INL/CON-24-77270-Revision-0

Resumption of SFR Overpower Testing and Post-Transient Examination of the THOR-C-2 Irradiation Test

October 2024

Changing the World's Energy Future

Jason L Schulthess, Allison Probert, Colby B Jensen, William C Chuirazzi, Aaron E Craft

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/CON-24-77270-Revision-0

Resumption of SFR Overpower Testing and Post-Transient Examination of the THOR-C-2 Irradiation Test

Jason L Schulthess, Allison Probert, Colby B Jensen, William C Chuirazzi, Aaron E Craft

October 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Resumption of SFR Overpower Testing and Post-Transient Examination of the THOR-C-2 Irradiation Test

A. Jason L. Schulthess[1*], B. Allison Probert[2], C. Colby B. Jensen[1], D. William Chuirazzi[3], and E. Aaron Craft[3]

1: Nuclear Fuels and Materials Division, Idaho National Laboratory, 2: University of Florida, 3: Characterization and Post-Irradiation Examination Division, Idaho National Laboratory, INL/CON-24-77270

Abstract

Transient overpower testing for fuel safety research and development has resumed at Idaho National Laboratory. The THOR-C-2 commissioning test has been performed and post-transient examination has been performed revealing the intended creep rupture failure near the top of the fuel zone. This paves the way for future testing on previously irradiated fuels that will support fuel development and qualification.

Keywords: Nuclear Fuels, Advanced Reactors, Transient Testing, Fuel Safety, Transient Overpower, U-10Zr, Post-irradiation Examination

Introduction

Sodium cooled fast neutron spectrum nuclear reactors have advantages that include high fuel-utilization capacity, and improved safety through inherent feedback mechanisms, which have been demonstrated during historic safety testing campaigns [1-3]. However, additional improvements in the fuels for this reactor system, and expanded use to higher burnups are desired to support qualification and deployment of advanced reactors based on sodium cooling and fast neutron spectrum designs [4]. In support of these objectives, the United States Department of Energy has resumed Transient Testing by restarting the Transient Reactor Test (TREAT) facility at Idaho National Laboratory (INL) [5, 6].

INL has resumed performing transient testing, specifically transient overpower testing on both fresh fuel, and historic archival fuel which had been irradiated in the Experimental Breeder Reactor-II (EBR-II). Post-transient examinations have been performed on the initial commissioning experiment along with the first transient performed on previously irradiated fuel from EBR-II. This work will focus on the results of the post-transient examinations performed on these experiments.

Irradiation Experiment

The irradiation experiments were conducted at INL's Transient Reactor Test facility, which is a transient reactor capable of performing dynamic power maneuvers to drive desired overpower and under cooling mismatches [5, 6]. For these experiments, a new specifically designed irradiation capsule was developed to provide the necessary thermal hydraulic boundary condition, as well as provide structure to support the fuel experiment and in-situ instrumentation. Specific details of the irradiation capsule, dubbed the Transient Heatsink Overpower Response (THOR) vehicle have been described elsewhere and for brevity won't be repeated here [7]. However, important aspects to know include that

* Corresponding author. Email:Jason.schulthess@inl.gov

the capsule provides a sodium bond between the fuel pin, U-10wt%Zr in HT9 cladding, and an integral heat sink to achieve the desired thermal boundary condition and contains 21 thermocouples which are distributed both axially and azimuthally along the fueled region of the fuel pin to measure in-situ time resolved temperature response during the transient. The THOR-C-2 test, was specifically designed to simulate the conditions of the historic M8 test which was never conducted [2] and drive a creep rupture failure near the top of the fuel zone. Calculations shown in Figure 1 indicate that the fuel centerline was predicted to be 1670 K, while the inner clad temperature was predicted to be 1560 K, both above the UFe_2 eutectic temperature (1273 K)[8].

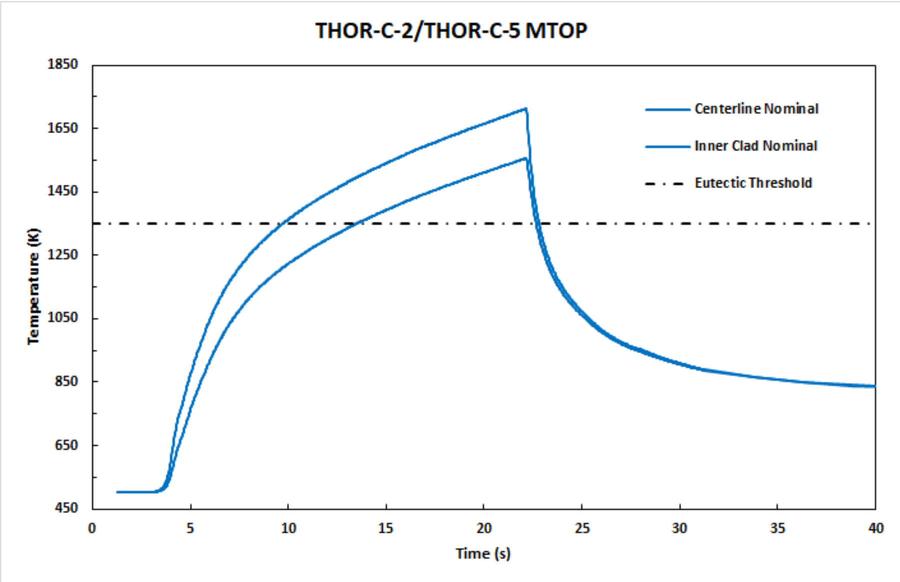

Figure 1. Calculated temperatures for the THOR-C-2 commissioning test.

Post-Transient Examination Results and Discussion

Following the transient, the fuel pin, still inside the capsule was imaged by neutron computed tomography (nCT) to allow for three-dimensional visualization of regions of interest [9, 10]. The spatial resolution of these images is approximately 52.9 µm per voxel. Using FIJI software, 3D projections of the regions of interest were generated from the raw nCT data as shown in Figure 2. From the images, features such as failure of the fuel pin, cladding deformation, and relocated fuel and the formation of a central void can be identified. Examples of these features are also shown in Figure 3.

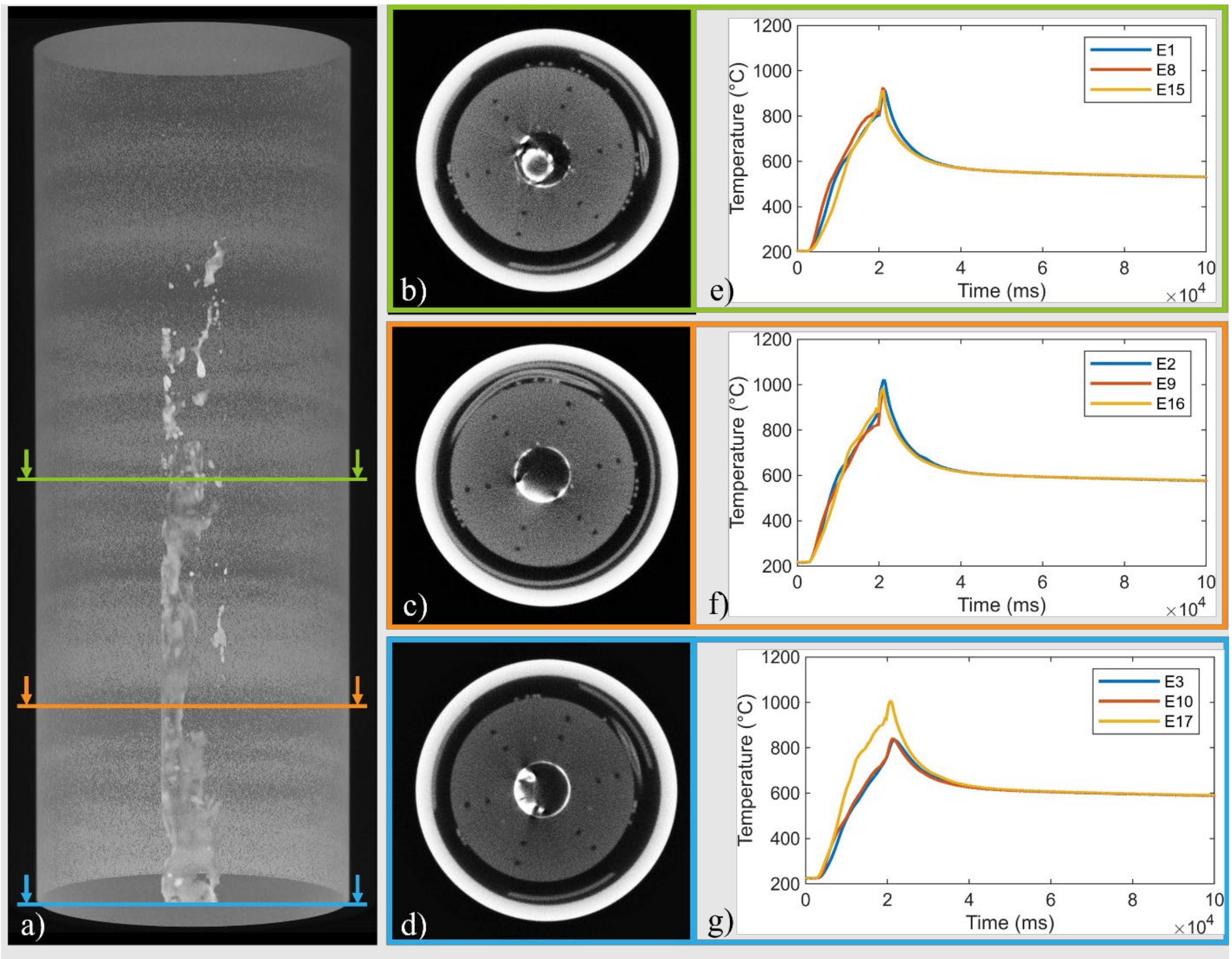

Figure 2. 3D nCT projection of the upper region of interest for THOR-C-2, (a) individual nCT slices showing three thermocouple placements within the Ti heatsink at each of the axial positions (b) 29.7 cm, (c) 25.4 cm, and (d) 23.9 cm, and accompanying heat sink temperatures measured from the TCs at axial positions (e) 29.7 cm, (f) 25.4 cm, and (g) 21.1 cm. The axial positions are derived from the bottom of the fuel pin.

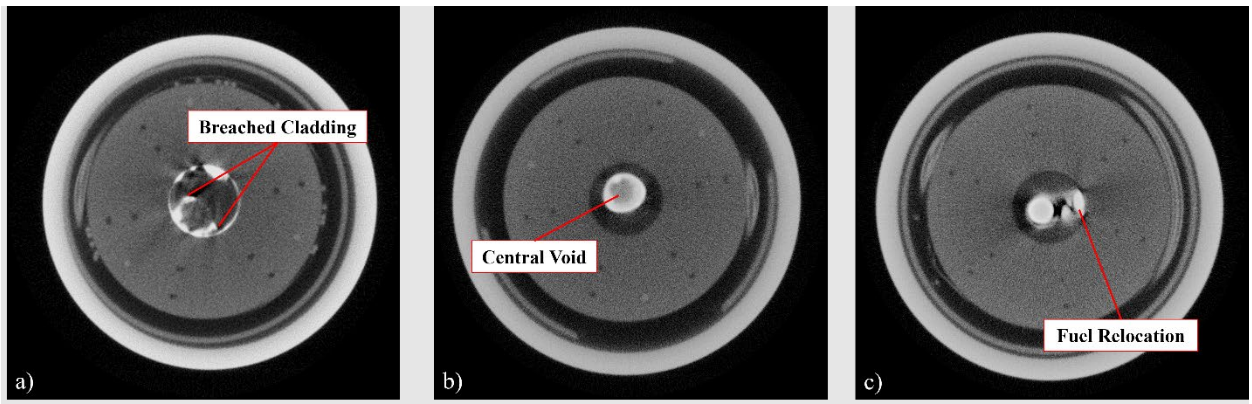

Figure 3. Transverse nCT radiographs showing breached cladding at (a) 30.0 cm, (b) central void at 5.3 cm, and © relocated fuel at 0.7 cm above the beginning of the fuel column. The axial positions are derived from the bottom of the fuel pin.

Cladding burst is evident in the nCT slices from approximately 29.2 cm above the bottom of the fuel column to the lower boundary of the radiograph at approximately 23.9 cm. Melted fuel was expelled from the pin, and it collected along the side of the cladding (an event known as candling) and in the bottom of the capsule. The candling of the relocated fuel can be seen primarily from 2.2 cm above the bottom of the fuel column until the bound of the lower ROI radiograph at approximately 13.5 cm above the bottom of the fuel column. Fuel also collected at the bottom of the capsule's fuel-pin chamber from about 2.1 to 0.9 cm below the bottom of the fuel column. A redistribution of fuel along one side of the heatsink wall from 0.9 cm below the bottom of the fuel column extending approximately 4.6 cm, axially. The relocated fuel left behind a central void within the fuel pin, evident from approximately 4.9 to 5.9 cm from the bottom of the fuel stack.

Conclusions

Safety testing for advanced reactor fuels has resumed at INL. Commissioning tests include the THOR-C-2 irradiation transient which drove the fuel to creep rupture near the top of the fuel zone. nCT results confirm the disruption of the fuel pin near the top of the fuel column. Thermocouple temperature measurements taken from the heat sink in near proximity to the fuel, show the time resolved temperature, and show a sudden increase in temperature, likely corresponding to the moment of fuel failure. For the upper region of interest, where the fuel pin failed by creep rupture, one set of thermocouples showed discrepancy for one thermocouple which read higher than the other two. This likely corresponds to the fuel shifting toward that thermocouple as it failed. Future work includes additional analysis such as microscopy on the failed fuel regions shown in this work, and post-transient analysis of experiments performed on previously irradiated EBR-II fuel.

References

[1.] Carmack, W.J., et al., *Metallic fuels for advanced reactors.* Journal of Nuclear Materials, 2009. **392**(2): p. 139-150.

[2.] Bauer, T.H., et al., *Behavior of Modern Metallic Fuel in TREAT Transient Overpower Tests.* Nuclear Technology, 1990. **92**(3): p. 325-352.

[3.] Wachs, D.M., L. Capriotti, and D. Porter, *Behavior of metallic fast reactor fuels during an overpower transient.* Journal of Nuclear Materials, 2021. **557**: p. 153304-153304.

[4.] Aitkaliyeva, A., *Recent trends in metallic fast reactor fuels research.* Journal of Nuclear Materials, 2022. **558**: p. 153377-153377.

[5.] Wachs, D.M., *Transient testing of nuclear fuels and materials in the United States.* JOM, 2012. **64**(12): p. 1396-1402.

[6.] Folsom, C.P., et al., *Resumption of water capsule reactivity-initiated accident testing at TREAT.* Nuclear Engineering and Design, 2023. **413**.

[7.] Bess, J.D., et al., *EBR-II MOX Fuel Characterization Enabling ARES Phase I Testing.* Nuclear Science and Engineering, 2023. **197**(8): p. 1845-1872.

[8.] Matthews, C., et al., *Fuel-Cladding Chemical Interaction in U-Pu-Zr Metallic Fuels: A Critical Review.* Nuclear Technology, 2017. **198**(3): p. 231-259.

[9.] Craft, A.E., et al., *Neutron Radiography of Irradiated Nuclear Fuel at Idaho National Laboratory.* Physics Procedia, 2015. **69**: p. 483-490.

[10.] Chuirazzi, W., et al., *Image fusion for neutron tomography of nuclear fuel.* Journal of Radioanalytical and Nuclear Chemistry, 2022. **331**(12): p. 5223-5229.