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Structural integrity of a high-burnup spent fuel rod under drop impact considering pellet-clad interfacial bonding influence

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ABSTRACT

Variation of several uncertain properties of an irradiated fuel assembly would result in changes in the buckling and bending resistance that could lead to fuel rod failure in a drop accident. Dynamic analysis of the fuel rod composite is a very complicated process due to limited knowledge on important parameters relevant to design safety, such as the material properties of the irradiated cladding and the interaction between fuel pellets and cladding. In order to better understand the behavior of a spent nuclear fuel (SNF) rod in a drop impact, a detailed finite-element (FE) model for a single fuel rod was developed considering post-irradiated fuel conditions. Free-drop analyses of two bounding cases were conducted using FE analysis, with ten assumed generalized interface bonding and de-bonding configurations to demonstrate the pellet-clad interfacial bonding influence on fuel rod behavior. It is revealed that the interfacial bonding between pellet and cladding shows a significant influence on the magnitude of the maximum principal plastic strain and its location, and on the overall structural resistance. The key feature of the proposed analysis procedure is seen in its capability to consider a range of parameters that can be included in the FE model, in addition to providing a more realistic and descriptive prediction of fuel rod behavior. The procedure and methodology developed for the numerical simulation in this work can be further extended to support the development of guidelines for safe handling of SNF when augmented by realistic data obtained experimentally.

1. Introduction

Handling and transportation operations of spent nuclear fuel (SNF) need to be evaluated based on the safety requirements stipulated in related regulations. The U.S. Nuclear Regulatory Commission (NRC) requires that fuel cladding integrity must be maintained to withstand physical loads and to guarantee transportability and retrievability of SNF for further processing or disposal, as defined in Code of Federal Regulations, Title 10, Part 71 for packaging and transport and Part 72 for storage (U.S. NRC, 2009, 2010). The main scope of the regulatory requirements is to avoid any gross rupture of fuel, and otherwise that fuel must be confined in such a way that will not pose operational problems regarding its removal from wet or dry storage (U.S. NRC, 2003). Thus, the structural integrity of spent fuel assemblies is a key element for the flexible and economic management of SNF considering repackaging in a disposal site, delivery, and reception in reprocessing facilities.

The physical and mechanical properties of SNF are essential inputs for the evaluation of storage package capabilities to protect the fuel assemblies from physical loads under specific impact conditions. Variation of such properties regarding burnup and storage history makes reliable predictions of the dynamic behavior of the fuel rods even more difficult. Some behavioral characteristics of SNF change as burnup progressively increases, which may lead to undesirable consequences on the fuel cladding integrity. This is an important issue for risk assessment since the cladding is considered as the first barrier against the release of fission products into the environment. For instance, it is a known fact that as burnup increases, cladding material is susceptible to degradation as a result of oxygen and hydrogen uptake, irradiation, and temperature change. These effects could alter the mechanical performance of the cladding and may lead to a transformation from being a ductile material to a brittle material, as so-called cladding embrittlement. This phenomenon decreases the fracture resistance of the cladding; subsequently, the probability of fuel cladding damage under normal or accident conditions during transportation will increase. Furthermore, it was found in a number of reactors that bonds

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are formed between pellets and cladding during irradiation caused by chemical and mechanical interaction during reactor operation. This is another phenomenon that could greatly influence the stiffness of a fuel rod, thereby increasing or decreasing the critical buckling load or nominal bending stress under an energetic loading as a result (Adkins et al., 2013). Accordingly, variations in cladding material properties and pellet-cladding interaction (PCI) characteristics, as safety-related fuel degradation sources, should be investigated as a major technical issue for the safe handling and transport of SNF.

The mechanical interaction between pellets and cladding has been well studied (Cox, 1990; Ayu & Walker, 1990; Walker et al., 1992). Numerous experimental and advanced modeling studies related to PCI have been conducted to explain the major complex physical phenomena of nuclear fuel rods in normal operation and power transient conditions. Most previous studies focused on local effects of fuel cladding interaction based on thermos-mechanical aspects using two or three-dimensional (2D/3D) finite-element (FE) models (Cheon et al., 2004; Marchal et al., 2009; Klouzal and Dostál, 2014; Kim et al., 2017). In addition, some quasi-static procedures were proposed to investigate the potential impact of interfacial bonding efficiency on SNF structural performance during normal back-end operations (Jiang et al., 2016). However, these studies are concerned with physical contact in a gauge section model rather than a full-length fuel rod model under dynamic impact conditions. Further studies evaluated the fuel response to mechanical loadings using analytical methods to calculate the buckling loads of the fuel rod for a vertical (end) drop impact, and bending stress for a horizontal (side) drop impact assuming that the fuel pellets do not transfer their weight to the cladding (Chun et al., 1987; Bjorkman, 2010). In these studies, the fuel pellet stiffness was ignored in the buckling/bending load calculations, but the proportion of fuel mass that participates with the cladding was adjusted in the calculations since the assumption that all fuel mass is supported by the cladding without any support of the fuel itself is too conservative. Other studies idealized the full-length fuel rod as a continuous beam or column supported at each spacer grid (SG) using beam or continuum FE-based models with the same assumption that the fuel mass of the pellets is lumped into the cladding without increasing the stiffness of the rod (Sanders et al., 1992; NUREG-1864, 2007; NUREG-2125, 2012). These approaches are conservative and miss some important behaviors of the fuel rod in reality that depend on different sources of uncertain parameters pertinent to design safety. Therefore, it is necessary to develop a more sophisticated, science-based approach combining modeling, and experiment to help in understanding SNF rod behavior under drop accident conditions, and to provide realistic or at least bounding criteria for buckling or bending loads of SNF rods with various histories for safe handling and transportation.

This study is limited to a dynamic analysis of a full-length single fuel rod under given vertical and horizontal drop orientations as a part of a bigger research on the structural integrity of cask-loaded SNF assemblies. The drop impact FE analysis in this paper augments previous studies by providing a more detailed fuel rod model considering the post-irradiated fuel conditions, specifically the pellet-clad interfacial bonding usually observed in high-burnup fuel (HBF) (fuel with a peak rod average burnup greater than 45 GWd/MTU). This paper presents a FE model of a single fuel rod, associated important input parameters for HBFs, assumptions, technical bases, and an integrity evaluation methodology, while not including detailed analyses of chemical-physics and thermos-mechanical aspects of PCI.

This paper is organized as follows. Section 2 briefly outlines the conventional methods for the two drop cases. Section 3 discusses the storage and post-storage transportation conditions of interest for the analysis. Section 4 describes the modeling procedure of the fuel rod composite and the impact conditions. Section 5 discusses the simulation results of the single fuel rod response in vertical and horizontal drops. Finally, the paper is closed with concluding remarks in Section 6.

2. Conventional methods

In this section, we briefly review the previous analytic methods to calculate the critical g-load (times gravity) of a fuel assembly subject to vertical and horizontal drop conditions introduced in references (Chun et al., 1987; Bjorkman, 2010). For the buckling analysis under the vertical drop condition, the fuel and cladding are supported as concentric columns with lateral contact. Idealized as beams, each column independently supports its own inertial load during impact but both are constrained to deform together. The critical axial inertia load and g-load for rod buckling, which have intermediate supports at each SG, can be computed using the Euler buckling approach:

$$\alpha_{cr} = \frac{\pi^2}{l^2}\frac{(E_c I_c + E_f I_f)}{(W_c + W_p)} \tag{1}$$

where α_{cr} is critical axial buckling load (g), l is the length of the fuel rod segment between two adjacent transverse SGs (in), W_c is the weight of the cladding column (lb), W_p is the weight of the fuel column (lb), and $E_c I_c$ and $E_f I_f$ are the flexural rigidity (product of the Young's modulus and area moment of inertia) of the cladding and fuel (psi.in^4), respectively. Flexural rigidity is difficult to determine as it is subjected to considerable uncertainties, such as the various pellet-clad bonding conditions. Therefore, previous studies neglected the flexural rigidity of the fuel $E_f I_f$ in calculations for conservatism (Bjorkman, 2010).

In the horizontal drop case, the fuel rod is idealized as a continuous beam supported at each SG. Using the continuous beam theory, the maximum bending moments and corresponding stresses in the cladding due to inertial load can be calculated to predict the critical impact g-load that causes the bending stresses to reach the yield strength of the cladding (Chun et al., 1987).

$$\sigma_{bending} = \frac{M_{\max} r_o}{I_c} \tag{2}$$

$$M_{\max} = 0.1058wl \tag{3}$$

$$I_c = \frac{1}{4}\pi (r_o^2 - r_i^2) \tag{4}$$

$$g_y = \frac{\sigma_y - \sigma_{axial}}{\sigma_{bending}} \tag{5}$$

Here, $\sigma_{bending}$ is bending stress (psi), g_y is the g-load required to reach yield strength (g) of cladding material, M_{max} is maximum bending moment (lb-in), r_i and r_o are the inner and outer radii of the cladding (in), I_c is the area moment of inertia of cladding cross section (in^4), $\sigma_y$is yield strength of the cladding (psi) material, w is the lateral loading (lb/in) which is equal to the total mass of the fuel rod divided by its total length, l is the length of the fuel rod segment between two adjacent transverse SGs (in), and $\sigma_{axial}$is axial tensile stress (psi) which can be generated by rod internal pressure. Table 1 shows the results of such calculations from the references (Chun et al., 1987; Sanders et al., 1992; NUREG-1864, 2007). The above-mentioned conventional analytic methods cannot calculate the critical g-load considering the several possible pellet-clad bonding configurations and percentages along the length of the fuel rod. Therefore, the present numerical analysis method is developed in order to account for more detailed fuel rod parameters in the load resistance calculations.

3. Storage condition

This study focuses in particular on HBF that is more susceptible to the effects of hydrogen, irradiation, and temperature on the performance of fuel cladding during storage and post-storage transportation conditions. In the case of temperature, plastic deformation upon fracture shortens and cladding tends to become brittle as the temperature decreases. During the storage pool stage, the temperatures are roughly maintained at 30 °C, while the initial temperature at the vacuum drying