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PCI analysis of a commercial PWR using BISON fuel performance code

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ABSTRACT

Through the early 2000's, nuclear fuel cladding failure resulting from pellet-cladding interaction in commercial pressurized water reactor fuel was managed successfully by incorporating power ramp restrictions. Within the past decade, however, cladding failures have again begun to appear, often correlated to missing pellet surface defects, and further aggravated by modern reactor operating strategies demanding higher fuel duty operations. In response, renewed efforts in fuel behavior modeling and simulation are being pursued to improve our understanding of the conditions that can lead to missing pellet surface related cladding failure. This paper describes a methodology used to model pellet-cladding interaction related failures observed in commercial pressurized water reactors using the BISON fuel performance code developed at Idaho National Laboratory. In order to accomplish this goal, a three-step process is followed: 1) A failure-stress threshold is developed by using BISON code to model ramp test with known pellet-clad interaction related failures, 2) BISON analysis is applied to a commercial pressurized water reactor cycle startup with one rod confirmed to contain a missing pellet surface defect, and 3) an missing pellet surface sensitivity study of a cycle startup of the same commercial pressurized water reactor which contained a failed fuel rod of un-identified type. The analysis results described in this paper serve to illustrate the BISON code capabilities for modeling pressurized water reactor fuel subjected to higher duty power events.

1. Introduction

Pellet cladding interaction in light water reactor (LWR) fuel is a coupled thermal-chemical-mechanical process that can lead to cladding breach and subsequent release of radioactive fission products into the reactor coolant under certain conditions of operating history, power change, and fuel rod design characteristics (Cox, 1990; Lyons et al., 1963; Roberts and Gelhaus, 1979; Garzarolli et al., 1979). Reactor operating restrictions, which limit power maneuvering, have been established to mitigate PCI, but these restrictions can limit operational flexibility, leading to loss of power generation. To better understand the underlying mechanisms of pellet-clad interaction (PCI) and to help develop appropriate methods for minimizing operational threats to PCI, a high-fidelity analysis capability is needed. Such capability exists in the multi-dimensional fuel performance code BISON developed by the Consortium for Advanced Simulation of Light water reactors (CASL), and considers the code to be the most advanced computation system for the treatment of PCI and related problems. This paper presents an evaluation of the BISON fuel modeling capabilities through an analysis of a commercial pressurized water reactor (PWR) fuel cycle in which fuel failure was observed to occur.

PCI failures generally occur following an increase in local power over a short period of time in previously irradiated fuel. PCI stress corrosion cracking (PCI-SCC) failure is driven by localized strains in the vicinity of a pellet crack, as well as the presence of aggressive chemical species, such as iodine, cesium, and cadmium, that induce stress-corrosion-cracking in the cladding (Montgomery et al., 2013; Capps et al., 2015). Radial fuel pellet cracks form in brittle ceramic pellets as a result of large temperature gradients, and are believed important in the PCI failure mechanism (Montgomery et al., 2013; Capps et al., 2015). During a local power increase from a condition of reduced or closed pellet-clad gap, pellet expansion produces a high contact force between the fuel pellet and the clad. Furthermore, during the rapid thermal expansion of the pellet, the fuel cracks can further open, transferring tangential shear forces onto the cladding. These tangential shear forces are a function of the equilibrium pellet-clad gap or residual contact pressure prior to a power maneuver, power level at gap closure, interfacial friction, and the maximum local power.

Non-classical PCI failure is associated with the presence of a missing pellet surface (MPS) defect Montgomery et al., 2013; Capps et al., 2015. These MPS defects can form through fuel mishandling during the manufacturing process, where the pellet is chipped leaving a visible

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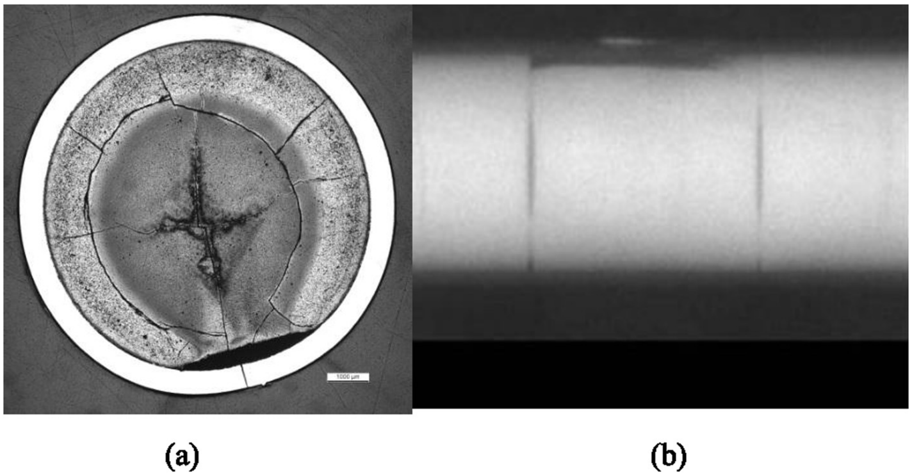

Fig. 1. a) Cross-section and b) Neutron Radiograph of failed fuel rod M16S_O05, as determined by hot-cell analysis, and reproduced from Ref. (Aleshin et al., 2010).

flaw on the outer pellet surface. The presence of an MPS defect during a localized power increase can induce severe bending moments in the clad, further aggravating the localized cladding stress in the vicinity of the MPS, when the fuel undergoes rapid thermal expansion due to the local power increase. Furthermore, a localized region near the MPS also experiences a different temperature distribution compared to when an MPS is not present, resulting in a localized hot spot in the fuel and cold spot in the cladding.

Both classical and non-classical PCI are significantly influenced by the geometry of fuel pellet defects, e.g. radial pellet cracks or MPS. The purpose of this paper is to assess the capability of BISON as a 3-D fuel performance code by modeling fuel rod behavior in a US commercial power reactor (PWR1), and validating code predictions to hot-cell examination of failed and non-failed fuel rods. In the early 2000s, leaking fuel rods were observed in a US reactor following cycle startup, as well as a mid-cycle return to power (Aleshin et al., 2010). The rods that failed were integral fuel burnable absorber (IFBA) rods, for which a root cause analysis concluded that the leakers were likely due to 'flaw assisted PCI, most likely a missing pellet surface (MPS)' Aleshin et al., 2010. Fig. 1, reproduced from Ref. (Aleshin et al., 2010), shows a cross-section of the rod M16_O05, which failed as a result of MPS-induced PCI. The PWR1 fuel rods studied in this report span a range of rod average burnups from about 20–33 GWd/tU, and build upon past CASL activities (Montgomery et al., 2013; Capps et al., 2015). Exelon supplied power history data for two rods from a single assembly (M16S_O05 and M16S_O04) which experienced similar rod average burnup and power history, and for which only one of these two rods failed. This provides a strong opportunity for inter-comparison and assessment of the BISON fuel performance predictions for PCI/MPS failure. This article will describe the PCI analysis approach used, develop a PCI stress failure threshold using ramp test data, and lastly, apply the stress failure threshold to failed and un-failed commercial reactor rods.

2. PCI failure analysis approach

The approach in this paper follows very closely to the methodology developed by Rashid and colleagues (Rashid et al., 1988; Groeschel et al., 2002; Sunderland et al., 1999; Nesbit et al., 2009) for 2-D analysis and extends that methodology for 3-D analysis. The fuel rod analysis effort consists of four main steps, which together are used to determine the PCI margin to failure relationship between previously irradiated fuel and power operation. The failure methodology is described pictorially in Fig. 2 through Fig. 5.

Step 1. The first step consists of a steady state R-Z depletion calculation for the first cycle of operation, which establishes the fuel rod conditions, such as pellet-cladding gap, plenum pressure, and released fission gas, following the first cycle of operation, illustrated in Fig. 2. The steady state R-Z analysis provides initial fuel rod conditions used for the local effects simulations, which will be discussed later.

Step 2. The second step consists of a full-length R-Z analysis of the second cycle startup immediately following the first cycle of operations, illustrated in Fig. 3(a). The purpose of this analysis is to identify the axial position in the fuel rod where the maximum cladding hoop stress occurs, as illustrated in Fig. 3(b). The second-step results provide an axial location to extract input conditions from step 1 for step 3 and 4, which are the local-effects analysis step. Important input conditions are listed in Table 1.

Step 3. The third step involves the initial simulation of local effects, and uses Table 1 output parameters from the R-Z simulations in Step 1 and 2. The data is utilized as input for the 2-D radial-circumferential (R-θ) geometric model corresponding to the axial location identified in Step 2. As for crack length geometry, the assumption is to use the worst-case scenario, which is described in Ref (Capps et al., 2015). This is illustrated in Fig. 4.

Step 4. In concert with the 2-D R-θ simulations, Step 4 addresses 3-D geometric effects. Fig. 5 shows a 3-D geometric representation of pellet radial cracks and an MPS defect, which give rise to three-dimensional stress concentrations in the cladding at the pellet-cladding interface. The results of the analysis performed in this step are used to evaluate the failure potential for each rod analyzed in the 2-D R-Z representation. Furthermore, the assumption for the crack geometry assume the worst-case scenario from Ref (Capps et al., 2015).

3. BISON modeling of ramp test rods

3.1. BISON fuel performance code

BISON is built upon the Multi-Physics Object-Oriented Simulation Environment (MOOSE) Gaston et al., 2009 developed at Idaho National Laboratory (INL). MOOSE is a parallel finite element computational system that uses a Jacobian-free, Newton-Krylov (JFNK) method to solve coupled systems of non-linear partial differential equations. In addition, the MOOSE framework provides the ability to effectively use parallel computational capabilities needed to create high fidelity 3-D models of a fuel rod, as well as full-length R-Z rods, and R-θ geometric representation (Montgomery et al., 2013, 2012; Capps et al., 2015; Williamson et al., 2012; Williamson et al., 1047).

3.2. Approach

The objective has been to develop a fuel performance modeling methodology to calculate, for commercial rod operating conditions, when and where a fuel rod failure will occur. However, before this goal