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Fuel performance simulation of iron-chrome-aluminum (FeCrAl) cladding during steady-state LWR operation

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ABSTRACT

Alternative cladding materials have been proposed to replace the currently used zirconium (Zr)-based alloys, in order to improve the accident tolerance of light water reactor (LWR) fuel. Of these materials, there is a particular focus on iron-chromium-aluminum (FeCrAl) alloys that exhibit much slower oxidation kinetics in high-temperature steam than Zr-alloys. This behavior should decrease the energy release due to oxidation and allow the cladding to remain integral longer in the presence of high temperature steam, making accident mitigation more likely. Within the development of these alloys, suitability for normal operation must also be demonstrated. This article is focused on modeling the integral thermo-mechanical performance of FeCrAl clad UO_2 fuel during normal reactor operation. Finite element analysis has been performed to assess commercially available FeCrAl alloys (namely Alkrothal 720 and APMT) as a candidate fuel cladding replacement for Zr-alloys, using the MOOSE-based fuel performance code BISON. These simulations identify the effects of the mechanical-stress and irradiation responses of FeCrAl and provide a comparison with Zr-alloys. In comparing these cladding materials, fuel rods have been simulated for normal reactor operation and simple steady-state operation. Normal reactor operating conditions target the cladding performance over the rod lifetime (~4 cycles) for the highest-power rod in the highest-power fuel assembly under reactor power maneuvering. These power histories and axial temperature profiles input into BISON were generated from a neutronics study on full-core reactivity equivalence for FeCrAl using the 3D full core simulator NESTLE. The fuel rod designs and operating conditions used here are based on the Peach Bottom BWR with representative GE-12/14 fuel geometries, and design consideration was given to minimize the neutronic penalty of the FeCrAl cladding by changing fuel enrichment and cladding thickness. Individual sensitivity analyses of the fuel and cladding creep responses were also performed, which indicated the influence of compliance for each material, separately, on the stress state of the fuel cladding. These parametric analyses are performed using steady-state operating conditions such as a simple axial power profile, a constant cladding surface temperature, and a constant fuel power history.

1. Introduction

In the wake of events at the Fukushima Daiichi Nuclear Power Plant, interest has been revived in pursuing iron-chrome-aluminum (FeCrAl) alloys as alternative nuclear fuel cladding to traditional zirconium-based alloys. This focus is largely driven by the search for better cladding performance during accident scenarios where the fuel cladding is exposed to a high temperature steam environment. It is important to point out that type 304 stainless steel cladding was used in multiple light water reactors, including Yankee Rowe, San Onofre, and Indian Point (Strasser et al., 1982). FeCrAl alloys, currently under consideration, do not contain any nickel and have reduced parasitic neutron absorption.

During a severe accident scenario, such as a beyond design basis loss-of-coolant-accident, the radial temperature gradient inside the fuel rod rapidly decreases to a nearly uniform temperature distribution once the fission reaction is shutdown (Terrani et al., 2014a), but the average temperature begins to increase, quickly reaching temperatures sufficient to boil off the coolant. This reduces the coolant level in the core and eventually uncovers the fuel, also significantly reducing the heat transfer coefficient, further increasing the average fuel temperature. In the case of traditional zirconium-based alloys, when the cladding temperature reaches ~1200 °C, rapid oxidation kinetics occur (Cathcart et al., 1977; Moalem and Olander, 1991). This highly exothermic oxidation reaction consumes and embrittles the Zr-alloy cladding while releasing large amounts of H_2 gas into the reactor pressure

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vessel (Hofmann, 1998), as well as releasing significant heat which further increases fuel temperatures.

In order to increase the safety margin of LWR fuel in severe accident scenarios, several alternative cladding materials have been proposed (Zinkle et al., 2014). Of these materials, there is a particular focus on a class of iron-chrome-aluminum (FeCrAl) alloys because of significantly slower oxidation kinetics in high-temperature steam than zirconium-based alloys (Terrani et al., 2014b). Increased oxidation resistance may give more time to mitigate any further damage resulting from an accident. For example, MELCOR simulations have indicated several hours of additional coping time for a short-term station black-out accident scenario, in which the FeCrAl cladding would delay the onset of lower head dryout to 8.5 h from 4 h (Ott et al., 2014; Robb, 2015).

However, it is also important to point out that the core neutronics will change by replacing Zr-based alloys as the fuel cladding. FeCrAl alloys show a thermal neutron cross-section nearly ~12–16× greater than Zr-alloys. This decreases the reactivity of the core, subsequently decreasing the potential cycle length for operation (George et al., 2015b). To counteract this, increased fuel enrichment or increased fuel mass have been considered. Alternatively, the cladding thickness might be decreased, effectively reducing the neutronic penalty from using the alloy. In this study, we have performed modeling analysis in which all three changes are considered.

Since little is known regarding the performance of FeCrAl alloy based LWR fuel cladding, it is necessary to confirm both normal in-reactor performance, as well as the transient or accident behavior of this fuel. Thus we have performed fuel performance simulations using the BISON code (Williamson et al., 2012). While the database on material properties and complex mechanical fuel-cladding interactions are not yet complete for this class of alloys, we have evaluated a range of possible behaviors using a parametric approach to help identify key unknowns and uncertainties that will require further experimental and computational modeling investigation.

This article initially provides a detailed description of the modeling approach (Section 2), including a summary of the reactor operating history and local power profiles. Section 3 provides the results from our modeling analysis of FeCrAl cladding performance relative to traditional Zr-alloys. Section 3.1 details the fuel behavior that arises from using fairly aggressive power operation. After fuel-cladding mechanical contact occurs, large hoop stresses are formed in the cladding, which are later, in Section 3.3, shown to be a consequence of modelling the fuel as an elastic material. In Section 3.2 the cladding creep response to high stress conditions is analyzed for a variety of thermal and irradiation creep parameters. Finally, in Section 3.3, the effects of fuel thermal and irradiation creep on the cladding stress state are analyzed, providing the most realistic results by incorporating fuel creep deformation. Section 4 presents a discussion of the most important aspects of our analysis, including important material behavior that requires further assessment, as well as possible fuel design considerations in utilizing FeCrAl cladding for enhanced accident tolerance. Section 5 summarizes the most salient observations from this work and our recommendations for future research activities.

2. Modeling approach

In order to compare the predicted in-reactor performance of FeCrAl cladding with traditional Zircaloy cladding, and assess effects from irradiation creep, thermal creep, and swelling, several geometric and material models were implemented in the BISON fuel performance code. BISON is a finite-element simulation tool for nuclear fuel elements that is based on the Multiphysics Object Oriented Simulation Environment (MOOSE) framework (Williamson et al., 2012). It utilizes a Jacobian-Free Newton-Krylov method to solve coupled systems of non-linear partial differential equations while leveraging the scalability of parallel computing. Because of the expandability of the MOOSE framework (Gaston et al., 2009), BISON can incorporate a host of materials as well as behavioral models for integral fuel performance modeling. It has the capability to model complex thermo-mechanical behavior from both discrete and smeared pellet fuel meshes, fuel-cladding gap and plenum, and the evolution of various fuel and cladding materials over their operation.

Two separate analyses were performed using BISON. The first analysis is a comparison of FeCrAl with Zircaloy-4 fuel cladding for different operating scenarios of boiling water reactor performance. This analysis compares the Zircaloy cladding, using the previously developed cladding models in BISON, with recently implemented FeCrAl cladding models based on available data at this time. These new models are also used to examine the effects of creep and swelling on the in-reactor performance of the fuel cladding. However, fuel pellet creep and cracking mechanisms are ignored in these analyses, meaning that this initial analysis is performed with elastic only fuel pellets.

The second analysis is motivated by the results from this initial comparison of FeCrAl compared to Zircaloy cladding for the different BWR power operation scenarios, and consists of individual examination of the FeCrAl cladding and UO_2 fuel creep models. For this analysis, separate evaluations are performed for each cladding and fuel combination. FeCrAl thermal and irradiation creep properties are examined to provide performance bounds for future FeCrAl alloy development, where little data is available. Fuel creep is also evaluated in this study, and this fuel property has a significant impact in stress evolution in the cladding once the gap is closed. This analysis specifically evaluated the cracking behavior and fuel compliance without explicitly modeling fracture in a fuel performance code. This evaluation aims to identify a range of expected fuel behavior by examining the irradiation and thermal creep rate currently implemented in BISON and described in MATPRO (Hagrman et al., 1995). Without sufficient stress relief mechanisms, such as cracking, the calculated fuel creep might be greatly over predicted; this can influence the mechanical interaction between the fuel and cladding and ultimately over predict calculated cladding stresses.

This study expands upon a previous core equivalence study (George et al., 2015a) targeting the cycle length effects of using iron-chrome-aluminum alloys as alternative fuel cladding for the Peach Bottom BWR by incorporating aspects of integral fuel performance. Data from this previous study was used in order to create representative reactor operation data for the fuel simulations in BISON.

2.1. Geometric models

Geometric models for this study are based on available data for the Peach Bottom BWR (Larsen, 1978). Where data is unavailable, representative values have been assumed. Two-dimensional, axisymmetric fuel rod geometries (shown in Table 1) were created for both Zircaloy and FeCrAl. The cladding thickness, fuel radius, and fuel

Table 1
Fuel geometry specifications for 2D axisymmetric fuel performance analyses.

Cladding Material	Fuel Radius (μm)	Gap Thickness (μm)	Cladding Thickness (μm)	Fuel Length (m)	Cladding Length (m)	Enrichment (% U-235)
Zircaloy	4400	100	600	3.66	4.08	4.11
FeCrAl	4700	100	300			4.68

- This produces a total outer radius of 0.51 cm for both cladding types.