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FY23 Post-LOCA Characterization of Irradiated Fuel - NSUF Award 17-12985

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Nuclear Energy and Fuel Cycle Division

FY23 POST-LOCA CHARACTERIZATION OF IRRADIATED FUEL NSUF AWARD 17-12985

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Prepared by
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SUMMARY

This report summarizes the sample preparation and data collection for fuel pins following integral loss-of-coolant accident (LOCA) testing in the Severe Accident Test Station at Oak Ridge National Laboratory. The test sample cross sections show the post-transient fragmentation behavior of UO_2 that was commercially irradiated above 67 MWd/kgU. The cladding segments were subjected to ring compression testing, and hydrogen measurements were taken.

1. EXPERIMENT BACKGROUND

This Electric Power Research Institute (EPRI)-led Nuclear Science User Facility (NSUF) project aims to disposition the high burnup fuel fragmentation issue in light-water reactor (LWR) fuels by (1) performing simulated loss-of-coolant accident (LOCA) testing in-cell and (2) analyzing additional information collected using reconditioned fuel in transient reactor conditions. The in-cell simulated LOCA transient testing of fuel segments was performed at the Oak Ridge National Laboratory (ORNL) 3525 hot cell facility in the Severe Accident Test Station (SATS) [1–4]. Simulated LOCA tests were performed on two segments of fuel irradiated in the North Anna Nuclear Power Station [4]. These experiments are referred to as North Anna #1 (NA#1) and North Anna #2 (NA#2). The North Anna #1 segment was taken from the rod designated as P16 in the original assembly, and North Anna #2 was taken from the rod designated as A8. A simulated LOCA test was also performed on a sample irradiated at the H.B. Robinson reactor, and this experiment is designated HBR#1.

This report describes the sample preparations for characterization of the fuel segments following the integral-LOCA testing, hydrogen measurements, and ring compression testing (RCT) of cladding segments.

2. MICROSTRUCTURAL SPECIMEN PREPARATION

Extensive sample preparation steps are necessary to prepare samples from irradiated fuel in both the as-irradiated and post-LOCA test states. This is especially true when samples are removed from the hot cell and loaded into electron microscopes (i.e., scanning electron microscopes or dual beam focused ion beams). Prior to LOCA testing, samples of material from areas adjacent to the LOCA tested segments were sectioned and preserved for microscopy. Analysis of this material provides an opportunity for understanding the microstructure of LWR fuel at high burnup prior to the LOCA test. Likewise, similar samples can be prepared from the post-LOCA test [5, Fig. 2]. An as-irradiated sample from NA#1 is shown in Figure 2.1, and a post-LOCA test sample from NA#1 is shown in Figure 2.2. Dose rates of full cross sections such as those present in these samples are prohibitive both for personnel loading samples into an electron microscope and for the electron microscopes themselves. To reduce the dose rate, the full cross sections are sub-sized into sectors using the process illustrated in Figure 2.3. In the sub-sizing process, the full cross section is divided into a set of sectors, 6 of which are illustrated here. The mount is then rotated so that the face of the mount can be removed. Typically, 1–2 mm of the face of the sample is removed. Each sector is recovered, and select individual sectors can be remounted and repolished for electron microscopy. Samples for microscopy were prepared in this manner for the as-irradiated and post-LOCA tests for NA#1 and NA#2. A similar technique was also applied earlier to produce as-irradiated samples from HBR#1. The preparation of HBR#1 post-LOCA test samples is currently underway at this writing.

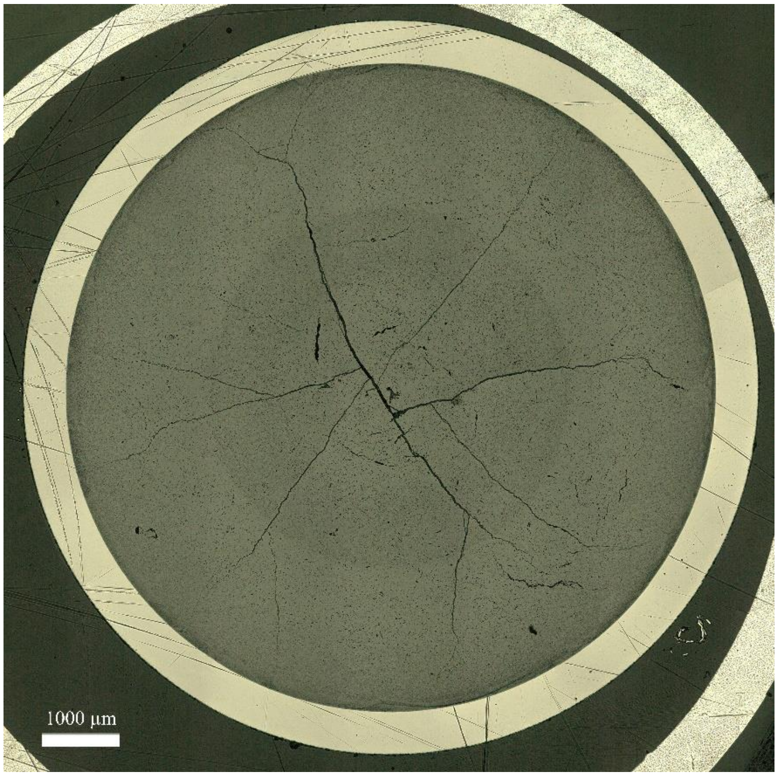


Figure 2.1 Optical microscopy from an as-irradiated sample taken from material adjacent to the segment from the NA#1 LOCA test.

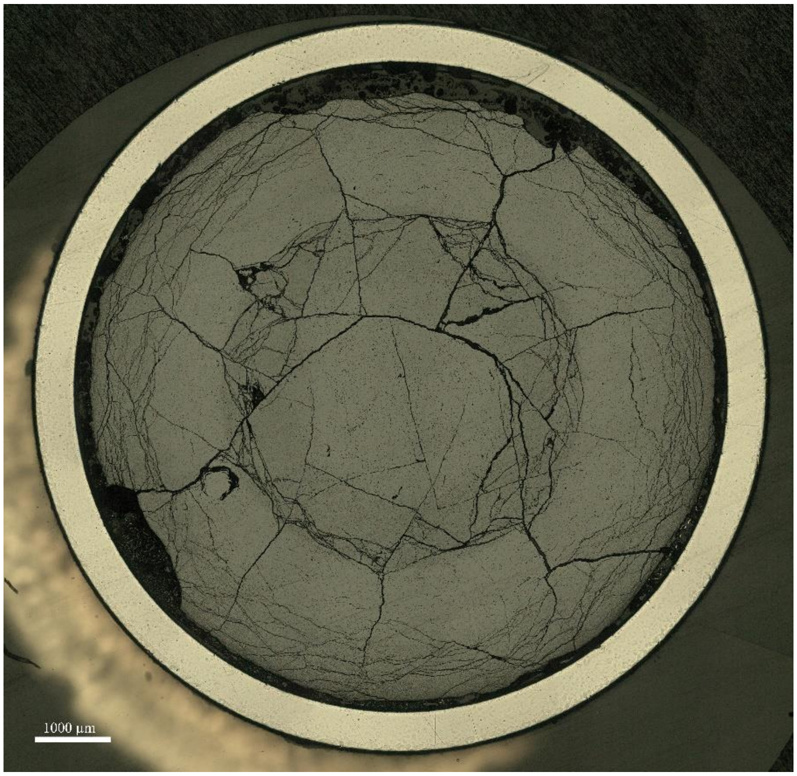


Figure 2.2 Optical microscopy from a post-test sample taken from the segment tested in the NA#1 LOCA test.

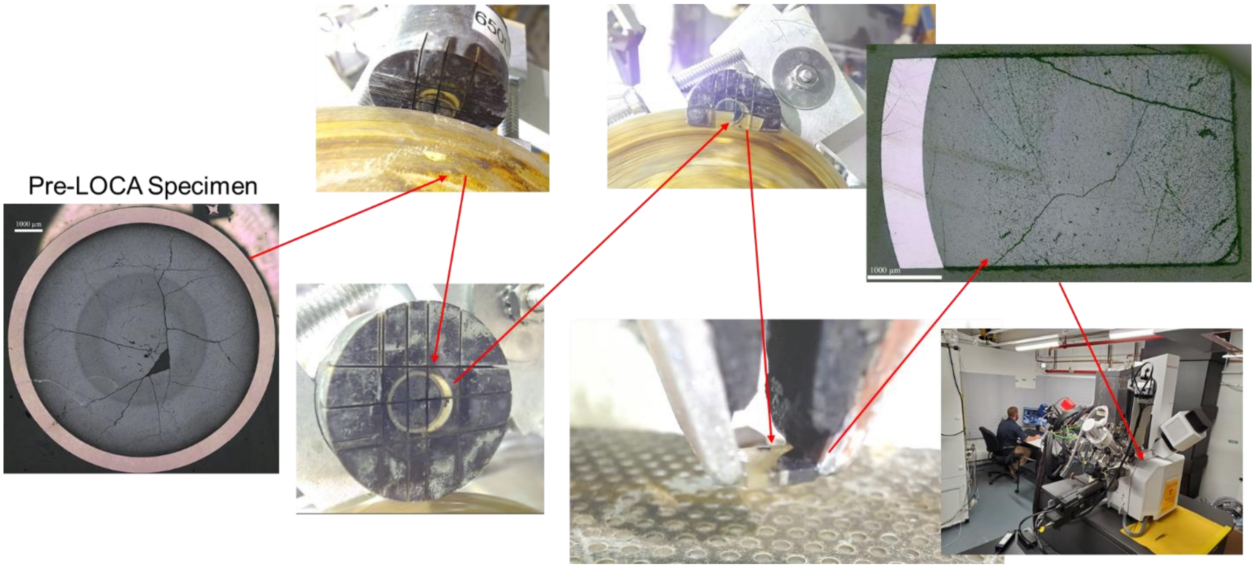


Figure 2.3 Workflow of the sub-sizing process used to create samples for electron microscopy.

3. HYDROGEN MEASUREMENTS

Hydrogen measurements were performed on samples of cladding from the NA#1 segment and the NA#2 segment. Hydrogen is measured using the inert gas fusion technique with a Leco Model 836 ONH analyzer. The methodology used to collect this data follows the standard technique published by Leco for refractory metals and a helium carrier gas with the power of the instrument reduced by 10% to reduce dust formation. When using this method, the graphite crucibles are filled with approximately 50 mg of graphite powder to ensure good contact between the crucible and the sample capsule. The sample is loaded into a Ni capsule to ensure melting and to ensure that the odd-shaped samples fall through the instrument into the analysis crucible. The analyzer is calibrated with Ti and Zr standards with known amounts of dissolved hydrogen prior to undergoing a series of analyses. The samples were 3 mm rings of cladding cut at different distances away from the burst opening. Each ring was thoroughly defueled in low-temperature nitric acid for 24 to 48 hours. The rings were then decontaminated by ultrasonic cleaning in water. The 3 mm rings were further divided into quarters using a specialized low-speed saw fixture that was developed for this purpose. Each quarter ring was then run as a separate sample to evaluate the hydrogen content at different distances from the burst opening.

The as-irradiated hydrogen content for this material is expected to be 120 parts per million (ppm) or less by weight. The measured average hydrogen for samples from the post-LOCA test samples is shown in Table 3.1, and most samples show some signs of hydrogen pickup. The magnitude of the hydrogen pickup for NA#1was quite large for such a short hold time at 1,200°C, indicating that significant hydrogen pickup occurred at the burst and away from the burst early in the LOCA transient. Enough hydrogen was released to the cladding interior as a result of oxidation during the ramp to result in high hydrogen pickup. The hydrogen pickup of the NA#2 is much lower than that of NA#1, as the NA#2 was steam oxidized at only 1,000°C. The averages are reported here, but it is notable that there was significant scatter in the data between samples harvested from the same ring, indicating some azimuth variation in hydrogen pick-up. Additional samples from NA#2 are scheduled for analysis before the end of the fiscal year.

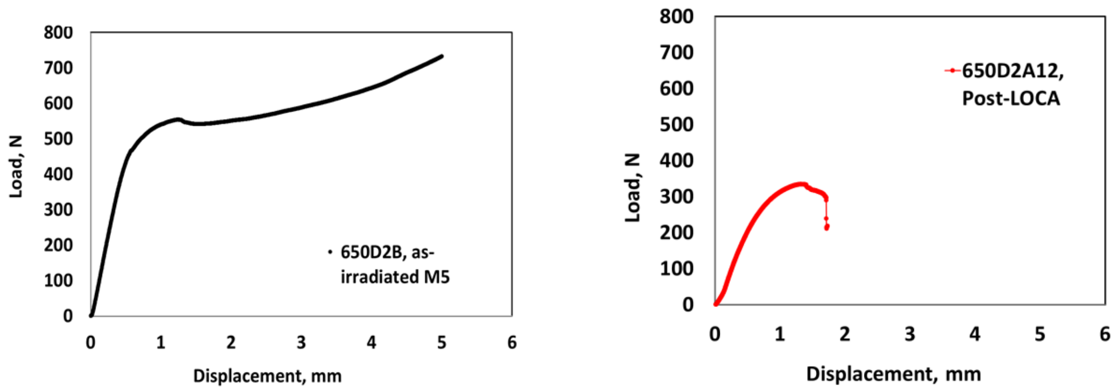
Table 3.1 Hydrogen content of samples taken from post-LOCA test specimen

	Sample	Distance from Burst Center (mm)	Average H Content (ppm)
NA#1	A3	0	1020 ± 294
Data	A6	13	1300 ± 127
	A13B2	64	345 ± 54
	A11	49	317 ± 12
NA#2	T1	0	58 ± 7
Data	T2	3	86 ± 34
	T3	6	162 ± 82
	T4	9	228 ± 92

4. RING COMPRESSION TESTING

After LOCA testing, RCT was performed to analyze the cladding performance in areas such as cladding ductility and strength. Although the LOCA tests were conducted at Argonne National laboratory (ANL), no mechanical testing of the post-test LOCA sample had been performed in the United States. In this effort, ≈10 mm long fuel segments were sectioned at the burst center, 12 mm, 50 mm, and 80 mm away from the burst center of LOCA sample NA#1, and then they were placed into a beaker filled with ~100 mL of nitric acid to cover the fuel segment. This beaker was then placed into a steel pan on top of a hot plate to ensure that no fuel or acid would be spilled on the work surface. The leaching process was left to proceed for a few hours at just below the boiling point of the acid bath. Once the leaching process was completed, the defueled segment is taken out of the beaker and the fuel leach result was measured to ensure that no residual fuel remained inside the cladding specimens.

An Instron 5967 Material Test System was used to perform the RCT. The instrument was subjected to an annual verification of calibration for measurement of compressive loads by load cell, determination of crosshead displacement, and determination of crosshead speed. Calibration verification was performed and documented by Instron. After sectioning, the ring length and diameters were measured to within one decimal place (e.g., 10.0 mm). The crosshead displacement rate for ring compression was 0.033 mm/s (2 mm/min). The offset displacement was determined from the load displacement curve. This means that the specimen was mathematically unloaded at the load just before the steep load drop. The linearized slope (i.e., ring stiffness in kN/mm) of the initial loading curve was used to perform the mathematical unloading. Generally speaking, the offset strain increased as the distance of the RCT specimen to the burst center increased. The ductility of post-test LOCA specimens dropped significantly compared to the as-irradiated specimens (see Figure 4.1). Detailed analyses of the RCT results are being performed at this writing and will be reported in the future.



(a) (b)

Figure 4.1. Load-displacement data for an as-irradiated NA high burnup cladding sample (a) and a post-test LOCA defueled ring sample at 50 mm above the burst center of NA#1 LOCA sample (b).

5. SUMMARY

Several characterization techniques were applied to post-LOCA test samples and sibling samples in their as-irradiated states. These characterization techniques required some development to ensure that they were applicable to irradiated fuels. Data collected will further understanding of fuel and cladding behavior during a LOCA. The techniques developed here will be applied to post-test characterizations of future simulated LOCA tests.

6. REFERENCES

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