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An investigation of FeCrAl cladding behavior under normal operating and loss of coolant conditions

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HIGHLIGHTS

- Material and behavior models for FeCrAl have been added to the BISON fuel performance code.
- A failure criterion for FeCrAl alloys has been developed.
- Under normal operation FeCrAl performs as well as Zircaloy-4 with improved oxidation kinetics.
- First generation FeCrAl alloys have similar burst behavior as Zircaloy-4.

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ABSTRACT

Iron-chromium-aluminum (FeCrAl) alloys are candidates to be used as nuclear fuel cladding for increased accident tolerance. An analysis of the response of FeCrAl under normal operating and loss of coolant conditions has been performed using fuel performance modeling. In particular, recent information on FeCrAl material properties and phenomena from separate effects tests has been implemented in the BISON fuel performance code and analyses of integral fuel rod behavior with FeCrAl cladding have been performed. BISON simulations included both light water reactor normal operation and loss-of-coolant accidental transients. In order to model fuel rod behavior during accidents, a cladding failure criterion is desirable. For FeCrAl alloys, a failure criterion is developed using recent burst experiments under loss of coolant like conditions. The added material models are utilized to perform comparative studies with Zircaloy-4 under normal operating conditions and oxidizing and non-oxidizing out-of-pile loss of coolant conditions. The results indicate that for all conditions studied, FeCrAl behaves similarly to Zircaloy-4 with the exception of improved oxidation performance. Further experiments are required to confirm these observations.

1. Introduction

In light of the events that occurred at the Fukushima Daiichi nuclear power plant in March 2011 there has been an increased research effort into accident tolerant fuel and cladding materials. Accident tolerant materials are defined as those that provide significantly increased response time in the event of an accident while providing similar or improved performance as the standard UO_2/Zircaloy-4 fuel rods during normal operation [1]. In particular, qualitative attributes for materials with enhanced accident tolerance include improved reaction (e.g., oxidation) kinetics with steam, resulting in slower hydrogen (or other combustible gases) generation rate, while maintaining acceptable thermo-mechanical properties, fuel-clad interactions, and fission-product behavior [1]. Through its Office of Nuclear Energy the United States Department of Energy (U.S. DOE) has accelerated research in this area through the Fuel Cycle Research and Development (FCRD) Advanced Fuels Campaign (AFC). The goal of the AFC Accident Tolerant Fuel (ATF) program is to guide selection of promising concepts for insertion into a commercial reactor as part of a lead test rod or assembly in 2022.

Given the aggressive development schedule, it is impossible to perform a comprehensive set of experiments to provide material

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characterization data. Therefore, the AFC is utilizing computational analysis tools in an effort to understand the proposed accident tolerant materials. One of the most significant issues in the Fukushima Daiichi accident was the oxidation of Zircaloy that led to a large inventory of hydrogen within the core. One of the leading ATF concepts being pursued by the AFC and General Electric is iron-chromium-aluminum (FeCrAl) alloys for use as a cladding material due to its low oxidation rate. General Electric has current plans for a lead test rod(s) insertion into a commercial power plant in 2018 [2]. Oxidation rates for FeCrAl are 1–3 orders of magnitude lower than the oxidation rates of Zircaloy [3–6]. In addition, the stiffness of FeCrAl is roughly twice that of Zircaloy [4], while the yield stress is higher by a factor of four for select alloys [3]. The melting point range of FeCrAl alloys (Fe with 0-16 wt% Cr and 5-8 wt% Al) is within 1525–1540 °C [7].

Even with low oxidation rates there is the potential of corrosion products (ionized Fe, Cr) being released to the coolant. However, the entirety of the LWR coolant system is composed of Fe-based alloys, which are mostly austenitic. These alloys form similar spinel films that form on the surface of FeCrAl alloys. Accordingly, the dissolved Fe, Cr, and Ni are currently, and in abundance, present in the PWR and BWR coolants and are not of concern.

While the oxidation characteristics of FeCrAl are a benefit for accident tolerance, the thermal neutron absorption cross section of FeCrAl is about ten times that of Zircaloy. This neutronic penalty necessitates thinner cladding. This allows for slightly larger pellets to give the same cold gap width in the rod. However, the slight increase in pellet diameter is not sufficient to compensate for the neutronic penalty and enriching the fuel beyond the current 5% limit appears to be necessary [8]. Current estimates indicate that this neutronic penalty will impose an increase in fuel cost of 15–35% [3,4]. In addition to the neutronic disadvantage, it is anticipated that tritium release to the coolant will be larger because the permeability of hydrogen in FeCrAl is about 100 times higher than in Zircaloy [9]. Also, radiation-induced hardening and embrittlement of FeCrAl need to be fully characterized experimentally [10].

Crack growth rates under stress corrosion cracking tests of ferritic alloys is shown to be roughly two orders of magnitude smaller than austenitic alloys [11]. Accordingly, they are deemed inconsequential for cladding applications.

In this paper, we add material and behavior models for FeCrAl to the BISON fuel performance code and perform analyses of light water reactor (LWR) fuel rod behavior with FeCrAl cladding. A failure criterion for FeCrAl is developed and implemented in the code, based upon recent burst experiments under out-of-pile loss of coolant conditions. Fuel performance simulations are completed to assess the response of FeCrAl using these models for three different scenarios: (1) normal operating conditions, (2) non-oxidizing loss of coolant conditions, and (3) oxidizing loss of coolant conditions. The behavior of FeCrAl is compared to that of Zircaloy-4 under the same conditions to assess the compliance of FeCrAl with the above mentioned attributes for usage as an accident tolerant cladding material in LWRs.

2. Fuel performance modeling

Fuel performance modeling is the use of computational tools to assess the thermo-mechanical behavior of fuel and cladding materials under reactor conditions. For alternative materials such as FeCrAl where experimental data is limited, fuel performance simulations can be used to help guide experimentalists into the important areas of further research. Furthermore, the computational tools may be used to guide the material development activities by providing optimal performance targets for that material (e.g., optimal creep rate, geometry). In particular, fuel performance codes provide a framework that permits combining the information from separate effects experiments into a global fuel rod thermo-mechanics model. In this way, investigation of integral in-reactor fuel rod behavior can be performed.

The Nuclear Energy Advanced Modeling and Simulation (NEAMS) program in the DOE has for some time been developing computational analysis tools. These tools include BISON [12–15] and Marmot [16], which have been developed at the Idaho National Laboratory (INL) and are tailored for nuclear fuel performance at the engineering and grain scales, respectively.

An advantage of the BISON fuel performance code over existing codes such as FRAPCON [17] or FALCON [18] is that new material types can easily be implemented into the code. In this case fuel performance models have been incorporated into the BISON framework for FeCrAl cladding. Specifically, the FeCrAl alloy of interest in this study is the laboratory optimized alloy known as C35M under development and testing at the Oak Ridge National Laboratory (ORNL) [19,20]. This alloy (or similar) is a contender to be included in a lead test rod or assembly in 2022 as irradiation testing is currently underway in both the Halden Reactor in Norway [21] and the Advanced Test Reactor (ATR) at INL [22]. The present work benefits from the most recent information on C35M properties from experimental work at ORNL and Halden.

Many groups of researchers have investigated the behavior of the commercial FeCrAl alloy manufactured by Sandvik AB known as Kanthal APMT™ [23] using the BISON code. Xu et al. [24] performed Zircaloy and APMT™ comparisons under normal operation using a 10-pellet rodlet irradiated using a simplified power history. Two simulations were completed, one where creep of the FeCrAl cladding was neglected and one in which the Zircaloy creep models were used to provide the bounding cases on FeCrAl creep.

Galloway and Unal [25] investigated the mechanical response of APMT™ cladding of varying thicknesses under operational data from the TSQ002 experiment irradiated in a commercial US PWR 16 × 16. The stresses within the cladding were found to be much higher in FeCrAl than Zircaloy.

Sweet et al. [26] performed full length rod comparisons between Zircaloy and APMT™ cladded rods fueled with UO_2 fuel. They utilized neutronics calculations to generate the power histories for FeCrAl cladded rods based upon the Peach Bottom (BWR) commercial reactor. The results obtained showed large stresses well above the ultimate tensile strength in the FeCrAl cladding cases. The authors attributed the large stresses to pellet-cladding mechanical interaction (PCMI) with the elastic fuel approximation, which was used in the BISON simulations. In their analysis no plasticity model for the cladding was used which also contributed to the large stresses observed. All analyses were for normal operating conditions.

3. Material and behavior models

3.1. FeCrAl cladding

In order to perform fuel performance modeling of FeCrAl claddings, material and behavioral models need to be added to the BISON code base. Based upon the existing data for the C35M alloy, empirical models have been developed and added to BISON. For areas where C35M experimental data is non-existent (e.g., thermal conductivity and specific heat), data from the commercial alloy Kanthal APMT™ [23] are used. Models have been added for thermophysical properties as a function of temperature, thermal and irradiation creep, volumetric swelling, and oxidation. A failure criteria for FeCrAl during transient conditions is developed in the next section which is required for performance analyses under