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Fuel Performance Analysis of Accident-Tolerant Fuel (ATF) Rod with Multi-Layered Cladding During Load Follow Operations

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1. Introduction

Load-follow operation capability, which enables nuclear power plants to operate economically by varying reactor power to match power demand, is becoming a critical requirement in the design of nuclear power plants [1]. In the case of daily load follow operations, it is necessary to analyze the damage caused by pellet–cladding interaction (PCI) and fatigue to ensure the integrity of the fuel rod. In this study, a finite element analysis (FEA) system was established for modeling that reflects the multiphysics behavior of a multi-layered cladding with inner and outer surfaces coating to prevent severe oxidation and hydrogen generation of conventional zirconium-based cladding material. Through the developed finite element analysis system, multiphysics analysis of multiple-layered cladding was performed under the daily load follow cyclic load.

2. Methods and Results

2.1 Simulation conditions

The schematic of the multi-layered cladding used in this study is shown in Fig. 1. In the present work, the FEA system is configured based on ABAQUS^{TM} framework and the calculations were performed considering the external coating with pure Chromium (Cr) case as shown in Fig. 1 (a) and the simultaneous internal and external Cr coating case as shown in (b). For UO_2 and Zr-4 properties, detailed material thermo-mechanical models of elasticity, plasticity, fission gas release, creep, swelling, thermal conductivity, and thermal expansion were input through user-subroutines using FRAPCON-4.0 and MATPRO property databases [2,3]. As in the case of Cr coating, various property models including thermal conductivity, creep, and plasticity was applied to this model [4]. For the pellet-cladding gap conductance, the gas mixture conductivity due to initial gap gas and fission gas release was considered, and the contribution of radiation and contact to the gap conductance was also modeled by user-subroutine GAPCON [5].

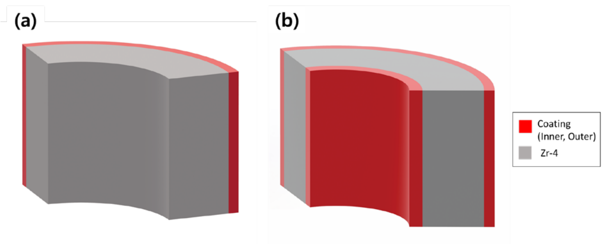

Fig. 1. Schematic of the multi-layered cladding with (a) outer coating and (b) inner and outer coating

The CAX4T element (4-node axisymmetric thermally coupled quadrilateral, bilinear displacement, bilinear displacement, and temperature) is chosen for the meshing scheme and the element type. In order to consider the stress concentration due to the contact of the edge of the pellet with the cladding, the FEM model was built with two independent half-length pellets. Axial direction symmetry boundary conditions and pressure boundaries were applied. Also, the constant heat transfer coefficient condition was assumed. The mechanical contact between pellet and cladding is calculated by the hard contact and penalty-based contact condition assuming firction coefficient of 0.3.

2.2 Thermo-mechanical behavior of the ATF cladding

As a preliminary study, the fuel performance calculations were performed assuming that the reactor is operated in load follow condition as illustrated in Fig 3. at a hot zero power (HZP), in which case the discharged burnup of the nuclear fuel is 0.0 GWd/tU. The maximum power is set to 20 kW/m, assuming a load follow scenario of 100 - 30 - 100. The results of the temperature analysis are shown in Fig. 3 and Fig.4. As shown in Fig. 4, the fuel centerline temperature was calculated to be approximately 1650 K at 100% power level and 850 K at 30% power level.

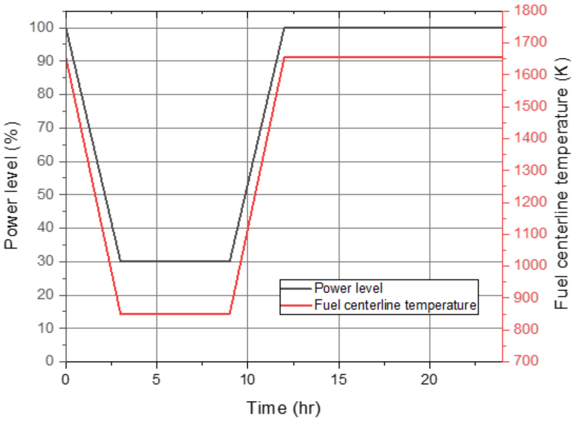

Fig. 2. Power profile of the daily load follow condition

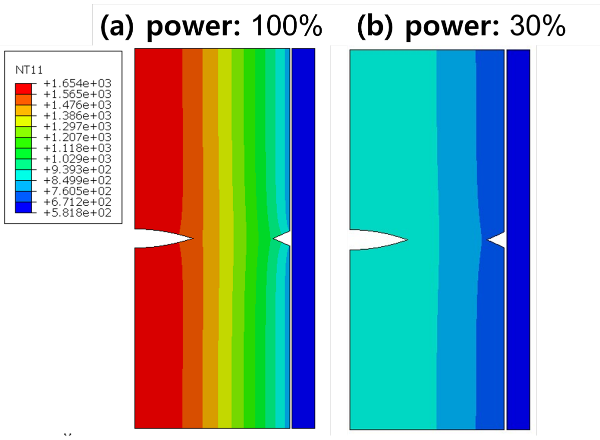

Fig. 3. Temperature distribution profile during the daily load follow condition within the ATF fuel rod containing double-layered cladding

Mechanical analysis at various power levels was performed. Fig. 4 shows the distribution profile of the effective stress after the first load follow cycle. Since it is early in the operation of the nuclear fuel rods, the pellet-cladding mechanical interaction (PCMI) has not yet occurred because both the swelling of the pellet and the inward creep of the cladding are not sufficient. Therefore, stresses in multi-layered cladding are caused by internal and external pressure differences in the rods and bonded constraints between cladding and coating materials.

Subsequently, as the load follow cycle increases and PCMI occurs through sufficient swelling of the nuclear fuel and inward creep of the cladding, a stress gradient is created in the multilayered cladding by contact pressure. These PCMI calculations were used to determine the cladding failure by comparing the cladding failure stress and to evaluate the health of the nuclear fuel rods by calculating the fatigue failure factor.

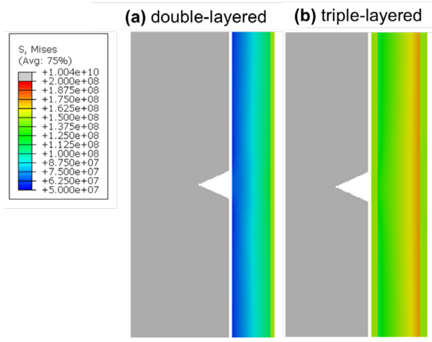

Fig. 4. Effective stress calculation results at the power level of 100% before the pellet-cladding contact

3. Conclusion

In this study, the PCI risk in load follow operation was carried out through the FEA-based multi-layered ATF analysis platform developed through previous studies. The mechanical behavior of the ATF cladding was evaluated under daily load follow conditions. In addition, this model may be used for design studies to optimize multi-layer cladding such as coating layer thickness.

ACKNOWLEDGMENT

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