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Changing the World's Energy Future

Robert J Armstrong, Colby B Jensen, Charles P Folsom, Nicolas E Woolstenhulme

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INTRODUCTION

The U.S. nuclear industry is looking to extend light water reactor (LWR) fuel burnup and enrichment limits. Industry is currently pursuing increases in burnup and enrichment from the current licensed limits of 62 GWd/t and 5 wt.% ^{235}U enrichment up to 75 GWd/t and approximately 8 wt.% ^{235}U. Increasing to these limits allow for utilization of fuel management strategies that present the opportunity for substantial economic benefits. One such economically favorable fuel management strategy that is made possible with these increased limits is transitioning pressurized water reactor (PWR) plants from the current standard of an 18-month operating cycle to a 24-month cycle. This reduces the frequency of refueling outages allowing plants to increase their electricity generation. Other economic benefits from this strategy include fuel cost savings and dry cask savings [1]. It should be noted that industry is pursuing an incremental step to a burnup limit of 68 GWd/t while building the licensing basis to support 75 GWd/t [2].

In support of the burnup extension efforts, the U.S. Department of Energy (DOE) Advanced Fuels Campaign (AFC) is engaging with key stakeholders in the nuclear community, identifying potential data gaps, and executing research and development to aid industry in their preparation of licensing topical reports and the regulator in their review of said topical reports. The behavior of high burnup (HBu) fuel during a loss-of-coolant accident (LOCA) has been identified as an important R&D opportunity for DOE laboratory support, where phenomena known as fuel fragmentation, relocation, and dispersal (FFRD) may become of concern. To investigate FFRD, an in-pile experiment vehicle designed to perform LWR fuel safety testing within the Transient Reactor Test (TREAT) facility at Idaho National Laboratory (INL) will be used to perform LOCA experiments. The experiment vehicle is known as the Transient Water Irradiation System for TREAT (TWIST). Prior to performing experiments on HBu fuel specimens, a commissioning test series will be conducted on fresh fuel specimens. The main purpose of the Loss-of-Coolant-Commissioning (LOC-C) test series is to qualify the TWIST device and in-situ instrumentation, validate power coupling between TREAT and the TWIST fuel rod, and validate the thermal-hydraulic and fuel performance simulation codes which will be used to design the subsequent HBu fuel experiments. The LOC-C experiments are planned to begin in 2023. This paper discusses the analysis methodology that is being used to design the LOC-C test series. Application of this methodology, which utilizes coupled thermal-hydraulic and fuel performance simulations, is demonstrated through the presentation of simulation predictions based on the current LOC-C test matrix.

BACKGROUND

FFRD includes the process of fuel fragmentation during a LOCA, with fuel axially relocating to the portion of the fuel rod in which ballooning is taking place and being dispersed into the coolant channel upon potential cladding rupture. HBu FFRD was first observed in 2006 during LOCA experiment IFA-650.4 performed in the Halden Boiling Water Reactor (HBWR) where the test rodlet was of very high burnup (~92 GWd/t) [3]. Further testing in the HBWR and subsequent out-of-pile furnace tests performed between 2009 and 2011 at Studsvik, sponsored by the U.S. Nuclear Regulatory Commission (NRC) [4], confirmed the FFRD phenomena observed in the IFA-650.4 experiment and found that there is a burnup threshold related to fine fuel fragmentation. In the time from these initial tests where FFRD was observed up to the present day, many integral-type and separate effects experiments have been performed to investigate FFRD. Detailed reviews of experimental work can be found in [5-8]. Here, a brief overview of the current FFRD landscape is provided to give context to the motivation of this work.

In December 2021, drawing from the current experiment database relevant to HBu LOCA, the NRC Office of Nuclear Regulatory Research released a Research Information Letter (RIL) containing the staff's interpretation of this data and generated conservative, empirical boundaries describing FFRD-related phenomena [9]. The database used for this analysis comes from four experimental programs. In addition to the aforementioned in-pile LOCA experiments performed in the HBWR and NRC-sponsored out-of-pile furnace experiments, data from the third phase of the Studsvik Cladding Integrity Project (SCIP-III) and tests performed in the Severe Accident Test Station (SATS) at Oak Ridge National Laboratory (ORNL) were included. The SCIP-III and SATS experiments were also hot cell furnace experiments.

The main conclusions of the RIL for this data include: fine fragmentation is limited to fuel above 55 GWd/t pellet average burnup and axial fuel relocation is limited to regions of the fuel rod where cladding strain is greater than 3%. Given that these thresholds are based purely on observations of the empirical data and only described as a function of burnup, their range of applicability is limited to materials and conditions within the experiment database.

For instance, the thresholds do not apply to Accident Tolerant Fuel (ATF) concepts such as doped fuel or coated cladding as the RIL only analyzed UO_2-fueled Zirconium alloy-based-clad fuel systems and these ATF concepts may behave differently. While the RIL uses burnup to describe FFRD behavior, it recognizes that fuel characteristics such as porosity, stress within the fuel, and microstructural properties such as grain growth and the formation of subgrains may be more directly correlated with FFRD behavior. Further research into these areas may provide a more mechanistic description of FFRD.

As for the representativeness of the empirical database to prototypic LWR LOCA conditions, the RIL as well as a Letter Report issued by the NRC Advisory Committee on Reactor Safeguards following their review of the RIL [10] caution that the experimental conditions often differed significantly from conditions that may exist if a PWR were to undergo a LOCA from steady-state operating conditions. These non-prototypicalities, which depend on the exact nature of the LOCA scenario of interest, include linear heat rate, heating rate of the fuel and clad, and peak cladding temperature reached during the LOCA.

In a LOCA event where the coolant in the core flashes to steam in the first few seconds after pipe rupture, a rapid redistribution of the stored energy in the fuel causes temperatures in the central region of the fuel to decrease at rates of ~100 K/s while the cladding is heating up at this same rate. In this scenario, application of the empirical thresholds described in the RIL may not be fully representative of the FFRD behavior as the heating rates in the experimental database range from 2-9 K/s and separate effects tests have shown that heating rate affects transient fission gas release (a key parameter related to FFRD) [11]. Rupture temperature of cladding is also known to be positively correlated with heating rate [12]. The peak temperature in some of the tests within the experimental database reached 1473 K, this may not be representative of LWR LOCA scenarios as peak temperatures for HBu fuel rods where FFRD is of concern is expected to be much lower than this [13].

Experiments to be performed in the TWIST LOCA vehicle aim to explore these data gaps while taking advantage of the significant existing database and knowledgebase. To achieve this goal, an integral LOCA test plan has been developed under the DOE AFC program [14]. Complimentary tests performed in-pile in the TWIST LOCA vehicle at INL and out-of-pile furnace experiments performed at ORNL's SATS facility will systematically assess the impact of prototypic LOCA conditions and fuel microstructure on FFRD behavior.

While integral RIA and varied separate effects testing of LWR fuels have been underway in the TREAT facility for several years, the LOCA experiment design, TWIST, has been developing for first reactor deployment in 2023. The first integral LOCA experiments in the new TREAT TWIST device are the LOC-C series with the primary goal of fully commissioning LOCA testing in TREAT.

EXPERIMENT DESIGN AND MODELING

The TWIST experiment vehicle sits in the center of the TREAT core. TREAT is an air-cooled reactor consisting of uranium dioxide dispersed within graphite blocks enclosed in Zircaloy where the graphite acts as both a moderator and heat sink. Hydraulically driven transient control rods allow for virtually any power history to be prescribed, within the constraints of available reactivity. Depending on the desired power levels, shaped transients in TREAT generally are on the milliseconds to several minutes. Further details regarding TREAT and its capabilities can be found in [15, 16]. Combined with the TWIST device, these unique power shaping capabilities allow for simulating LOCA events starting from prototypic PWR operating conditions in the fuel.

TWIST Design

The TWIST experiment vehicle consists of two capsules stacked vertically. The upper vessel is a pressurized static water capsule containing the nuclear fuel rod to be tested. The lower capsule is a low-pressure expansion tank. A controllable valve connects the upper capsule with the lower expansion tank. During a LOCA experiment, this valve is opened at a specified moment during the experiment, in coordination with reactor power, causing rapid depressurization and rapid water movement from the upper capsule into the expansion tank.

The upper capsule is designed to house a test specimen with a fueled length up to 50 cm and supports a wide variety of instrumentation connections. This allows for instrumentation packages to be configured on a per-experiment basis depending on specific experiment objectives. Some TWIST instrumentation of note includes optical-fiber-based infrared pyrometry to allow for non-contact temperature measurements of the cladding surface, fuel centerline thermocouples, cladding thermocouples, and an electroimpedance sensor to measure clad ballooning and phase change in the capsule. Timing of cladding rupture will be measured using a linear variable differential transformed-based pressure transducer. More details and further information can be found in [14]. Axial flux sleeves also surround the top and bottom portions of the rod to mitigate end-peaking effects. A schematic overview of the TWIST design is shown in Fig. 1.

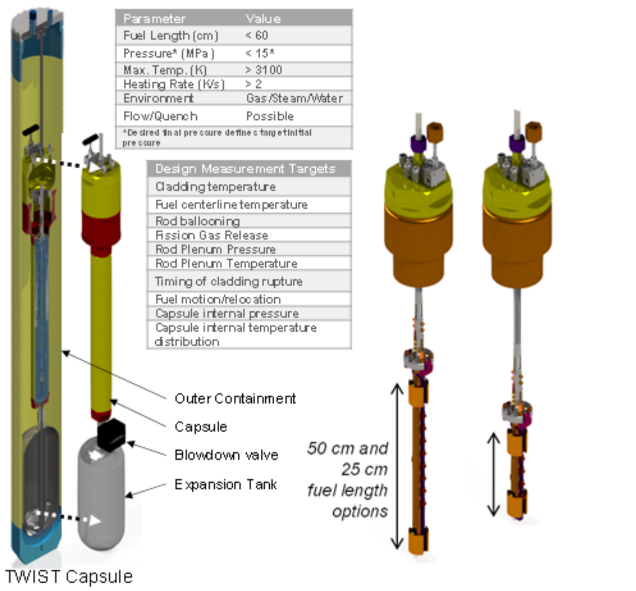

Fig. 1. Schematic overview and key specifications of the TWIST LOCA device.

The nominal experiment sequence for a TWIST LOCA experiment consists of two transient segments–Transient Segment 1 (TS-1) and Transient Segment 2 (TS-2). The main purpose of TS-1 is to bring the fuel rod up to temperatures that are consistent with a PWR rod at operating conditions. This is done by ramping up the TREAT reactor power over a period of tens of seconds, then holding the power constant for an additional ~20-30 seconds. This results in a radial temperature profile throughout the fuel that is consistent with a PWR rod at operating conditions; except, instead of the heat being removed from the cladding outer surface by forced single-phase convection, it is removed via nucleate boiling by the water in the capsule for a short duration.

The end of TS-1 and start of TS-2 is marked by opening the controllable valve to the expansion tank while simultaneously reducing the reactor power of TREAT to a level that simulates decay heat in the test fuel. This causes a rapid depressurization and removal of liquid water in the upper capsule. With the rod now in a steam environment, and at a low power, the radial temperature profile that existed at the end of TS-1 quickly flattens, raising the fuel periphery and cladding temperature rapidly up to approximately 100 K/s while simultaneously decreasing the fuel centerline temperature at the same rate until the stored energy is redistributed. As TS-2 continues in time, the low level of power provided to the rod can be tuned to achieve the temperature history of interest.

This two-segment approach allows for more prototypic simulation of LOCA scenarios where a rapid redistribution of stored energy in the fuel results in a large cladding temperature increase over a short period of time. From this point forward, this will be referred to as stored energy heat-up (SEH). While this two-segment approach will be the nominal experiment sequence for TWIST LOCA experiments, LOCA experiments consisting of TS-2 may also be performed at a wide range of heating rates from ~2 K/s and up. This type of experiment will be used to tieback to the existing experiment database where heating rates are ~5 K/s. Experiments consisting just of TS-1 may also be performed. During this mode of operation, the rod is brought up to full power conditions; however, the blowdown valve is never opened. This approach is useful for characterization and qualification purposes, but also for integral RIA experiments not discussed further in this paper. An illustration of the nominal TWIST LOCA experiment sequencing is shown in Fig. 2.

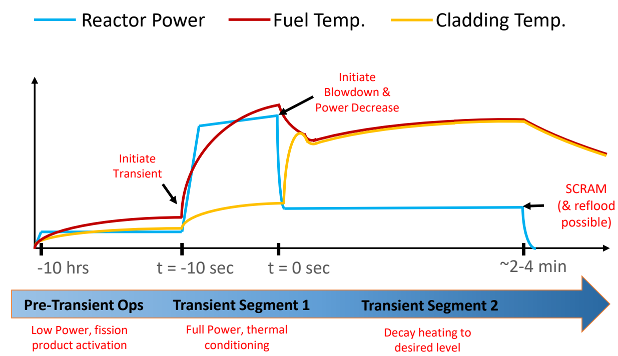

Fig. 2. Illustration of the TWIST LOCA experiment sequence.

TRACE Model

The thermal-hydraulic conditions of the TWIST device were simulated using the NRC-developed systems code TRACE [17]. The model described in Fig. 1 was converted into a TRACE model. A nodalization diagram of TWIST is shown in Fig. 3. Pipe components are shown in black, heat structures in red, and the junctions between the pipes are represented by the arrows. Components initially occupied by water are shaded in blue, while volumes occupied by gas have no color.

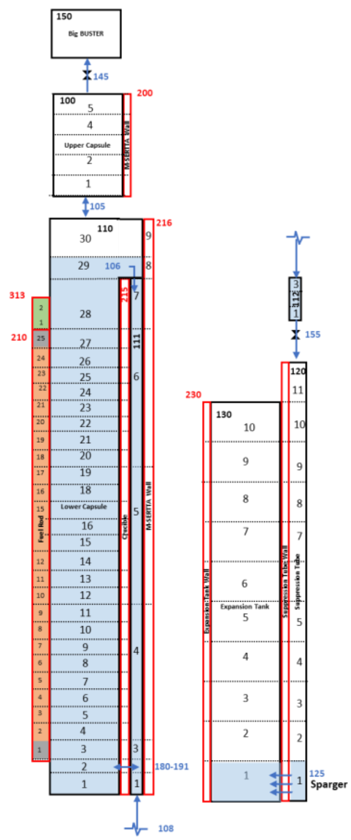

Fig. 3. TRACE nodalization diagram of the TWIST LOCA device.

Bison Model

For detailed evaluation of fuel and cladding thermomechanical behavior, the Bison fuel performance code [18], was used to model the TWIST fuel rod. Bison, built on the Multiphysics Object-Oriented Simulation Environment (MOOSE) framework, is a multi-dimensional finite-element based fuel performance code which includes capabilities to simulate a wide variety of nuclear fuel types including LWR fuels, metallic fuels, and TRISO fuel types. In addition to standard UO_2/Zry LWR fuels, models for ATF concepts such as doped-fuels, coated Zry claddings, and FeCrAl claddings have also been incorporated into the code [19].

BlueCRAB

To take full advantage of coupled thermal-hydraulic and fuel performance physics over the lifetime of a fuel rod, a tool known as BlueCRAB (CRAB is the Comprehensive Reactor Analysis Bundle) was developed to allow for tight coupling between the TRACE and Bison codes. BlueCRAB is a MOOSE-based application which allows the relevant data between the Bison and TRACE to be transferred between each other through an ExternalMesh. Given that TRACE will automatically renodalize a fuel heat structure to obtain higher resolution when a steep axial temperature gradient is present, an additional interface within BlueCRAB known as FineMeshTransfer was developed to accommodate this. A more detailed description of the development of BlueCRAB and an initial capabilities demonstration can be found in [20]. A schematic of the TRACE/Bison coupling through BlueCRAB is shown in Fig. 4.

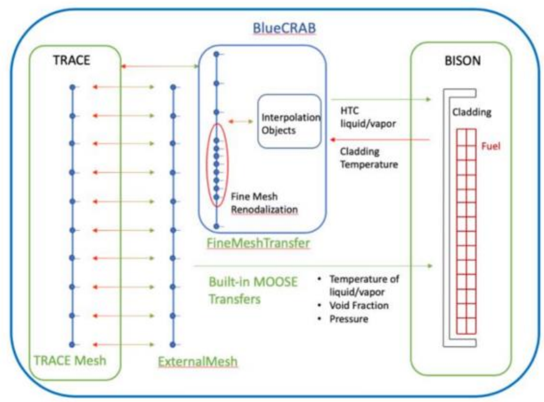

Fig. 4. Illustration of TRACE/Bison coupling through the BlueCRAB MOOSE-Wrapped application [21].

COMMISSIONING TEST SERIES MATRIX

The purpose of the TWIST LOCA commissioning test series, LOC-C, is to qualify the TWIST device for LOCA testing including in-pile demonstration of all in-situ instrumentation and diagnostics. This goal will be accomplished via measured validation of the power coupling between the TREAT reactor and the TWIST fuel rod as well as the thermal-hydraulic and fuel performance predictions used to design the experiments. The LOC-C test series consists of 9 total experiments performed on 5 fuel rods (LOC-C-3-A thru E will be performed on the same rod). Each experiment within this test series plays a crucial role in enabling the TWIST LOCA platform. For all experiments, a PWR fuel rod segment with an enrichment of 3.2 wt% ^{235}U clad in Zry-4 will be used. This enrichment level was chosen as it has a similar power coupling factor to that of the HBu fuel specimens to be tested. This allows for similar TREAT transients to be used for the fresh fuel commissioning tests and the HBu test campaign. The initial capsule pressure for all experiments besides LOC-C-2 is 3.5 MPa. Since LOC-C-2 begins in the post-blowdown state, the starting pressure will be near atmospheric conditions. Table I presents an overview of the current LOC-C test matrix.

Table I: LOC-C test matrix.

Test ID	Peak Temperatures (K)	Purpose	Fuel Rod Parameters
LOC-C-1	Clad – 520 Fuel – 1600	TS-1 fuel power calibration	Fuel Length 25 cm Free Volume 15 cc Rod Pressure 0.1 MPa
LOC-C-2	Clad – 1173	TS-2 fuel power calibration	
LOC-C-3-A	Clad – 520 Fuel – 2000	TS-1 thermal-hydraulic characterization above and below nominal temperature targets	
LOC-C-3-B	Clad – 520 Fuel – 1200		
LOC-C-3-C	TS-1 Clad – 520 Fuel – 1600 TS-2 Clad – 1173	Full LOCA sequence TS-1→TS-2	
LOC-C-3-D	Clad – 1073	TS-2 thermal-hydraulic characterization below and above nominal temperature targets	
LOC-C-3-E	Clad – 1273		
LOC-C-4	TS-1 Clad – 520 Fuel – 1600 TS-2 Clad – 1173	Pressurized rod to drive clad ballooning and burst	Fuel Length 25 cm Free Volume 15 cc Rod Pressure 15 MPa
LOC-C-5		Long rod evaluation. Pressurized rod to drive clad ballooning and burst	Fuel Length 50 cm Free Volume 15 cc Rod Pressure 15 MPa

- **LOC-C-1/LOC-C-2:** The primary purpose of the first two experiments is to measure the power that is input into the fuel rod. Fuel centerline thermocouples will provide a direct measurement of this based on temperature rise in the fuel. Post-transient gamma spectroscopy will be used to define the power axially along the rod. This information will provide a term known as the power coupling factor which relates the power of TREAT to the power in the fuel rod. To minimize uncertainties for both transient segments (TS-1 and TS-2), the power coupling factor will be measured separately for each segment; LOC-C-1 for TS-1 and LOC-C-2 for TS-2.

- **LOC-C-3:** LOC-C-3 is comprised of multiple power transient to simulate a wide range of thermal-hydraulic conditions on a single specimen/capsule. These results will be used to help validate simulation predictions. The first two transients LOC-C-3-A and B will be performed using TS-1 at power levels above and below the nominal targeted peak fuel/clad temperatures in a water-filled capsule. LOC-C-3-C will be ran using the full LOCA transient sequence (TS-1 and TS-2) reaching the nominal target temperatures, starting with a water-filled upper capsule, and ending with "dry" capsule. LOC-C-3-D and E will be run on TS-2 below and above the nominal temperature targets with a "dry" upper capsule. Multiple transients are able to be performed on this rod as it is not pre-pressurized, ensuring that cladding ballooning will not occur.

- **LOC-C-4:** The LOC-C-4 experiment will use a pressurized rod with the intention to drive cladding ballooning and burst.

- **LOC-C-5:** The LOC-C-5 experiment is planned to commission the TWIST vehicle for LOCA experiments on 50 cm fueled length specimens. Conditions will be consistent with those of LOC-C-4 to validate power distribution and other rod length effects on experiment performance.

RESULTS

This section presents the results of the Bison/TRACE simulations coupled through BlueCRAB. The results here informed the test matrix shown in Table I and while specifics of the final LOC-C test matrix may change, the results presented below demonstrate the methodology and show demonstrative results for the current test matrix.

LOC-C-1

BlueCRAB simulations of the LOC-C-1 transient found that the targeted nominal fuel and cladding temperatures of approximately 1600 K and 520 K can be achieved with an average linear heat rate (LHR) in the fuel of ~30 kW/m (Fig. 5). The system is designed to provide flexibility to target desired pre-transient thermomechanical conditions. The target specimen power can be adjusted with the primary effect of adjusted fuel centerline temperature. The goal is to generate a radial temperature profile through the fuel that is consistent with a PWR rod at steady-state operating conditions and may be tailored to the particular test specimen end-of-life condition. This is shown in Fig. 6 with a comparison to the radial temperature profile of a PWR operating at steady state. Note that the thermal boundary condition provides comparable heat removal rate as prototypic but is not exactly the same such that LHR may not be prototypic.

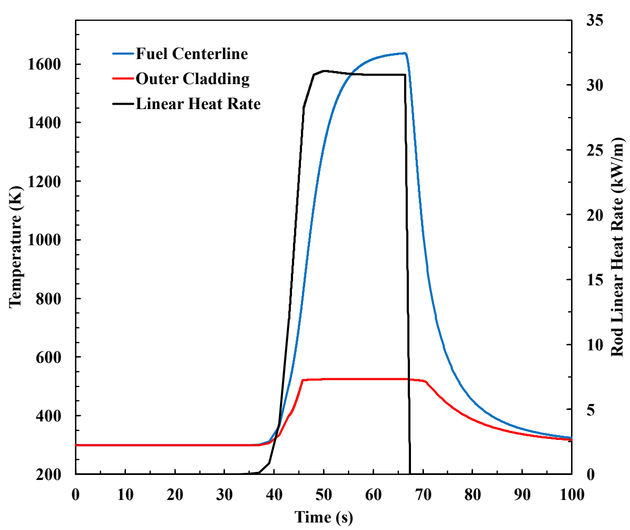

Fig. 5. LOC-C-1 temperature and linear heat rate history during the transient.

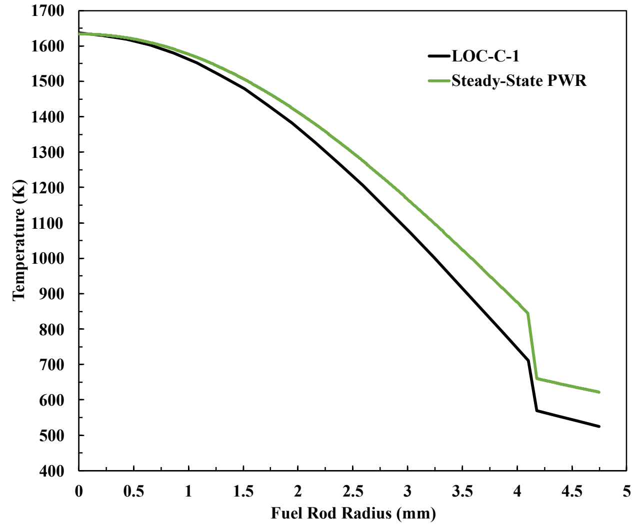

Fig. 6. LOC-C-1 during constant power portion and PWR steady-state radial temperature profiles.

LOC-C-2

The goal of the LOC-C-2 transient is to determine the power coupling between the TREAT reactor and the fuel specimen in the TS-2 configuration ("dry" capsule). In this experiment, a targeted peak cladding temperature of approximately 1173 K is desired. To reach this temperature, TREAT is operated at a low level of power such that the heat generated in the fuel specimen increases the cladding temperature at a rate of ~5 K/s. This heating rate was chosen as it is consistent with the current experimental database for FFRD experiments. The first planned TWIST LOCA experiment on HBu fuel will target this heating rate as well with a goal to tieback the TWIST results to the existing database. BlueCRAB predictions of this transient are shown in Fig. 7.

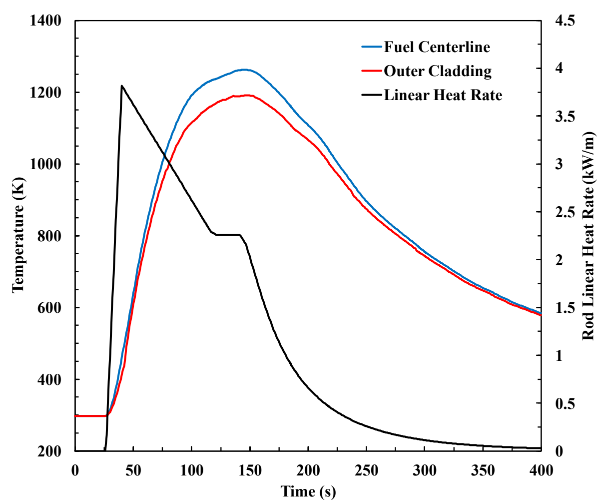

Fig. 7. LOC-C-2 temperature and linear heat rate history during the transient.

LOC-C-3-A & B

The objectives of LOC-C-3-A and LOC-C-3-B are to characterize the thermal-hydraulic conditions during TS-1 above and below the nominal temperature targets that are reached in LOC-C-1. In this study, peak fuel temperatures of 2000 K and 1200 K were chosen. BlueCRAB simulation results show that these target temperatures can be reached with LHRs of approximately 42 kW/m and 19 kW/m, respectively. Fig. 8 shows the LOC-C-3-A & B radial temperature profiles in comparison with the nominal targets of LOC-C-1.

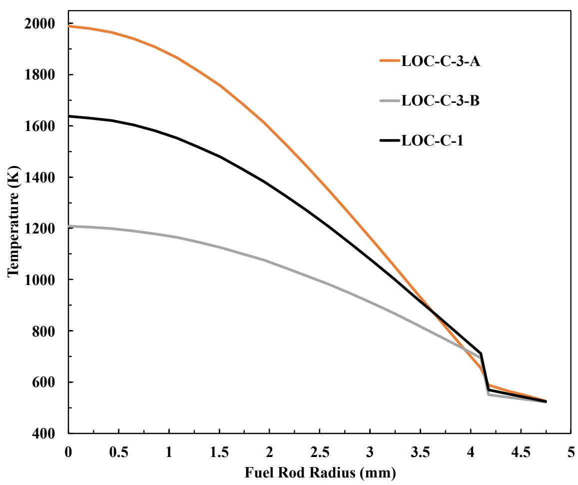

Fig. 8. LOC-C-3-A & B and LOC-C-1 radial temperature profiles.

LOC-C-3-C

The LOC-C-3-C transient is the first transient to perform the full transient sequencing, where targeted conditions during TS-1 are approximately1600 K in the fuel and 520 K in the cladding and a peak cladding temperature of 1173 K is targeted in TS-2. The results from this transient are centered about the transition from TS-1 to TS-2. Where at time zero, the blowdown valve is opened, and the reactor power is dropped to simulate decay heat in the test fuel specimen. Fig. 9 shows that the cladding temperature rapidly increases over the first few seconds after blowdown, while the fuel centerline temperature decreases.

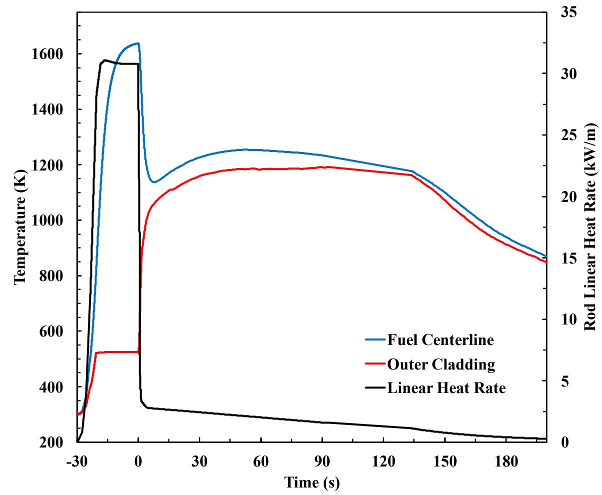

Fig. 9. LOC-C-3-C temperature and linear heat rate history during the transient.

The evolution of the radial temperature profile through the fuel rod at various points through the transient is shown in Fig. 10. Directly prior to the blowdown (Time: 0 sec), the fuel temperature profile is parabolic and achieves the goal of generating a radial temperature profile through the fuel that is consistent with a PWR rod at steady-state operating conditions. Immediately following the blowdown, the stored energy in the fuel begins to redistribute, flattening the radial temperature profile. Approximately 10 seconds after blowdown, the temperature profile in the fuel is approximately flat. As time continues, the temperature of the fuel rod rises isothermally until the targeted peak temperature is reached (Time: 40 sec). In this case, the peak temperature was held until a time of ~140 seconds when the power is then dropped, and the rod begins to decrease in temperature. The time that the rod is held at this temperature is a controllable parameter and depends on the experiment objectives.

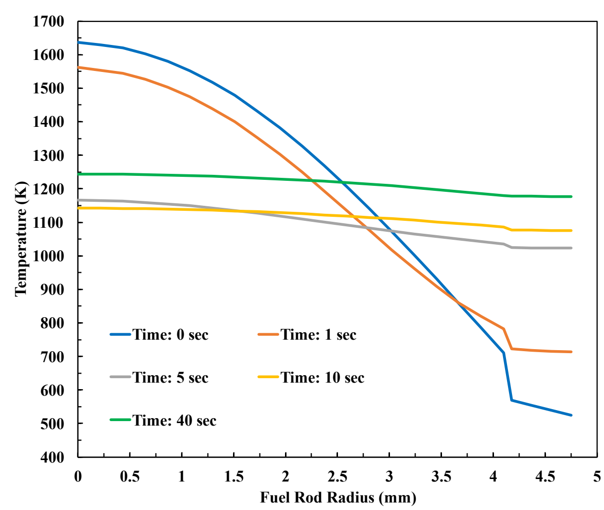

Fig. 10. LOC-C-3-C evolution of radial temperature profile.

LOC-C-3-D & E

After the LOC-C-3-C transient is performed, the capsule will be in a post-blowdown "dry" state. To further characterize the thermal-hydraulic conditions in this state, LOC-C-3-D & E will be performed. These transients are very similar to LOC-C-2; however, the targeted peak temperatures will be below and above the nominal temperature target reached in LOC-C-2. To achieve this goal, TREAT power is either reduced earlier in time so that a lower peak temperature of 1073 K is reached (LOC-C-3-D), or held for a longer period of time to reach the higher targeted temperature of 1273 K in LOC-C-3-E.

LOC-C-4 & 5

The LOC-C-4 and LOC-C-5 transients will consist of pre-pressurized fuel rods to drive cladding balloon and burst at a certain burst condition. LOC-C-4 will be on a rod with a 25 cm fueled length and LOC-C-5 is to be on a longer rod with a 50 cm fueled length. For the purposes of demonstrating the methodology here, results from LOC-C-4 simulations are presented; however, the observations hold true for LOC-C-5 as well.

LOC-C-4 represents the first test in the series with a pre-pressurized fuel rod. The power history used in this experiment is the same as that of LOC-C-3-C (Fig. 9). A specific goal of this experiment is to provide a full evaluation of test design tools and the experimental system to provide best-estimate target conditions to balloon and burst the cladding. Best-estimate capability for heating and cladding performance will be very important to LOCA FFRD experiment design. Given that the current FFRD experiment database and many models that describe cladding failure are based on or validated on experiments with relatively slow heating rates [9, 12], predicting failure during the SEH portion of the LOCA where the cladding is heating up at a rapid rate has more uncertainty. An initial rod pressure of 15 MPa was chosen as it represents a prototypic pressure differential between an HBu fuel rod and reactor vessel approximately 5 seconds into a PWR large break LOCA event.

Based on the BlueCRAB simulation of this transient, four failure models for Zry cladding that are implemented in Bison were assessed relative to one another. The logic behind all the models is the same. That is, when the cladding exceeds a specified criterion, it is assumed to have failed. The criterion used is dependent on the model chosen.

The simplest of the four models assessed is the overstrain model. In this model, cladding failure occurs when the maximum cladding permanent hoop strain exceeds 33.6%. This is the simplest model in the sense that the strain at which the failure occurs is independent of the condition of the cladding (temperature, oxygen concentration, etc.).

The second model included in this assessment is an overstress model, where failure occurs once the maximum hoop stress in the cladding exceeds a limiting burst stress. The limiting burst stress is calculated through an empirical correlation and is a function of the temperature and oxygen concentration in the cladding [22]. The correlation is shown in Eqn. 1 where σ_b is the burst stress in MPa, a and b are experimental determined constants, T is temperature and η is the oxygen weight fraction in the cladding.

$$\sigma_b = a\exp(-bT)\exp\left[-\left(\frac{\eta-\eta_0}{9.5\times10^{-4}}\right)^2\right] \qquad (1)$$

The third model uses a strain rate criterion based on cladding effective plastic strain rate exceeding a value of 2.78 s^{-1} [23].

The final criterion employed is a rupture temperature model where rupture occurs once the cladding surface temperature exceeds the calculated rupture temperature. The rupture temperature is calculated from an empirical correlation that is a function of the cladding heating rate and hoop stress. This model is documented in NUREG-0630 [12] and shown in Eqn. 2, where T_R is the rupture temperature in °C, σ is the engineering hoop stress (kpsi), and H is the ratio between the cladding heating rate and 28 K/s.

$$T_R = 3960 - \frac{20.4\sigma}{1+H} - \frac{8.51\times10^6\,\sigma}{100\,(1+H)+2790\sigma} \qquad (2)$$

The current implementation of this model in Bison requires the user to define the cladding heating rate to be used in the correlation. For this work, a heating rates of 5 K/s and 28 K/s were analyzed (the correlation assumes that ramp rate effects saturate at 28 K/s). A summary of each of these models and how they were implemented can be found in the Bison Reference Manual [18].

Fig. 11 shows the fuel and cladding temperature histories, the capsule pressure, and pressure difference between the fuel rod and capsule through the transient. The time and temperature for failure predicted by each model is overlaid on top of the cladding temperature.

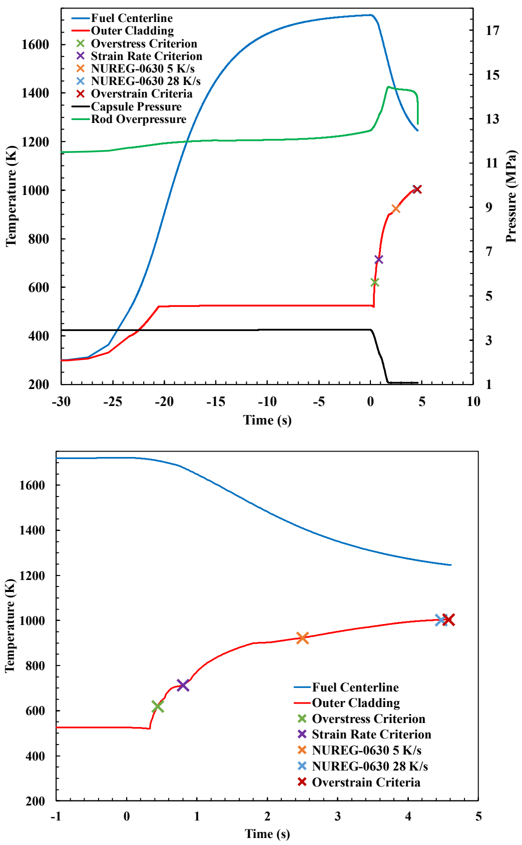

Fig. 11. LOC-C-4 temperature and rupture predictions.

Although failure is predicted by each model within the first five seconds after the blowdown, there is a large discrepancy in the predicted rupture temperature ranging from 620 K in the overstress model up to 1004 K in the overstrain model. In addition to the wide-ranging predictions of rupture temperature, the degree of cladding ballooning at time of predicted failure varies significantly as well (Fig. 12).

The large variation in cladding rupture behavior shown in Figs. 11 and 12, indicates the large amount of uncertainty associated with predicting failure during high temperature ramp rates. These model results show that experiment data in this region are needed to ensure that the correct description of cladding failure is being used when designing future HBu FFRD LOCA tests in TWIST.

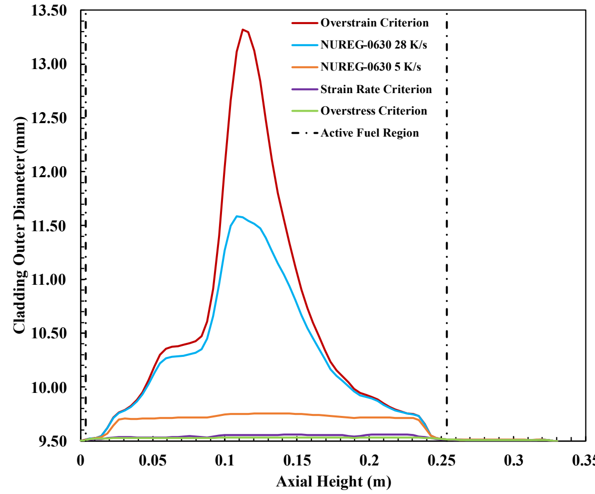

Fig. 12. LOC-C-4 cladding outer diameter at time of predicted failure for various failure models.

CONCLUSIONS

Building upon the existing HBu FFRD knowledgebase and experimental database, the TREAT LOCA program aims to explore data gaps using the in-pile TWIST LOCA vehicle. Prior to performing experiments on HBu fuel specimens, a commissioning test series will be conducted on fresh fuel specimens. The purpose of the LOC-C test series, beginning in 2023, is to qualify the TWIST device and in-situ instrumentation, validate power coupling between TREAT and the TWIST fuel rod, and validate the thermal-hydraulic and fuel performance simulation codes, which will be used to design the subsequent HBu fuel experiments.

This paper presented an analysis methodology that is being used to design the LOC-C test series. Simulation predictions using BlueCRAB, which couples the Bison fuel performance code and the systems code, TRACE, are shown for the current LOC-C test matrix. The presented results show the TWIST LOCA vehicle capabilities of simulating representative PWR LOCA scenarios where a rapid cladding temperature increase occurs as stored energy in the fuel is redistributed. An assessment of cladding failure models for this scenario was performed. It was shown that a large amount of uncertainty exists when predicting cladding failure under high temperature ramp rates. To reduce uncertainties and to determine the best model to use for cladding failure, recommendations for the initial rod pressure were made for the LOC-C-4 experiment.

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