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Fuel performance of chromium-coated zirconium alloy and silicon carbide accident tolerant fuel claddings

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ABSTRACT

The U.S. Department of Energy's Accident Tolerant Fuel program is focused on extending the time for fuel failure during postulated severe accidents compared to the standard UO_2-Zr alloy fuel system. This paper investigates the feasibility of two different chromium-coated cladding concepts, one of which is zirconium-alloy based and the other is composite-SiC based. Both claddings had 50 μm coatings, deducted from the base layer thicknesses. The claddings were studied, using the multi-physics fuel performance tool BISON, under steady-state PWR operating conditions as well as under two transients: a power ramp and a loss-of-coolant accident (LOCA). The chromium-coated claddings showed comparable thermo-mechanical performance to the reference Zircaloy-4 cladding. As chromium is reported to provide an order of magnitude improvement in oxidation resistance, it is expected to be a better alternative in accident scenarios. Simulation results for both concepts show that further experimental investigation as well as modeling of beyond design-basis accidents is warranted.

1. Introduction

The Fukushima accident in 2011, triggered by a massive 9.0 magnitude earthquake followed by a tsunami, had a devastating effect on the status and prospects of nuclear power worldwide. Alarmed by the incident and the following large release of radioactive material to the atmosphere and the surrounding land and ocean (Stohl et al., 2012), Japanese authorities mandated a shutdown of its nuclear capacity (Huenteler et al., 2012). Longer term effects included Japan's later announcement of plans to reduce dependency on nuclear power and to revise their Basic Energy Plan (Huenteler et al., 2012). In addition, Germany and Switzerland have announced plans to phase-out nuclear energy in the foreseeable future (Jorant, 2011).

As a result of the accident, a renewed interest was generated in addressing the shortcomings of the traditional zirconium-based (so-called "Zircaloy") claddings under accident conditions. Current light water reactors (LWRs) use a fuel system composed of uranium dioxide (UO_2) pellets, zirconium-alloy cladding and a helium filled pellet-cladding gap. The choice of zirconium alloys as the primary cladding material is due to its low neutron absorption, good corrosion resistance and structural integrity under operating conditions (Lemaignan, 2012). However, under design-basis accidents (DBAs) and beyond DBAs, zirconium alloys can rapidly lose their integrity due to their interaction/oxidation in high-temperature steam (Terrani et al., 2014). This has led to a large research effort to mitigate and possibly eliminate high temperature oxidation of the fuel system currently used in LWRs. The proposed solutions are called accident tolerant fuels (ATFs) (Zinkle et al., 2014).

ATFs are fuels which in comparison with the standard UO_2-Zr system, can tolerate loss of active cooling in the core for a considerably longer time period (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations (Carmack et al., 2013). These improved properties are mainly focused on reducing the oxidation rate and hydrogen (or other combustible gases) production at high temperatures. Additional, targeted improvements include increasing the cladding melting point and its strength at high temperature in comparison to current Zircaloy cladding. Improvements to the fuel are also under investigation, especially in the areas of improved fission gas retention, higher temperature margin to fuel melt and increased thermal conductivity (Zinkle et al., 2014).

Numerous candidates are currently under investigation as alternatives to the UO_2-Zr system. To list a few, Pint et al. (2015) looked into the oxidation kinetics of FeCrAl, SiC, Molybdenum and MAX-phase alloys (Ti_3SiC_2, Ti_2AlC). Deck et al. (2015) experimentally

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investigated SiC properties for ATF deployment. Mo-Zr and Mo-FeCrAl duplex claddings were investigated by Cheng et al. (2016). Iron based alloys have been proposed by Terrani et al. (2014). Extensive experimental investigation of FeCrAl properties is being carried out mainly by Oak Ridge National Laboratory (Yamamoto et al., 2015; Field et al., 2015; Field et al., 2017). Recently, Gamble et al. (2017) investigated FeCrAl claddings under PWR normal operating and loss-of-coolant conditions, as have Wu et al. (2015) and Galloway et al. (Galloway and Unal, 2016). Chromium-coated claddings have been studied by Ševeček et al. (2018), Shah et al. (2017), Koo et al. (2014), Brachet et al. (2017, 2015, 2014) and Katoh et al. (2017). This list is not complete by any means but rather highlights the magnitude of the current research efforts (both experimental and modeling and simulation) and identifies some of the promising candidates.

The focus of this paper is to investigate two proposed Chromium-coated ATF cladding system concepts, using thermo-mechanical modeling under both steady-state and transient conditions. The aim of this investigation is to compare the performance of each concept relative to a standard Zirconium alloy cladding. The most promising concepts could be then further investigated experimentally to test their performance and possible performance enhancement under simulated accident conditions. Further experimentation would also provide more data for feedback into the modeling/simulation codes, as data is one of the limitations to developing physical/realistic models. However, as experiments are rather costly and time intensive, it is essential to limit them to the most promising ATF concepts and to determine the properties that have the greatest impact on performance. Therefore, simulations and modeling can help focus the experimental efforts and provide an informed judgement on the concepts expected to be the most promising.

2. Methodology

The multi-physics fuel performance tool BISON (Williamson et al., 2012) is used for the thermo-mechanical modeling of the fuel concepts considered in this paper. BISON is a finite element-based nuclear fuel performance code built on the MOOSE framework (Gaston et al., 2009), which is a framework capable of solving general systems of coupled non-linear equations. The BISON code is capable of solving the fully coupled thermo-mechanics and diffusion equations for multidimensional (up to 3D) representations of the geometry. The code includes fuel models that represent temperature and burnup dependent material properties, such as swelling, fuel densification, thermal and mechanical properties, fission gas production and release, and irradiation and thermal creep. Models for several cladding materials are included as well, such as Zricaloy-2/4. The standard set of models for material behavior are augmented by this work, which added models for additional materials including Chromium and Silicon Carbide. These material properties were coded using object oriented C++ and added as new modules in the program, and are described in Section 3.

2.1. ATF concepts

The paper will focus on two types of cladding, Zirc-4 based cladding and SiC based cladding, as shown in Fig. 1. The coating thickness is limited to 50 μm in both cases. The SiC cladding dimensions shown in Fig. 1 were kept constant for all cases in this study. For the Zr4 cladding, the Zircaloy thicknesses varied slightly for each simulation as we attempted to re-create experimental conditions. The thickness of the coating for Zr4 cladding is stated in the test description for each simulation. The simulations will compare the performance of each ATF concept against a reference Zr4 cladding. The fuel-systems will be subjected to steady state simulations, followed by power ramps, and finally LOCA simulations.

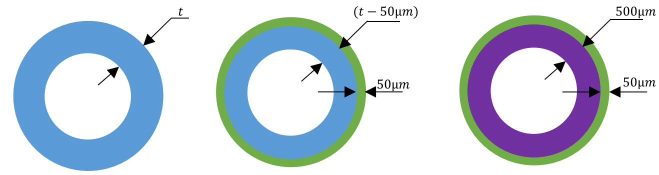

Fig. 1. Different Zr4-based claddings and proposed coating thicknesses.

3. Material properties

3.1. Chromium

Pure chromium properties are not commonly studied, as it is usually used as an alloying element. This section compiles properties for chromium and discusses the limitations of the data. For this section, temperature (T) is in units of Kelvin unless stated otherwise.

3.1.1. Thermal properties

Thermal properties were obtained for commercially available pure chromium Ducropure (trademark of Metallwerke Plansee AG, Austria) (Holzwarth and Stamm, 2002). The Specific heat (C_p) in the range between 300 and 1300 K is expressed as (Holzwarth and Stamm, 2002):

$$C_P(T) = (-1.28 \times 10^{-7}T^3 + 3.39 \times 10^{-4}T^2 - 0.09T + 483.2)\mathrm{J.kg^{-1}K^{-1}} \quad (1)$$

Thermal Conductivity (between 300 and 1300 K) (Holzwarth and Stamm, 2002):

$$\lambda(T) = (-2.07 \times 10^{-8}T^3 + 4.85 \times 10^{-5}T^2 - 0.06T + 101.75)\mathrm{WK^{-1}m^{-1}} \quad (2)$$

3.1.2. Mechanical properties

The Elastic Modulus as a function of temperature E(T) (between 300 and 1500 K) is extracted from (Armstrong Harry, 1964). The data can be fitted to the following polynomial:

$$E(T) = (-2.50 \times 10^{-5}T^2 - 0.01T + 264.11)\mathrm{GPa} \quad (3)$$

with R^2 = 0.9934. At room temperature, Eq. (3) gives a value of ~261 GPa which is in close proximity to values obtained from nanoindentation of Cr coating (233.6 ± 26.4 GPa) that was exposed to steam oxidation at 500 °C for 20 days (Ševeček et al., 2018).

The Poisson's ratio can be approximately considered as a constant (Simmons, 1965):

$$v = 0.22 \quad (4)$$

The mean thermal expansion coefficient (between 300 and 1300 K), with a reference temperature of 293 K is (Holzwarth and Stamm, 2002):

$$\alpha(T) = (1.27 \times 10^{-10}T^3 + 5.41 \times 10^{-7}T^2 + 0.0015T + 7.87) \times 10^{-6}\mathrm{K^{-1}} \quad (5)$$

3.1.3. Thermal creep

The thermal creep rate of chromium can be calculated using a Norton creep law: