# Out-of-pile Characteristics of Advanced Fuel Cladding (HANA alloys)

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## 1. Introduction

Zircaloys have been used as cladding materials for LWR fuel because of their excellent properties in the viewpoints of neutronics, corrosion and creep during the operation period in nuclear power plant. Recently, however, many LWR plants have been steadily increasing fuel discharging burn-up and power level. The improved zirconium-based alloys should be a prerequisite to meet the requirements of high burn-up fuel. The research and developments of the advanced fuel for high burn-up was started in 1997 by Korea Atomic Energy Research Institute (KAERI) in collaboration with Korea Nuclear Fuel Company (KNFC) and several universities in order to meet the global demand on the extension of the fuel discharge burn-up.

## 2. Parameter study

A number of parameter studies have been performed to develop the advanced zirconium alloys for high burn-up fuel claddings [1-3]. The Nb-containing Zr alloys were characterized to determine the optimum composition and heat-treatment conditions to develop new zirconium alloys. The effects of alloying elements and heat treatment on the corrosion of the alloys were systematically investigated by changing the alloying elements such as Nb, Sn, Fe, Cr, Cu, Mn, V, Sb, Ag, Te, Ta, Ge and Au. The corrosion resistance of Nb-containing Zr alloys was very sensitive to the Nb contents and heat treatment conditions. The Cu addition into Nb-containing Zr was found to be more effective than the other alloying elements in the improvement of corrosion resistance. The creep properties were also evaluated by changing the Nb and Sn contents in the Nb-containing Zr alloys. To evaluate the phase stability in Zr-rich region of Zr-Nb binary alloy system, microstructure characterization was carried out using OM, SEM and TEM for the specimens containing the variety of Nb contents with different annealing condition, and the phase transformation behavior was also examined using DSC.

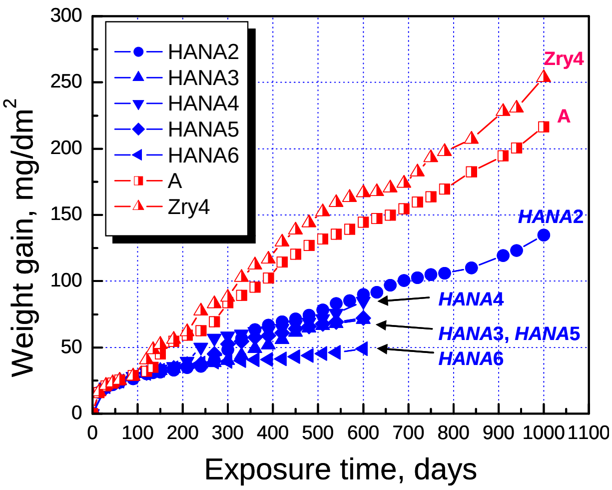
Based on the results of the parameter studies, KAERI developed HANA claddings, the advanced zirconium fuel claddings for high burn-up fuel. Six kinds of HANA claddings were manufactured by KAERI with international collaborations. Each cladding was subjected to the 24 different annealing conditions to optimize the heat treatment for the balanced properties. The out of-pile properties of HANA claddings were evaluated for the manufactured HANA claddings.

## 3. Out-of-pile performance of HANA cladding

*1. Corrosion*

The corrosion behavior of HANA claddings was investigated in 360°C water, 400°C steam and 360°C PWR-simulating loop system containing 2.2 ppm Li and 650 ppm B in a manner consistent with the ASTM G2-88. HANA claddings showed a better corrosion resistance than Zircaloy-4 and A-claddings in all the three corrosion conditions. HANA claddings maintained a lower corrosion rate up to 1000 days while corrosion rates of Zircaloy-4 and A-claddings were changed periodically. The weight gains of HANA3 and HANA6 were about 40% and 30% as compared to Zircaloy-4 at 600 days in 360°C PWR-simulating loop condition as shown in Figure 1.

Figure 1. Corrosion behavior of HANA claddings in PWR-




simulating loop containing 2.2 ppm Li and 650ppm B.

*2. Microstructure*

Microstructure characterization with an emphasis on the SPP characteristics was performed for HANA3 and HANA6. The beta-Nb with bcc structure and $Zr(Nb,Fe)_2$ with hcp structure were observed in HANA3 while beta-Nb with bcc structure and $(Zr,Nb)_2Fe$ with fcc structure in HANA6. The beta-Nb was found to be dominant in both alloys. However, the micro-chemical analysis revealed that the beta phase was more stable in HANA6 as compared to HANA3. It was found that the size distribution of precipitates in HANA alloys claddings was finer as compared to Zricaoly-4, which was considered to be the main reason for a better corrosion resistance of HANA claddings.

*3. Creep*

Thermal creep behavior of HANA claddings was also investigated. Each cladding showed a steady state secondary creep behavior with a similar creep resistance as Zircaloy-4. From the results of thermal creep, the optimization of final heat treatment temperature as well as alloying elements caused a great influence on the improvement of creep resistance.

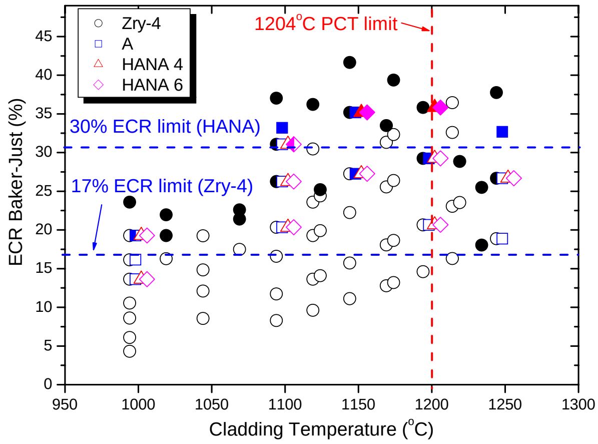
*4. Tensile strength*

Tensile tests for HANA cladding tubes and Zircaloy-4 cladding tubes were carried out according to ASTM B811-97 at room temperature and 400℃. The yield strength and the elongation of HANA cladding tubes were about 12% and 10% higher at room temperature and about 8% and 17% higher at 400℃ than those of Zircaloy-4 cladding tube, respectively. But the ultimate tensile strength of HANA cladding tubes was almost equivalent to that of Zircaloy-4 cladding tube.

*5. LOCA properties*

Maintaining fuel integrity in a postulated design-based accident like LOCA is of importance in designing advanced cladding. LOCA study was focused on investigating the behavior of HANA claddings in LOCA conditions. HANA cladding was oxidized in a flowing steam at a desired temperature and time followed by water quenching to simulate LOCA and subsequent ECCS process. It was shown that threshold ECR value of HANA cladding increased compared to Zircaloy-4. Figure 2 shows the failure map of HANA claddings under simulated LOCA conditions in which thermal shock followed by high temperature oxidation is conducted. Commercial low tin Zircaloy-4 failed during water quenching when the fraction of oxide thickness exceeds 17% level. Nb-contained HANA claddings showed soundness at 17% oxidation in which Zircaloy-4 failed. Threshold oxidation of HANA cladding reached nearly 30% level, indicates that excellent safety margin can be obtained.

Figure 2. Failure map of HANA claddings under simulated LOCA conditions. Open symbol denotes cladding survived




during water quenching. Closed one failed.

*6. Fretting wear*

Sliding wear tests have been performed in room temperature air and water in order to evaluate the wear resistance of HANA claddings. It was found that HANA claddings have a similar wear resistance to Zircaloy-4 cladding.

## 3. Summary

The performance of HANA claddings was evaluated in out-of-pile conditions. All the performance test results revealed that HANA claddings were superior to the reference claddings such as Zircaloy-4 and A-cladding. Corrosion resistance was improved by 60 to 70% compared to the commercial claddings. Creep, burst, tensile, LOCA, wear and microstructural properties were shown to be as good as the commercial claddings.

## Acknowledgements

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