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Changing the World's Energy Future

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INTRODUCTION

Idaho National Laboratory (INL)'s Transient Reactor Test (TREAT) Facility, which first operated from 1959 to 1994, is an air-cooled, graphite-moderated test reactor designed to perform transient tests on nuclear materials and fuels in situations ranging from off-normal conditions to severe accident scenarios. In 1994, TREAT was placed in standby mode. This lasted until 2017, when the Department of Energy restarted the facility to resume transient testing, with a focus on accident-tolerant fuels for current light-water reactors (LWRs) as well as fuels for advanced reactors [1].

In 2018, the first fueled irradiations occurred in TREAT since the restart [2]; in 2019, commissioning tests for a static water pool experiment vehicle were performed. This experiment vehicle, developed to simulate reactivity-initiated accidents, was designed to fit within the Minimal Activation Retrievable Capsule Holder (MARCH) irradiation vehicle system [3] and was given the name MARCH Static Environment Rodlet Transient Test Apparatus (M-SERTTA). Experiments utilizing the M-SERTTA capsule in TREAT have so far consisted of commissioning tests on fresh fuel rodlets and transient critical heat flux tests which replace the nuclear fuel rod with a novel borated stainless-steel rod. Experiments using fuel rodlets irradiated in INL's Advanced Test Reactor are planned for late 2020.

At about the same time as the development and initial TREAT transients utilizing the M-SERTTA capsule, it was unexpectedly announced that the Halden Boiling Water Reactor (HBWR) would be shutting down many of its experimental programs and begin the decommissioning process [4]. This was a great loss to the fuel safety community, as the HBWR had been a major contributor to research on nuclear materials and fuels for decades. One of the HBWR's premier capabilities was its in-pile loss-of-coolant accident (LOCA) testing program, which, prior to its shutdown, provided the only in-pile LOCA testing facility in the Western world available to researchers, industry, and regulators [4]. The unexpected shutdown of the HBWR and its associated LOCA capabilities prompted research staff at INL to investigate the possibility of modifying the M-SERTTA capsule into a LOCA experiment test vehicle (termed the "LOCA-SERTTA") to meet near-term data needs [5]. Results of the investigation showed this concept to be viable.

To be more economically competitive, industry is evaluating the possibility of increasing the enrichment of LWR fuel to up to 6–7% ^{235}U/U to extend the lifetime of nuclear fuel. To accomplish this, regulatory burnup limits need to be increased from 65 to about 70–80 GWd/MTU. Current LWR fuel/cladding configurations and accident-tolerant fuel designs are both being evaluated. One issue needing investigation to determine whether regulatory burnup limits can be increased is the phenomenon of fuel fragmentation, relocation, and dispersal (FFRD). FFRD describes the process of fuel fragmentation during a LOCA transient, with the fuel axially relocating to the portion of the fuel rod in which the ballooning is taking place and being dispersed into the coolant channel once the cladding bursts. The FFRD phenomenon was first experimentally observed during HBWR LOCA tests with a high-burnup fuel rod as the test subject. Further out-of-pile experiments reproduced the FFRD phenomenon. It is hypothesized that fission gas trapped in the fuel at these high burnups, along with the thermomechanical stress evolution of the fuel during the LOCA transient, play an important role in FFRD; however, a complete understanding of the process remains elusive, and experts interpret the experiment results in various ways [6].

One area not thoroughly examined is the impact of the fuel's thermomechanical stress evolution on FFRD under conditions that would be seen if a commercial LWR underwent a LOCA. Prior to a LOCA occurring in an LWR, the reactor would be at steady-state conditions, meaning that the radial temperature profile within the fuel would have a parabolic shape. Once the LOCA occurs, the power trips, causing the center portion of the fuel pellet to decrease in temperature while the periphery of the pellet increases in temperature due to decreased coolant heat transfer. At this point, the temperature profile throughout the pellet is relatively flat and will continue to rise until equilibrium is reached or additional cooling is introduced. In general, out-of-pile experiments cannot capture this parabolic-to-flat temperature evolution, as heating for these tests typically comes from infrared heaters surrounding the fuel rod, resulting in outward-in heating of the rod and an inverted parabola temperature profile. LOCA tests in the HBWR also did not fully capture this temperature evolution, since pre-LOCA linear heat rates (LHRs) were not high enough to drive a parabolic temperature profile in the fuel [7]. The LOCA-SERTTA experiment vehicle, along with the power and flexibility of TREAT, enables the simulation of the temperature profile evolution expected for a commercial

LWR during a LOCA. Presented in this summary are thermal-hydraulic modeling results for LOCA-SERTTA, which are then compared to LOCA simulation results for a commercial LWR.

EXPERIMENT DESIGN AND MODELING

LOCA-SERTTA Design

As stated in the previous section, the LOCA-SERTTA experiment vehicle is based on a modified static water pool capsule termed M-SERTTA. LOCA-SERTTA consists of two capsules: the upper one being a pressurized static water capsule consisting of the fuel rodlet and instrumentation, and the lower being a low-pressure blowdown tank. A remotely triggered valve connects the upper capsule to the blowdown tank. To simulate a LOCA, this valve is opened, resulting in rapid depressurization and the water quickly draining from the upper capsule into the blowdown tank.

The fuel rodlet in the LOCA-SERTTA experiment has a 20-cm fueled length with various options for instrumentation, depending on experiment objectives. Axial-flux-shaping sleeves also surround the top and bottom portions of the rod to mitigate end-peaking effects and ensure that clad ballooning occurs in the central portion of the rodlet. Fig. 1 shows a design rendering of LOCA-SERTTA.

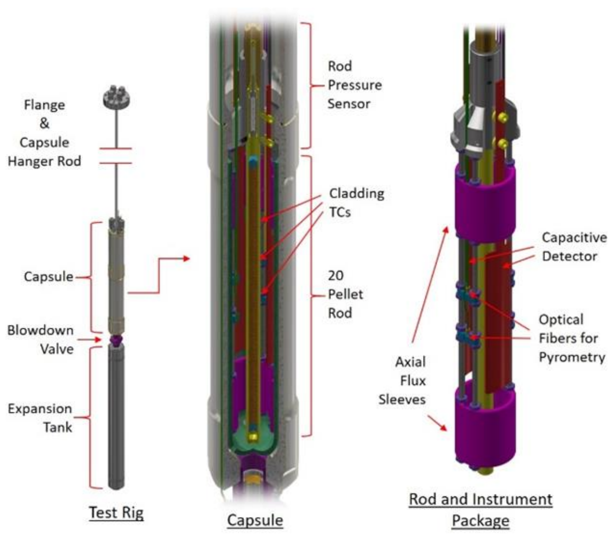

Fig. 1. LOCA-SERTTA design rendering.

The LOCA-SERTTA experiment consists of two segments. In the first, the fuel rodlet is brought up to quasi-steady-state conditions meant to mimic the operating conditions of a commercial LWR. This is done by ramping up the reactor power over a period of ~30 seconds, then holding the power constant for another ~30 seconds. This results in a temperature profile throughout the fuel and LHR that is consistent with commercial LWRs; except, instead of the clad removing heat via forced convection, it is removed via nucleate boiling in the static water pool. After the desired temperatures are reached, segment two begins. The blowdown valve is opened, and the reactor power is reduced to simulate decay heat.

RELAP5-3D Model

To analyze the thermal-hydraulic design of LOCA-SERTTA, a RELAP5-3D [8] model was created. A nodalization diagram of the model is shown in Fig. 2. The volume components are shown in black, heat structures in red, and the junctions between the volumes are represented as arrows. Components initially occupied by water are shaded in blue, and gas volumes have no color.

The fuel rodlet is shown to have 22 pellets, the top and bottom pellets being non-fueled insulator pellets (grey) and the remaining 20 pellets being UO_2 (orange). The gas plenum of the fuel rodlet is shown in green. An axial flux profile that takes into account the axial-flux-shaping sleeves was applied to the rod, so the power becomes peaked in the center of the rodlet.

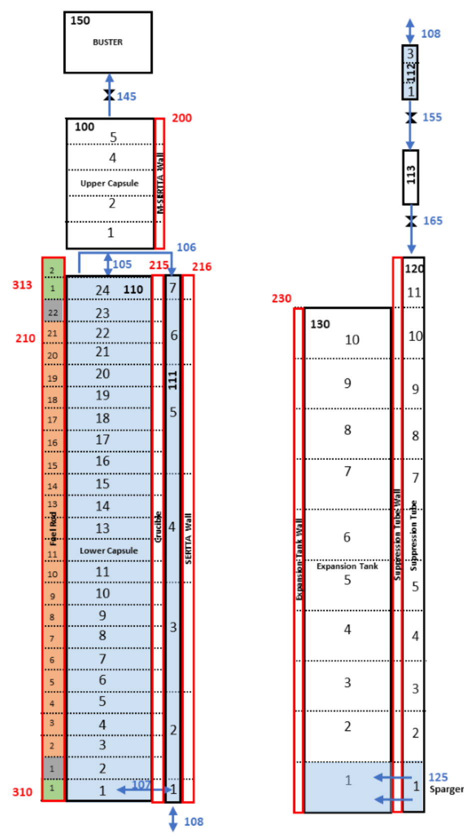

Fig. 2. RELAP5-3D nodalization diagram of LOCA-SERTTA.

RESULTS

To determine how well LOCA-SERTTA simulated the temperature profile evolution, its RELAP5-3D simulation results was compared to a legacy RELAP5-3D model of a 3-loop Westinghouse pressurized-water reactor (PWR) in which a large-break LOCA was simulated. In the legacy PWR model, the peak LHR in the rod of interest was 41 kW/m. More information on this model can be found in [9, 10]. To achieve similar fuel and cladding temperatures prior to LOCA initiation, the LOCA-SERTTA model ramped up to the same LHR of 41 kW/m over a period of 30 seconds. As described above, the power was then held constant for another 30 seconds to achieve quasi-steady-state conditions. Then blowdown was initiated, and the power was reduced to 3 kW/m, steadily decreasing as the transient progressed. The rod LHR and capsule pressure for this LOCA-SERTTA RELAP5-3D simulation are shown in Fig. 3.

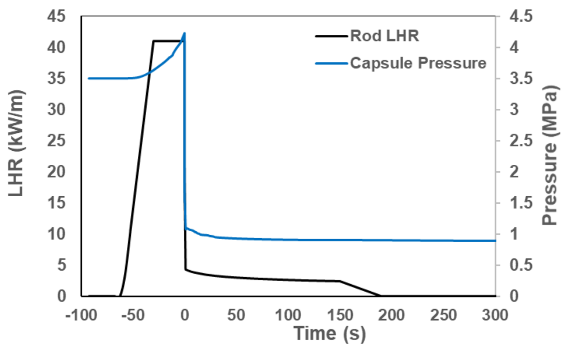

Fig. 3. LOCA-SERTTA rod LHR and capsule pressure; blowdown at 0 s.

Fig. 4 shows the centerline and cladding temperatures for the LOCA-SERTTA case compared to the legacy PWR model. The temperatures in the LOCA-SERTTA and legacy PWR models are in very strong agreement. More temperature fluctuations are predicted by the legacy PWR model since it models the entire reactor and events such as cross flow and flow reversal are present.

The LOCA-SERTTA and legacy PWR models were also compared in regard to radial temperature profiles at certain times after blowdown, as this dictates the thermomechanical stress through the radius of the fuel (Fig. 5). Qualitatively, this comparison shows that LOCA-SERTTA is good at reproducing the temperature profiles expected during a commercial PWR LOCA.

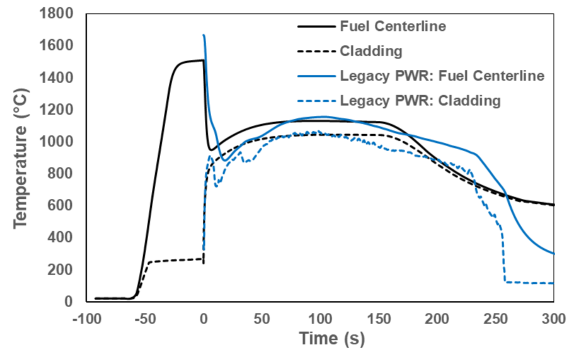

Fig. 4. LOCA-SERTTA fuel and cladding temperatures compared to those in the legacy PWR model; blowdown at 0 s.

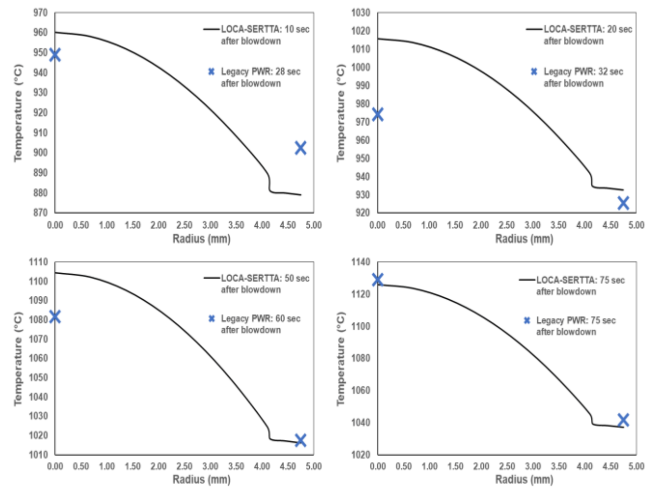

Fig. 5. Comparison of radial temperature profiles between the LOCA-SERTTA and legacy PWR models.

CONCLUSIONS

Increasing the regulatory burnup limit would enable current LWRs to be more economically competitive. One issue needing investigation to determine whether regulatory burnup limits can be increased is the FFRD phenomenon that can occur at high burnup. A complete understanding of this phenomenon remains elusive; however, it is believed that fission gas trapped in the fuel at these high burnups, along with the thermomechanical stress evolution of the fuel during the LOCA transient, play an important role. Out-of-pile experiments as well as in-pile LOCA experiments at the HBWR cannot produce prototypic temperature profiles in the fuel prior to LOCA initiation, due to their heating restrictions. Investigation of the LOCA-SERTTA experiment vehicle designed for TREAT found that it can create the temperature profile evolution seen in a commercial LWR during a LOCA transient. This will allow researchers to conduct further studies to better understand the impact that thermomechanical stresses have on the FFRD phenomenon.

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