# Fuel Performance Analysis of Advanced Ferritic Steel Cladding for Accident Tolerant Fuel

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## 1. Introduction

Since 2017, KEPCO NF has started to research and develop Advanced Ferritic Steel (AFS) [1], which is considered as a candidate alloy for accident tolerant fuel (ATF) cladding to replace the existing Zr-based alloy cladding. Main advantage of AFS cladding over conventional Zr-based alloy cladding is its superior high-temperature oxidation resistance in water and steam environment of accident condition [2]. Since stable $Cr_2O_3$ and $Al_2O_3$ scales are formed at metal surface, it is prevented that the direct reaction of Fe and steam for hydrogen gas production. So it can reduce the risk of hydrogen explosion like Fukushima reactors, and allows additional time to cope with severe accidents. However, AFS cladding causes a loss of reactivity due to its higher neutron absorption cross-section than Zr-based alloy cladding [3]. In order to reduce neutron penalties to a level similar to the current fuel cycle, design for AFS fuel rod such as cladding thickness, pellet diameter and U-235 enrichment has been modified in the previous study [4].

In this study, fuel rod performance was analyzed for the modified AFS fuel rod design and preliminary evaluation was conducted to determine optimal geometry for AFS cladding fuel rod based on the rod performance analysis results.

## 2. Methods and Results

### *2.1 AFS Fuel Rod Performance Analysis*

AFS Fuel rod performance analysis were conducted using modified version of ROPER code, the fuel rod performance analysis code developed by KNF. The AFS alloy material properties and performance models implemented in modified version of code are based upon experimental data and the existing FeCrAl alloy data [5]. Table I shows the geometry of AFS cladding fuel rod modified in the previous study and Zr alloy fuel rod geometry (reference rod).

Table I. Fuel rod geometry

(unit: mm)

| *Cladding* | *Fuel Diameter* | *Gap Size* | *Clad Thickness* | *Clad Outer Diameter* |
|---|---|---|---|---|
| Zr-alloy (ref.) | 8.192 | 0.0826 | 0.57 | 9.5 |
| AFS | 8.633 | 0.0826 | 0.35 | 9.5 |

The cladding thickness was reduced from 0.57 mm to 0.35 mm, and the pellet outer diameter was increased from 8.192 mm to 8.632 mm to maintain the same gap size between pellet and cladding. Reduced cladding thickness and increased fuel mass can compensate the neutronics. However, fuel pellet were unchanged and U-235 enrichment was maintained at 4.65 wt.% due to fuel enrichment limit, .

A hypothetical fuel rod with bounding power history covering all fuel rods in the core was analyzed according to the fuel rod design procedure. The design target referred to APR1400 type reactor and PLUS7 fuel assembly. Core neutronics with AFS cladding fuel rods was calculated using ASTRA, the core analysis code developed by KNF, and the cycle length and power histories were changed due to the modified fuel rod specifications. The bounding power histories for the reference rod (PH1) and AFS cladding fuel rod (PH2) used in the calculation are shown in Figure 1. The rod average burnup of the AFS cladding fuel rod at the end-of-life is as short as about 48 GWD/MTU due to the high neutron absorption cross-section, despite an increased pellet outer diameter. Up to about 20 GWD/MTU, linear heat generation rate of AFS cladding fuel rod is higher than the reference rod, and remains low thereafter.

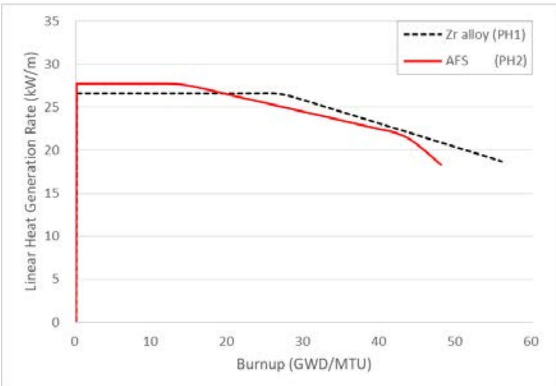


Fig. 1. Bounding power histories for Zr-based alloy cladding and AFS cladding fuel rods.

### *2.2 Rod Performance Analysis Results*

In order to investigate the impact of AFS claddings on fuel rod performance, fuel centerline temperature evolution over the local burnup of the hottest axial node was analyzed. And the thermal gap size between pellet and cladding was analyzed to understand the thermal behavior of the fuel rods. Increasing the gap size reduces the gap conductance between pellet and cladding, which leads to an increase in pellet temperature. It is difficult to directly compare the performance of two claddings using different power histories, but the general behavior anticipated in a core can be predicted. Further calculation for AFS cladding fuel rod assuming the same cycle length and bounding power with reference rod (AFS with PH1) was carried out additionally to compare two cladding materials under the same conditions.

Fuel centerline temperature of reference rod decreases rapidly (~100 ℃) as the thermal gap closes in the early stage of operation, as shown in Figure 2. After the thermal gap closure, temperature gradually increases due to the effect of pellet thermal conductivity degradation (TCD), and then finally decreases again as the power decreases. AFS with PH1 also has a similar behavior, except that the gap closes slowly compared to reference rod as shown in Figure 3. Because of the higher creep resistance of AFS cladding, there is less deformation due to the coolant pressure, which leads to a later gap closure despite the higher amount of pellet thermal expansion. Due to late thermal gap closure, fuel centerline temperature is higher (~130 ℃) than reference rod in low-burnup region (~20 GWD/MTU). This indicates that the stored energy of fuel is high, which means that there may be a shortage of thermal margin under accident conditions. Compared to this, AFS with PH2 shows even higher temperature in low-burnup region and lower in later, which is consistent with the difference shown in bounding power.

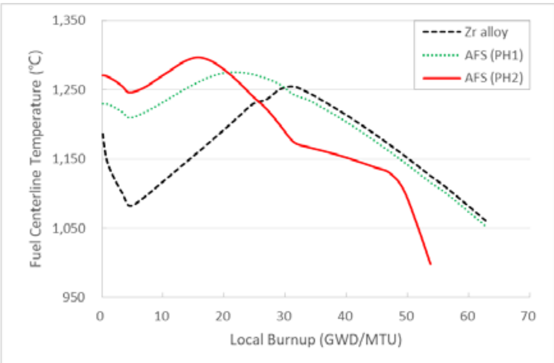


Fig. 2. AFS fuel centerline temperature vs. local burnup

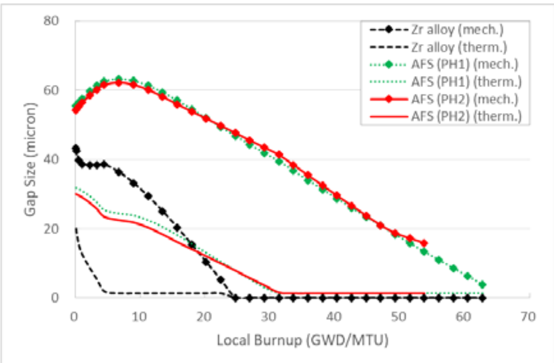


Fig. 3. AFS fuel mechanical and thermal gap between pellet and cladding vs. local burnup

Figure 4 displays the cladding mid-wall hoop stress. The hoop stress of reference fuel cladding is changed from compressive to tensile near 25 GWD/MTU, at which point the mechanical gap is completely closed, as shown in Figure 3. On the other hand, the hoop stress of AFS claddings are remained compressive because the mechanical gap is not closed until the end-of-life, regardless of the power history.

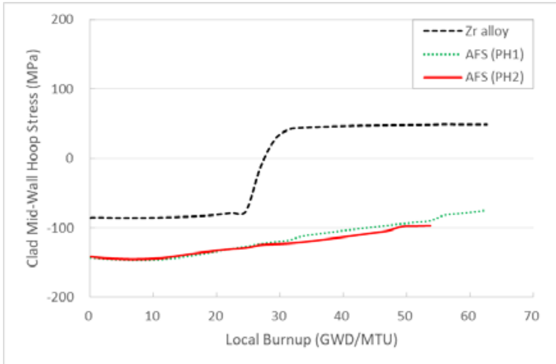


Fig. 4. AFS cladding mid-wall hoop stress vs. local burnup

### *2.3 Fuel Rod Geometry Optimization*

As a result of the fuel rod performance analysis, there is a problem that the centerline temperature of AFS fuel rod is higher (~130 ℃) than reference rod in the low-burnup region (~20 GWD/MTU). This occurs because the gap size of AFS fuel rod decreases slowly compared to reference rod, so that heat transfer between pellet and cladding is poor in low-burnup region. In the previous calculations, initial gap size of AFS fuel rod was same with reference rod, so we can consider reducing initial gap size of AFS fuel rod to lower the fuel temperature in the low-burnup region. Reducing the initial gap size while maintaining the fuel rod outer diameter makes the pellet outer diameter slightly larger. Two additional cases–AFS case1 and AFS case2–were calculated for initial gap size optimization, and the fuel rod geometries in each case are shown in Table II.

Table II. Fuel rod geometry for gap size optimization
(unit: mm)

| *Case* | *Fuel Diameter* | *Gap Size* | *Clad Thickness* | *Clad Outer Diameter* |
|---|---|---|---|---|
| Zr-based alloy | 8.192 | 0.0826 (3.25 mil) | 0.57 | 9.5 |
| AFS base case | 8.633 | 0.0826 (3.25 mil) | 0.35 | 9.5 |
| AFS case1 | 8.646 | 0.0762 (3.00 mil) | 0.35 | 9.5 |
| AFS case2 | 8.659 | 0.0699 (2.75 mil) | 0.35 | 9.5 |

Neutronic analysis for each case showed no significant changes in bounding power, because the volume change of pellet according to the gap size is negligible and other conditions like fuel loading pattern and U-235 enrichment remain unchanged.

Figure 5 displays the fuel centerline temperature calculation results for each case. It can be seen that as the initial gap size is reduced, fuel centerline temperature in the low-burnup region decreases. A reduction in initial gap size of 0.0063 mm (0.25 mil) results in a a maximum temperature drop of about 30 ℃, and a maximum fuel centerline temperature similar to Zr-based alloy fuel rod was calculated in AFS case1.

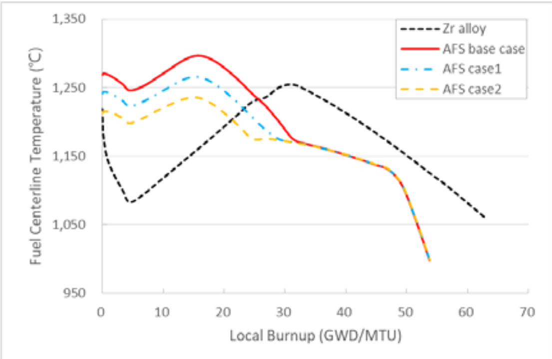


Fig. 5. Fuel centerline temperature calculation result for AFS gap size optimization

Mechanical and thermal gap between pellet and cladding for each cases are shown in Figure 6. Even in AFS case2, where the initial gap size is the smallest, it appears that no mechanical gap closure has occurred until the end-of-life. However, a mechanical gap closure is expected assuming high-burnup above 62 GWD/MTU. When the mechanical gap is closed, the cladding hoop stress is changed from compressive stress to tensile stress.

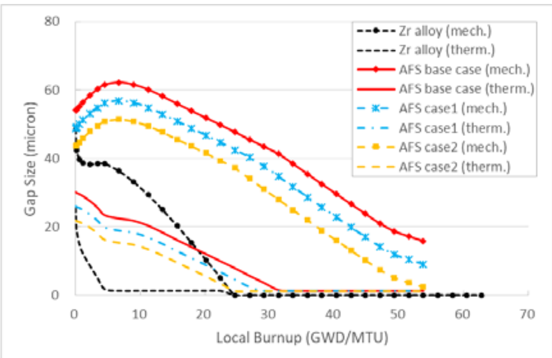


Fig. 6. Mechanical and thermal gap between pellet and cladding calculation result for AFS gap size optimization

Cladding mid-wall hoop stress was calculated for AFS case1 and 2 under the same cycle length and bounding power as reference rods, and the calculation results are shown in Figure 7. It can be seen that the cladding mid-wall hoop stress increases sharply from the time when the mechanical gap is closed. The hoop stress increases up to 150 MPa with the smallest initial gap size, and further increases may occur if operation continues.

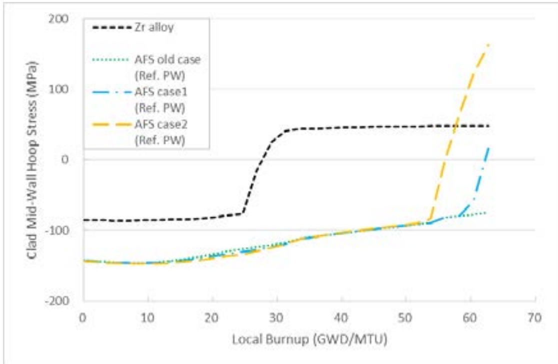


Fig. 7. Cladding mid-wall hoop stress for AFS with reference rod power history

## 3. Conclusions

The thickness of AFS cladding can be reduced due to its higher neutron absorption cross-section and higher strength than conventional Zr-based alloy cladding. Reducing the cladding thickness while maintaining the outer diameter of the fuel rod increases the outer diameter of pellet, resulting in changes in the core neutronics. Performance analysis for the in-core behavior of AFS cladding fuel rods according to the modified neutronics showed that the fuel centerline temperature is higher than that of conventional fuel rods in low-burnup region, and the gap between pellet and cladding is closed slowly.

Additionally, since the mechanical gap is not closed until the end-of-life, optimization for fuel rod geometry were performed to confirm that the initial gap size could be reduced to lower the fuel centerline temperature in the low-burnup region. The results showed that reducing the initial gap size from 0.0826 mm to 0.0762 mm lowered the fuel centerline temperature in the low-burnup region to a level comparable to the maximum centerline temperature of conventional fuel rods, and no mechanical gap closure occurred by the end-of-life. If the initial gap size is reduced to 0.0699 mm, a tensile hoop stress can increase to about 150 MPa by the contact between pellet and cladding. In conclusion, it is advantageous to reduce the gap size in terms of fuel temperature, but excessive reduction can cause larger tensile hoop stress in the cladding at the end-of-life.

However, this calculation results are preliminary evaluation without considering increase of U-235 enrichment, so the cycle length is shorter than that of the conventional fuel rods despite the increase of pellet diameter. In the future, further analysis will be carried out in consideration of U-235 enrichment, the loading pattern of the core and the burnable poison rods.

## 4. Acknowledgements

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