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LOCA Fragmentation Test with High Burnup HBR Fuel Rod

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Reactor & Nuclear Systems Division

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ACRONYMS

ANL	Argonne National Laboratory
BDBA	beyond design basis accident
HBR	H. B. Robinson
IFEL	Irradiated Fuels Examination Facility
INL	Idaho National Laboratory
LWR	light water reactor
LOCA	loss-of-coolant accident
NSUF	Nuclear Science User Facilities
ORNL	Oak Ridge National Laboratory
SATS	Severe Accident Test Station

1. INTRODUCTION

Fuel rod cladding is the first barrier for retention of fission products in light water reactor (LWR) cores, in which the structural integrity of the cladding ensures safe operation of the reactor and coolable core geometry. Zirconium-based alloys have been optimized for use in LWRs over the past five decades, focusing on, among other characteristics, decreasing the waterside corrosion rate and hydrogen pickup under normal operating conditions to increase the operational economy and safety margin. However, nuclear utilities are now confronted with two pressing safety issues: higher-burnup fuel operation and used-fuel dry storage. In relation to the first issue, the damage to the Fukushima Daiichi nuclear facilities in Japan caused by the loss-of-coolant accidents has underscored the importance of factoring severe accidents into nuclear reactor safety research and analyses. In terms of used-fuel dry storage, the United States has focused efforts on disposing of used nuclear fuel in a geologic repository. This project is intended to generate data to inform industry and regulatory agencies to enable them to best address fuel fragmentation in standard LWR fuel designs irradiated to high burnup.[1] This approach will require reconditioning of irradiated fuel in a reactor at specific power levels and simulated loss-of-coolant accident (LOCA) testing in hot-cell furnaces.

The high-temperature steam oxidation behavior of zirconium alloy cladding under design basis LOCAs and over a broader set of conditions has been studied at several facilities around the world.[2–9] Table 1 summarizes the available international LOCA testing capabilities. Oak Ridge National Laboratory (ORNL) has developed the Severe Accident Test Station (SATS), located at the Irradiated Fuels Examination Facility (IFEL) at ORNL, that is capable of testing nuclear fuel rods subjected to a range of accident scenarios. The capabilities of SATS include exposing a fuel rod segment to conditions typical of design basis accident and beyond design basis accident (BDBA) scenarios. The specifics of the SATS design have been extensively covered in previous ORNL reports.[10,11] SATS consists of two modules: one for integral testing of LOCA scenarios and the other with a high-temperature furnace for testing fuel segments.

Table 1. Summary of international accident testing capabilities

Lab	Heating Method	Temperature Control	Temperature Measurement	Out of Cell	In Cell	Fuel	Target Max. Temperature	Ref. #
ORNL's SATS	Radiant + (Resistance)	Computer	TCs	Yes	Yes	Yes	1,200°C (1,600°C)	This report
ANL	Radiant	Computer	TCs	Yes	Yes	No	1,200°C	4, 6
CEA-Saclay	Resistance	Manual	Preset	Yes	No	No	1,200°C	7
Halden	Reactor+ Heaters	Preset	TCs	No	No	Yes	1,200°C	10
JAEA	Radiant	Computer	TCs	Yes	Yes	No	1,200°C	5, 11
Studsvik	Radiant	Computer	TCs	No	Yes	Yes	1,200°C	12

ANL: Argonne National Laboratory
CEA: Commissariat à l'énergie atomique
JAEA: Japan Atomic Energy Agency
ORNL: Oak Ridge National Laboratory
SATS: Severe Accident Test Station
TC: thermocouple

This report documents the test train fabrication, SATS fuel fragmentation test, and post-SATS test characterization under the US Department of Energy Office of Nuclear Energy Nuclear Science User Facilities (NSUF) program.

2. TEST TRAIN FABRICATION

SATS was installed in the ORNL 3525 Hot Cell in 2017.[11] Several LOCA benchmark tests were performed with unindicated Zry-4 cladding specimens before and after the installation.[12] For irradiated fuels, specimen fabrication for the LOCA fragmentation testing includes fuel rod sectioning, metallographic mounting and polishing, fuel leaching, outer oxide layer removal, inner fuel/cladding bond layer and fuel removal, and end-plug welding. The details of the LOCA sample preparation are provided in previous reports.[12, 13]

Figure 1 shows the LOCA test train with as-fabricated cladding. The test train is supported at the top to minimize specimen bowing. The quartz tube encasing the test train provides an enclosed volume for steam flow and water quench, both of which are introduced through the bottom of the unit. The test train is centered within the quartz tube by means of two perforated spacer disks. Swagelok fittings are used above the specimen to connect to the high-pressure gas line and top pressure gauge and below the specimen to connect to the bottom pressure-gauge line. For out-of-cell benchmark tests, Type S thermocouples are spot-welded directly to the specimen surface. The signal from one thermocouple is used to control the furnace power to achieve the desired temperature ramp, hold temperature, and cooling rate prior to quench.

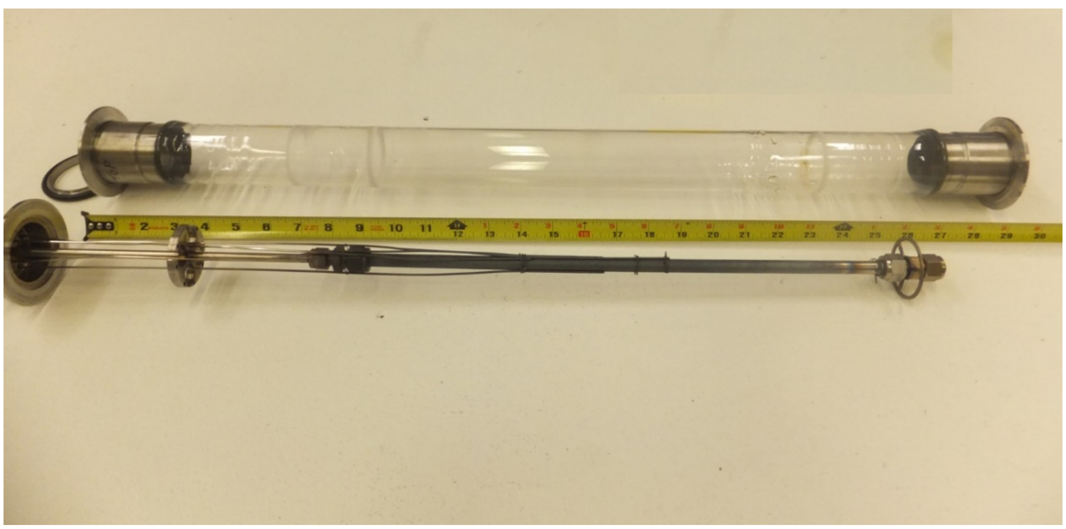


Figure 1. LOCA test train assembly and quartz tube. The 300-mm-long specimen is centered with two centering disks.

For in-cell LOCA tests, Type S thermocouples are strapped to the irradiated fuel specimen with platinum wire at 50 mm above the midplane of a 12-in.-long specimen. A LOCA specimen assembly device was fabricated to assemble the fuel segment, as shown in Figure. 2.

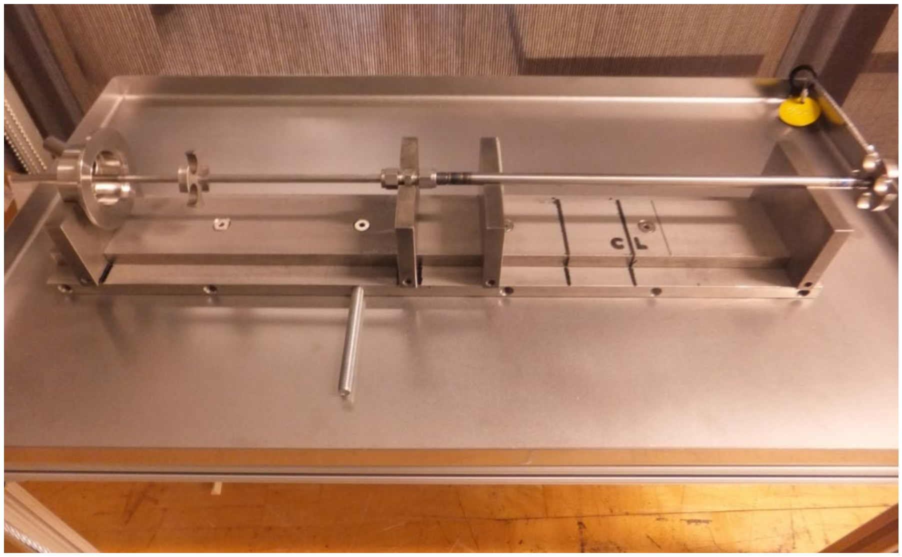


Figure 2. LOCA specimen assembly device.

3. SATS FUEL FRAGMENTATION TEST

The SATS LOCA test apparatus for this experiment is shown in Figure 3. Figure 4 shows the temperature and pressure histories for the in-cell LOCA fragmentation test HBR#1. A high burnup pressurized water reactor H. B. Robinson (HBR) segment was used for the fuel fragmentation test. After the fuel specimen was assembled to the test train, two Type-S thermocouples were strapped to the outer surface of the cladding approximately 2 in. above the sample centerline. One of these was used to control the furnace power to give a hold temperature of 1,000°C at that location. The other thermocouple, adjacent to the control thermocouple, was used as a backup thermocouple to record temperature in the event that the control thermocouple failed. Based on out-of-cell benchmark testing of unirradiated 17×17 Zry-4, the difference in output between a strapped and a welded thermocouple at the same location is <10°C. The fragmentation test was conducted in steam at 1,000°C, but without water quench. The full LOCA fragmentation test sequence included

- heating in flowing steam to 300°C and pressurizing fuel segment to 1,200 psi,
- heating in flowing steam at 5°C/s from 300°C to 1,000°C,
- holding in steam for 120s at 1,000°C,
- cooling at 3°C/s to 800°C, and
- furnace cooling from 800°C to room temperature.

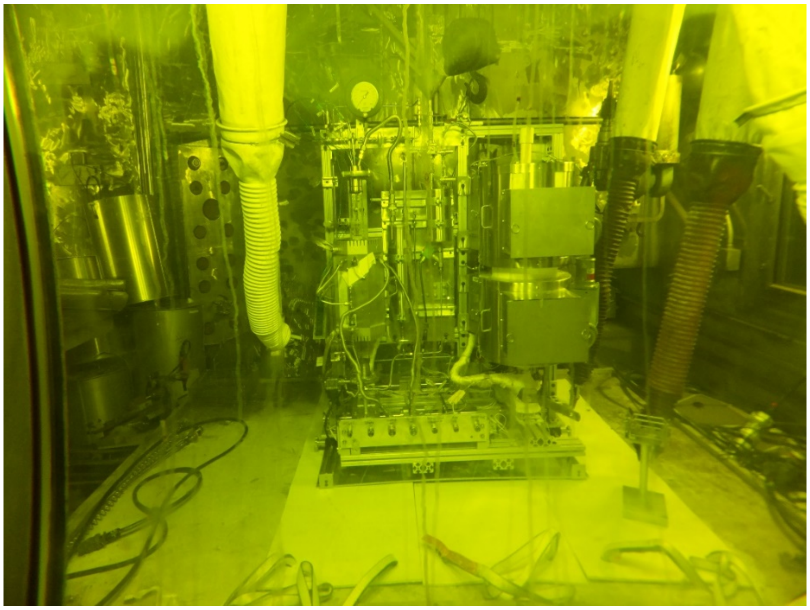


Figure 3. The Severe Accident Test Station pictured after it was placed in-cell at the IFEL. The test station includes the integral LOCA testing module (left) and the BDBA high-temperature furnace test apparatus (right).

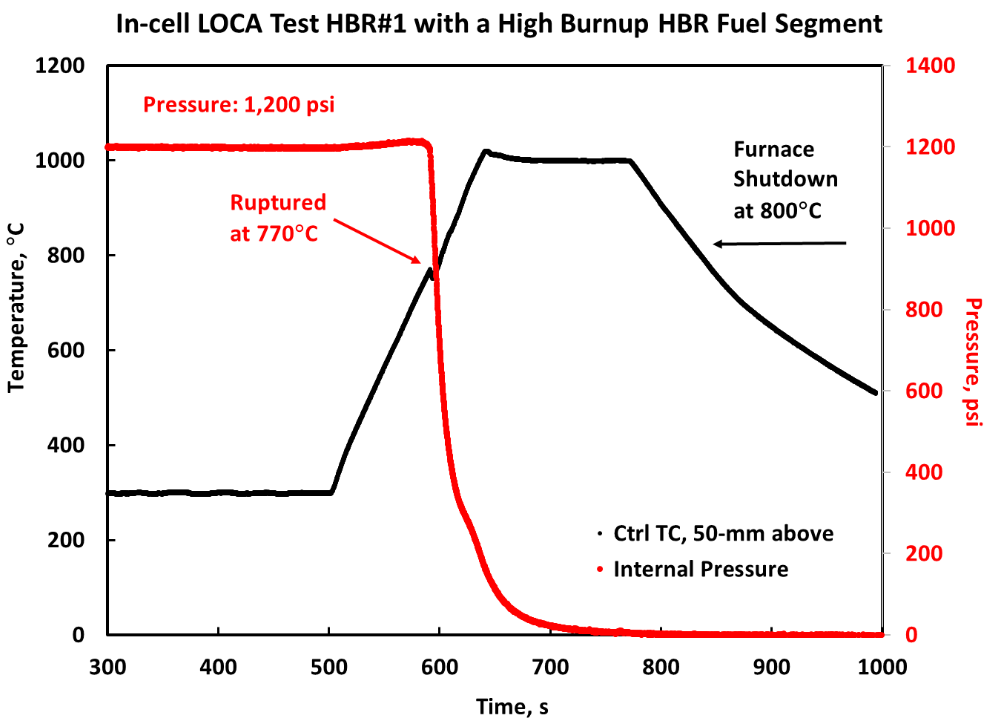
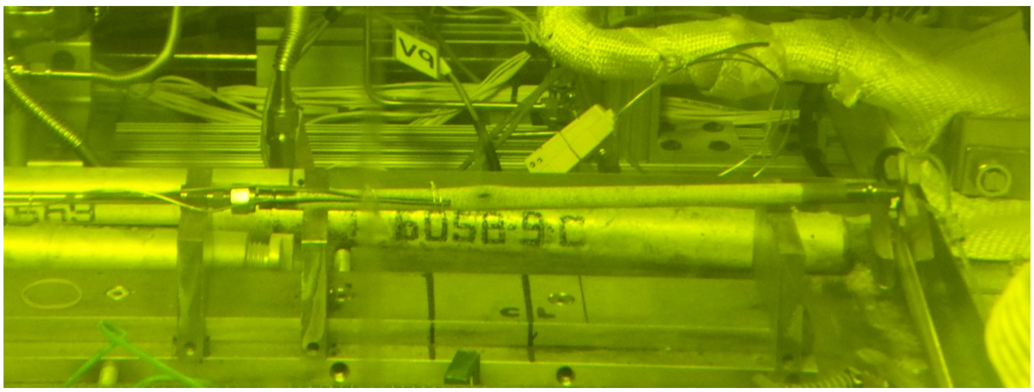


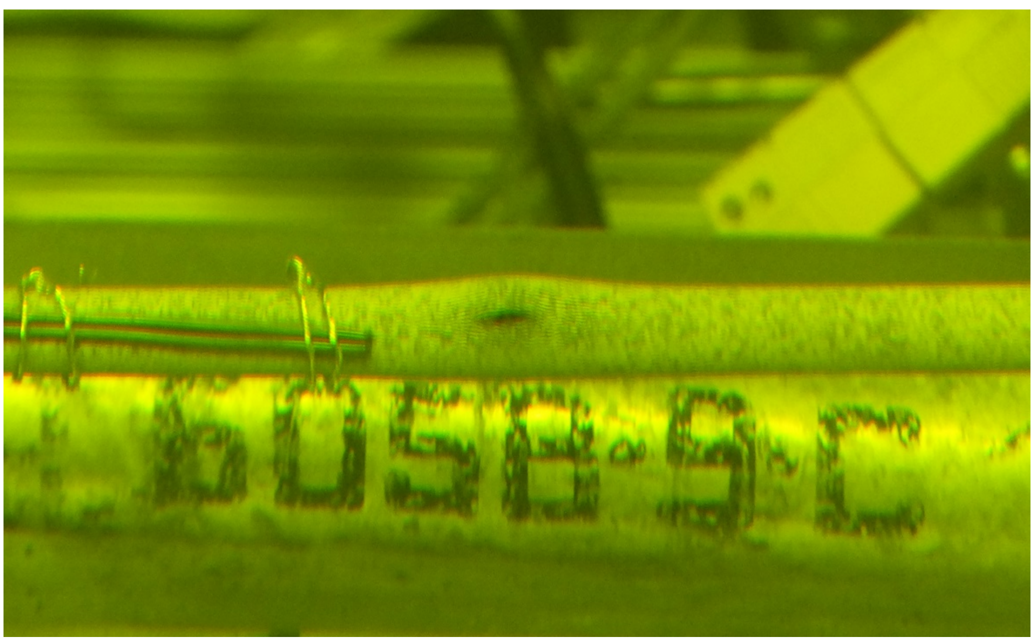
Figure 4. Temperature and pressure histories for the in-cell LOCA fragmentation test HBR#1.

4. POST–SATS TEST CHARACTERIZATION

Figure 5 shows the post-test LOCA fragmentation test HBR#1 sample. Sieve analysis and strain measurement were performed. Table 2 summarizes the result of the two ORNL in-cell tests with high burnup North Anna and HBR cladding specimens and the result of a LOCA test that was conducted with high burnup Limerick Zry-2 at Argonne National Laboratory (ANL). The ORNL North Anna specimen[13] was tested in a full LOCA sequence similar to the test conditions of ANL ICL#4, and the ORNL HBR specimen was tested up to 1,000°C without water quench. Although the cladding geometry and cladding material were different between these tests, their burst temperatures were remarkably close. However, the HBR sample had a relatively small balloon and burst opening, as shown in Table 2. The profile of diametral strain for HBR#1 is shown in Figure 6.



(a)



(b)

Figure 5. Posttest appearance of LOCA fragmentation test sample HBR#1 in (a) low-magnification and (b) high-magnification images.

Table 2. Comparison of the ORNL in-cell LOCA fragmentation/integral tests with a previous test performed at ANL on a high burnup specimen

Parameter	ORNL HBR#1	ORNL NA#1	ANL ICL#4
Fuel	H.B. Robinson	North Anna	Limerick
Materials	Zircaloy-4	M5	Zircaloy-2
Burnup, GWd/MT	63–67	67	54–57
Outside diameter, mm	10.76	11.18	9.5
Wall thickness, mm	0.76	0.71	0.57
Internal pressure at 300°C, psi	1,200	1,200	1,200
Temperature ramp from 300°C, °C/s	5	5	5
Peak internal P_g, psi	1,213	1,214	1,285
Temperature at burst, °C	770	791	790
Hold temperature, °C	1,000	1,200	1,200
Hold time, s	120	90	300
Cool-down rate to 800°C, °C/s	3	3	3
Quench initiation temperature, °C	-	800	800
Burst shape	Oval	Oval	Oval
Burst length, mm	7	16	15
Max. burst width, mm	~2	~3	5.1
Max. strain $(\Delta C/C_m)_{max}$, %	25	41	36

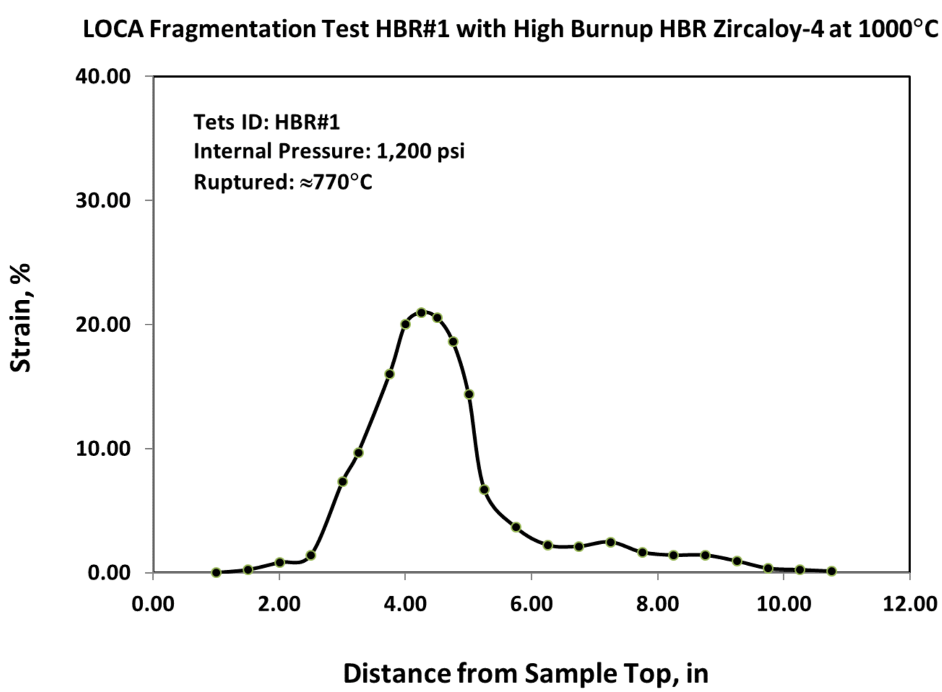


Figure 6. Outer-diameter strain for in-cell LOCA fragmentation test HBR#1 sample. The sample was ramped to 1,000°C, held at1,000°C for 120 s, cooled to 800°C at 3°C/s, and then furnace-cooled to room temperature.

Images of the fuel rod and fuel fragments from HBR#1 are shown in Figure 7. The total fuel collected from HBR#1 was 59.8 g. A few fine particles can be seen in Figure 7. The fragment size distribution of the fuel collected after LOCA fragmentation and shake testing of the HBR#1 sample was quantified, and the result is shown in Figures 8 and 9.

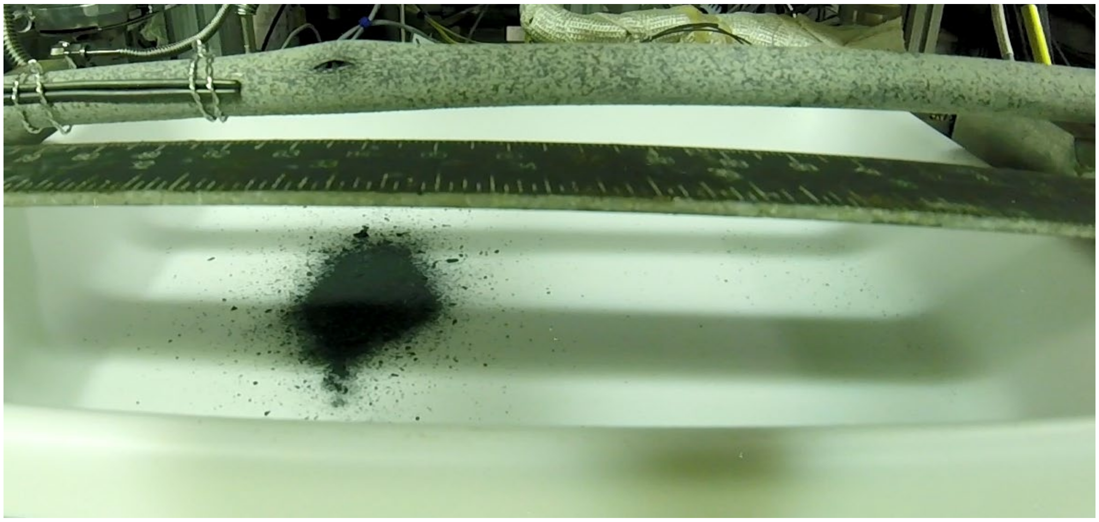


Figure 7. Fragmented fuel particles collected from LOCA fragmentation test HBR#1.

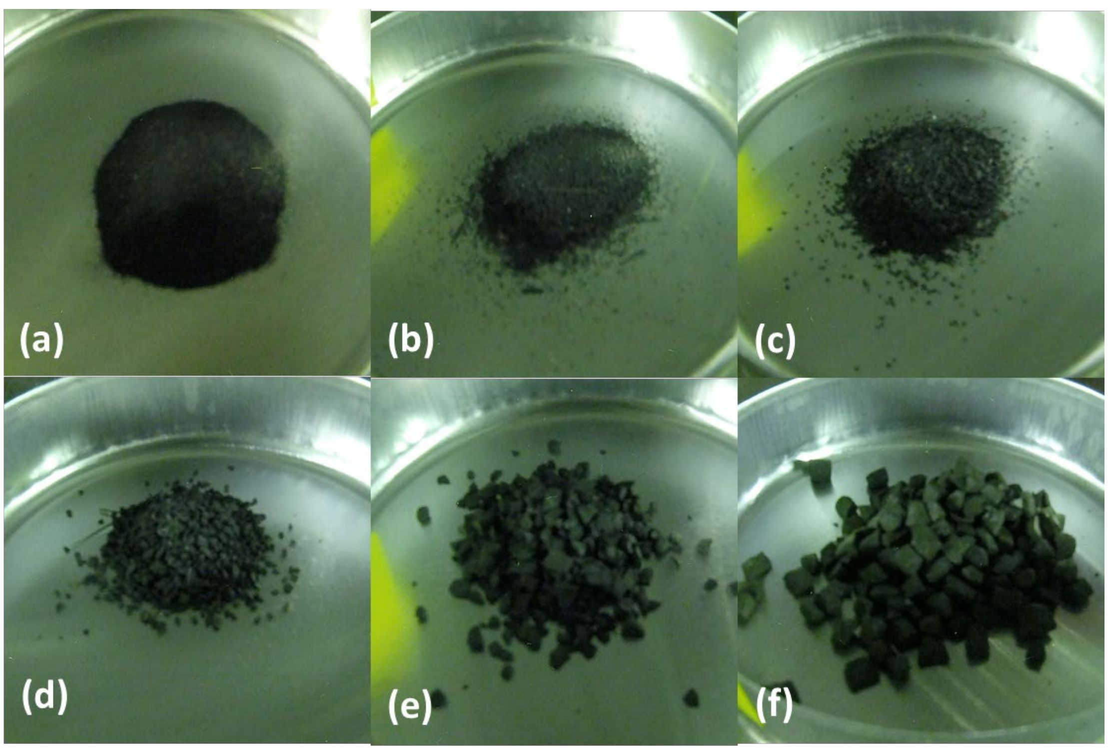


Figure 8. Images of fragmented fuel particles collected from LOCA fragmentation test HBR#1: (a) <0.125 mm; (b) 0.125–0.250 mm; (c) 0.250–0.500 mm; (d) 0.500–1.00 mm; (e) 1.00–2.00 mm; and (f) >2.00 mm.

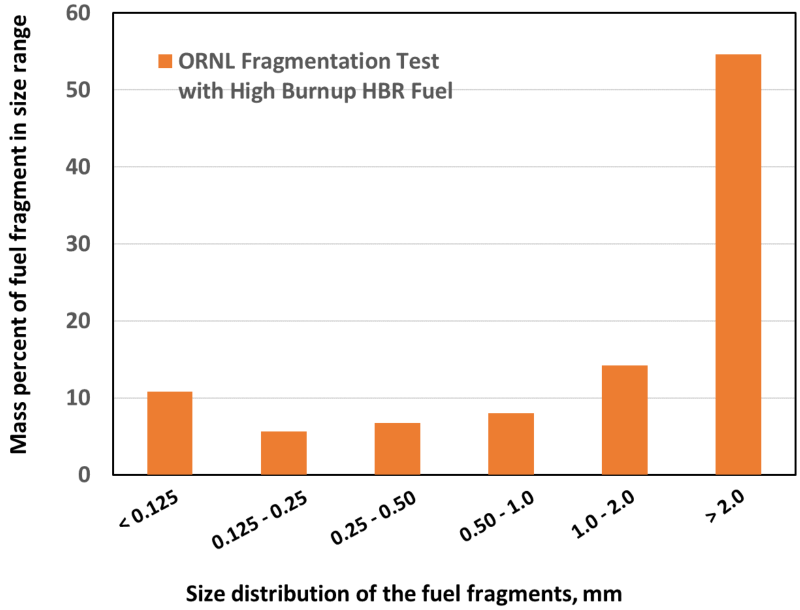


Figure 9. Size distribution of fuel fragments collected after ORNL LOCA fragmentation and shake testing.

5. CONCLUSION AND PATH FORWARD

SATS was successfully used to perform a LOCA fragmentation test with a high burnup HBR fuel segment. Experimental data is necessary to inform industry and regulatory agencies on the fuel fragmentation behavior of standard LWR fuel designs irradiated to high burnup.

In addition, the results from integral LOCA tests, including those that will be performed in SATS, provide valuable data for code and modeling validation, which enhances the ability to predict the behavior of fuel systems during accident scenarios. Validation of nuclear fuel performance codes, such as BISON, will provide results that can either act as a screening tool for future experiments or be coupled with experimental data to validate the behavior of a fuel system during safety testing.[14,15]

The NSUF award supporting this work will continue with ORNL refabrication of commercial fuel into rodlets for irradiation to higher burnup at the Idaho National Laboratory (INL) Advanced Test Reactor. Fuel fragmentation of these higher burnup rodlets during transients can then be tested at the INL Transient Reactor Test Facility, known as “TREAT.”

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