metallic fuels will be irradiated utilizing a separate-effects approach to isolate alloy composition, irradiation temperature, burnup, and power. This investigation is termed the Disc Irradiation for Separate Effects Testing with Control of Temperature (DISECT) project. The research involves a collaborative effort with the Studiecentrum voor Kern-energie, Centre d'Étude de l'énergie Nucléaire (SCK•CEN) in Mol, Belgium and the Nuclear Science User Facilities (NSUF) utilizing capabilities at Idaho National Laboratory, Purdue University, and the Belgian Nuclear Research Center. In order to improve the mechanistic understanding of fuel behavior and performance. This international collaboration will be a first-of-a-kind NSUF experiment that will conduct irradiations in the Belgian Reactor 2 (BR2), located at SCK•CEN and shown in Figure 1, that have been designed, fabricated, and characterized at U.S. facilities (i.e., INL and Purdue University).

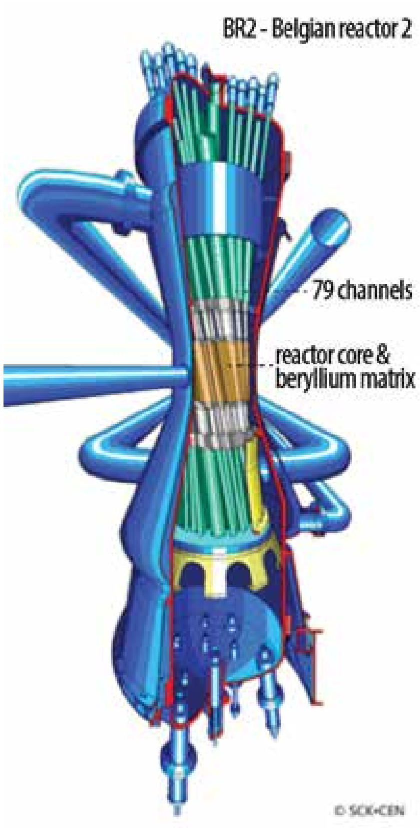

Figure 1. Cutaway illustration of the BR2 reactor. The hyperboloidal arrangement of the 79 channels provides a closely arranged core while retaining a large working space on the extremities. This feature is exceptional for the insertion of complex and instrumented vehicles [5].

Project Description

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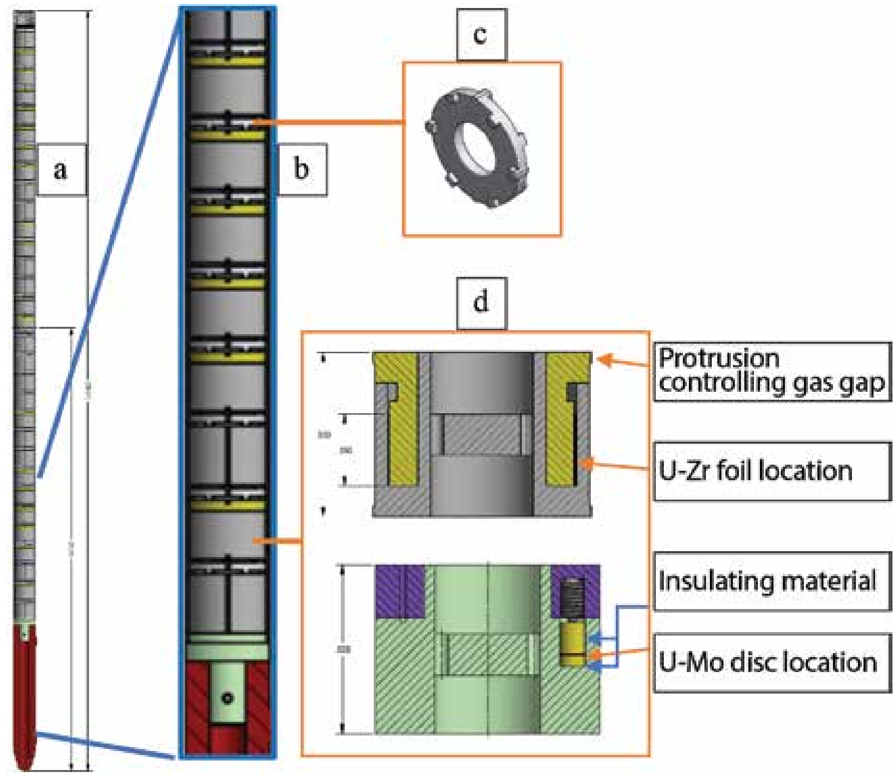

Figure 2. a) In-core portion of the test vehicle. b) Enlarged section of vehicle illustrating the stack-up of specimen holders separated by insulators. c) Insulators utilizing gas gaps to isolate specimen holders. d) Specimen holders for the U-Zr alloy foils (top) and the U-Mo alloys disks (bottom).

to enable a more comprehensive understanding of in-pile phenomena. The instrumented in-pile irradiation vehicle designed for insertion into BR2 is shown in Figure 2. The test vehicle is comprised of an outer capsule that serves as the housing for individual fuel samples and customizable instrumentation, such as thermocouples or other developmental in-pile instrumentation requiring testing. The in-core portion of the device is shown in Figure 2 (label a).

A unique aspect of the device is the customizable internals that keep individual samples isolated from one another in sealed sample enclosures separated by insulators that utilize gas gaps to isolate thermal effects from adjacent specimens, shown in Figure 2 (label b and c). This allows for in-pile conditions, such as atmosphere, temperature, composition, geometry, and power, to vary between samples in a single device. Such a device is able to provide the unique capability to target various phenomena of interest on a per sample basis. It also has the ability to be implemented for future work without a large-scale redesign or qualification. Figure 2 (label d) shows the sample enclosures for the U-Zr alloy foils (top) and the U-Mo alloys disks (bottom).

Low-enriched (19–20% weight U-235) U-Mo and U-Zr alloys of varying compositions were selected as the alloy compositions for this

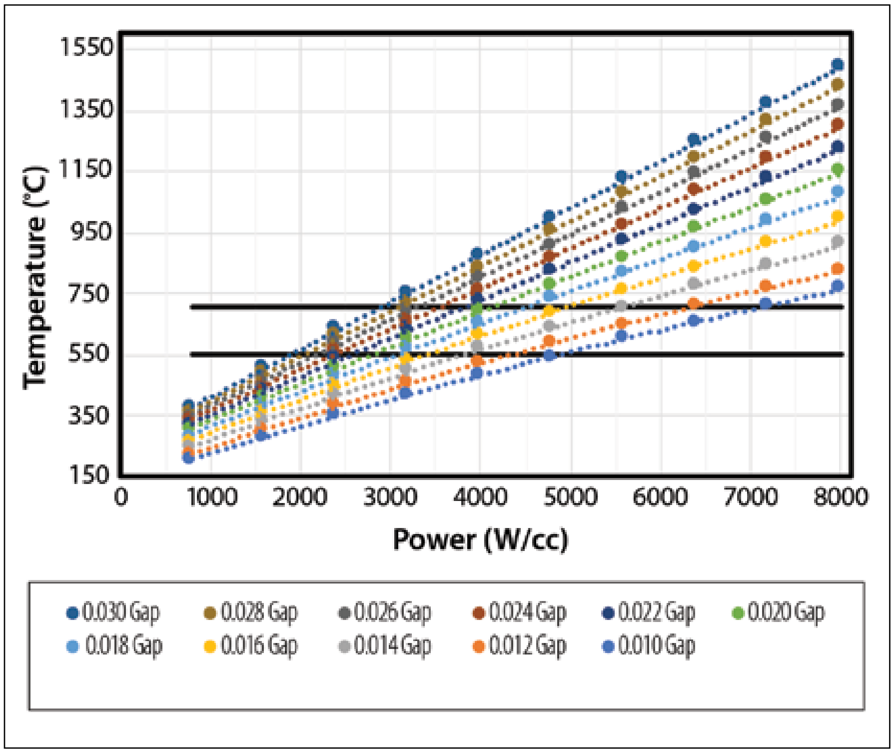

Figure 3. U-Zr foil temperature as a function of power for 1.5 W/g gamma heating. The black horizontal lines represent target specimen irradiation temperatures. The gap refers to the gas gap between specimen holder and vehicle wall in inches.

experiment. Fuel compositions for U-Mo include 7, 10, and 12 weight percent Mo, fabricated as discs (3 mm in diameter and 250 μm in height). The compositions for U-Zr include 6, 10, 20, and 30 weight percent Zr, fabricated as foils (180 μm thick, 72.75 mm long, and 8.9 mm wide), with the first irradiation including only U-10Zr and U-30Zr.

The U-Zr foil specimen holder design allows for a discrete sample temperature to be obtained by varying the insulating gas gap between the holder and vehicle wall. This feature allows for otherwise identical fuel samples to reach different temperatures without modifications to power, specimen geometry, alloy composition, or enrichment. Figure 3 indicates the ideal gas gap required for a target temperature and a given power.

In contrast, the desired irradiation temperature for the U-Mo discs is obtained by optimizing the spacer material surrounding the specimens with varying thermal conductivities to obtain desired irradiation temperatures. This method allows for higher power densities to be achieved at lower temperatures due to the contact of the specimen holder with the outer wall

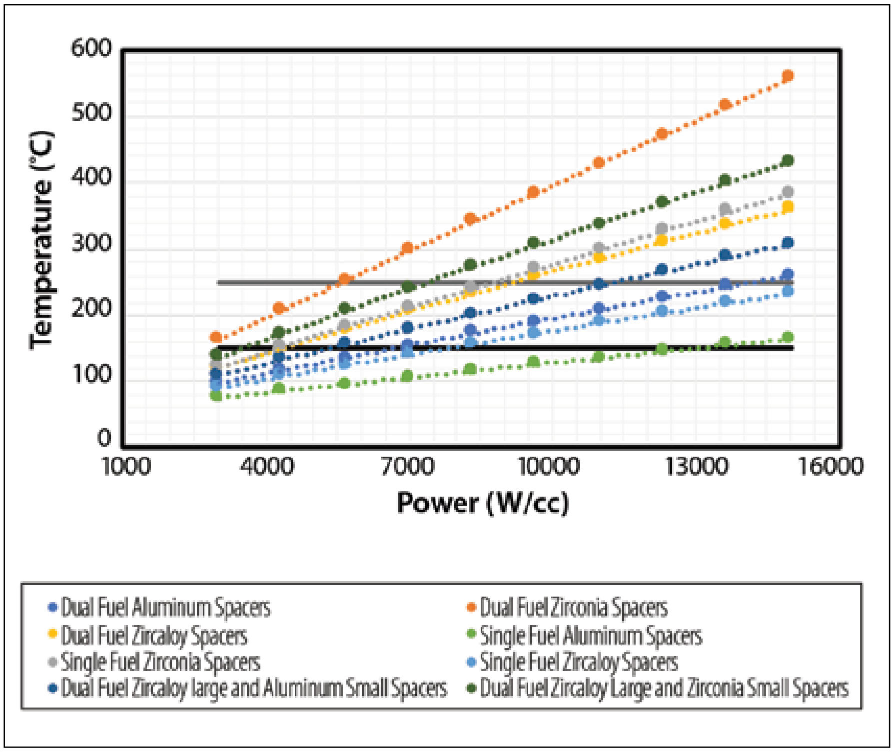

Figure 4. U-Mo disc temperature as a function of power for 1.5 W/g gamma heating. The black horizontal lines represent target specimen irradiation temperatures. Various materials are considered for spacers, including aluminum, zirconia, and zircaloy, to achieve the desired irradiation temperatures.

of the irradiation vehicle. This contact is ensured by the use of ball detents on the side of the specimen holder opposite the specimens. Figure 4 shows the optimization of desired irradiation temperatures for the U-Mo alloys with varying powers and spacer materials.

Accomplishments

A Phenomenon Identification and Ranking Table (PIRT) analysis was performed on both fuel systems to identify the phenomena to investigate and select the in-pile parameters to isolate. Following the PIRT findings, the DISECT project has completed the design review (INL) and the first stage of the committee for the evaluation of experiments for reactor insertion (SCK•CEN). The preliminary neutronics, preliminary thermal analysis, fuel fabrication, and precursory characterization of the U-Zr and U-Mo alloys were completed in FY 2018. Detailed thermal models are shown in Figure 5 for both the U-Mo disc and the U-Zr foil. These models were built with ABAQUS (v. 6.14-2) and using nominal neutronics information for the estimated insertion cycle. This model will be used to guide the specific irradiation-temperature conditions for post-irradiation characterization. Moreover, these localized models allow for discrete identification and, thus, a further understanding of phenomena such as constituent redistribution, porosity growth, fuel polygonization, and fission-gas superlattice formation as functions of temperature and/or power.

The fuel was fabricated at INL based on thermal and neutronics calculations and designs. Preliminary characterization has been conducted on both the U-Zr and U-Mo alloys.

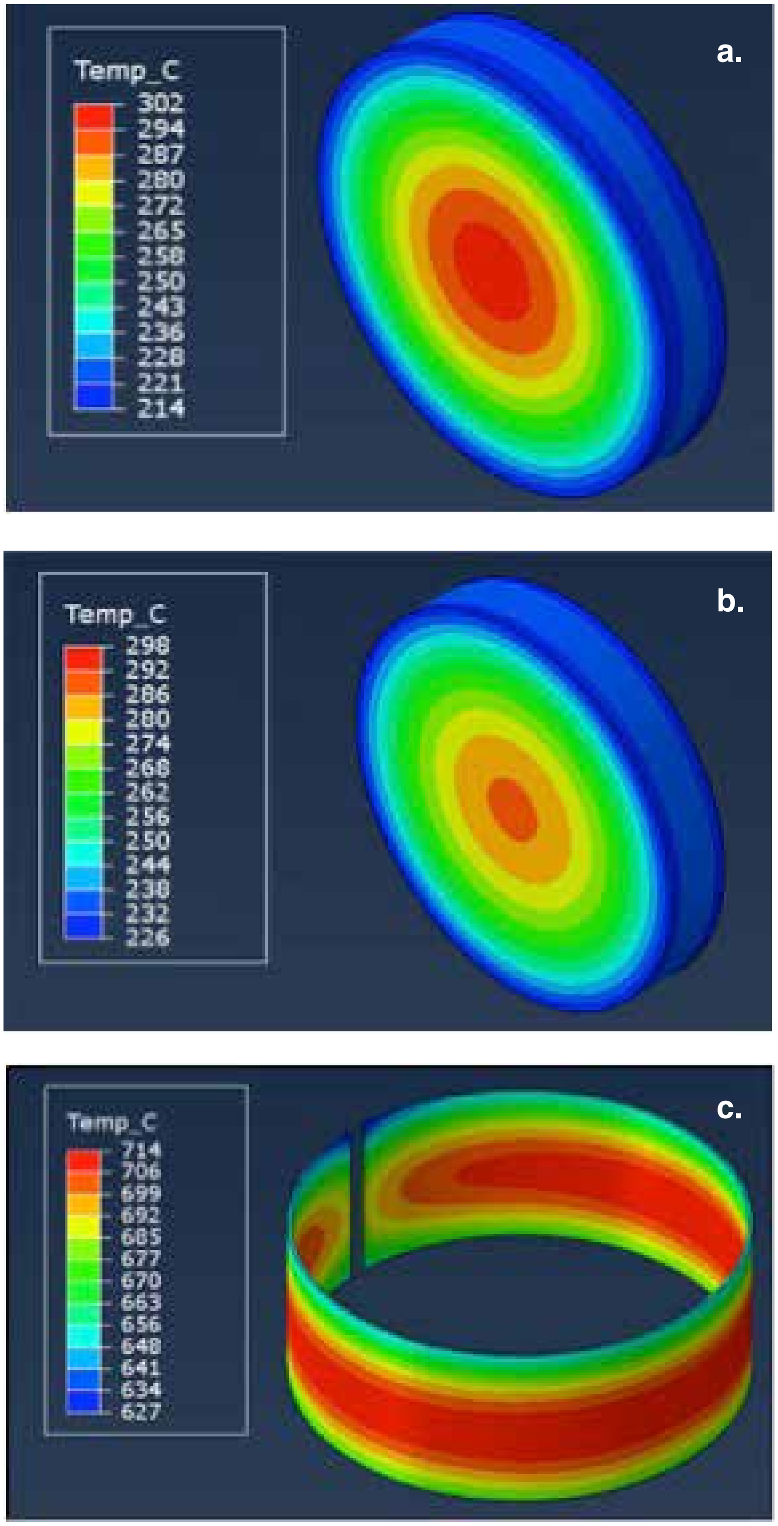

Figure 5. The estimated cost at INL for installation is $200K which should be the expected cost at other labs

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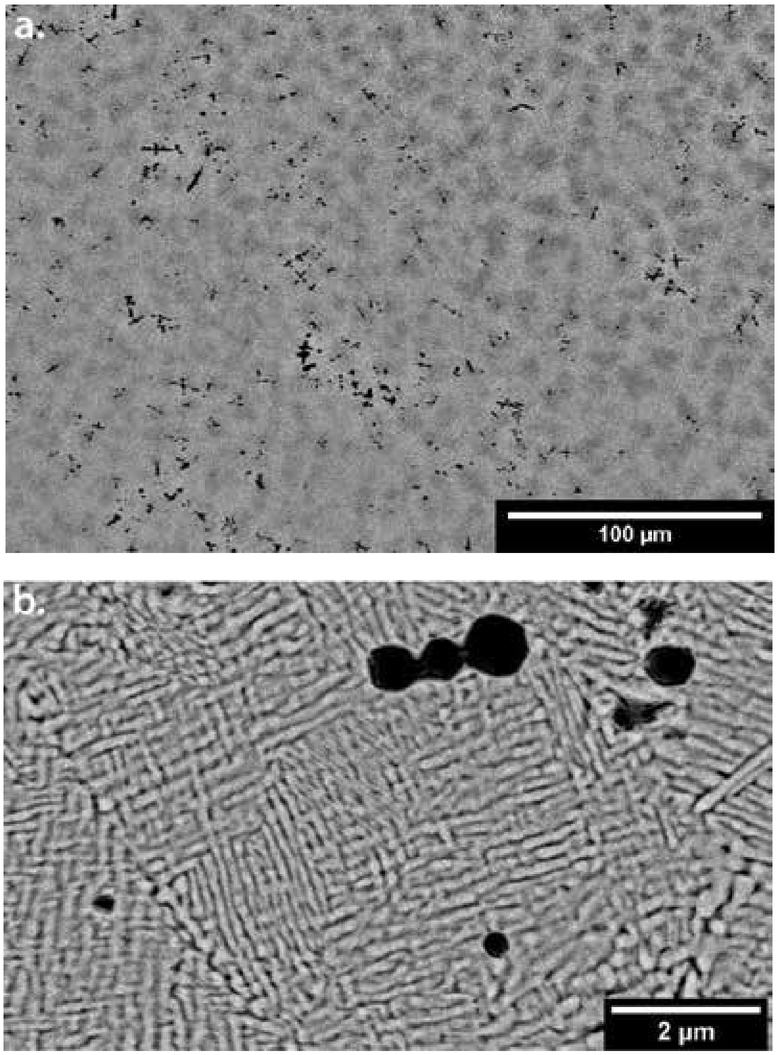

Figure 6. Scanning electron microscopy backscatter micrograph of U-Zr samples following fabrication from an (a) as-cast and (b) rolled and annealed foil. The dark regions are Zr-rich while the light regions are U-rich.

Figure 6 (label a) shows the as-cast microstructure of U-10Zr, which exhibits in-solution variation of U and Zr content. Figure 6 (label b) shows the rolled and annealed U-10Zr alloy exhibiting a typical lamellar microstructure. The irradiation-vehicle fabrication is currently underway. An example of a U-Zr foil that is loaded into a Zr specimen holder is pictured in Figure 7.

Future Activities

The irradiation vehicle is slated for irradiation in the BR2 reactor in the fall of 2019. Prior to this, multiple awarded rapid-turnaround experiments (RTEs) are scheduled. These RTEs include *in situ* neutron-diffraction experiments to investigate texture, crystallography, and microstrain evolution, as well as phase transitions during thermal cycling. Following this experiment, *in situ* thermal treatments during transmission electron microscopy will be carried out on identical samples to investigate phase-transformation kinetics. This pre-irradiation characterization will provide a reference point for the post-irradiation characterization of this fuel, as well as provide a more in-depth understanding of the crystallography and kinetics of the U-Zr and U-Mo fuel systems.

Publications

[1.] M.K. Meyer, J. Gan, J.F. Jue, D.D. Keiser, E. Perez, A.B. Robinson, D.M. Wachs, N. Woolstenhulme, G.L. Hofman, Y.S. Kim, "Irradiation performance of U-Mo monolithic fuel," Nucl. Eng. Technol. Vol. 46 (2014), pp. 169–182.

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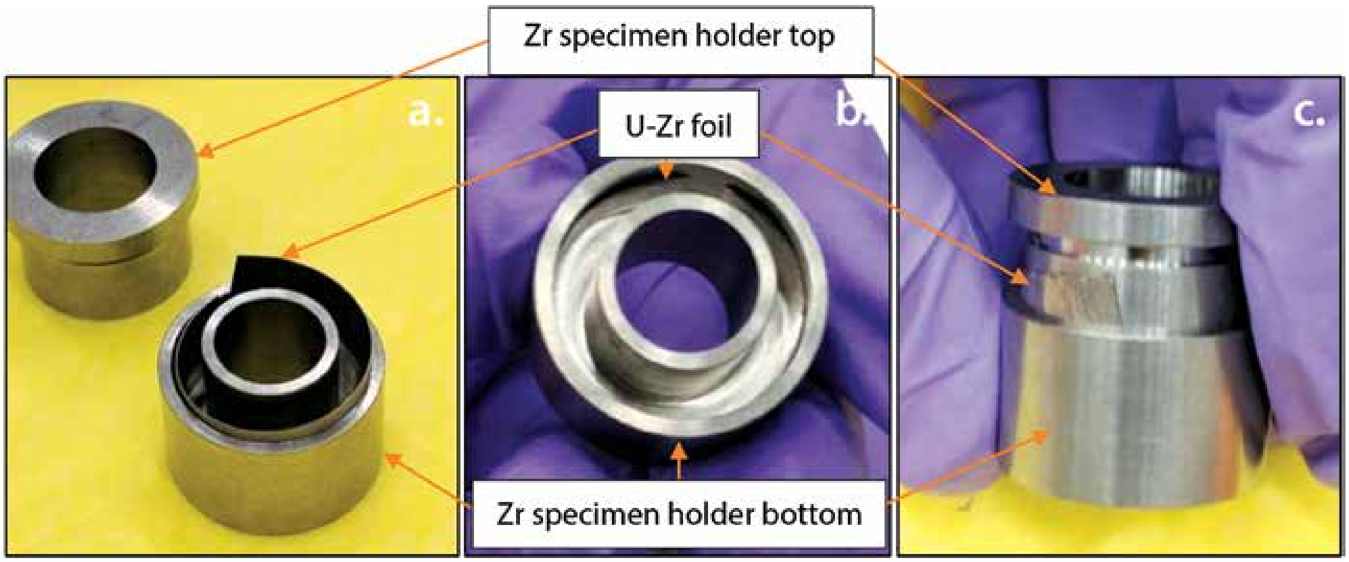

Figure 7. (a) Loading of a U-10Zr fuel foil into the Zr specimen holder. (b) U-Zr foil placed in bottom of specimen holder. (c) Holder top inserted prior to being welded shut for atmospheric containment. (Foil protrusion shown for visualization only.)

Distributed Partnership at a Glance

NSUF and Partners	Facilities and Capabilities
Center for Advanced Energy Studies	Microscopy and Characterization Suite
Idaho National Laboratory	Fuels and Applied Sciences Building, Experimental Fuels Facility, and Electron Microscopy Laboratory
Purdue University	Interaction of Materials with Particles and Components Testing (IMPACT) Experimental Facility
SCK•CEN	Belgian Reactor 2
Collaborators	
Idaho National Laboratory	Cody Hale (collaborator), Daniel Wachs (co-principal investigator), Mike Sprenger (collaborator), Tom Maddock (collaborator)
Purdue University	Maria Okuniewski (co-principal investigator), Walter Williams (co-principal investigator)
SCK•CEN	Ann Leaners (collaborator), Emre Sikik (collaborator), Geert Van den Branden (collaborator), Gitte Borghmans (collaborator), Patrice Jacquet (collaborator), Steven Van Dyck (collaborator), Sven van den Berghe (co-principal investigator)