FUEL PERFORMANCE ANALYSIS FOR ENHANCED CHARATERISTICS OF THE ACCIDENT TOLERANT FUEL UNDER LOSS-OF-COOLANT ACCIDENT CONDITIONS

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ABSTRACT

Research and development on accident tolerant fuel to enhance the safety of nuclear fuel under accident conditions have been conducted by many research groups. The Korea Atomic Energy Research Institute is also developing coating claddings for decreasing the oxidation and improving the mechanical behavior, as well as metal microcell UO2 pellets for increasing the thermal conductivity as a short-term applicable technology of accident tolerant fuel. Accident tolerant fuel should have similar or better performance under normal operation conditions and design basis accidents as well as in beyond design basis accidents compared to conventional nuclear fuel. In this analysis, the fuel performance of the accident tolerant fuel was evaluated using FRAPTRAN, which is a computer code for the transient analysis of fuel rods for a large break loss-of-coolant accident as a representative design basis accident.
For the fuel performance code, some material properties from an out-of-pile test were modified in the FRAPCON/FRAPTRAN code. The increased thermal conductivity of a metallic microcell pellet was modified as a function of temperature for the fresh fuel conditions. For the accident tolerant fuel cladding, the corrosion, oxidation, and hydrogen pick-up model was modified based on an out-of-pile test. The accident tolerant fuel performance results are compared to results of UO2 and Zircaloy reference fuel.

1 Introduction

After the Fukushima accident, research and development on accident tolerant fuel (ATF) to enhance the safety of nuclear fuel under the accident conditions have been conducted by many research groups. The major goals for the development of ATF are well suggested in the DOE-Program: Accident tolerant fuel should have a similar or better performance under normal operation conditions and during design basis accidents, as well as in beyond design basis accidents compared to a conventional nuclear fuel [1,2].

The Korea Atomic Energy Research Institute (KAERI) is also developing coated claddings for decreasing the oxidation and improving the mechanical behavior, and metal or ceramic microcell UO2 pellets for increasing the thermal conductivity or improving the capture-ability for highly radioactive and corrosive fission products [3, 4]. An analysis was conducted to assess the effects of replacing a conventional reactor fuel for neutronics and safety performance with the ATF concepts of KAERI [5]. In a large break loss-of-coolant accident (LBLOCA) analysis, the performance for the high-temperature oxidation resistance of the coated cladding did not sufficiently appear because the cladding surface was exposed at a high temperature for a short time. And due to the limitation of the fuel performance of the system code such as RELAP5, the ATF characteristics were evaluated only in terms of the cladding temperature.

In this paper, the fuel performance of KAERI's ATF candidates was evaluated using FRAPCON [6] for the normal operation conditions, and FRAPTRAN [7] for LBLOCA conditions, as a representative design basis accident. Some material properties from the out-of-pile test were modified in the FRAPCON/FRAPTRAN code for the ATF analysis. The main purpose of this study is to apply the major property changes of ATF to the fuel performance analysis code FRAPCON and FRAPTRAN and to preliminarily analyze the effects.

2 Characteristics and Modeling of ATF

KAERI has been developing Cr-alloy coated cladding and metal microcell UO2 pellets as one of the candidates for ATF. As the coating material, CrAl or FeCrAl was coated on the Zircaloy base cladding by Arc ion plating or a 3D laser coating technique. Various tests were conducted to evaluate the coated cladding performance such as the corrosion, oxidation, creep, wear, and so on [3]. As an ATF pellet, ceramic and metallic microcell UO2 pellets are being developed. The enhanced pellet thermal conductivity is the distinct feature of a metallic microcell UO2 pellet to effectively decrease the fuel temperature. The out-of-pile tests were performed to evaluate the thermo-physical properties, such as the thermal conductivity, the linear thermal expansion, steam oxidation, and so on [4]. Only the thermal conductivity of a 5 vol%-Mo added metallic microcell UO2 pellet is evaluated in this study.

In FRAPCON, the corrosion rate and hydrogen pick-up for the cladding and thermal conductivity of a pellet were modified based on out-of-pile test data, as shown in Figs. 1 and 2. The burn-up effect is assumed to be the same as the conventional Zircaloy and UO2. The high-temperature oxidation rate in the FRAPTRAN was reduced to 1/1000 of the Cathcart-Pawel model [8]. The input conditions such as the power history and the cladding temperature for the analysis were obtained from the results of a neutronics and system analysis based on [5].

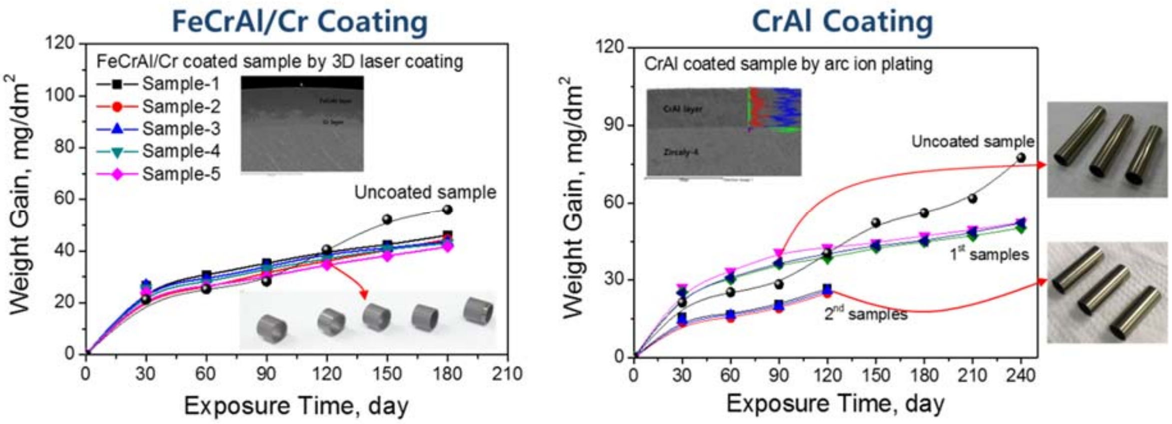

Fig. 1 Corrosion test results in PWR simulation loop of surface modified-Zr cladding developed at KAERI [3].

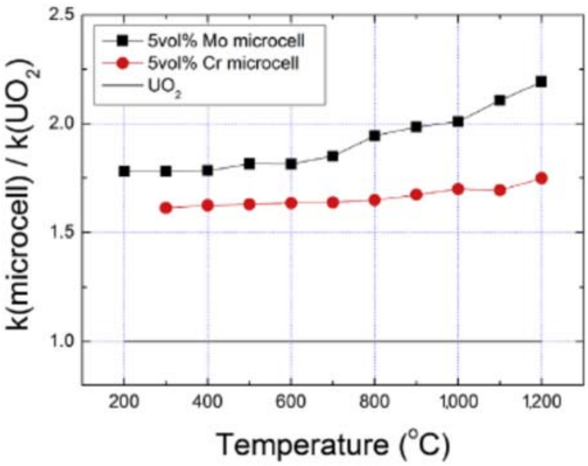

Fig. 2 thermal conductivity measurement results of metallic microcell UO2 pellets [4].

3 Results and Discussion

3.1 Normal operation condition

The performance of a preliminary ATF fuel was compared to a conventional UO2-Zircaloy fuel. The fuel rod used in the analysis was a fuel rod with the highest burn-up after the end of life of three cycles in the reactor core. The power history for the reference condition and ATF according to the EFPD (Effective Full Power Day) is shown in Fig. 3. The burn-up cycle length of ATF is reduced due to the decrease in UO2 volume weight of 5 vol% and the high cross section of the added molybdenum. The rod average power of the ATF is lower in the first cycle and higher in the third cycle as compared with the reference.

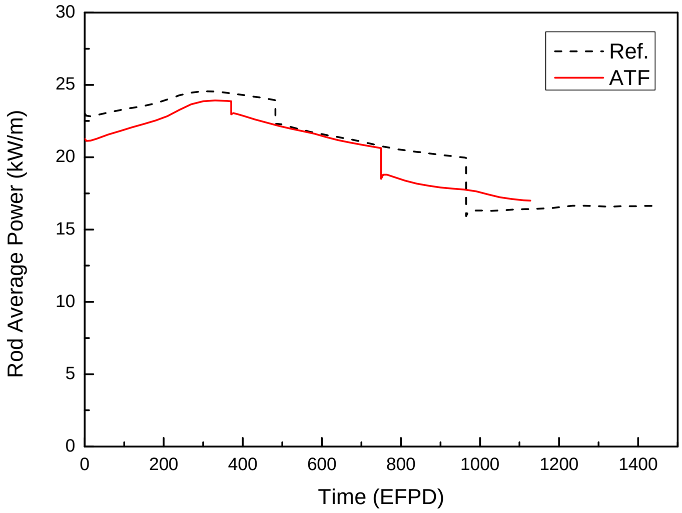

Fig. 3 Rod average power history of reference fuel and ATF.

The centerline temperature is compared in Fig. 4. This centerline temperature is that at axial node 4, which has the highest burn-up of all axial nodes. The centerline temperature of ATF is about 300 K lower than the reference temperature. This includes not only the increased thermal conductivity of the metallic microcell pellet but also the low rod average power described above. It also reflects the difference in gap between the pellet and cladding due to the thermal expansion of the pellet.

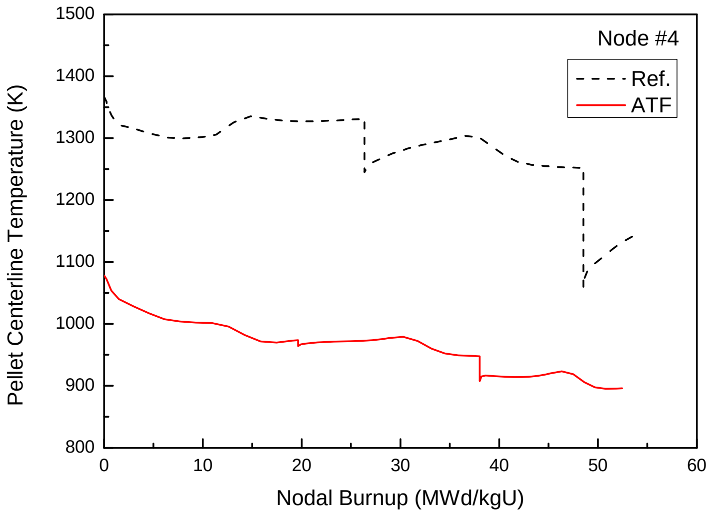

Fig. 4 Pellet centerline temperature at the node 4.

The behaviors of the rod internal pressure and the fission gas release are compared in Figs. 5 and 6, respectively. The rod internal pressure of ATF is lower than that of the reference fuel because of the low pellet temperature. The movement of the fission products in the pellets is also delayed owing to the low pellet temperature of the ATF, resulting in a significant reduction in FGR after 40 MWd/kgU.

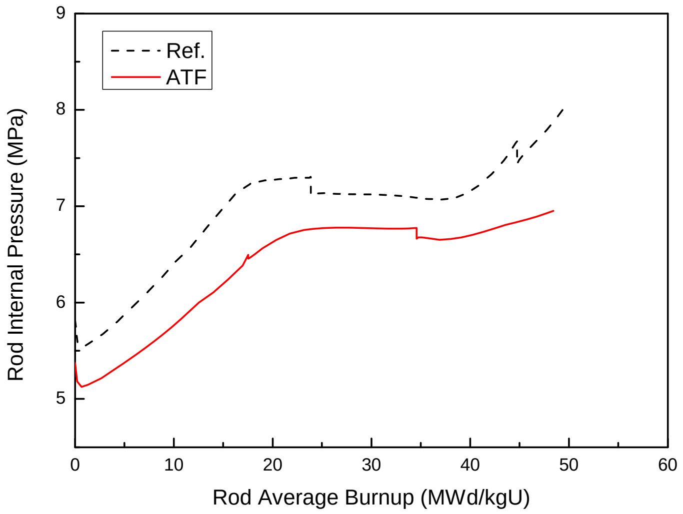

Fig. 5 Rod internal pressure of reference fuel and ATF.

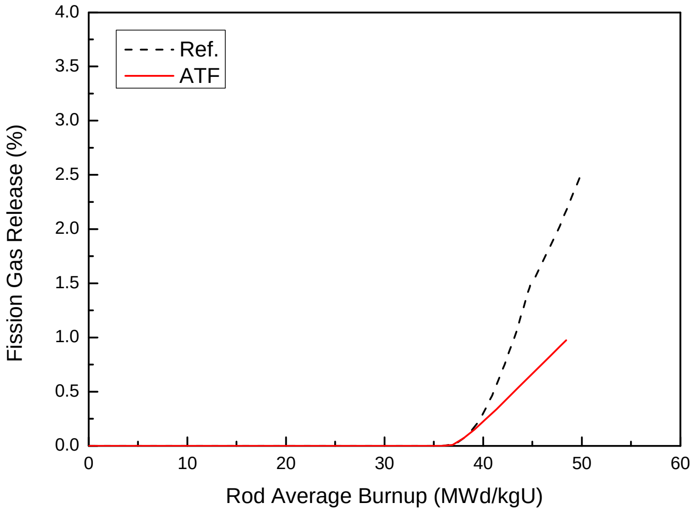

Fig. 6 Fission Gas Release (FGR) of reference fuel and ATF.

The cladding oxide thickness under normal operation conditions is shown in Fig. 7. Owing to the high oxidation resistance of the CrAl, which is the coating material of the ATF cladding, the oxide thickness shows a considerable difference. At a burnup of 45 MWd/kgU, the oxide thickness of ATF is about 4.2 microns, which is 10 times smaller than that of a typical Zircaloy cladding tube with an oxide thickness of about 60 microns.

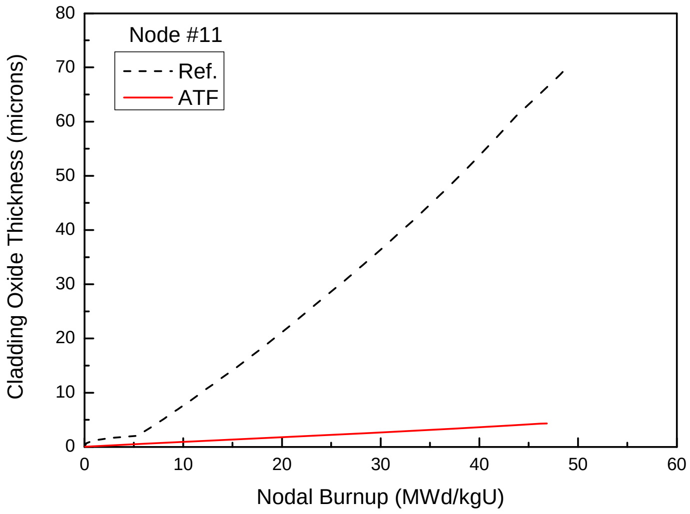

Fig. 7 Cladding oxide thickness of reference fuel and ATF.

The hoop stresses of the cladding are compared in Fig. 8. The hoop stress gradually increases with burnup, but increases rapidly when the contact occurs between the pellet and cladding inner surface. An initiation of the contact between the pellet and cladding occurred at a burnup of 20 MWd/kgU for the reference fuel and of 25 MWd/kgU for ATF. The thickness of the coated cladding for ATF is 50 μm thicker than that of the reference fuel due to the coated layer. The effect of the increased thickness was compared in Fig. 9. When the ATF has the same cladding thickness with the reference fuel, the behavior of the mechanical gap was similar to that of the thicker cladding. From this result, it is considered that the increased thickness effect of the ATF cladding is not large. It can be seen that the reduced fuel temperature according to the increased fuel thermal conductivity has a large influence on the change in the gap between fuel pellet and cladding. Consequently, the mechanical integrity of ATF is expected to be similar or superior to the reference fuel of Zircaloy and UO2.

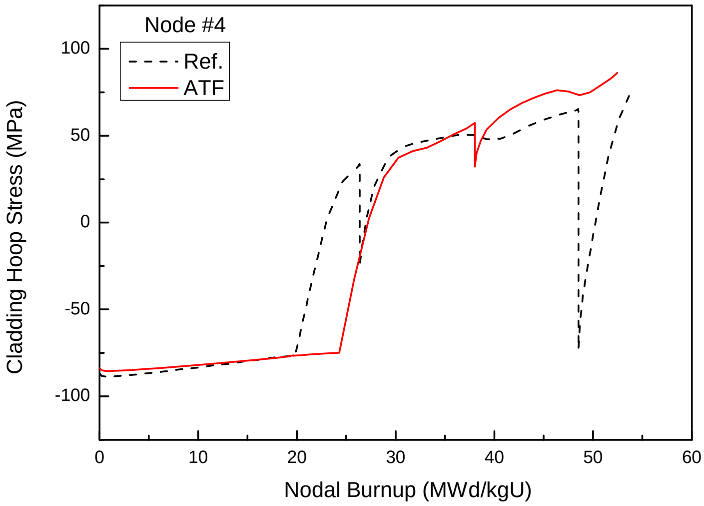

Fig. 8 Cladding hoop stress of reference fuel and ATF at node 4.

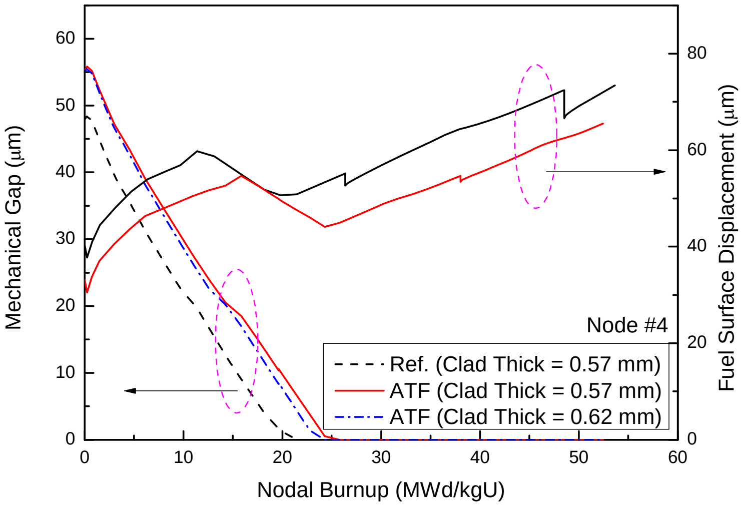

Fig. 9 Mechanical gap and fuel surface deformation at node 4.

3.2 LBLOCA condition

The temperature of the fuel cladding obtained from the system analysis with RELAP5 is shown in Fig. 10 at axial node 11 with the highest axial power. According to the scenario of LBLOCA applied to the present analysis, the cladding temperature reaches a maximum temperature of 1000 K or more in the blowdown phase, and as low as 700 K in the reflooding phase. Under the accident conditions, the time to remain above 1000 K where the high-temperature oxidation model is applied is very short, at about 3.5 s. Therefore, it is difficult to show the high-temperature oxidation resistance characteristics of ATF.

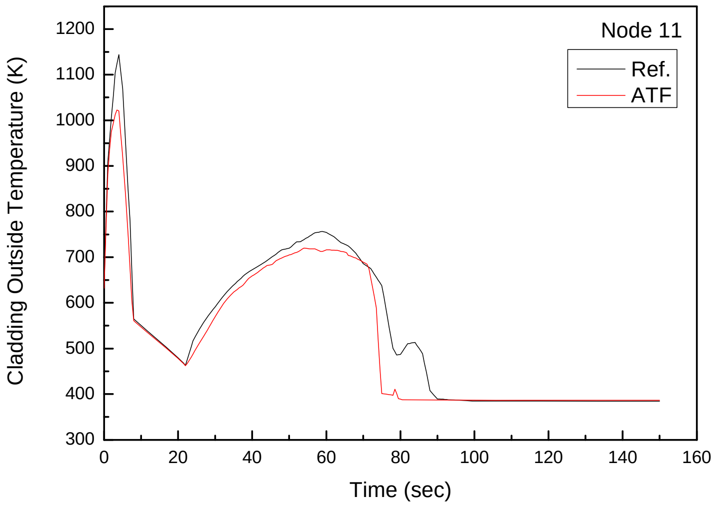

Fig. 10 Peak cladding temperature of LBLOCA condition from results of system analysis code, RELAP5 [5].

The rod internal pressure behavior and centerline temperature of the pellet at axial node 11 are compared in Figs. 11 and 12. Because the difference in the surface temperature of the cladding given as the boundary condition from the system analysis results was small, the difference in the rod internal pressure was not large. For the pellet centerline temperature, the difference in the initial pellet temperature obtained from the results of FRAPCON is large. Thus, at the beginning of the accident, there is a large temperature difference, but thereafter the difference is not large and the behavior was similar to the cladding temperature.

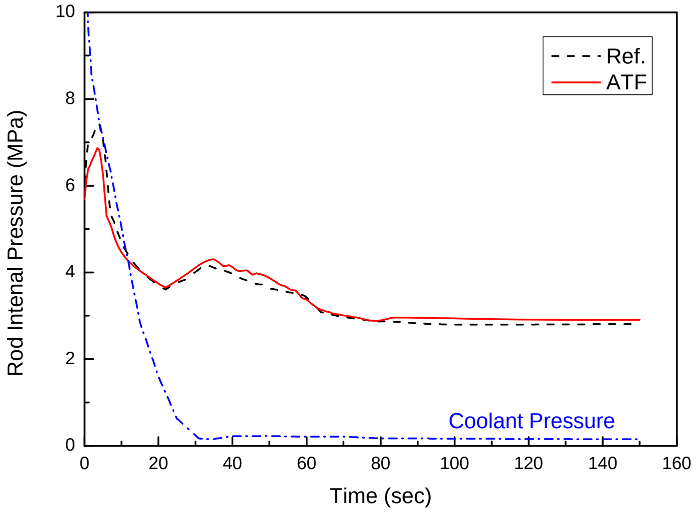

Fig. 11 Rod internal pressure and coolant pressure under LBLOCA conditions.

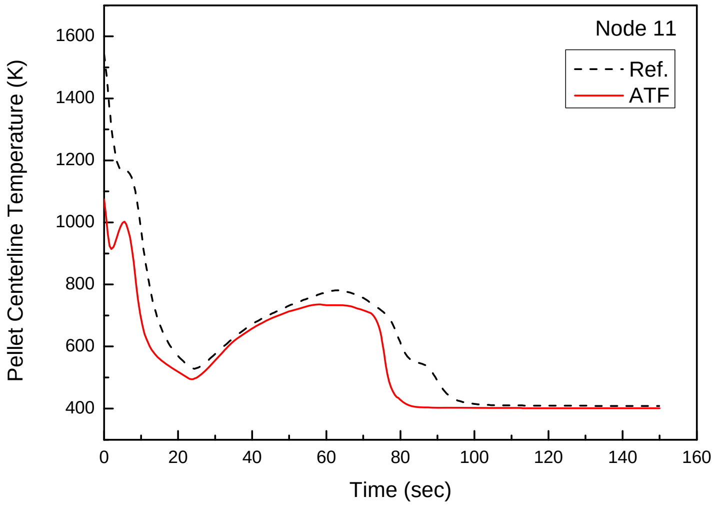

Fig. 12 Pellet centerline temperature under LBLOCA conditions.

4 Conclusion

This study summarizes the preliminary analysis results of the fuel performance code, FRAPCON and FRAPTRAN with several material properties of ATF developed by KAERI. The code was modified based on out-of-pile properties of ATF and the differences compared to a conventional UO2-Zircaloy fuel was assessed.

From the FRAPCON results of the normal operation condition, ATF shows a significant advantage in the reduction of the fuel centerline temperature, cladding oxidation thickness, fission gas release, and so on because of the increased thermal conductivity of the metallic microcell pellet and the oxidation resistance of the CrAl coated cladding.

In the LBLOCA analysis of FRAPTRAN, the advantages of ATF were not sufficiently expressed because the difference in the cladding surface temperature, which is the boundary conditions given by the system analysis, was small and the exposure time to high temperature was short. In the accident condition, the mechanical property is also important to estimate the cladding ballooning and burst behavior. However, because the experimental data for modeling the mechanical characteristics have not been enough, tests are underway to measure the thermo-mechanical property and behavior for ATF.

Furthermore, because the in-pile test data is insufficient, the burnup effect was not reflected in all models. It is necessary to secure the in-pile data, which requires additional updating of models. The sensitivity analysis will be carried out under various conditions in order to evaluate the influence of the change in ATF characteristic more precisely.

Acknowledgements

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5 References

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