

Hot Cell Installation and Demonstration of the Severe Accident Test Station

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August 30, 2017

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SUMMARY

A Severe Accident Test Station (SATS) capable of examining the oxidation kinetics and accident response of irradiated fuel and cladding materials for design basis accident (DBA) and beyond design basis accident (BDBA) scenarios has been successfully installed and demonstrated in the Irradiated Fuels Examination Laboratory, a hot cell facility at Oak Ridge National Laboratory. Two test station modules provide various temperature profiles, steam, and the thermal shock conditions necessary for integral loss-of-coolant accident (LOCA) testing, defueled oxidation quench testing, and high-temperature BDBA testing. Installation of the SATS system restores the domestic capability to examine postulated and extended LOCA conditions on spent fuel and cladding and provides a platform for evaluating advanced fuel and accident-tolerant fuel cladding concepts.

This document reports on the successful in-cell demonstration testing of unirradiated Zircaloy-4. It also describes the integral test facility's capabilities, installation activities, and out-of-cell verification testing to calibrate and optimize the system.

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ACRONYMS

ANL	Argonne National Laboratory
ATF	accident-tolerant fuel
ATR	Advanced Test Reactor (at Idaho National Laboratory)
BDBA	beyond design basis accident
DBA	design basis accident
ECR	equivalent clad reacted
IFEL	Irradiated Fuels Examination Laboratory
INL	Idaho National Laboratory
LOCA	loss-of-coolant accident
R	roentgen
SATS	Severe Accident Test Station
TREAT	Transient Reactor Test Facility (at Idaho National Laboratory)

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ACKNOWLEDGMENTS

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HOT CELL INSTALLATION AND DEMONSTRATION OF THE SEVERE ACCIDENT TEST STATION

1. INTRODUCTION

The Severe Accident Test Station (SATS), installed at the Irradiated Fuels Examination Facility (IFEL), a hot cell facility in Building 3525 of Oak Ridge National Laboratory (ORNL), is an integral test facility capable of studying the response of irradiated fuels and materials to design basis accident (DBA) and beyond design basis accident (BDBA) scenarios. The motivation behind the development of this capability lies in restoring a domestic capability to perform integral testing of irradiated materials and to evaluate advanced nuclear fuel cladding concepts with enhanced accident tolerance in what is known as accident-tolerant fuel (ATF). The in-cell capability provides a platform for evaluation of cladding structural integrity, which is the first barrier for retention of fission products in light water reactor cores.

The high-temperature steam oxidation behavior of zirconium alloy cladding under design basis loss-of-coolant accidents (LOCA) and over a broader set of conditions has been studied at several facilities around the world ([1]–[8]). Currently only a limited number of facilities domestically and internationally can examine the oxidation behavior and post-quench ductility of cladding materials (Table 1). DBA evaluation of Zr-based alloys using the LOCA Integral Test system was originally developed at Argonne National Laboratory (ANL) and provided significant contribution to the US Nuclear Regulatory Commission test criteria for LOCAs [5]. After the ANL unit was decommissioned, the domestic capability was lost. In the aftermath of the Tōhoku earthquake and tsunami and the resulting Fukushima Daiichi nuclear accident, research goals have been directed towards developing novel materials with enhanced accident tolerance in light water reactor designs. These materials require evaluation in comparison to current UO₂/Zr-based alloy fuel systems to understand the DBA response and enhanced safety margins of BDBA scenarios.

To develop a single platform capable of evaluating both DBA and BDBA scenarios, design parameters were discussed and developed in two workshops in 2012, the Severe Accident Test Station Definition Workshop in San Diego, and the International Meeting on Examination of Current and Advanced Nuclear Fuels under Simulated Accident Conditions in Berkeley, California. The test station currently deployed in Building 3525 and described in this document is the outcome of design input from these workshops. The test station, which includes two modules on a single test stand, is capable of various temperature profiles, steam, and the thermal shock conditions necessary for LOCA testing, defueled oxidation quench testing, and high-temperature BDBA testing. This milestone report documents the in-cell capabilities of the SATS system, benchmark testing, installation, and demonstration testing at ORNL.

2. SEVERE ACCIDENT TEST STATION

As shown in Table 1, SATS is an internationally unique capability combining already developed out-of-cell testing capabilities with an in-cell integral LOCA test apparatus and a high-temperature BDBA furnace for examining oxidation behavior and post-quench ductility of fuel rod segments. This section briefly describes the testing capabilities of SATS's two modules.

Table 1. Summary of domestic and international accident testing capabilities

Lab	Heating method	Temperature control	Temperature measurement	Out of cell	In cell	Fuel	Target maximum temperature (°C)	Ref. #
ORNL SATS	Radiant + (resistance)	Computer	Thermocouples	Yes	Yes	Yes	1200 (1700)	This work
ANL	Radiant	Computer	Thermocouples	Yes	Yes	No	1200	[3], [5]
CEA-Saclay	Resistance	Manual	Pre-set	Yes	No	No	1200	[6]
Halden	Reactor + heaters	Pre-set	Thermocouples	No	No	Yes	1200	[9]
JAEA	Radiant	Computer	Thermocouples	Yes	Yes	No	1200	[4], [10]
Studsvik	Radiant	Computer	Thermocouples	No	Yes	Yes	1200	[11]

The working principles and a detailed review of SATS are described in an exhaustive design report from FY 2015 [12]. Sections 2.1 through 2.4, describing each module and testing type, are reproduced here from that report in summary form for the convenience of the reader.

2.1 Test Station Overview

Figure 1 provides an overview of the test station prior to in-cell insertion; it consists of two modules on a single test stand. The integral LOCA test apparatus is outlined in blue, while the high-temperature test furnace is outlined in red. The SATS system was initially deployed out-of-cell to examine nonirradiated materials. The same modules were then replicated and modified for in-cell operation (i.e., in ORNL’s fuel hot cell in Building 3525) to examine irradiated fuels and materials. Throughout the design of the SATS system, operational constraints within the hot cell (e.g., spatial and other constraints from the use of manipulators to operate the unit, and limits on the volume and types of gases released from the system) have been thoroughly captured to enable an efficient transition from the out-of-cell module to the in-cell capability. Table 2 summarizes the range of test parameters for each module and test type.

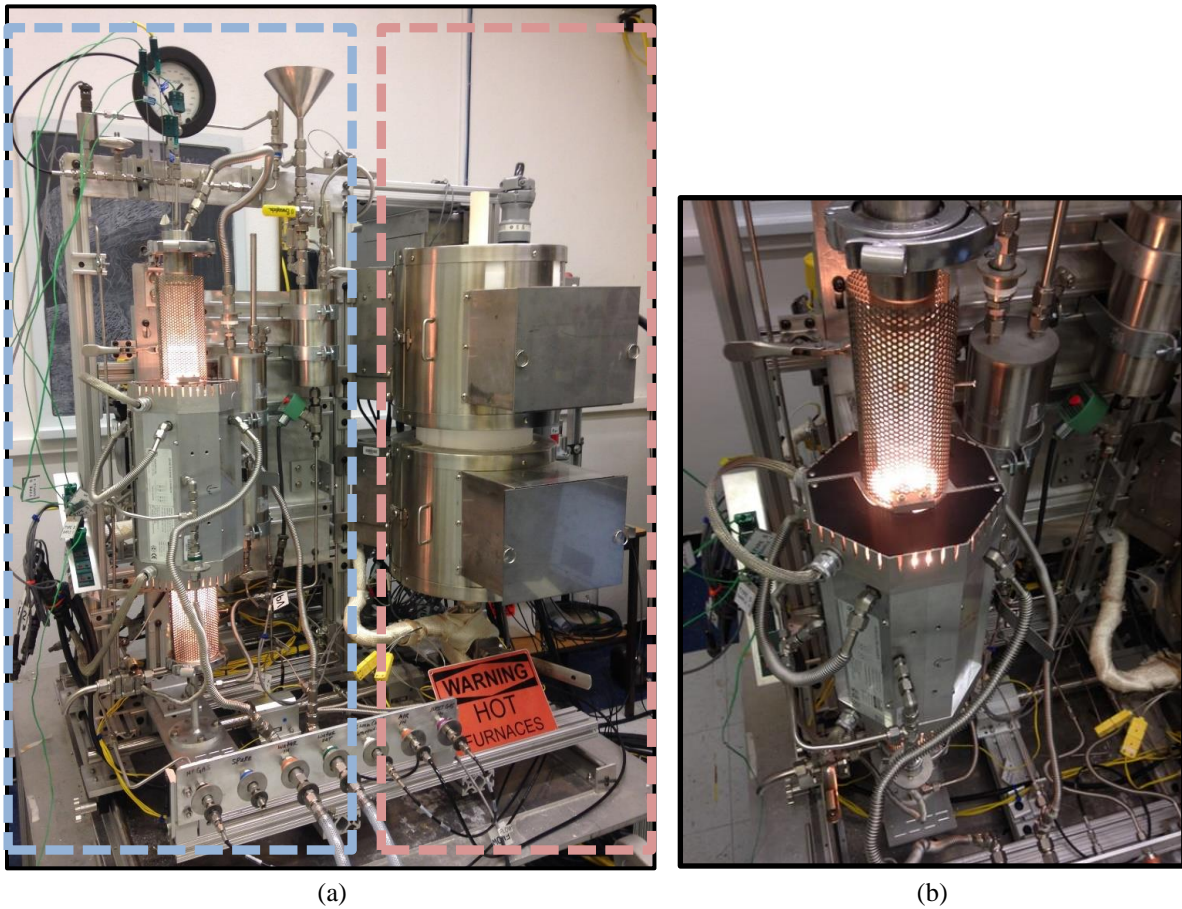


Figure 1. (a) The Severe Accident Test Station is a single unit with two modules, one for design basis accident integral LOCA testing (outlined in blue) and one for beyond design basis accident high-temperature testing (outlined in red). (b) LOCA integral test apparatus.

Table 2. Summary of test parameters for each module and test type

	DBA module		BDBA module
	LOCA integral test	Oxidation-quench test	High-temperature test station
Sample spec	Fueled rod	Defueled rod	Rod or coupon with 3 mm hole
Sample segment, mm	~200–300	~25–50	~25–50
Pressure, MPa	~8, max 20	0.1	0.1
Max temp, °C	1200	1200	1700
Heating rate, °C/s	5	5; max 20	.25; max .33
Steam flow rate, mg/cm ² ·s	~5.7	~5.7	3.0–7.0
Gas environment	Steam or argon	Steam or argon	Steam or argon
Quench, °C	@ 20–800	@ 20–800	None
Quench condition	Rising water around sample	Rising water around sample	None
Quench flow rate, mm/s	≥15	≥15	None
Test time, min	≥30	≥30	Multiple days

2.2 DBA (Integral LOCA) Test Station Module

The *US Code of Federal Regulations* covers postulated LOCAs in 10 CFR 50.46. LOCA integral tests were designed to investigate the performance of high-burnup irradiated fuel that has undergone ballooning and rupture under LOCA conditions. The LOCA integral test train was designed to externally heat a 300-mm-long fuel rod segment up to 1200°C by an infrared (IR) radiation furnace under initial high internal pressure (~8 MPa inside the tube). The internal pressure is generated by high-pressure argon gas, and the pressure is monitored using a digital output pressure transducer.

Temperature control and monitoring are extremely important in conducting LOCA integral and oxidation quench tests, because the time at temperature for the transition between ductile and brittle behavior is a strong function of temperature. The furnace power and the sample temperature are controlled by feedback from the designated type S (Pt/Pt-Rh) thermocouple output through a proportional-integral-differential (PID) controller to the furnace power. Each test sample is fitted with up to four thermocouples, two placed at the specimen midplane 180° apart, one positioned 50 mm above the midplane, and one positioned 50 mm below the midplane. Sample heat-up occurs quickly for short samples, but temperature overshoot can be avoided by an integrated and well-instrumented control system.

A quartz tube provides an enclosed volume for steam flow and water quench of the 300 mm rod segment; both steam and water 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. The test train for the LOCA integral tests is supported at the top to minimize specimen bowing. Figure 2. LOCA test train. provides more detail of the test train.

Figure 3 shows a schematic of the temperature history of the LOCA integral tests used for both out-of-cell and in-cell testing. Because of the high thermal mass of the sample and the thermocouples welded (nonirradiated) or wrapped (irradiated) around the LOCA sample, temperature control is easier than for the short, defueled cladding oxidation-quench samples (see the temperature history in Figure 1). For example, the reference control parameters for current boiling water reactor cladding are 8.28 MPa (1200 psig) internal pressure with argon at room temperature and 300°C, 5°C/s heating rate, 1200°C hold temperature, variable hold time, 3°C/s cooling rate from the hold temperature to 800°C, and rapid cooling from bottom-flooding water quench at 800°C.

As these parameters are controlled by software (LabView), they can be adjusted from test to test. Online data of interest include the time response of the bottom pressure transducer at room temperature and 300°C, burst temperature, and burst pressure.

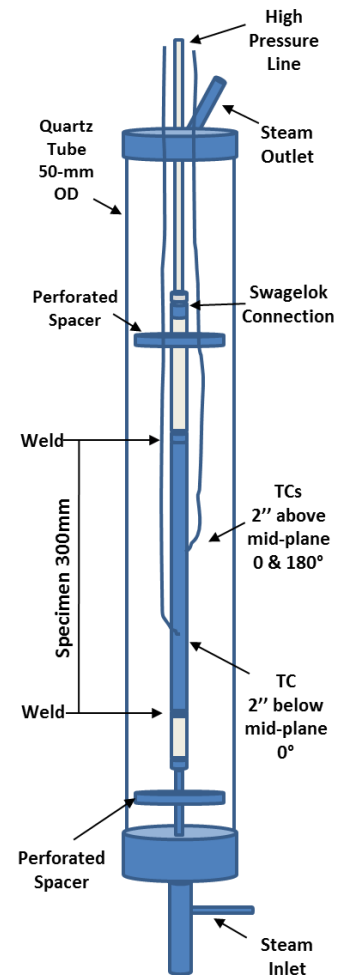


Figure 2. LOCA test train.

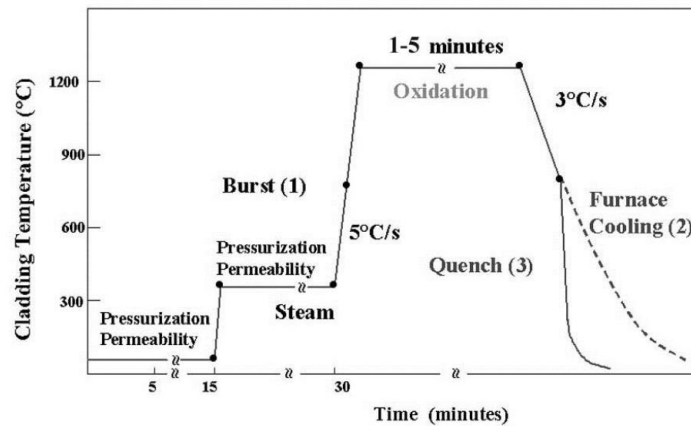


Figure 3. Schematic of thermal history used for LOCA integral tests with 300-mm-long samples.

2.3 Oxidation-Quench Test

Oxidation tests conducted on defueled high-burnup cladding samples are needed to characterize the evolution with time at temperature of the oxygen pickup and of the oxide thickness and morphology. The oxidized high-burnup samples are also used to determine post-test ductility as a function of corrosion layer thickness, hydrogen content, and high-temperature oxidation level. These data are used as a guideline to determine the test parameters of the LOCA integral tests.

Oxidation-quench tests do not require a high-pressure connection or pressure transducers. Steam, at near-atmospheric pressure, flows up through the quartz-tube test chamber at $0.32 \pm 0.05 \text{ g/cm}^2/\text{min}$ (5.3 g/min for a 48 mm internal diameter quartz tube) and exits the chamber into a condenser or exhaust. Following oxidation and slow-cooling phases, steam flow is turned off, and quench water is introduced through the bottom of the quartz tube, filling the tube to provide very rapid sample cooling to 70–100°C at the desired time and temperature during cooling. NRC-specified temperature profiles for the oxidation-quench testing using the ANL-proposed procedure include temperatures up to 1200°C and a ramp rate of $\geq 20^\circ\text{C/s}$, starting from 300°C, to within 200°C of the target temperature and $\geq 2^\circ\text{C/s}$ thereafter [3]. The cooling rate is known to significantly affect the post-quench ductility of the oxidized samples [13], and exact details on how post-quench ductility is affected by the cooling rate are not fully understood. The recommended average cooling rate to the 800°C quench temperature is $\approx 12 \pm 2^\circ\text{C/s}$.

The LOCA module of the SATS system was designed and built to meet all requirements for these oxidation test parameters. By fabricating oxidation test trains and performing benchmarking tests using both the out-of-cell and in-cell test stations at ORNL, the oxidation-quench test can also be made available for irradiated fuels and materials research.

2.4 BDBA (High-Temperature) Test Station Module

The objective of the high-temperature test station module is to provide a facility where samples of candidate fuel and cladding materials can be exposed to conditions more severe than the generally recognized LOCA test conditions. More specifically, the system is capable of exposing samples to rapidly flowing steam or a steam/gas mixture at temperatures of at least 1600°C. For this system, two molybdenum disilicide, resistance-heated, clamshell furnaces were chosen to create the very high temperature environment used for sample exposure (see Figure 1). The system is suitable for testing short sections of a radioactive fuel rod hanging from high-purity alumina holders as shown in Figure 4 and Figure 5.

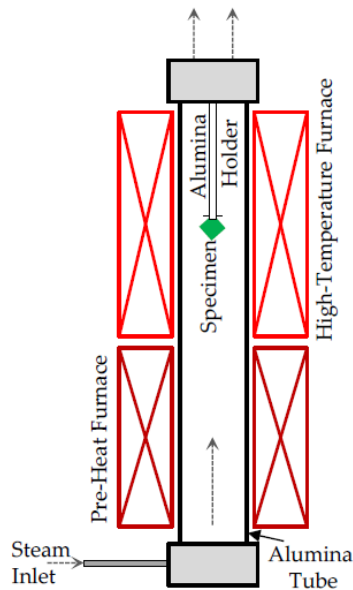


Figure 4. High-temperature furnace and experiment schematic.

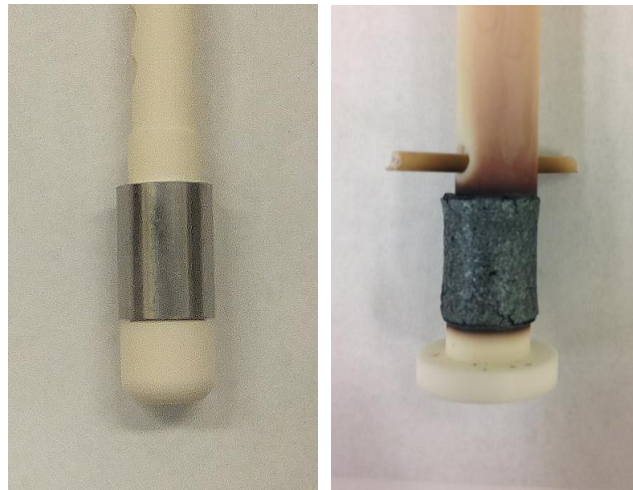


Figure 5. Two types of BDBA module high-purity alumina holders supporting short (<50 mm) cladding segments that are exposed to extreme temperatures (>1600°C) and flowing steam or steam/gas mixtures.

3. PRE-INSTALLATION VERIFICATION TESTING

Before moving the SATS system into the hot cell, many thermal verification LOCA tests were performed to aid in optimizing the apparatus and the test train for remote operation in the hot cell. These tests were conducted with specimens made from 17×17 pressurized water reactor Zircaloy-4 (300 mm long, 9.50 mm outer diameter, 0.570 mm wall thickness) filled with dense zirconia pellets leaving a cold radial gap of ≈0.1 mm. For the quad-elliptic radiant furnace, specimen bowing induced significant axial (ΔT_z) and circumferential (ΔT_θ) variations in temperature. This problem was solved by supporting the test train at the top.

Figure 6 shows a LOCA sample within the test chamber of the LOCA apparatus. 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 test train. The total gas volume in the test sample is 10 cm³, most of which is outside the heated zone. To verify uniform temperature across the centerline of the LOCA test specimen, benchmark testing was conducted with four type S thermocouple lead wires fed through the top flange: two were positioned at the specimen midplane 180° apart, one was positioned 50 mm above the midplane, and one was positioned 50 mm below the midplane (Figure 7a). These thermocouples are accurate to ±3°C at 1200°C. The tests showed a 10°C variation in temperature (ΔT) at these four locations during a full LOCA test (Figure 7b), confirming a uniform temperature across the centerline.



Figure 6. ORNL's integral LOCA furnace and test train within a quartz tube.

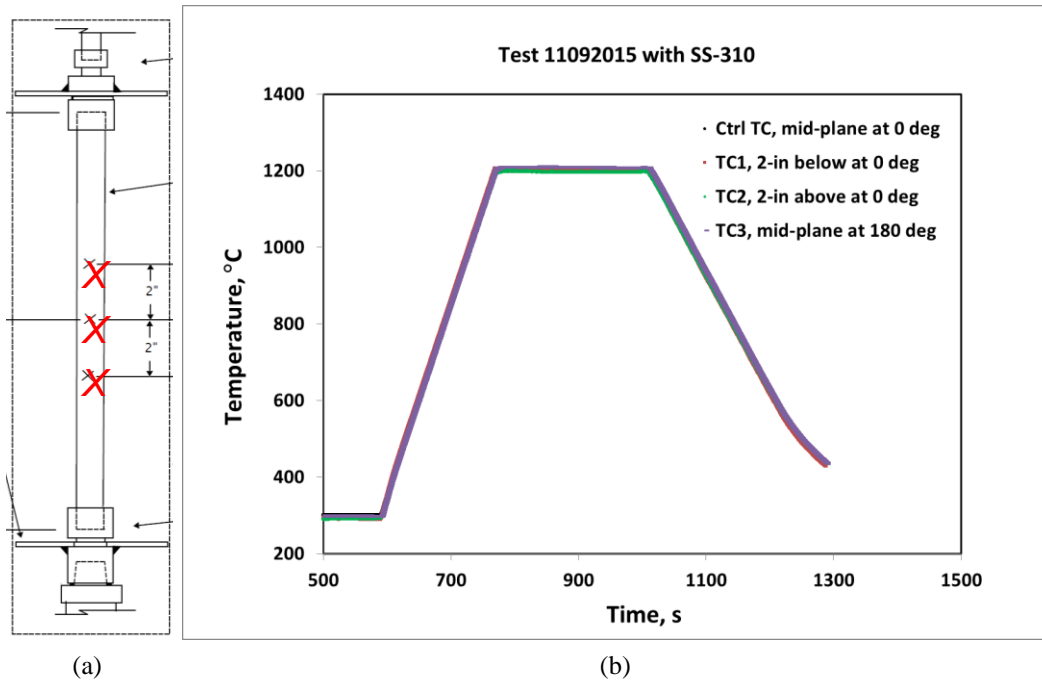


Figure 7. Verification testing of uniform temperature gradient at specimen centerline, which confirmed good agreement between thermocouple measurements. (a) Four type S thermocouples two were positioned at the specimen midplane 180° apart, one was positioned 50 mm above the midplane, and one was positioned 50 mm below the midplane. (b) 10°C ΔT among four type S thermocouples.

The signal from the top thermocouple is used to control the furnace power to achieve the desired temperature ramp and hold temperature. In-cell testing of fueled samples may be conducted using a strapped thermocouple instead of a welded thermocouple to decrease the likelihood of the thermocouple coming off during the LOCA burst event (Figure 8a,b). Additional comparison of strapped versus welded thermocouple measurements showed a slight (3°C) difference in the temperature values (Figure 8c). These measurements, validating agreement between the two methods, provide confidence that either approach can be used in-cell.

Figure 9 shows a typical temperature and pressure profile for the integral LOCA tests performed on ORNL's SATS.

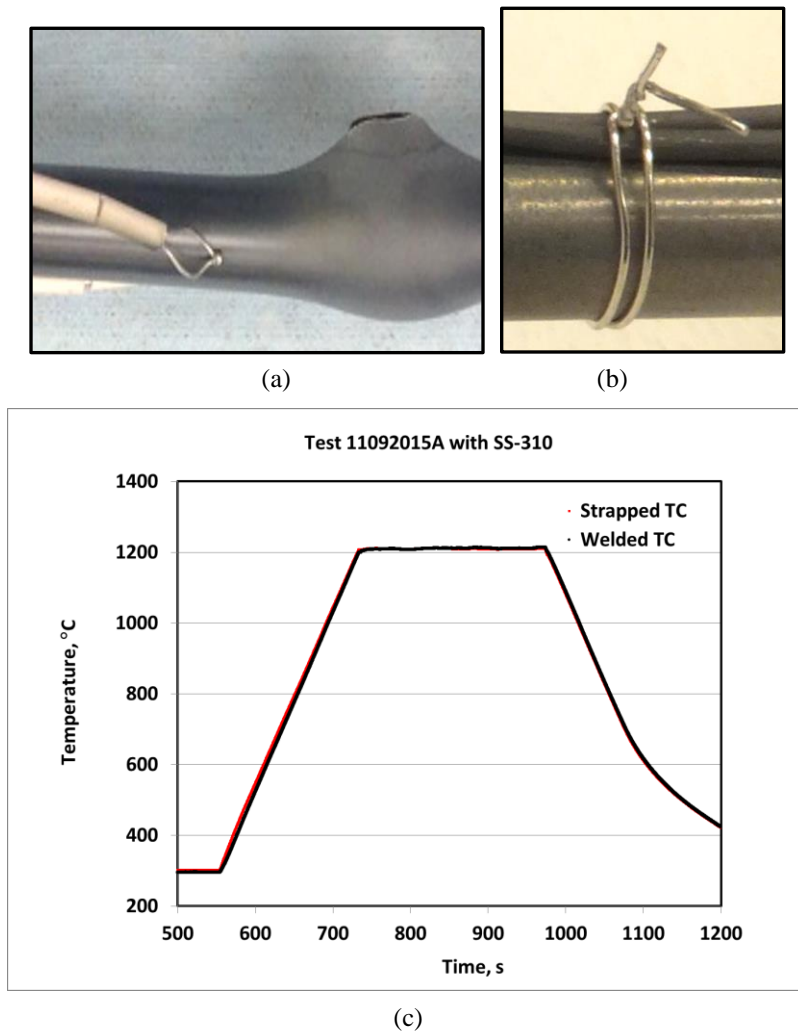


Figure 8. Comparison testing of strapped versus welded thermocouples. (a) Spot-welded thermocouple. (b) Strapped thermocouple. (c) The graph appears as one line because the temperature difference between the two methods is only 3°C . These results provide confidence that either method will produce a uniform temperature reading.

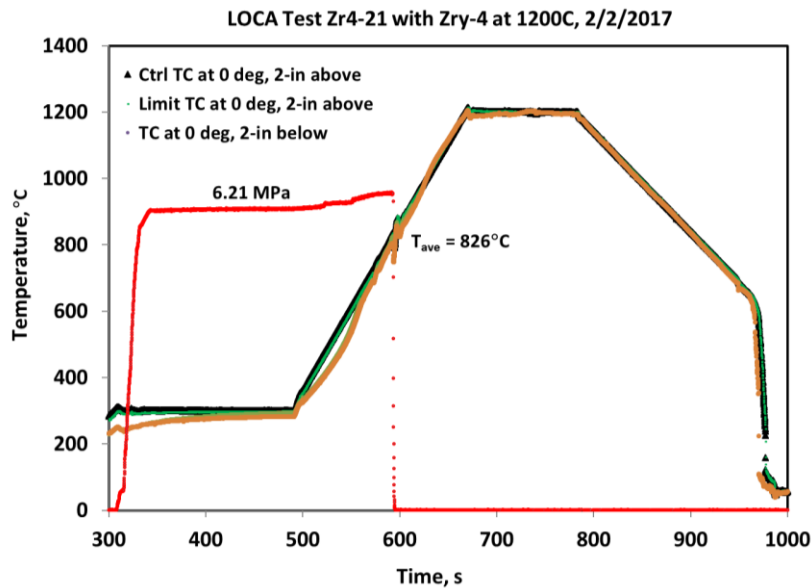


Figure 9. Pressure and temperature histories for LOCA integral test Zr4-21.

The results from a series of four out-of-cell integral LOCA tests are summarized in Table 3. All four tests were run at 1200°C, with the only difference being the internal pressure applied. Test Zr4-19 was conducted at 1200°C without internal pressure. Test Zr4-23 was pressurized to 4.14 MPa and burst occurred at ≈866°C. Test Zr4-21 was pressurized to 6.21 MPa and burst occurred at 826°C. For Test Zr4-22, the sample was pressurized to 8.27 MPa and burst occurred at a lower temperature (≈790°C). Figure 10 shows the post-LOCA test samples.

Table 3. LOCA integral test results for unirradiated Zircaloy-4 cladding filled with zirconia pellets

Parameter	Zr4-19	Zr4-23	Zr4-21	Zr4-22
Internal pressure at 300°C, MPa	0	4.14	6.21	8.27
Temperature ramp from 300°C, °C/s	5	5	5	5
Peak internal P _g , MPa	-	4.37	6.58	8.46
Temperature at burst, °C	No burst	866	826	790
Hold temperature, °C	1200	1200	1200	1200
Hold time, s	287	135	110	90
Cool-down rate to 800°C, °C/s	3	3	3	3
Quench initiation temperature, °C	700	700	700	700
Burst center relative to midplane, mm	-	-19	31	-19
Burst shape	-	Dog bone ^a	Dog bone	Dog bone
Burst length, mm	-	7	11	9
Maximum burst width, mm	-	1.8	2.0	2.5
Maximum strain [(ΔC/C _m) _{max}], %	0	27	37	47
Reference minimum wall thickness for ECR calculation, mm	0.57	0.45	0.42	0.39
Target ECR, % calculated (CP-Model)	17	17	17	17

^aDog-bone shape refers to the burst opening decreasing across the center versus an oval opening that continues to expand across the center of the opening.

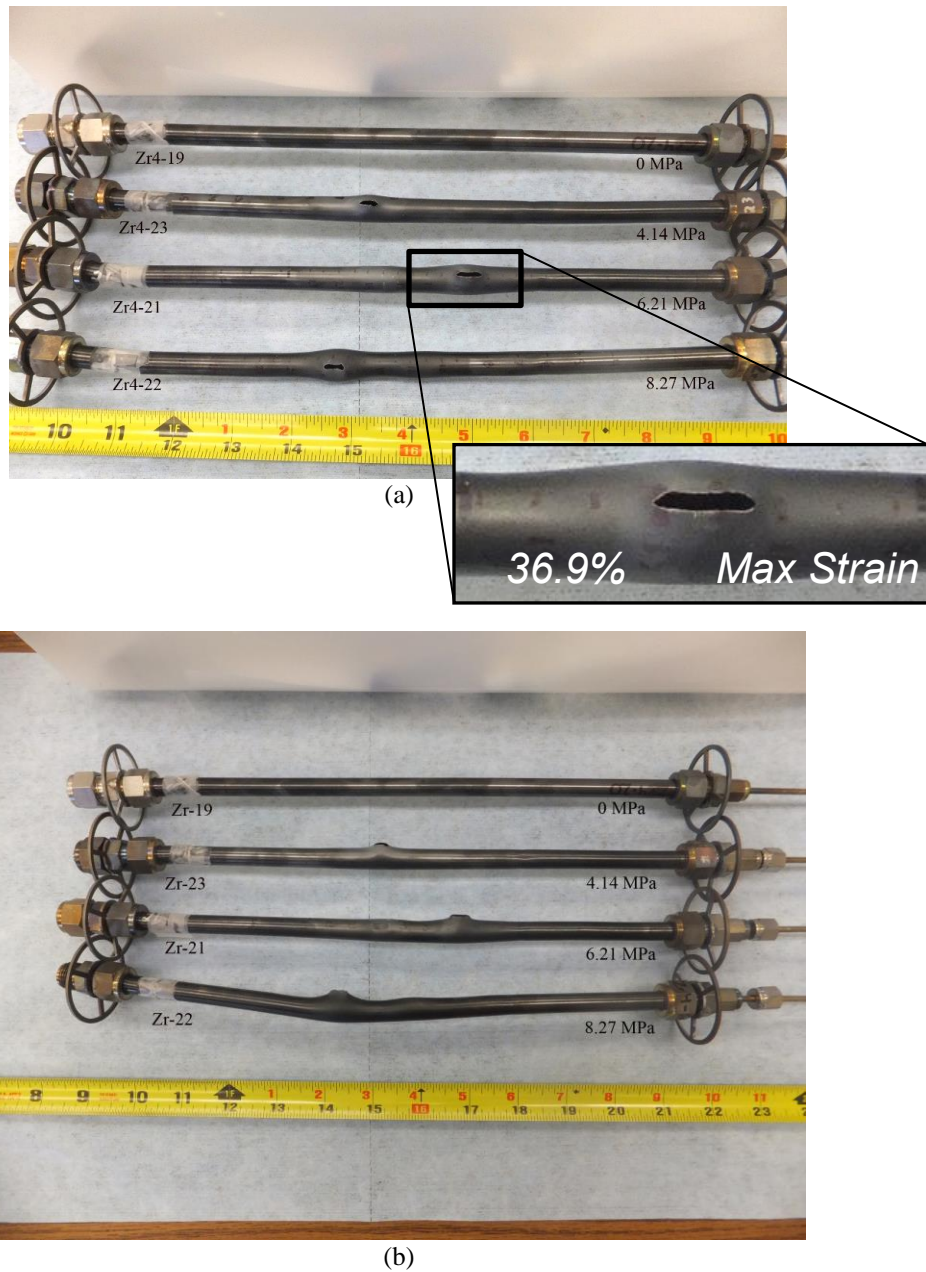


Figure 10. Top view (a) and side view (b) of four post-LOCA test samples tested at 1200°C with internal pressurization of 0.0, 4.14, 6.21, and 8.27 MPa. Close-up of (a): Zr4-21 at 6.21 MPa burst with maximum strain of 36.9%. All maximum strain values are provided in Table 3.

Characterization has been performed on post-LOCA test specimens to determine axial profiles of hydrogen pickup, oxygen pickup, and equivalent clad reacted (ECR). Transverse metallography and oxygen analysis have also been done at several axial locations to determine the circumferential variation of metal thickness prior to oxidation and of oxygen pickup. Both microstructure and oxygen concentration results suggest a cross section that varies from very brittle near the burst edges to ductile 180° from the burst opening.

4. HOT CELL INSTALLATION

When benchmark testing was complete, the SATS system was successfully installed into the main hot cells of the IFEL, Building 3525. The control panel is positioned in the operating area against the outside wall as shown in Figure 11. The corner hot cell workstation provides an optimal location with two windows oriented 90° apart, one facing north and the other facing west. The dose rate of the SATS workstation was about 70 R/h prior to preparing the table for this installation (Figure 12a). Removing some radioactive waste material and adding some lead sheets to the tabletop (Figure 12b), reduced the dose rate to 10–15 R/h. The reduction of dose rate in the area will reduce the radiation damage to SATS and extend its operational lifetime.

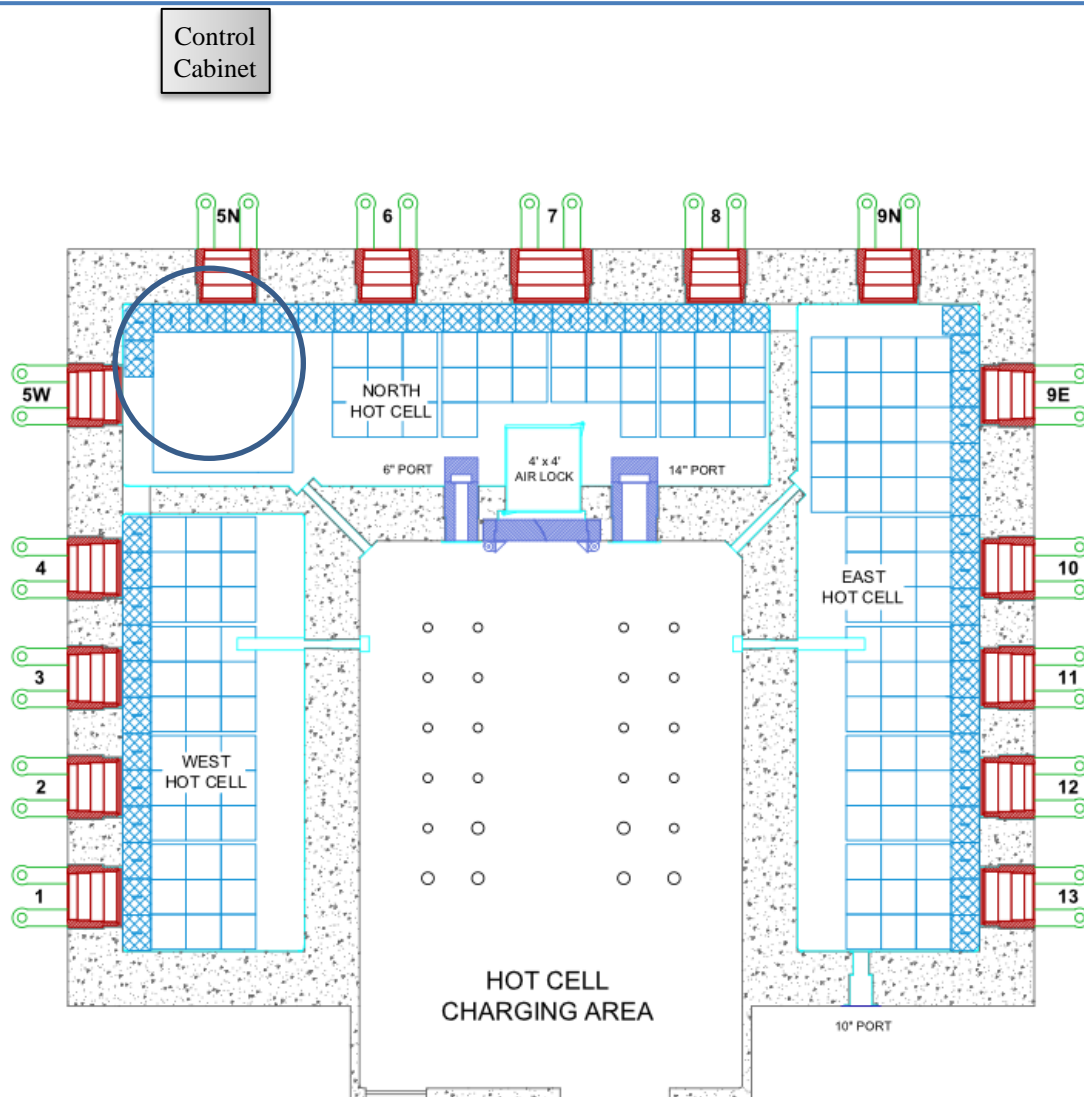
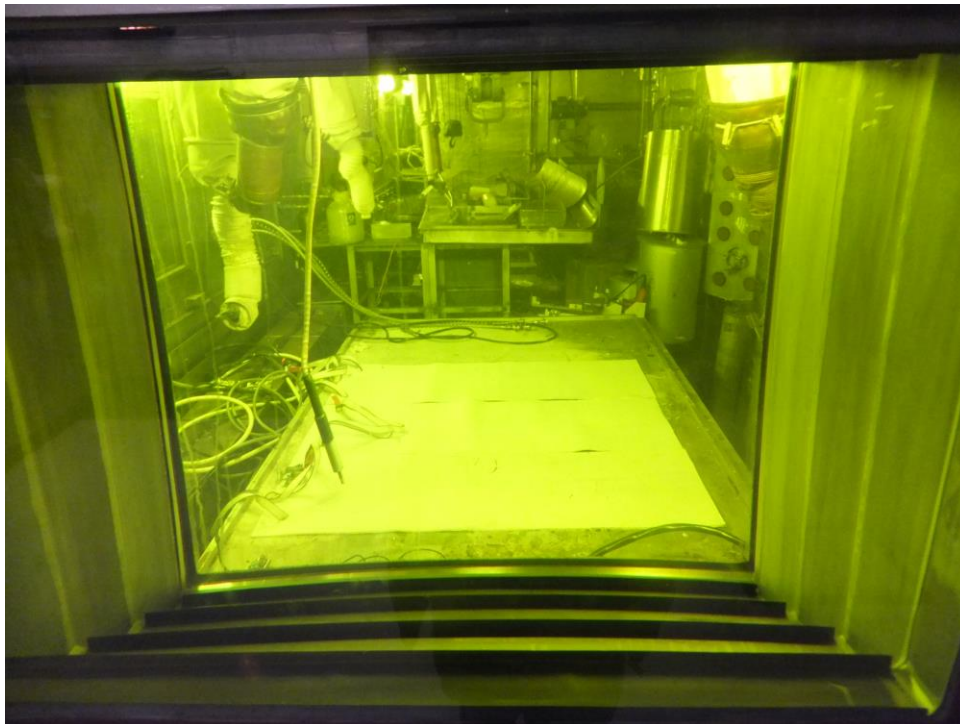


Figure 11. Overhead view of the Irradiated Fuels Examination Laboratory (IFEL), Building 3525. The Severe Accident Test Station faces workstation 5N (circled above) with the control cabinet positioned against the north operating wall.



(a)



(b)

Figure 12. SATS workstation before (a) and after (b) removing the radioactive materials. A lead sheet (painted white) was placed on the tabletop to reduce the dose rate.

SATS installation began with the removal of old equipment and waste material (see Figure 12a) located in workstation 5. The in-cell table also required cleaning and additional plates of lead shielding to reduce the dose coming through the table from below (see Figure 12b). Technicians disconnected all cables and pipes running to SATS out-of-cell and handed them over to hot cell operations for preparation of the alpha and lead plugs (Figure 13). Hot cell operators installed three service plugs in the hot cell wall as shown in Figure 14. The control cabinet was moved into the work area across from workstation 5 (see Figure 11). SATS was then lifted and moved through the charging area (Figure 15). Electricians and pipefitters made the out-of-cell utility connections of cables and pipes (Figure 16) after the cooling system, high-pressure system, and inert gas cylinder were placed in the area next to workstation 5 (Figure 17). Finally, the hot cell operators made the connections of lines in-cell to the SATS system.

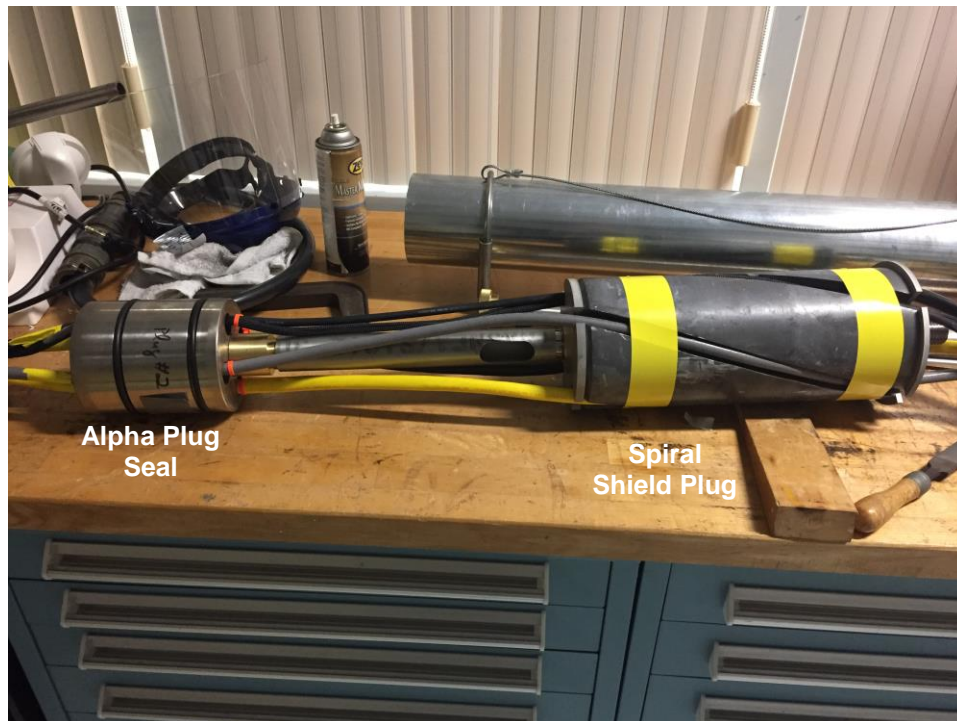


Figure 13. A service plug for power line penetration through the hot cell wall.

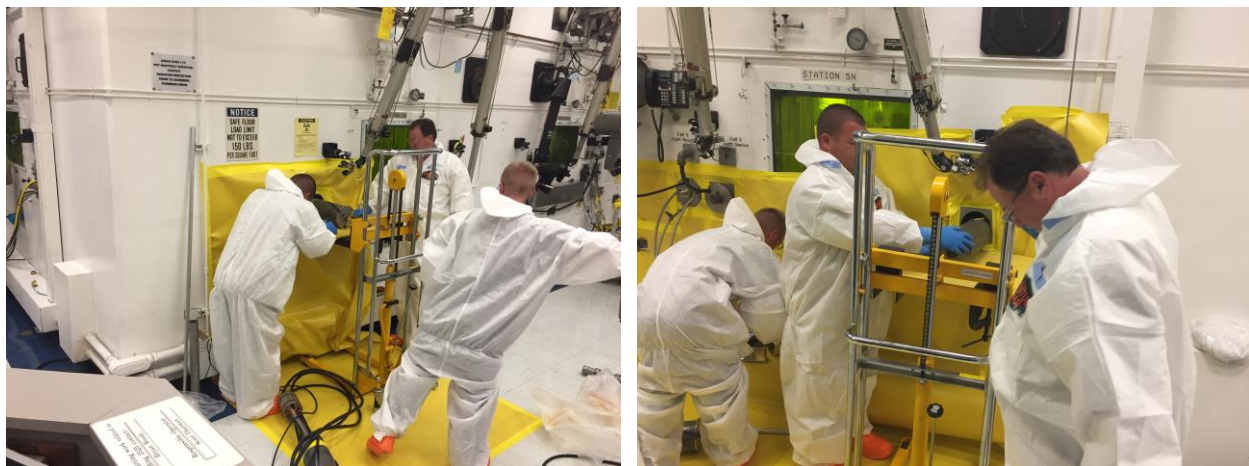


Figure 14. Installation of a service plug for SATS into the hot cell wall.



Figure 15. Installation of SATS into the main hot cell of the IFEL.

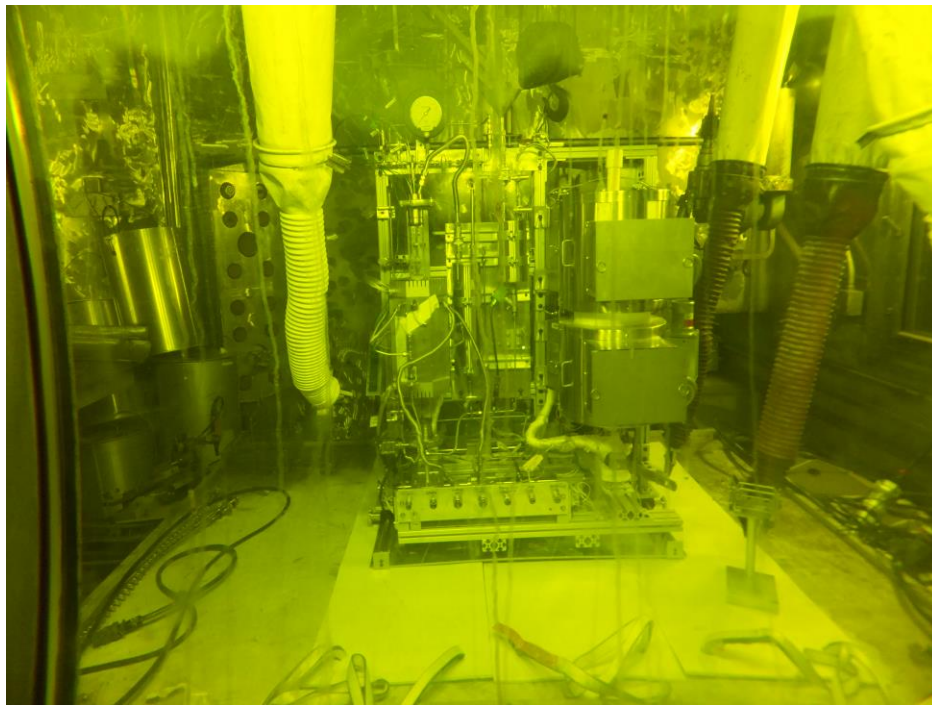


Figure 16. SATS in the main hot cell of the IFEL.



Figure 17. Water cooling system and high-pressure system for the in-cell LOCA apparatus.

5. SATS DEMONSTRATION TEST RESULTS

This section describes the demonstration test results obtained from in-cell testing of unirradiated samples.

5.1 LOCA Demonstration Test Results

After successfully installing the SATS system into the hot cell, the LOCA furnace was aligned to aid in optimizing the apparatus and the test train for remote operation in the hot cell. Figure 18 shows a LOCA sample within the test chamber (a quartz tube). 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 test train. Four type S thermocouple lead wires were fed in through the top flange: two were positioned at the specimen midplane 180° apart, one was positioned 50 mm above the midplane, and one was positioned 50 mm below the midplane. The signal from the top thermocouple is used to control the furnace power to achieve the desired temperature ramp and the hold temperature.



Figure 18. A LOCA test train within a quartz tube.

A full sequence LOCA test was conducted with the SATS system on August 7, 2017 (Figure 19). A LOCA integral test with 300-mm-long samples consists of the following sequential steps: stabilize temperature, internal pressure, and steam flow at 300°C; ramp the temperature ($\approx 5^\circ\text{C/s}$) through ballooning and burst to $\approx 1200^\circ\text{C}$; hold at 1200°C for 1–5 min; slow cool ($\approx 3^\circ\text{C/s}$) to 700–800°C; and finally water quench. Figure 20 shows the temperature and pressure profile for integral LOCA test Zr4-26, performed on the in-cell SATS.

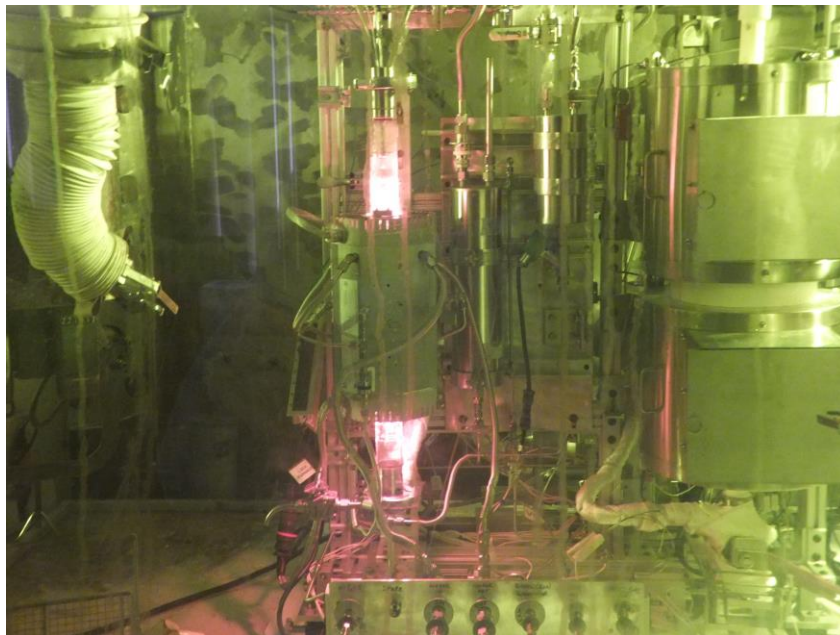


Figure 19. LOCA in-cell demonstration test in the IFEL.

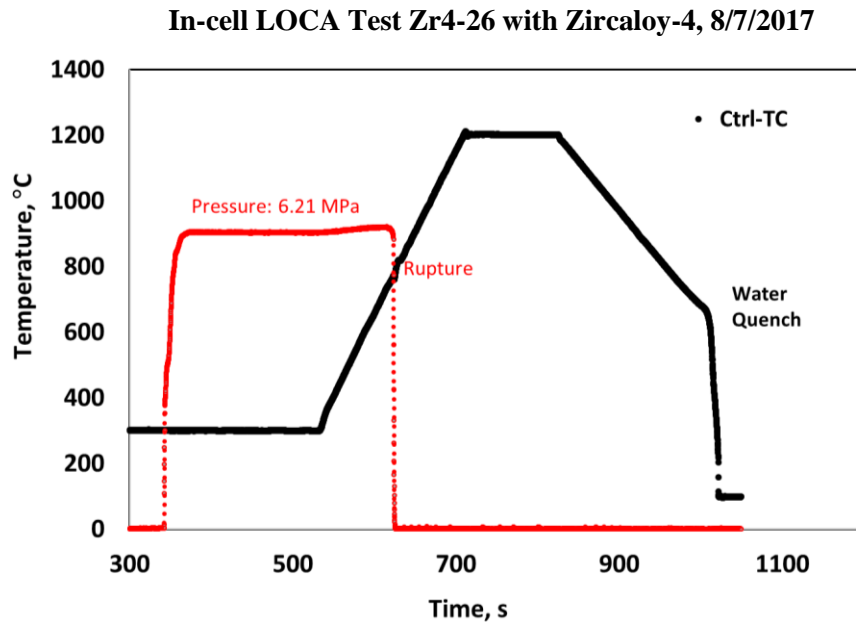


Figure 20. Pressure and temperature histories for in-cell LOCA integral test Zr4-26.

5.2 High-Temperature Furnace Demonstration Test Results

In addition to LOCA testing, a high-temperature steam oxidation test was conducted with SATS's high-temperature furnace (Figure 21). The target temperature was 1400°C, and the furnace was ramped at a controlled heating rate of 15°C/min.

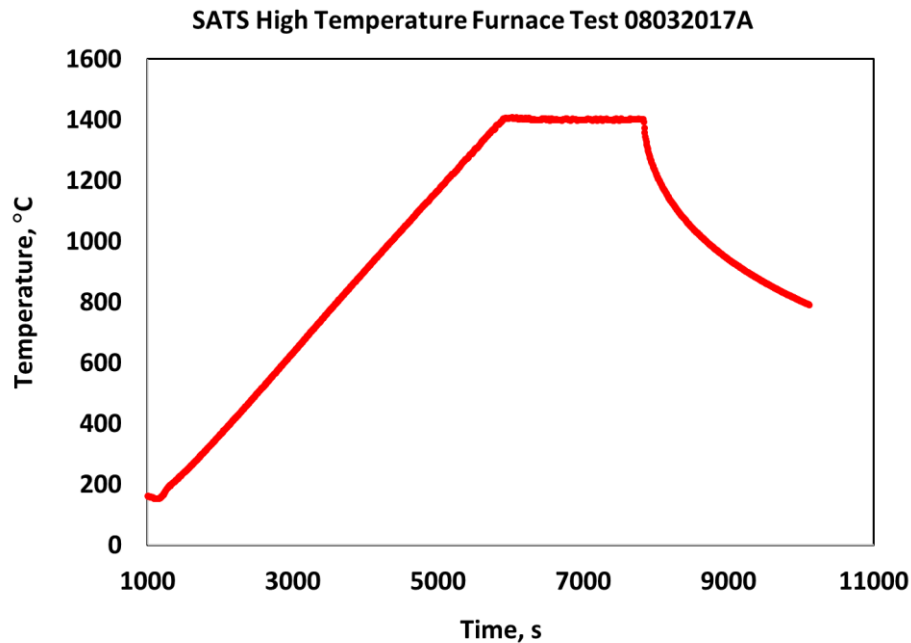


Figure 21. Temperature history for the in-cell high-temperature steam oxidation test performed August 3, 2017.

6. SUMMARY AND FUTURE WORK

The Severe Accident Test Station (SATS) was successfully installed and demonstrated in the Irradiated Fuels Examination Laboratory at ORNL. The test facility is designed to examine fuel and cladding response to LOCA transients during design basis accident and beyond design basis accident scenarios by exposing irradiated samples to various in-core conditions, including high temperatures, steam, and the direct quench anticipated during emergency core cooling. This document reports on the first use of the integral test facility and the results obtained for unirradiated Zircaloy-4. It also details the installation process and test setup.

Future test plans include in-cell benchmarking testing using commercial Zr-based alloys, high-temperature oxidation of fueled ATF-1 rodlets, and separate effects testing ahead of the Transient Reactor Test Facility (TREAT) in-core experiments summarized below.

The ATF-1 rodlets, which were irradiated in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL), consist of FeCrAl cladding and UO_2 (Figure 22). The rodlets have undergone initial post-irradiation examination at INL and have been prepared for shipment to ORNL. The rodlets include holes to permit hanging in the SATS high-temperature furnace and will provide the first data on fuel-cladding interaction and the fueled severe accident response of FeCrAl cladding.

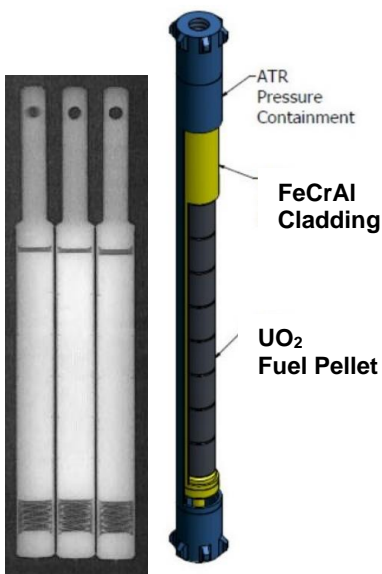


Figure 22. ATF-1 rodlet irradiated in ATR, with FeCrAl cladding and UO_2 pellets designed for post-irradiation testing using SATS.

A successful Nuclear Science User Facility proposal by the Electric Power Research Institute and the US Nuclear Regulatory Commission [14] will utilize SATS to benchmark LOCA high-burnup target fuels out-of-core; these fuels will be reconditioned into rodlets for higher burnup in ATR. The final in-pile LOCA simulation will be performed on the TREAT Super-Static Environment Rodlet Transient Testing Apparatus (Super-SERTTA) irradiation test device at INL.

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