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Pellet-clad mechanical interaction screening using VERA applied to Watts Bar Unit 1, Cycles 1–3

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ABSTRACT

The Consortium for Advanced Simulation of Light Water Reactors (CASL) aims to provide high-fidelity multiphysics simulations of light water nuclear reactors. To accomplish this, CASL is developing the Virtual Environment for Reactor Applications (VERA), which is a suite of code packages for thermal hydraulics, neutron transport, fuel performance, and coolant chemistry. As VERA continues to grow and expand, there has been an increased focus on incorporating fuel performance analysis methods. One of the primary goals of CASL is to estimate local cladding failure probability through pellet-clad interaction, which consists of both pellet-clad mechanical interaction (PCMI) and stress corrosion cracking. Estimating clad failure is important to preventing release of fission products to the primary system and accurate estimates could prove useful in establishing less conservative power ramp rates or when considering load-follow operations.

While this capability is being pursued through several different approaches, the procedure presented in this article focuses on running independent fuel performance calculations with BISON using a file-based one-way coupling based on multicycle output data from high fidelity, pin-resolved coupled neutron transport–thermal hydraulics simulations. This type of approach is consistent with traditional fuel performance analysis methods, which are typically separate from core simulation analyses. A more tightly coupled approach is currently being developed, which is the ultimate target application in CASL.

Recent work simulating 12 cycles of Watts Bar Unit 1 with VERA core simulator are capitalized upon, and quarter-core BISON results for parameters of interest to PCMI (maximum centerline fuel temperature, maximum clad hoop stress, and minimum gap size) are presented for Cycles 1–3. Based on these results, this capability demonstrates its value and how it could be used as a screening tool for gathering insight into PCMI, singling out limiting rods for further, more detailed analysis.

1. Introduction

The US Department of Energy–sponsored Consortium for Advanced Simulation of Light Water Reactors (CASL) (CASL, 2014) aims to provide high-fidelity multiphysics simulations of light water reactors (LWRs) by coupling a variety of codes within the Virtual Environment for Reactor Applications (VERA) (Turner et al., 2016). As the coupled neutronics–thermal-hydraulics (TH) capabilities within VERA have become more robust, there has been an increased focus on incorporating fuel performance analysis methods. CASL has identified several challenge problems, one of which is to estimate local cladding failure through pellet-clad interaction (PCI) (Pawlowski et al., 2014). PCI consists of both a mechanical component (pellet-clad mechanical interaction, PCMI) and a chemical component through PCMI-induced stress corrosion cracking (SCC) (Cox, 1990; Piro et al., 2017). The focus in this work is on PCMI, but it sets the stage for future work to consider SCC and the chemical effects of that contribute to cladding failure. This challenge problem is important for at least couple reasons: (1) clad integrity prevents fission products from being released into the primary loop and (2) while PCI failures occur infrequently in currently operating reactors, conservative restrictions are placed on operational power ramp rates. Allowing for more aggressive ramps rates could translate into better plant economics, but a sufficiently accurate estimate of the stresses observed and risk of failure are imperative to proceed with

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confidence with higher ramps. Additionally, some plants are being considered for load-follow operations, and there are several concerns about the clad integrity in the operations.

Capabilities that address the PCI challenge are being pursued through several different approaches, such as with Tiamat (Pawlowski et al., 2015; Clarno et al., 2015) which is a simulation tool within VERA that directly couples the MPACT (MPACT Team, 2015; Collins et al., 2016; Kochunas et al., 2017) neutron transport solver, the COBRA Two-Fluid (CTF) (Salko and Avramova, 2015; Salko et al., 2015, 2013) TH solver, the Oak Ridge Isotope Generation and Depletion Code (ORIGEN) (SCALE Team, 2011), and the Multiphysics Object Oriented Simulation Environment (MOOSE)-based (Gaston et al. (2009)) BISON fuel performance code (Williamson et al., 2012; Hales et al., 2015). However, a standalone BISON capability is also being pursued within CASL through VERA. This approach is more consistent with traditional fuel performance analysis which typically focus on one-way coupling between nodal core simulators and more empirical fuel performance codes (Worrall and DiGiovine, 2009; Alapour et al., 2010).

The process in this paper focuses on running independent fuel performance calculations with BISON using the multicycle output data from coupled neutron transport–TH simulations and is unique from previous work in that it is coupling high-resolution, pin-resolved core simulation to a high-fidelity, finite element fuel performance solver. In recent work within CASL, the first 12 cycles of Watts Bar Unit 1 (WBN1) have been simulated using the VERA core simulator capability based on MPACT and CTF (Godfrey et al., 2015). Using the output power and temperature distributions from these simulations, standalone BISON results can be obtained without rerunning the core simulations while providing some insight into PCMI.

Several quantities are of interest when considering PCMI and subsequent fuel rod failures, including clad hoop stress, maximum centerline fuel temperature, fuel-clad gap size, and cumulative damage index, which is effectively a probability of rod failure (Hales et al., 2015), particularly as a function of time. In this work, two-dimensional (2D) axisymmetric (RZ) single-rod BISON simulations were performed using VERA-calculated power and thermal boundary conditions, providing high-resolution results for these parameters of interest and a number of other quantities. While it is understood at smeared pellet fuel performance models can significantly underestimate the clad hoop stress when compared to discrete pellet models, this capability can be used as a screening tool, using relative stress magnitudes to identify potential failure locations on fuel rods for further analyses.

Development of this standalone capability of BISON through VERA was initiated around August 2015. By December, initial results for the first three cycles of WBN1 were obtained (Stimpson et al., 2016a,b), demonstrating the type of information that could be gathered. With these results, it was decided that this capability would be used as a screening tool in support of a 2016 CASL milestone for PCMI analysis. It was also decided that Cycles 6 and 7 of WBN1 would be the focus of the analysis as PCMI failures were reported in each (Capps et al., 2016). By May 2016, the analysis of these cycles was complete (Stimpson et al., 2016c), and 51 rods were selected for further analysis (Capps et al., 2016). From there, more detailed BISON calculations were performed to account for more explicit 3D effects and assess the impact that missing pellet surfaces (MPS) would have on the likelihood of failure (Capps et al., 2016). These initial reports were limited to 2D core distributions of data, but recent efforts extending the post-processing capabilities to include 3D data have allowed for a greater understanding of the fuel performance results. Additionally, recent work provided an initial demonstration and assessment of using VERA tools for load-follow operations, evaluating expected clad hoop stresses during power oscillations (Stimpson, 2016; Stimpson, 2017).

In the following sections, background on pellet clad mechanical interaction is given, the codes used in this work (VERA, MPACT, CTF, ORIGEN, and BISON) are briefly described, and the WBN1 core, relevant power history, and core layouts for Cycles 1–3 are presented. The quarter-core BISON results for parameters of interest for each cycle are then shown, demonstrating how the capability can be used to identify rods that are more likely to encounter PCMI issues.

While it should be noted that PCI and PCMI failures occur very rarely in commercial power reactors, there were some failures later in the Watts Bar operating history (Cycles 6 and 7). While this paper is presenting a more general demonstration of this screening procedure on Cycles 1–3 with normal operating conditions, analyses on Cycles 6 and 7 have been performed (Capps et al., 2016), where several dozen rods were selected for more detailed analysis. Cycle 7 is noteworthy as substantial crud-induced power shift was observed, leading to conditions outside those expected for normal operations. Furthermore, results from this demonstration, which starts from a fresh core, could be useful to initial comparative analyses to other fuel performance codes.

2. Pellet-clad mechanical interaction

PCI and associated clad integrity failures are effectively the result of both a mechanical and chemical interaction (Olander, 1976; Cox, 1990). PCMI, the mechanical component, focuses on the direct forces that the pellet imparts on the clad as the rod undergoes volumetric changes resulting from a number of phenomena. For example, the fuel experiences thermal gradients and stresses that cause cracking early in life, particularly at higher linear heat rate values (Kramman and Freeburn, 1987). Relocation models in fuel performance codes attempt to model these effects. Another phenomenon is densification (Meyer, 1976), which is effectively the elimination of small pores in the ceramic fuel after sintering. This can lead to reduced pellet diameters, directly impacting the fuel-clad gap size, increasing the overall fuel temperature. As the reactor is operated and the fuel experiences burnup, it will produce a variety of fission products, some of which are gaseous and will form localized bubbles within the pellet, where the bubbles will form within the grains and diffuse to the grain boundaries (Uffelen, 2002). As a result, the fuel swells to accommodate the fission products, both gaseous and solid.

Throughout this process, thermal expansion also increases both the stack height and the pellet diameter. Because of the large temperature change experienced over the pellet radially, the expansion can be substantially different in the center of the pellet, which experiences higher temperatures compared to the surface; this causes the fuel to experience stresses and resultantly crack. These cracks can have substantial implications for how the fuel interacts with the clad when contact is eventually made. It is also important to note that some of the fission gases produced in the fuel will release into the fuel-clad gap and plenum (White and Tucker, 1983), which is typically filled with helium at beginning of life. As more fission gases infiltrate the fuel-clad gap, the thermal conductivity of the gap also decreases (IAEA, 1994). This is further complicated by fuel rods that contain an integral fuel burnable absorber (IFBA) ZrB_2 coating. During the first cycle of a rod history, the ^{10}B in the IFBA coating will burn out almost completely, converting to helium, which then also becomes part of the gap composition, impacting both the thermal properties as well as contributing significantly to the rod internal pressure.

In addition to changes in the fuel, the clad undergoes changes, as well. Thermal expansion drives most of the geometric changes initially, but clad irradiation creep becomes more significant during the course of operation, accelerating gap closure (Hoppe, 1991). With the fuel expanding and the clad shrinking, eventual contact is inevitable, which is the primary focus of PCMI. Initially, the hoop stress experienced by the clad is governed primarily by the difference between the rod internal pressure and the coolant pressure. Early in life the difference between these two is more substantial, with ~15 MPa coolant pressure