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The potential impact of enhanced accident tolerant cladding materials on reactivity initiated accidents in light water reactors ☆

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A B S T R A C T

Advanced cladding materials with potentially enhanced accident tolerance will yield different light-water reactor performance and safety characteristics than the present zirconium-based cladding alloys. These differences are due to cladding material properties, reactor physics, and thermal hydraulics characteristics. Differences in reactor physics are driven by the fundamental properties (e.g., neutron absorption cross section in iron for an iron-based cladding) and also by design modifications necessitated by the candidate cladding materials (e.g., a larger fuel pellet to compensate for parasitic absorption).

This paper describes three-dimensional nodal kinetics simulations of a reactivity-initiated accident (RIA) in a representative pressurized water reactor with both iron-chromium-aluminum (FeCrAl) and silicon-carbide fiber silicon carbide ceramic matrix composite (SiC/SiC) materials. This study shows similar RIA neutronic behavior for SiC/SiC cladding configurations versus reference Zircaloy cladding. However, the FeCrAl cladding response indicates similar energy deposition but with shorter pulses of higher magnitude. This is due to the shorter neutron generation time of the core models based on FeCrAl cladding. The FeCrAl-based cases exhibit a more rapid fuel thermal expansion rate than other cases, and the resultant pellet-cladding interaction may occur more rapidly. The conclusions in this paper are based on a limited set of simulated super prompt RIA transients.

1. Introduction

The reactivity-initiated accident (RIA) is a postulated design basis accident (DBA) in a light water reactor (LWR). The RIA takes the form of a control rod ejection accident in a pressurized water reactor (PWR) or a control rod drop accident in a boiling water reactor (BWR). The US Nuclear Regulatory Commission (NRC) General Design Criteria require that postulated RIAs must not damage the reactor coolant pressure boundary, and they must not significantly impair core coolability (Electric Power Research Institute [EPRI], 2002) as outlined in 10 CFR Part 50: Domestic licensing of production and utilization facilities. One possible cladding failure mode during RIA is pellet cladding mechanical interaction (PCMI), which occurs on a very rapid (millisecond) timescale.

Since the events at Fukushima Daiichi in 2011, the US Department of Energy Office of Nuclear Energy (DOE-NE) Advanced Fuels Campaign (AFC) has been studying nuclear fuel and cladding materials with potentially enhanced accident tolerance (Goldner, 2012; Terrani et al., 2014; Zinkle et al., 2014), also known as accident tolerant fuel (ATF). These fuel and cladding materials will affect the progression of RIA response. The focus of this paper is on the expected impact of two advanced cladding candidates, FeCrAl alloy and SiC/SiC composite, on the progression of a control-rod-ejection accident in a PWR at hot zero power (HZP) conditions.

Understanding the impact of an RIA is very important for candidate fuel/cladding concepts with new materials. RIA proceeds in two phases (Desquines et al., 2011). The first phase is also called the low-temperature phase, and the cladding performance is dominated by PCMI. The first phase occurs rapidly as the fuel pellet thermally expands due to the intense quasi-adiabatic energy deposition of the overpower transient. This is caused by a pulse in the fission rate in the fuel, which is turned around by the Doppler effect. Thus, the mechanical response of the cladding is mostly dri-

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ven by the dimensional change of the fuel pellet during an RIA transient. The extent and rate of dimensional change in the fuel pellet is proportional to the energy deposited during the RIA. The mechanical response of the fuel pin therefore depends strongly on the reactor kinetics.

The second phase of RIA is the high-temperature phase, where heat is transferred from the pellet, through the cladding, and into the coolant. Because of the large amount of energy deposited in the fuel, a boiling crisis during transport to the coolant is possible. If a boiling crisis occurs, a vapor film forms on the cladding surface, which impedes heat transfer to the coolant and drives up the fuel temperature. Fuel can fail due to melting or due to brittle fracture during the quench phase.

The safety criteria formulated in the 1970s focused only on this second phase since the early tests conducted on fresh or low burnup fuel segments did not reveal the potential for failure due to PCMI (U.S. Atomic Energy Commission, 1974). Accordingly, a limit of 170 cal/g of energy deposition in the oxide fuel was prescribed. However, international tests conducted during and after the 1990s on fuel segments with medium to high burnup indicated the potential susceptibility to fuel failure at lower energy deposition thresholds and post-test examinations indicated that failure mechanism was due to PCMI (Alvis et al., 2010). This was the case since at these burnup levels the gap between the fuel and cladding had decreased greatly or disappeared altogether while the ductility of the cladding had also plummeted due to radiation damage as well as hydrogen pickup (Fuketa, 2011; Sugiyama et al., 2009). Accordingly, In the US an amendment to acceptance criteria defined in NUREG-0800 was made (U.S. Nuclear Regulatory Commission, 2007) to ensure compliance with General Design Criterion (GDC) 10, within Appendix A to 10 CFR Part 50 along with similar modifications made internationally.

Both phases of an RIA could cause cladding failure. The focus of this paper is on PCMI that is the responsible mechanism for failure during the first phase. Some of the differences in RIA response in an LWR with an advanced cladding will be driven by the fundamental properties (e.g., neutron absorption cross section in iron for an iron-based cladding) and others by design modifications necessitated by the candidate cladding materials (e.g., a larger fuel pellet to compensate for parasitic absorption).

This paper describes an effort to use reactor core kinetics simulation capabilities to estimate differences in the ATF concept pulse response characteristics during hypothetical RIA events. The results of this study apply to future in-pile transient testing as well as to out-of-pile separate effects tests. Essentially these results will be used to inform future experimental studies with appropriate test conditions to study the mechanical response of the cladding.

The applicable conditions have been determined using three-dimensional nodal kinetics simulations of an RIA in a representative PWR with both FeCrAl and SiC/SiC cladding materials. The study yields pulse shape boundary conditions for use in future mechanical tests of candidate materials to simulate the RIA event, specifically peak unconstrained fuel thermal expansion and unconstrained fuel thermal expansion rate during the power pulse following the rod ejection. Other example information of interest includes the pulse width and the energy deposition in the fuel. The effort spans the parameter space of potential FeCrAl and SiC/SiC cladding design concepts for PWRs (Brown et al., 2015; George et al., 2015; Todosow et al., 2015; Younker and Fratoni, 2016).

2. Core modeling approach

This work informs on the qualitative and quantitative differences in RIA response of two leading candidate-cladding materials versus the reference zirconium-based cladding. The parameters that describe the conditions an RIA imposes on fuel and cladding include energy deposition, pulse magnitude, pulse width, and rate of fuel temperature increase. Not only do different cladding materials and fuel designs lead to different responses to these parameters, but they also influence the values of the parameters themselves (i.e., core loads of different fuel types responding differently to rod insertion or rod drop). These quantities, then, inform on differences relative to zirconium-based cladding in the boundary conditions of a PCMI separate effects test. The intent of a PCMI test is to determine the failure strain limit (%) for a particular cladding. The pulse width and rate of fuel temperature increase help determine the thermal expansion rates (%/second) experienced by the fuel pellets which can be used to estimate the displacement and displacement rate in the cladding for a variety of fuel concepts.

To generate these parameters, a three-dimensional PWR core model was developed for several candidate configurations: a reference Zircaloy-4 cladding case, two FeCrAl cladding configurations with parameters from the literature, and two SiC/SiC cladding configurations with parameters from the literature. In this context the differences between the configurations were the cladding material, fuel pellet diameter, and cladding thickness. The details of a similar methodology are outlined in Brown et al. (2014) in which different lattice configurations are used, along with a set of cross section branch parameters (fuel temperature, moderator density, moderator temperature, soluble boron concentration, and control rod) that bound hot zero power conditions. For each of the candidate configurations, an equilibrium cycle core model was generated using the Purdue Advanced Reactor Core Simulator (PARCS) (Downar et al., 2002), the US NRC's reactor-core simulator. PARCS is a well-established tool for simulation of RIA. Example applications of PARCS for RIA include Kozlowski and Downar (2006), as well as Hursin et al. (2013).

The equilibrium core configurations were calculated with a single burnable poison configuration in a multicycle calculation. An identical integral fuel burnable absorber (IFBA) configuration was used for all fuel assemblies. Within the fuel assemblies, 112 of the fuel pins used IFBA coating for reactivity control. The SCALE 6.1 lattice physics tool TRITON/NEWT was used for the generation of two-group cross sections (DeHart and Bowman, 2011). TRITON/NEWT was used with ENDF/B-VII.0 238-group cross sections collapsed to a problem-specific 49-group library. The selected branch parameters include conditions required to accurately simulate both hot full power and HZP conditions. The 17×17 Westinghouse assembly geometry used in the generation of the few-group cross sections for the PARCS model is shown in Fig. 1.

The lattice configurations considered as part of this study are shown in Table 1. The parameters are based on those used for scoping calculations in Brown et al. (2014, 2015), George et al. (2015), and Todosow et al. (2015). Differences from the reference Zircaloy cladding case are displayed in bold. The composition of the FeCrAl cladding assumes 71% iron, 21% chromium, 5% aluminum, and 3% molybdenum. Due to its relatively high chromium and molybdenum content, this FeCrAl composition is expected to bound the neutronic impacts of FeCrAl cladding. It should be noted that the chromium content of an eventual nuclear-grade FeCrAl would likely be lower (Yamamoto et al., 2015), which will reduce parasitic neutron absorption. Results from detailed calculations of the parasitic neutron absorption in FeCrAl are presented in Brown et al. (2015) and George et al. (2015).

The PARCS multicycle capability was used to calculate the equilibrium core models with a discharge burnup convergence criterion of 0.1 GWd/t. There were 157 assemblies in the core model, with a total thermal power of 3400 MW. In each cycle, the relevant fuel assemblies were shuffled according to a prescribed three-batch fuel-management scheme targeting an 18-month cycle