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MULTIPHYSICS ANALYSIS OF CMC SILICON CARBIDE AND ZIRCALOY CLADDING

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ABSTRACT

Nuclear fuel cladding is an integral part of nuclear reactors and choosing the proper material is imperative to the design of a reactor. In this paper, the neutronic properties and the fuel performance of a 17×17 Westinghouse Pressurized Water Reactor (PWR) assembly using ceramic matrix composites (CMC) Silicone Carbide (SiC) as a cladding material is investigated. The material analysis is compared against traditional Zircaloy-4 cladding used in a 17×17 Westinghouse PWR assembly. The codes used in the analysis are the Michigan Parallel Characteristics based Transport (MPACT) code coupled with CTF, the North Carolina State University version of the Coolant Boiling in Rod Arrays Two Fluids (COBRA-TF) code, and the fuel performance code BISON as well as the uncertainty analysis code DAKOTA. Additionally, annular geometry for the fuel pellet is modeled to assess its merit compared to ordinary CMC SiC or traditional Zircaloy-4 claddings. It is found that on the neutronics side, the CMC SiC shows lower achievable U-235 enrichments required to reach the same burnup and effective neutron multiplication factor as Zircalloy-4 claddings. These results are an advantage that can be seen in the economic cost analysis done and additionally from the reactor operation point of view. Also, it is found that the different criteria of safe operation of Westinghouse PWR assemblies like the plenum pressure, the fuel-cladding contact pressure, the peak fuel temperature, and the fission gas release criteria are all achieved with CMC SiC with some criteria having larger design margins than of the Zircaloy-4 cladding. Furthermore, a critical heat flux (CHF) study shows that CMC SiC has even larger thermal margins than the ordinary Zircaloy-4 cladding, resulting in a more profitable fuel cycle due to the greater amount of power that the fuel pins can be operated at. An uncertainty quantification for the CHF Ratio (CHFR) is also done to assess the largest magnitudes of importance that affect the CHFR calculated.

1. INTRODUCTION

To ensure the fuel and the resulting fission products do not leak into the coolant while still allowing heat to transfer sufficiently between the two, choosing the proper cladding material is imperative to the design of a reactor. Fuels and core structures in the current Light Water Reactors (LWR) are vulnerable to catastrophic consequences if loss of coolant or active cooling occurs, as unfortunately shown by the 2011 Fukushima Daiichi Nuclear Power Plant Accident. This can be attributed to the rapid oxidation kinetics of zirconium alloys in a water vapor environment at very high temperatures that results in the production of explosive hydrogen [1]. Current LWRs use Zr-alloys exclusively as the materials for fuel cladding and core structures. Silicon carbide (SiC) based materials like the continuous SiC fiber-reinforced SiC matrix ceramic composites (SiC/SiC composites or SiC composites) are among the candidate alternative materials for LWR fuel clads and core structures to enable so-called accident tolerant fuels (ATF) and accident-tolerant cores (ATC).

In this work, the neutronic properties and the fuel performance of a 17×17 Westinghouse PWR assembly when using CMC SiC as a cladding material are investigated. In section 2, the material properties of both Zircaloy and SiC are outlined and compared, while in section 3 following material characterization, the reactivity and power history for each cladding design is found using the Michigan Parallel Characteristics based Transport (MPACT) code [2] coupled with the sub-channel thermal-hydraulic code CTF (Coolant Boiling in Rod Arrays Two Fluids or COBRA-TF) [3]. Once the power history of SiC are assessed, we compare the fuel performance when using SiC and Zircaloy using BISON code [4] for both standard and annular geometries. Brief concluding remarks are given in section 4.

2. METHODS

2.1. Fuel Assembly Description and Parameters

This subsection describes the basic design and operating characteristics of the 17×17 Westinghouse PWR 4-loop reactor assembly used. The principal parameters of the reactor are given

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