INL/CON-19-52564-Revision-0

Separate-Effects Validation Experiments for Models of Fracture in Ceramic Nuclear Fuel

Benjamin W Spencer, Nicolas E Woolstenhulme, Leigh A Emerson, Juyuan Yeh, Devin D Imholte, Connie M Hill, Daniel B Chapman, Colby B Jensen, Travis W. Knight, Sobhan Patnaik, Sean M. McDeavitt, Luis Ortega, Delia Perez-Nunez, Heng Ban

September 2019

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/CON-19-52564-Revision-0

Separate-Effects Validation Experiments for Models of Fracture in Ceramic Nuclear Fuel

Benjamin W Spencer, Nicolas E Woolstenhulme, Leigh A Emerson, Juyuan Yeh, Devin D Imholte, Connie M Hill, Daniel B Chapman, Colby B Jensen, Travis W. Knight, Sobhan Patnaik, Sean M. McDeavitt, Luis Ortega, Delia Perez-Nunez, Heng Ban

September 2019

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

SEPARATE-EFFECTS VALIDATION EXPERIMENTS FOR MODELS OF FRACTURE IN CERAMIC NUCLEAR FUEL

Benjamin W. Spencer[1], Nicolas E. Woolstenhume[1], Leigh A. Emerson[1], Ju-Yuan Yeh[1], D. Devin. Imholte[1], Connie M. Hill[1], Daniel B. Chapman[1], Colby B. Jensen[1], Mary Lou Dunzik-Gougar[2], Travis W. Knight[3], Theodore M. Besmann[3], Sobhan Patnaik[3], Sean M. McDeavitt[4], Luis Ortega[4], Delia Perez-Nunez[4], Heng Ban[5]

[1]Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415-3840, benjamin.spencer@inl.gov
[2]Idaho State University, CAES, 995 MK Simpson Boulevard, Idaho Falls, ID 83401
[3]University of South Carolina, 300 Main Street, Columbia, SC 29208
[4]Texas A&M University, 210 Animal Industries, College Station, TX 77843-3133
[5]University of Pittsburg, Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261

Fracture plays an important role in the behavior of light water reactor (LWR) fuel, both during normal operation and during accident conditions. Recent advances have improved the ability to realistically represent fracture in fuel simulation codes, but there is a lack of experimental data directly applicable for validation of these models. This paper provides an overview of efforts currently underway to perform a series of separate-effects experiments that induce fracture in LWR fuel under conditions representative of the reactor environment.

I. INTRODUCTION

A number of advances have recently been made in modeling fracture initiation and propagation in ceramic light water reactor (LWR) fuel. These include the use of well-established techniques such as smeared cracking[1,2], as well as the more recent techniques such as peridynamics[3,4], the extended finite element method (XFEM)[5], and the discrete element method (DEM)[5,6]. Improved predictions of fracture in LWR fuel can benefit fuel performance simulations in a number of ways, with important implications for radial relocation, pellet-cladding mechanical interactions, and fragmentation during accident conditions.

The noted modeling approaches appear promising, however to-date most of their applications have been for fresh fuel. A major limitation in applying these approaches with confidence to a wider variety of conditions, such as fragmentation of high-burnup fuel, is that there is very limited data that can be directly used to validate the results of these fracture models. While fracture patterns are available from cross-sections of numerous irradiated fuel rods, these fuel rods have typically been subjected to complex irradiation histories. The authors are not aware of other experiments conducted on LWR fuel specifically for the purpose of characterizing the initiation and propagation of fracture under prototypical reactor thermal conditions. Data from such experiments is needed for validation of computational models of fuel fracture, and providing that data is the goal of the present work.

Under a multi-institutional U.S. Department of Energy Integrated Research Project (IRP) led by Utah State University currently underway, three series of separate-effects validation experiments are being conducted to provide model validation data on crack initiation and propagation in fresh LWR fuel under controlled conditions. The primary challenge in developing such an experiment is in providing conditions that result in a radial temperature distribution that is prototypical of LWR in-reactor conditions.

II. Thermal and Mechanical Environments in LWR Fuel

LWR fuel rods are long (~4 m) and slender (~1 cm diameter) and contain stacked cylindrical UO_2 fuel pellets in zirconium alloy tubing. Heat is generated by the fission process within the fuel and is removed by coolant water flowing axially along the fuel rod. In fresh fuel the volumetric heating due to fission is fairly uniform spatially, although with increasing burnup, self-shielding results in higher volumetric heating rates around the outside of the fuel pellets. Due to the high aspect ratio of LWR fuel rods, heat is primarily transferred radially outward through the fuel, across the fuel/cladding gap, through the cladding, and into the coolant. Within the fuel and cladding, heat transfer is governed by the heat equation[7]:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T - E_f \dot{F} = 0 \qquad (1)$$

where ρ is the density, C_p is the specific heat at constant pressure, T is temperature, t is time, k is the thermal conductivity, E_f is the energy per fission, and $\dot{F}$ is the volumetric fission rate.

The first term in Equation 1 accounts for thermal inertia, and has a negligible effect on the temperature fields except during rapid changes in the fission rate. During normal operation in LWRs, the power is changed

quite slowly to minimize stresses on fuel and reactor components. When fresh fuel is ramped up to full power, the ramp rates are slow enough that at a given point in time, the fuel experiences quasi-steady-state thermal conditions. Under such conditions, the radial temperature distribution is approximately parabolic, as illustrated notionally in Figure 1.

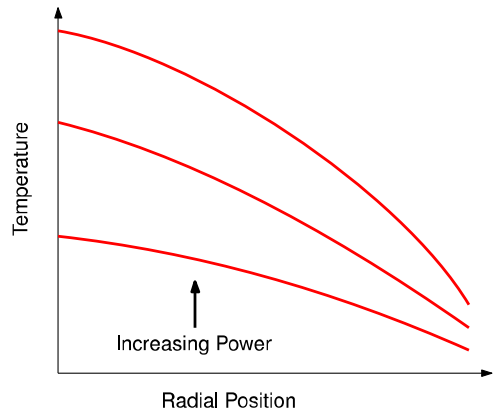

Figure 1. Notional plot of temperature profile in fresh LWR fuel during a ramp from hot zero power to full power conditions. As the power increases, the difference between the temperature at the fuel centerline and the outer surface increases.

In the absence of body forces such as gravity or inertial forces, deformation is governed by the equilibrium equation:

$$\nabla \cdot \boldsymbol{\sigma} = \mathbf{0} \qquad (2)$$

where $\boldsymbol{\sigma}$ is the stress tensor. In small strain theory this is computed as:

$$\boldsymbol{\sigma} = \boldsymbol{E} : \left(\frac{1}{2}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) - \alpha \Delta T\right) \qquad (3)$$

where $\boldsymbol{E}$ is the elasticity tensor, $\boldsymbol{u}$ is the displacement field, and α is the coefficient of thermal expansion. The temperature profiles of Figure 1 cause non-uniform thermal expansion in the fuel pellet, leading to stresses in the fuel that are compressive in the center of the pellet, and tensile on the exterior. Figure 2 shows a notional plot of the hoop stress as a function of radial position. This illustrates how as the power increases, the hoop stresses on the pellet exterior increase until they eventually exceed the tensile strength of the UO_2, leading to the formation of radial cracks at the pellet exterior that propagate inward to the pellet center in a stable manner under increasing power. Similar phenomena cause axial cracks that also initiate on the outer periphery of the pellet and propagate inward toward the center of the pellet with increasing power due to tensile axial stresses.

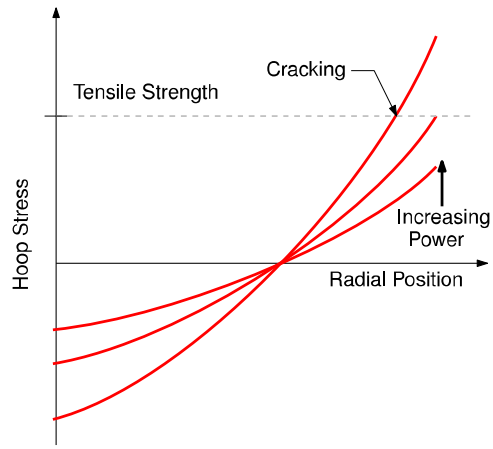

Figure 2. Notional plot of variation in hoop stress in fresh LWR fuel as a function of radial position during a ramp to full power. As the power increases the tensile hoop stress on the pellet exterior increase, eventually leading to radial cracking as they exceed the tensile strength.

III. Strategies for Replicating LWR Environment

The computational models mentioned previously that are used to simulate fuel fracture predict both the initiation and propagation of cracking. Although these models all predict radial cracking propagating from the outside to the inside of the pellets, there are significant differences in the number and depth of cracks predicted in these models, as well as in the amount of additional radial displacement of the pellet due to the loss of constraint that occurs with cracking.

An experiment to validate the ability of these computational models to predict fuel fracture at the engineering scale should have the following characteristics:

1. It should subject the fuel to a temperature profile that reasonably approximates the environment seen in the reactor.
2. It should allow for ready observation of the process of crack propagation with increasing power.
3. It should be as focused as possible on cracking in fuel and remove as many other unrelated phenomena as possible.

It is difficult to meet these needs with traditional integral fuel rod experiments, unless a transient testing reactor is used for short-duration ramps to varying power levels. It is also desirable to characterize the fracture surface at the microscopic scale, which is generally possible after any fracture experiment that meets the above conditions is conducted.

Instrumenting in-reactor experiments is inherently more difficult than those out of the reactor, so there is significant motivation to perform simple fracture

validation experiments out-of-pile. However, it is problematic to replicate the LWR fuel thermal conditions out-of-pile because the radial temperature profile is a result of the combination of volumetric heating and radial heat rejection to the coolant.

In the present study, three different series of fuel fracture experiments are being conducted which meet the goals outlined above to varying degrees. Two of these experimental series are being conducted out of the reactor and generate the desired temperature profile in very different ways. The first involves slowly heating a fuel pellet contained in a metal tube to a high temperature, and then quenching that rod in a cold bath using a test fixture that insulates the top and bottom surface of the pellet, resulting in predominately radial heat flux. As illustrated in Figure 3, the quenching process generates a temperature profile that momentarily approximates that seen an LWR fuel rod but reaches that by cooling from a spatially uniform high temperature, rather than by heating from a spatially uniform low temperature.

The second out-of-reactor experimental series achieves the temperature profile by passing an electrical current through the pellet, which generates volumetric Joule (resistive) heating that approximates the volumetric fission heating seen in an LWR. This experiment series better replicates the thermal behavior of LWR fuel because the pellet starts out at a uniform low temperature and ramps up to a profile that mimics that of an LWR, as illustrated in Figure 4. The top surface of the fuel in this experiment is not insulated, which is expected to result in a more significant axial thermal gradient than the first experiment.

The third experiment series will be conducted in the Transient Reactor Test (TREAT) facility at Idaho National Laboratory (INL), which provides a neutron source for fission heating and because of its design and that of the test capsule, for this experiment provides flexibility in the applied power history and facilitates instrumentation. The temperature profile history for this experiment is illustrated in Figure 5. Of the three series of experiments, this one best replicates the thermal environment experienced by LWR fuel. However, it is more costly to perform and has more limited instrumentation options.

These experiments are described in more detail in the following sections. These all have their advantages and drawbacks, with varying ability to reproduce actual LWR conditions and to use instrumentation for monitoring quantities of interest over the course of the experiment for subsequent validation of fracture models. For that reason, these different experimental approaches are complementary, and the combined results are expected to significantly improve confidence in the ability of computational models to simulate fracture in ceramic nuclear fuel.

As the primary purpose of these tests is to provide data for code validation, they do not strictly need to replicate LWR conditions, because if the experimental conditions are correctly represented in the simulation, it can be used for code validation. However, replicating LWR conditions as closely as possible makes the experiments more relevant.

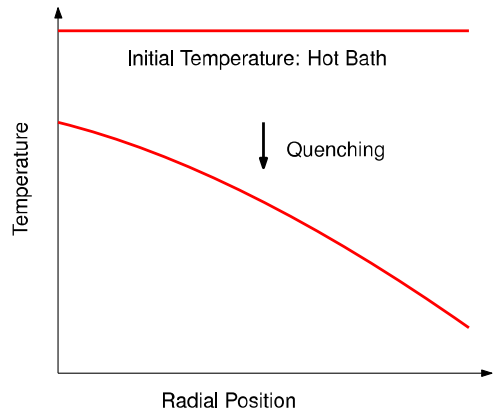

Figure 3. Evolution of the temperature profile in the fuel pellet in the quenching experiment series.

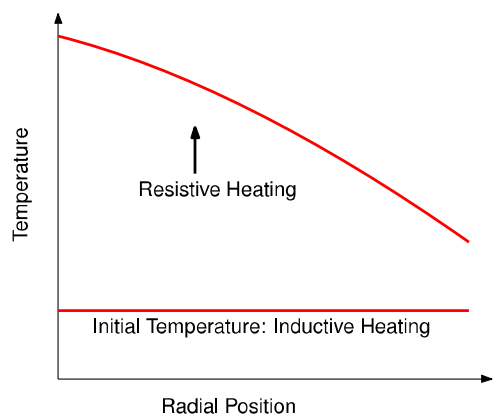

Figure 4. Evolution of the temperature profile in the fuel pellet in the resistive heating experiment series.

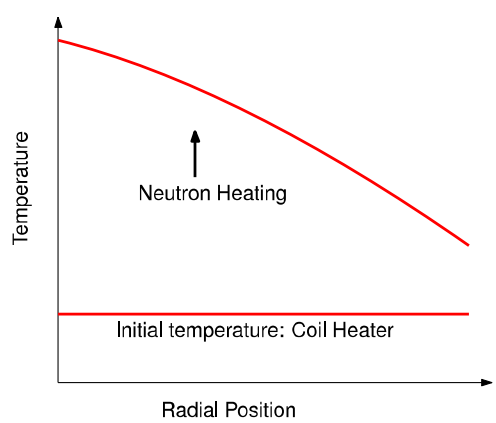

Figure 5. Evolution of the temperature profile in a fuel pellet in the TREAT experiment series.

The final fracture patterns in all three of these experiments will be characterized through microscopy. In addition, in-situ optical and thermal imaging will be employed in the Joule heating experiment to observe the propagation of fracture as the power is ramped up. Neutron computed tomography is also planned to be conducted on the fuel irradiated in the TREAT experiments to construct 3D maps of the fracture patterns.

III. Integrated Simulation and Experiment Design

In addition to the fact that the experiments being conducted are specifically for the purpose of validating fuel performance codes, simulations have played a central role in the planning of the three series of experiments. To achieve the goal of replicating the thermal and mechanical environment of an LWR being ramped to full power as closely as possible, models of each of the experiment designs have been developed in the Bison fuel performance code[7]. These models are being used to understand the effects of the selection of key experimental parameters, and to adjust those parameters as needed to align the experimental behavior with the targeted LWR behavior. Many such simulations for the out-of-reactor experiments are documented in Ref. 8.

IV. QUENCHING EXPERIMENTS

Inducing volumetric heating in ceramic fuel materials is inherently difficult. The two primary ways to accomplish this are through fission or Joule heating, which require either a nuclear reactor or other fairly complex hardware. Because of this, it is advantageous if an experiment can be devised that replicates the LWR temperature profile without the need for volumetric heating.

The basis of the quenching experiment series being performed at Texas A&M University, is replicating the LWR temperature profile by rapidly cooling from the exterior a pre-heated fuel pellet at relatively uniform temperature. This type of experiment is extremely simple, as it only requires a way to slowly heat the pellet (to avoid causing thermal gradients large enough to cause cracking during the heating process), an apparatus to hold the pellet and protect it from the coolant during the quenching process, and a means to provide rapid cooling.

The key advantage of the quenching experiments is that they are extremely simple. They simply require a way to hold a fuel pellet during the experiment, a way to slowly heat the pellet, and a way to rapidly cool the pellet. The cooling of the pellet should be done in a way that results in heat rejection primarily occurring in the radial direction, and the heat flux out of the pellet must be sufficient to generate a temperature profile similar to that in an LWR.

Figure 6 illustrates the hardware used to hold the pellet in the quenching experiments. The UO_2 fuel pellet is fixed within a copper tube having end fittings to ensure it is leakproof.

During the experiment, the entire assembly is allowed to equilibrate in a hot molten salt bath, and then quickly immersed in a cold bath of a mixture of water and ethylene glycol at -4 °C.

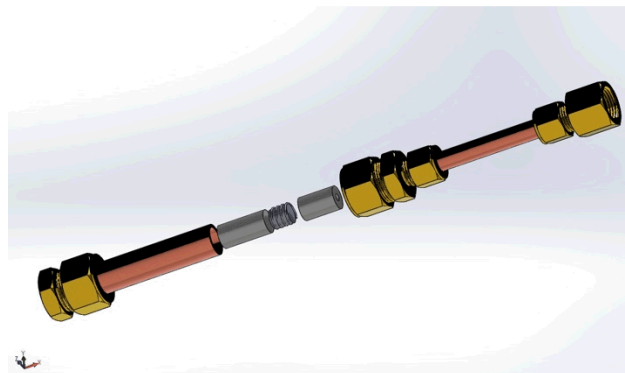

Figure 6. Hardware for quenching experiments.

This experiment is still under development, and the parameters have not been finalized. One challenge with the current design of this experiment is that the gap between the fuel and the copper tubing is larger than what would be ideal due to the fact that tubing in commonly available dimensions is being used. This results in poor heat transfer which decreases the heat flux, and as a result, also decreases the thermal gradient in the fuel. If the thermal gradient is not sufficiently high, the thermally induced stresses will not be adequate to cause representative cracking.

Simulations have been performed of this experiment using several sets of parameters[8]. Figure 7 shows a simulation result for one set of parameters, and demonstrates how the temperature is initially uniform in the hot bath temperature, and eventually assumes a profile that resembles that seen in the LWR environment. Figure 8 shows the computed time history of the hoop stress at the outer surface of the pellet. The tensile strength of the UO_2 is assumed to nominally be 150 MPa, and this plot shows how with this set of parameters, the hoop stress does briefly exceed this value, and is thus expected to result in crack initiation. To achieve extensive radial crack generation, a more aggressive thermal shock would be required. This could be achieved by having a higher hot bath temperature, lower cold bath temperature, higher gap conductance, or a higher convective heat transfer coefficient from the cladding to the coolant.

To characterize this convective heat transfer coefficient, a simplified version of the quenching experiment has been performed in which a solid copper

rod having roughly the same diameter as the tubing is quenched in the cold bath. The time history of the temperature at the centerline of the copper rod was obtained from a thermocouple, which is being used to calibrate the convective heat transfer coefficient.

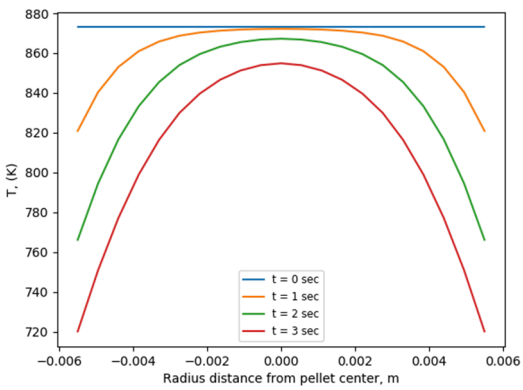

Figure 7. Predicted temperature profiles at several points in time during a quenching experiment. These simulations assume a hot bath temperature of 873 K, a cold bath temperature of 228 K, thermal conductivity of the fuel/tube gap of 10 W/(m-K), and a convective heat transfer coefficient of 1000 W(m^2-K).

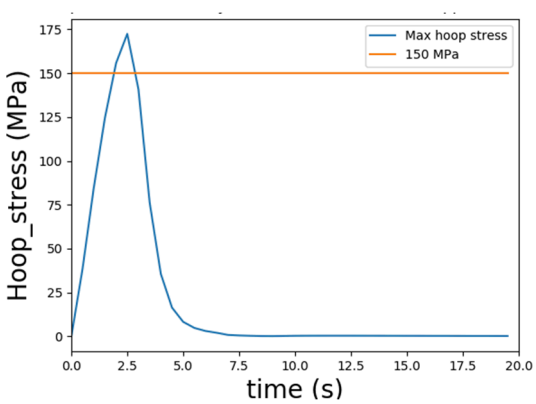

Figure 8. Predicted time history of the maximum hoop stress during a quenching experiment with the parameters described in Figure 7.

V. RESISTIVE HEATING EXPERIMENTS

The next series of experiments uses resistive heating to approximate the volumetric heating due to fission in the reactor. These are being conducted at the University of South Carolina. At room temperature, UO_2 is electrically insulating, but its conductivity increases significantly at elevated temperatures due to ionic conduction[9]. This property allows UO_2 to be volumetrically heated through Joule (resistive) heating by passing an electrical current through at sufficiently high temperatures. This concept has been used in a set of experiments performed in the late 1970s at Argonne National Laboratory, in which an electrical current was passed axially through a stack of fuel pellets[10,11].

An important advantage of using resistive heating is that it permits in-situ observations of the pellet and thus real-time formation of cracks, which provides very useful data for validation of fracture simulation models. To allow observation of cracking during the experiment, electrodes are placed on opposite sides of a fuel pellet. Because of the geometric characteristics of this arrangement, this leads to spatial variations in the volumetric heating that differ somewhat from the desired uniform conditions. However, this can be accounted for in the computational models of this experiment.
To bring the fuel pellet up to a sufficiently high temperature for it to become electrically conductive, a molybdenum susceptor which surrounds the pellet is inductively heated. Once the electrical resistance falls below a threshold value, resistance heating is possible using a high current, low voltage DC power supply. Figure 9 shows the test stand set-up for induction and resistive heating.

Figure 9. Test stand assembly with copper coils and Ni electrodes connected for induction and resistive heating respectively.

The pellet and susceptor are contained in the vacuum chamber shown in Figure 10, which is filled with Ar gas.

Simultaneous, real-time dual imaging of the pellet surface will be performed using optical and infra-red camera systems which will be mounted along axial and perpendicular directions to the pellet surface respectively, as shown schematically in Figure 11. A beam-splitter allows viewing with the two separate imaging systems. While one of the beams is transmitted from the splitter through a bandpass filter to obtain optical images (blue color, 450 nm CWL), the other beam is reflected from the splitter to a FLIR thermal camera to capture full field temperature gradients of the pellet surface during crack

initiation and propagation. In early testing of this system, a high temperature IRCON pyrometer (699-2200°) was used for recording and comparing the surface and centerline temperatures of surrogate pellets. Figure 11 shows a close-up image of the bream splitter hardware.

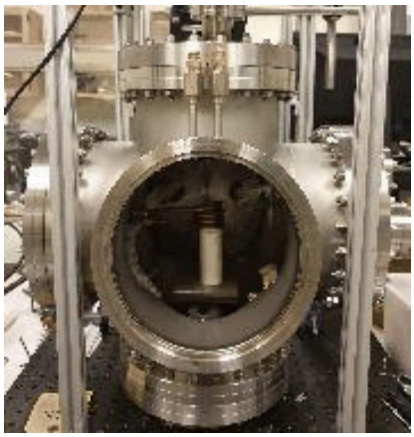

Figure 10. Vacuum chamber containing the test apparatus for the resistive heating experiments.

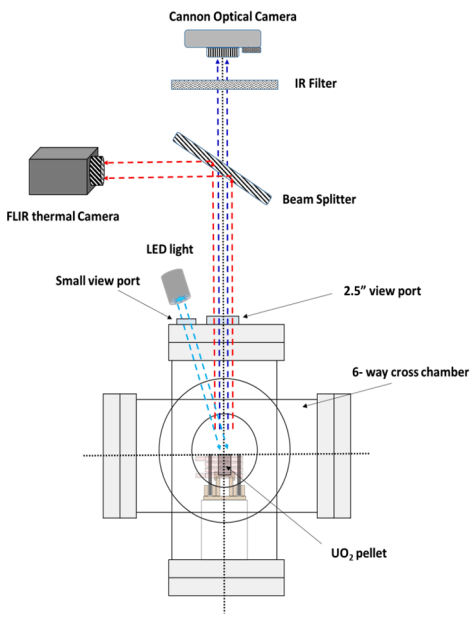

Figure 11. Schematic of dual imaging system.

In addition to in-situ imaging, surface characterization of the post-fracture pellets is being performed using scanning electron microscopy (SEM), to understand the crack patterns and their distribution on the surface of the pellet at different applied currents.

In this phase of apparatus and methodology development, ceria (CeO_2) and yttria-stabilized zirconia (YSZ) pellets are being used as surrogate fuel materials, and fracture experiments have been carried out demonstrating inductive and resistive heating. Cracking studies on the surrogate pellets have confirmed the readiness and robustness of the experimental set-up that will be used with UO_2 pellets.

Figure 12. Close-up of the dual imaging system and illuminating light source.

Tests with UO_2 will employ dual imaging of the pellet top surface with a FLIR infra-red camera, as noted, which will capture the two-dimensional surface temperature distribution. The optical camera system will capture time-dependent images of crack formation and propagation. Characterization will include microstructural analysis, porosimetry and pycnometry.

Simulations have been performed to understand the behavior of this experiment and the effects of parameters[8]. These simulations solve coupled partial differential equations describing the electrical, thermal, and mechanical fields of a 2D cross section of the fuel. However, this 2D model neglects heat loss from the top surface of the pellet, which may be significant because of the configuration of the experiment. 3D modeling will account for this effect.

Some of the important parameters for this model are still being defined, especially those concerning heat transfer between the outer surface of the pellet and the hardware surrounding the pellet. The simulations performed to-date should be regarded only as proofs of concept, as they make assumptions regarding some of these key parameters. Figure 13 shows a snapshot of the spatial distribution of the volumetric heating on the cross section in one such model. There is a small zone near the electrodes with high heat generation due to the high current near the electrodes. However, there is also a large distributed band in the region between the electrodes in which there is relatively uniform heat generation. Figure 14 shows a snapshot of the resulting temperature distribution, which is elongated somewhat because of the nature of the volumetric heating, but still produces thermal stresses through mechanisms similar to those in an LWR.

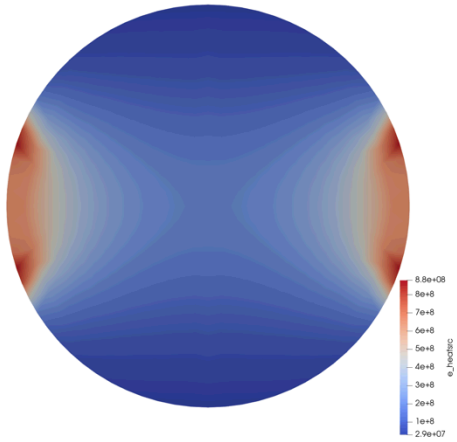

Figure 13. Predicted spatial distribution of volumetric heating (W/m^3) in a resistive heating experiment with curved electrodes on the two sides, an initial temperature of 573 K, a prescribed current of 2.3 A, and a heat transfer coefficient of 2,500 W/(m-K) on the outside surface.

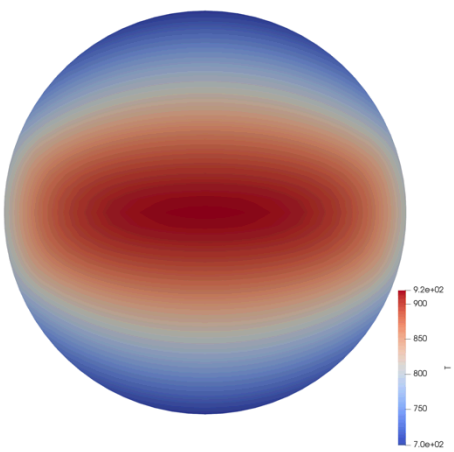

Figure 14. Predicted spatial distribution of temperature (K) in the resistive heating experiment under the conditions described in Figure 13.

Figure 15 shows a profile of the temperature along a horizontal cross-section of the model, compared with the temperature profile for an LWR at a steady-state power of 13.8 kW/m. While the shape of the resistive heating profile differs significantly from the LWR in the center of the pellet, it matches it reasonably well at the edges of the pellet. It is expected that under these conditions, the resistive heating experiment would develop cracks along the plane between the electrodes that would be similar to those seen in an LWR at that power level. It is important to note that the present model does not account for the effect of cracking on the electrical resistance of the fuel, which could have a significant effect and should be addressed in follow-on research.

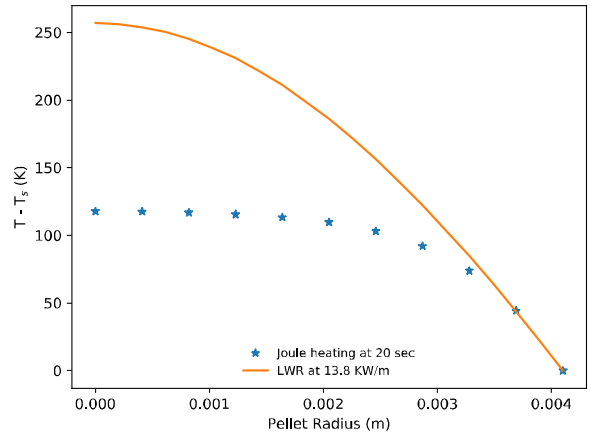

Figure 15. Computed temperature profile (shown as the difference between the temperature at a location and the surface temperature) along the horizontal cross-section in the resistive heating experiment shown in Figures 13 and 14.

VI. TRANSIENT REACTOR EXPERIMENTS

While the two out-of-reactor experiments described in the previous sections represent promising ways to test models of LWR operating conditions, it is clear that there are still important shortcomings. Application of neutron irradiation to induce fissions is ultimately the best way to generate representative volumetric heating.

As part of the current project, the Utah State University Pellet Cracking (USU-PC) experiments have been developed for testing in INL's TREAT reactor in the Fall of 2019. The TREAT reactor has some important characteristics that make it uniquely able to perform the kind of focused, separate-effects experiments needed for this study.

First, the TREAT core is not cooled during operation, making it much easier to install instrumentation and facilitates the rapid installation and removal of experiments.

Second, TREAT allows for great flexibility in transient irradiation. TREAT is often thought of as a pulsed reactor, but it can also be programmed to supply shaped transients, as long as they fit within certain limits. Also, a variety of transient prescriptions can be programmed into the system to support a series of measurements. Instead of inserting a set of experiments that are all subjected to the same irradiation history, each experiment can have its own irradiation history.

To replicate LWR conditions in the TREAT reactor, it is important to have volumetric heating supplied by fission, as well as heat removal from the outside surface of the pellets. It is possible to develop a test apparatus

with a coolant loop for heat removal in TREAT. This has been done historically, and such hardware is currently being developed for TREAT. However, such hardware is complex and costly, and makes experimental instrumentation more difficult.

Instead of relying on a coolant loop for heat rejection, the USU-PC experiments instead use a heat sink. A stack of 5 LWR fuel pellets is contained inside a stainless steel heat sink, as shown in Figure 16. This test fixture, known as DRIFT (Dry In-Pile Fracture Test), is placed inside a SETH (Separate Effects Test Holder) capsule, which is in turn placed inside a MARCH (Minimal Activation Retrievable Capsule Holder) test vehicle, which is inserted into the TREAT reactor.

Because this test is designed to specifically focus on the fuel behavior, there is no need to contain the fuel in a cladding, and the absence improves heat transfer between the fuel and the heat sink. There is a nominal 60 μm gap between the fuel and stainless steel, and the test fixture is filled with helium to maximize gap conductance.

In a standard LWR, because the fuel rods are surrounded by flowing coolant, the reactor can operate under a constant power and maintain a steady temperature profile in the fuel. In the proposed USU-PC experiments, however, the thermal conditions are constantly changing during the irradiation, and a desired temperature profile can only be obtained for an instant in time. Early on in a given experiment, the heat sink is at a low temperature, but as the experiment progresses and heat is rejected from the fuel into the heat sink, the temperature of the heat sink steadily increases, which decreases the heat flux from the fuel. The coil heater wrapped around the DRIFT test fixture is used to control the starting temperature of the experiment and is not used during the actual irradiation.

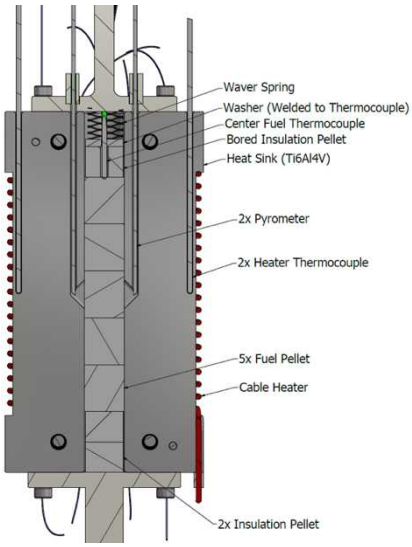

Figure 16. Cross-section view of DRIFT test holder for TREAT experiment showing stack of LWR fuel pellets, heat sink, coil heater, and instrumentation.

One of the main objectives of the USU-PC series of experiments is to obtain snapshots of crack progression in LWR fuel during the ramp to full power. Rather than attempt to have in-situ instrumentation, a series of tests will be performed, each with its own unique power history that will ramp the power up to a point where the temperature profile matches a desired LWR temperature profile at a given steady-state power level. Once each of those experiments reaches that condition, the reactor will be abruptly shut off, and the fuel will cool back down to ambient conditions. After the experiments, the pellets will be removed from the reactor, and the crack patterns will be documented in post-irradiation examination (PIE). Although the cracked pellets observed at different power levels will be different pellets with different cracking patterns, combining the crack patterns for the various power levels obtained from PIE will still provide useful information on the extent of cracking that is likely to occur in an LWR environment. Because each experiment contains 5 pellets, there will be a reasonably large set of samples for each power level.

The USU-PC experiments will contain significant thermal instrumentation. As shown in Figure 16, there is a thermocouple that passes through a hollow insulator pellet to measure the centerline temperature of the top fuel pellet. There are also holes in the heat sink for pyrometers that will measure fuel surface temperatures on opposing sides of the fuel stack. In addition, there are also multiple vertical holes through the heat sink at various radial and azimuthal positions to accommodate a fiber optic sensor that will provide temperatures at a large number of locations during the experiment. These temperature sensors will be used to assure that the simulations reasonably represent the actual test conditions.

The test series will consist of 5 tests that ramp up to temperature profiles that would be seen in a LWR fuel at several steady-state linear power levels of 5, 10, 15, 20, and 25 kW/m. A 1D BISON model of the fuel in the LWR environment was used to provide the target steady-state temperature profile. Similarly, a 1D BISON model of the USU-PC experiments test holder was developed and used to tune key parameters such as the starting temperature and power history to match the target LWR temperature profiles.

These simulations indicate that with the chosen design, the LWR temperature profile cannot be exactly duplicated during the entire power transient, but it can be matched at one point in that transient. In the development of the experimental power histories, it was found that if at a given point in the TREAT experiment, the experimental temperature profile matches three key parameters of the LWR temperature profile, the experiment provides a very good match to the full LWR temperature profile at that power. These are the surface temperature, the temperature difference between the centerline and outer surface, and the slope of the temperature at the surface.

Figue 16 shows a plot of the temperature difference between the centerline and outer surface as a function of the surface temperature for both the LWR reference case and the TREAT experiment from their respective BISON models. The LWR reference case shows the temperature history during a slow ramp up to a maximum linear power of 30 kW/m. Labeled points indicate the temperature and gradient at 5 kW/m increments. Ideally, the TREAT experiment would be able to exactly follow the LWR trajectory in this plot, but because of fundamental limitations of the heat sink system, it can only match the LWR conditions at one point.

As shown in Figure 17, the power history and initial temperature of one particular experiment were adjusted to closely match the LWR condition at 15 kW/m. Figure 18 shows a similar plot of the slope of the temperature at the fuel surface, and shows how the TREAT experiment also matches the LWR conditions at the 15 kW/m power level. Figure 19 shows the temperature profile of the TREAT experiment at various points in time during the power ramp and shows a close match with the LWR temperature profile at the target 15 kW/m power level. These plots clearly demonstrate that the proposed TREAT experiment can very closely match target LWR temperature profiles. Although they are not shown here, similar close matches to target LWR conditions are achieved at other power levels.

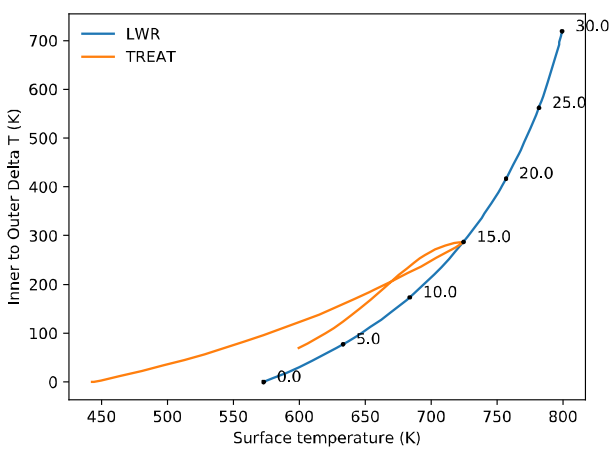

Figure 17. Plot of the difference between the centerline and outer surface fuel temperature as a function of the fuel surface temperature for the USU-PC TREAT experiment designed to match LWR steady state conditions at 15 kW/m, along with a plot of the equivalent for the LWR benchmark. This shows how the TREAT experiment (orange line) starts at a temperature difference of zero, ramps up until it matches the LWR condition, and then drops for some time after the reactor is shut off. The experiment would continue to cool off after the point at which the analysis was terminated (with a surface temperature of about 600 K.)

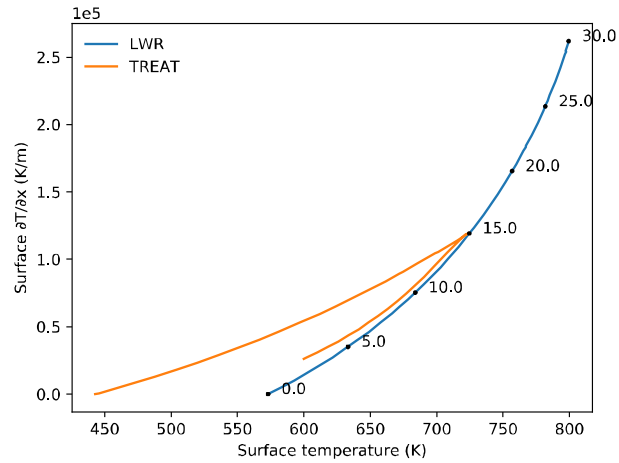

Figure 18. Plot of the temperature gradient at the fuel surface as a function of the fuel surface temperature for the USU-PC TREAT experiment designed to match LWR steady state conditions at 15 kW/m, along with a plot of the equivalent for the LWR benchmark. Similar to Figure 6, the TREAT experiment starts at a gradient of 0, ramps up until it matches the LWR condition, and then drops off until the analysis was terminated part-way through the cool-down.

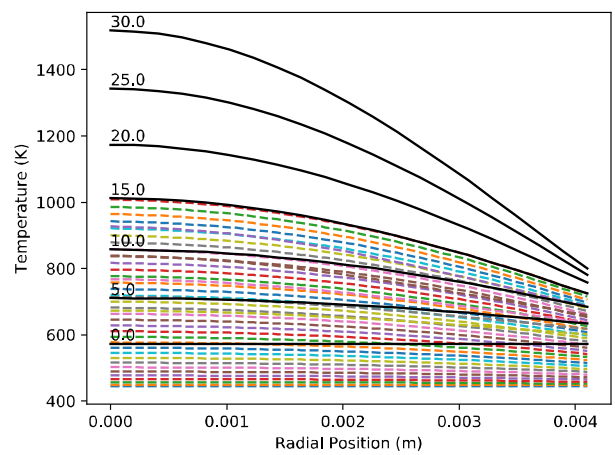

Figure 19. Temperature profiles at various points in time for the USU-PC experiment (shown in dashed lines) plotted together with target steady-state LWR temperature profiles at various power levels.

VI. CONCLUSIONS

This paper has summarized a series of separate-effects experiments planned for the purpose of providing validation data for computational models of fracture in LWR fuel pellets. Replicating the thermal conditions in an LWR that lead to fracture in an environment that can accommodate instrumentation is challenging because the nature of the temperature profile in an LWR is the result

of a combination of volumetric fission heating and heat removal through flowing coolant.

Two series of out-of-pile tests that use quenching and resistive heating to produce a temperature profile with the desired characteristics are being conducted. The advantage of these tests is that the environments in which they are conducted lend themselves to instrumentation. However, both of these tests provide only a fairly crude approximation of the thermal conditions experienced by LWR fuel. The proposed test series to be conducted in the TREAT reactor at INL will provide a much closer match to the desired temperature profile. Although instrumentation is a bigger challenge in the reactor, the characteristics of the TREAT reactor and the dry test holder open up possibilities for instrumentation that would be more challenging to provide in an integral fuel rod assembly in a coolant loop. All three of these experiment series are expected to provide valuable validation data, demonstrating that the experimental conditions can be represented in simulation models.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy NEUP IRP program under award agency number DE-NE-0008531. This manuscript has been authored by Battelle Energy Alliance, LLC under contract DE-AC07-05ID14517 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

REFERENCES

1. Y. Rashid. “Mathematical modeling and analysis of fuel rods,” *Nuclear Engineering and Design*, **29**(1):22–32 (1974).
2. B. W. Spencer and R. J. Gardner. “Improved LWR fuel rod mechanics models,” INL/EXT-18-44749, Idaho National Laboratory (2018).
3. S. Oterkus and E. Madenci. “Peridynamic Modeling of Fuel Pellet Cracking,” *Engineering Fracture Mechanics* (2017).
4. Y. Hu, H. Chen, B. W. Spencer, and E. Madenci. “Thermomechanical peridynamic analysis with irregular non-uniform domain discretization,” *Engineering Fracture Mechanics*, **197**:92–113 (2018).
5. B. Spencer, H. Huang, J. Dolbow, and J. Hales. “Discrete modeling of early-life thermal fracture in ceramic nuclear fuel,” *Proceedings of WRFPM 2014*, Paper No. 100061, Sendai, Japan, (2014).
6. H. Huang, B. Spencer, and J. Hales. “Discrete element method for simulation of early-life thermal fracturing behavior in ceramic nuclear fuel pellets,” *Nuclear Engineering and Design*, **278**:515–528 (2014).
7. R. L. Williamson, J. D. Hales, S. R. Novascone, M. R. Tonks, D. R. Gaston, C. J. Permann, D. Andrs, and R. C. Martineau. “Multidimensional multiphysics simulation of nuclear fuel behavior,” *J. Nuclear Materials*, **423**:149–163 (2012).
8. J.-Y. Yeh. “Fuel fracture experimental designs using Bison fuel performance code for out-of-pile separate-effects validation experiments,” Master’s thesis, Idaho State University (2018).
9. J. L. Bates, C. A. Hinman, and T. Kawada. “Electrical Conductivity of Uranium Dioxide,” *Journal of the American Ceramic Society*, **50**(12):652–656, (1967).
10. A. Alexas. “On the Simulation of Fast Breeder Reactor Pin Behavior Using UO 2 Pins with Direct Electrical Heating,” *Nuclear Technology*, **36**(1):129–138 (1977).
11. R. Christensen and R. Eilbert. “Temperature profiles in UO2 fuel under direct electric heating conditions,” *Journal of Nuclear Materials*, **96**(3):285–296, (1981).